20-sim 5.1 Reference Manual

© 2023, Controllab Products B.V.
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Reference

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# Table of Contents

1. **Welcome to 20-sim**
2. **What is new in 20-sim?**
3. **Requirements**
4. **Privacy Statement**
5. **Installation**
   - 5.1 Versions
   - 5.2 Requirements
   - 5.3 Installing 20-sim
   - 5.4 Uninstalling
   - 5.5 Deactivation
   - 5.6 Unattended Installation
   - 5.7 Unattended Uninstall
   - 5.8 Matlab
6. **Quick Tour**
   - 6.1 Running a Simulation
   - 6.2 Variables, Parameters, Initial Values and Constants
   - 6.3 Hierarchy
   - 6.4 Language
7. **Editor**
   - 7.1 Introduction
   - 7.2 Using Models
   - 7.3 Compiling
   - 7.4 Icon Editor
   - 7.5 Global Parameters and Variables
   - 7.6 Interface Editor
   - 7.7 Domains, Quantities and Units
   - 7.8 FMI Support
## 8 Simulator

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Introduction</td>
<td>96</td>
</tr>
<tr>
<td>8.2 Running a Simulation</td>
<td>98</td>
</tr>
<tr>
<td>8.3 Run Properties</td>
<td>126</td>
</tr>
</tbody>
</table>

## 9 Language Reference

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 Introduction</td>
<td>136</td>
</tr>
<tr>
<td>9.2 Keywords</td>
<td>146</td>
</tr>
<tr>
<td>9.3 Types</td>
<td>157</td>
</tr>
<tr>
<td>9.4 Functions</td>
<td>162</td>
</tr>
<tr>
<td>9.5 Operators</td>
<td>234</td>
</tr>
<tr>
<td>9.6 Statements</td>
<td>258</td>
</tr>
<tr>
<td>9.7 Matrices and Vectors</td>
<td>274</td>
</tr>
<tr>
<td>9.8 Advanced Topics</td>
<td>278</td>
</tr>
</tbody>
</table>

## 10 Toolboxes

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1 Toolboxes</td>
<td>285</td>
</tr>
<tr>
<td>10.2 3D Mechanics Toolbox</td>
<td>286</td>
</tr>
<tr>
<td>10.3 Animation Toolbox</td>
<td>324</td>
</tr>
<tr>
<td>10.4 Control Toolbox</td>
<td>360</td>
</tr>
<tr>
<td>10.5 Frequency Domain Toolbox</td>
<td>404</td>
</tr>
<tr>
<td>10.6 Scenario Manager</td>
<td>436</td>
</tr>
<tr>
<td>10.7 Mechatronics Toolbox</td>
<td>452</td>
</tr>
<tr>
<td>10.8 Real-Time Toolbox</td>
<td>520</td>
</tr>
<tr>
<td>10.9 Time Domain Toolbox</td>
<td>531</td>
</tr>
<tr>
<td>10.10 Scripting Toolbox</td>
<td>573</td>
</tr>
<tr>
<td>10.11 Unity Toolbox</td>
<td>591</td>
</tr>
</tbody>
</table>

## 11 Library

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1 Bond Graph</td>
<td>610</td>
</tr>
<tr>
<td>11.2 Iconic Diagrams</td>
<td>661</td>
</tr>
<tr>
<td>11.3 Signal</td>
<td>1006</td>
</tr>
</tbody>
</table>

## 12 Modeling Tutorial

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1239</td>
</tr>
</tbody>
</table>
12.1 Friction 1239
12.2 Bond Graphs 1249
12.3 Iconic Diagrams 1280

Index 1295
1 Welcome to 20-sim

This manual describes 20-sim 5.1 in full detail. It is intended as a detailed reference to the software. If you are a first time user you are advised to read the Getting Started manual first. If you are an experienced 20-sim user, you can read the change notes first and then search the topic of your interest.
2. What is new in 20-sim?

20-sim 5.1 has been updated with many small improvements and three large additions:

1. the extension of the 3D Mechanics Editor to allow parametric design;
2. a new tool called the Scenario Manager to define and run simulations automatically;
3. a new and faster simulation engine that generates its the simulation instructions based on the supported CPU instruction set (e.g. prefer AVX2 instructions when supported).

**General**

1. You can now store models as a processed model file. This means you don't have to process / compile these files before starting the simulator.
2. Loading and Processing large models has been speeded up.

**Editor**

1. A selected submodel is now better visible with a bold orange outline and better visible (centered) in the Editor when you click Go Up.
2. Navigate through the model hierarchy with ENTER and Backspace for submodel down and up.
3. Use the Home, End, PgUp, and PgDown keys for scrolling large models easily.

**Simulator**

1. You choose a Speed Factor for realtime simulation.
2. Plots can be disabled to save memory.

**Python Scripting**

1. New functions for loading and saving a processed model file.
2. New functions for loading and saving a simulation state.
3. The mouse coordinates are visible in the footer. This is useful when placing submodels in the Editor using scripting.

**Octave Scripting**

1. Support for Octave 8.1.0/8.2.0/8.3.0

**C-Code Generation**

1. You can now make code templates that support not just one data type (real) but four (boolean, integer, real, string). A template has been added for the Arduino that supports this. Also 20-sim 4C 3.0 will support this for the Bachmann template. As a result, the generated C-code of your model is more efficient, both in performance and in resource usage.
2. What is new in 20-sim?

**Bug-fixes and Improvements**

In addition to the above mentioned items, 20-sim 5.1 received more than 180 bug-fixes and minor improvements since 20-sim 5.0. See the 20-sim website for the full list of changes.
3 Requirements

20-sim is supported on on computers that meet the following requirements:

- Operating System: Windows 7, 8, 8.1 and 10 (32-bit or 64-bit).
- Processor requirements: 20-sim requires a CPU with SSE2 support. Supported: Intel Pentium 4 and above, AMD Athlon x64 and above.
- Memory: >= 3 GB
- Available Disk Space: 690 MB.
4 Privacy Statement

Controllab Products B.V. takes your privacy seriously. This privacy statement explains what personal data 20-sim collects from you and how we use it.

How do we collect data from you?
Controllab Products B.V. processes your personal data when you activate/deactivate 20-sim using a license key. Controllab Products B.V. uploads your 20-sim license to an on-line activation server (registerserver.net). This activation server stores information about the number of license activations and on which computers 20-sim is activated.

What type of information is collected from you?
20-sim collects the following details from your computer to check / activate and deactivate your 20-sim license:

Computer details
- Host Name
- IP-address
- Unique computer finger print calculated from serial numbers of several computer hardware components
- 20-sim Version Number
- Date & time of the activation/deactivation

Controllab Products B.V. uploads your 20-sim license to an on-line activation server. Your 20-sim license embeds the following personal data:

Company / Personal details
- Company Name (or First Name and Last Name for personal licenses)
- Department Name
- License Key

How is your information used?
The activation data is used to activate your 20-sim license key and to lock it to your computer. This data is processed in an automatic process running on our activation server to check and activate your 20-sim license. Controllab Products does not use your data for other purposes than license activation.

Controllab Products B.V. employees can access this data to provide support for license activation issues and transferring your license to a different computer.

Can this information be removed?
On your request (please contact us by e-mail or phone) we can remove all of your personal data from our servers. Note that without this data, there is no license key backup on our activation server anymore. This means that on-line activation is not possible anymore.
Questions?
If you have questions concerning this privacy statement, contact Controllab Products B.V.
5 Installation

5.1 Versions

20-sim is available in two versions: Viewer and Professional.

- **Viewer/Demonstration version**: This is a freeware version that allows you to load and run models and evaluate the package. Saving of models is not possible in this version.

- **Personal**: This version is for use at home, for students and personal education. Not for commercial, government, academic or other organizational use. This version is limited to models with maximum of 500 equations and a maximum of 3000 variables.

- **Professional**: This is the full version of 20-sim with standard toolboxes.

Next to the standard toolboxes that come built-in with 20-sim, additional toolboxes can be purchased. The table below shows in detail the options that are available:

<table>
<thead>
<tr>
<th>20-sim with standard toolboxes</th>
<th>Viewer</th>
<th>Personal</th>
<th>Professional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Library Models</td>
<td>v*</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Number of Variables</td>
<td>unlimited</td>
<td>&lt; 3000</td>
<td>unlimited</td>
</tr>
<tr>
<td>Number of Equations</td>
<td>unlimited</td>
<td>&lt; 500</td>
<td>unlimited</td>
</tr>
<tr>
<td>3D Mechanics Toolbox</td>
<td>v*</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Animation Toolbox</td>
<td>v*</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Control Toolbox</td>
<td>v*</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Frequency Domain Toolbox</td>
<td>v*</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Scenario Manager</td>
<td>x</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Mechatronics Toolbox</td>
<td>v*</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Real Time Toolbox</td>
<td>v*</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Time Domain Toolbox</td>
<td>v*</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Scripting Toolbox</td>
<td>x</td>
<td>v</td>
<td>v</td>
</tr>
</tbody>
</table>

**Additional toolboxes**

- 20-sim Unity Toolbox: x, x, p

v = included
p = has to be purchased separately
5. Installation

\*v* = included but no saving possible  
\*x = not available

20-sim is installed, using an Installation Manager that will lock 20-sim to your computer. There are three types of licenses available:

- **Free**: The demonstration version comes with a license that is not locked to your computer. No actions have to be taken after installation of the program.
- **Single License**: A single license locks 20-sim to a specific computer. After installation you have to register to get a valid license.
- **Floating License**: A floating license allows multiple users to work with 20-sim at the same time. After installation you have to register to get a valid license.

5.2 Requirements

20-sim is guaranteed to work on computers that will meet the following requirements:

- **Operating System**: Windows 10, Windows 11
- **Processor requirements**:
  - 20-sim requires a CPU with SSE2 support.
  - **Supported Intel CPUs**:
    - Pentium 4,D,M (since 2001)
    - Core 2 Duo/Quad/Extreme (since 2006)
    - Core i3/i5/i7/i9 (1st generation 2008 and newer; tested up-to 13th generation)
    - Xeon
  - **Supported AMD CPUs**:
    - Athlon x64 (K8, 2003-2014),
    - Athlon Phenom (K10, 2017-2023),
    - Zen core (2017-present): Ryzen 1st gen and newer.
- **Available Disk Space**: 690 MB.

5.3 Installing 20-sim

20-sim can be downloaded from the website www.20sim.com. This is an installation file that will install 20-sim on your computer. The first 4 steps are equal for all users. Depending on the type of license (single, floating) you have to follow different steps to activate 20-sim.
1. **Download** and **Install** 20-sim on your computer.

2. During Installation you will be asked to install the (optional) **Python 3.7 package**. We advise to keep the default setting: **Yes**.

3. **Start** 20-sim (from the **Windows Start Menu** choose **20-sim 5.1**). If a valid license of 20-sim 5.1 was activated before, the program will start automatically. If you have not installed 20-sim before, the **License Activation** dialog will open:

![20-sim License Activation Dialog](image)

4. If you have a valid license key or license file, press the **Activation** button to enter your license key or browse for the license file.

If you do not yet have a valid license, press the **Trial License** button request an trial license or press the **Buy** button to purchase a license. If you want to continue in **Viewer** mode (no save functionality), just close the dialog without activating 20-sim.

5. Select **which kind of license** you have and **who** should use the license.
Single License
If you are using a single license, you have to enter a license key or license file.

6. On the next dialog, select **I received a license key by e-mail** and enter the **key** in the next dialog. When you received a **license file**, you have to enter the **location** of the license file.

You will be asked for confirmation (click **Activate Now**) and activation will be carried out. After a successful activation process the License Information dialog will show the new license.
5. Installation

Floating License

Installing a floating license (Administrator)
If you are using a license that is shared by more users (floating license, also known as concurrent license or server license), you have enter the received license key and a location on the server (a normal Windows shared folder) first. This location on the server should be accessible to all users and have read/write permission. The floating license will be stored at the selected location.

6. On the next dialog, select First Installation and then enter the license key and the location on the server (Windows share).

On the location that you have given, a license file 20sim.lic will be installed. Remember the location of this file because every new user of 20-sim will need to enter it. You will be asked for confirmation (click Activate Now) and activation will be carried out. After a successful activation process the License Information dialog will show the new license.

Using a floating license (Other users, Administrator)
If you are using a floating license that was already installed you have to enter the location of the license file.

7. On the next dialog, select Administrator already installed server license and then enter the license location (the location of the file 20sim.lic).

After a successful entry of the location of the license location, the License Information dialog will show the new license.

5.4 Uninstalling
You can uninstall 20-sim by clicking the Uninstall command from the 20-sim start menu.

Warning: Uninstallation of 20-sim will not deactivate your license. If you want to move 20-sim to another computer, you have to deactivate your license first before uninstalling.

5.5 Deactivation
If you want to move 20-sim to another computer, you have to deactivate your license before uninstalling the program. On the new computer you can then install the program and activate the license. To deactivate your license:

1. From the Windows Start menu open 20-sim.
2. From the Help menu choose License Activation.
3. Press the Activation button.
5. Installation

You will be asked for confirmation and deactivation will start. After a successful deactivation, your version of 20-sim has turned into the demonstration version. You can now uninstall the software and reinstall it.

5.6 Unattended Installation

An unattended installation is an installation that is performed without user interaction during its progress or with no user present at all.

To perform an unattended installation the default 'program files' installation directory run the following command on the 20-sim installer:

```
20sim.exe /S
```

It is possible to set an alternative installation directory by specifying the /D argument. It must be the last parameter used in the command line and must not contain any quotes, even if the path contains spaces. Only absolute paths are supported.

```
20sim.exe /S /D=D:\My Installation Files\20-sim 5.1
```

5.7 Unattended Uninstall

An unattended uninstall is an uninstall that is performed without user interaction during its progress or with no user present at all.

To perform an unattended uninstall from the default 'program files' installation directory run the following command on the 20-sim uninstaller:

```
C:\Program Files (x86)\20-sim 5.1\Uninstall.exe /S
```

5.8 Matlab

In 20-sim you can exchange data with Matlab / Simulink in various ways:
- Export models as m-files
- Export models as dll-files
- Export a variable to Matlab
- Export a parameter to Matlab
- Pass a variable value to Matlab every simulation step
- Load a variable value from Matlab every simulation step
- Pass a command line string to Matlab every simulation step
- Export linear systems to Matlab
- Import Linear Systems from Matlab

Troubleshooting

If this fails check if the following three points have been fulfilled.
1. **Have the correct version of 20-sim and Matlab**

To make a connection with Matlab, make sure you have 20-sim 4.1.3.8 or higher installed and a recent version of Matlab (2007 or above). 64-bit versions of Matlab are supported starting with 20-sim 4.6.

2. **Check if it works**

To make the connection to Matlab, Matlab needs to be registered as a COM-component. Not all Matlab versions register the COM-component automatically.

1. In 20-sim, open the Simulator (Ctrl+R)
2. Open the Tools menu
3. Click the Matlab button

If Matlab starts (be patient this could take some time), the Matlab COM automation server is registered properly and you are finished. In case the error message "*Could not start Matlab. Make sure that Matlab is installed and that the Matlab COM automation server is enabled.*", proceed with step 3 and 4.

3. **Enable the Matlab COM automation server**

To make the connection to Matlab, Matlab needs to be registered as a COM-component. This can be done in the following manner from the command line (run: cmd):

```
matlab /regserver
```

The COM-registration only, is not enough for 20-sim to find the DLL's of Matlab. The next step (setting the PATH variable) must be performed also

4. **Matlab registration in PATH**

The standard registration of Matlab in the PATH is the following (assuming Matlab is installed in Program Files and the used version of Matlab is R2015b):

```
C:\Program Files\MATLAB\R2015b\bin
```

The following path should be added too in case of a 32-bit version of Matlab:

```
C:\Program Files\MATLAB\R2015b\bin\win32
```

In this additional path some important DLL's are present that are necessary to make the connection. for example: libeng.dll. Please check if this DLL is present at this path. If not try to find this DLL in your Matlab installation and add the found path to the PATH environment.

Changing the PATH environment variable can be done in the following manner:

1. From "My Computer", right mouse button: Properties:
2. On Windows: choose Advanced Properties and go further as Admin
3. Choose the tab: Advanced
6 Quick Tour

6.1 Running a Simulation

The best way to get started with 20-sim is to open the Getting Started manual. Here we will quickly explain the basics of 20-sim and then give detailed help on all the parts of the program. To open an model and run a simulation, you can best open an example model.

1. **Start** 20-sim.

20-sim consists of two main windows (Editor and Simulator) and a lot of tools. The Editor opens when you start 20-sim. In the Editor you can create your models.

![The 20-sim Editor.](image)

2. Select the **Library tab** to open the Library Browser (shows the 20-sim library).
3. In the *Library Browser* select **Examples - Control - Standard Control - Discrete Controller** and drag and drop this model to the main drawing. Like:

![The 20-sim Editor with the model DiscreteController.emx loaded.](image1)

5. In the *Model* menu select **Start Simulator**. Now the *Simulator* will be opened.

![The 20-sim Simulator with the model DiscreteController.emx loaded.](image2)

In the *Simulator* you can run a simulation and show the results in plots and animations. The *Simulator* contains various tools to analyze the simulation results.
6. In the **Simulation** menu select **Run**. Now a simulation run will be performed. Your **Simulator** should look like:

![The 20-sim Simulator with the simulation results.](image)

### 6.2 Variables, Parameters, Initial Values and Constants

Equations are the foundation for all models in 20-sim. At the lowest level of a model you will always find equations. Equations can be entered in the 20-sim **Editor**. An example equation model is shown below:

```plaintext
constants
    real g = 9.81 {m/s^2}; // gravity

parameters
    real m = 1.0 {kg}; // mass
    real g = 9.8 {m/s^2}; // gravity
    real K = 2.0 {N/m}; // spring constant
    real f = 1.0 {N.s/m}; // friction parameter

variables
    real v {m/s}; // velocity
    real interesting x {m}; // position
    real Fm {N}; // net-force applied to the mass
    real Fs {N}; // spring force
    real Fd {N}; // damper force

equations
    Fm = -m * g - Fs - Fd;
    v = (1/m) * int(Fm, 0);
    x = int(v, 0);
    Fs = K * x;
    Fd = f * v;
```
A 20-sim equation model starts with the declaration of parameters and variables. In the *Equation* section, the equations are entered. An equation is simply a variable on the left part of the equal sign and variables or functions at the right side. During a simulation, the equations are calculated over and over again, many time steps, while the resulting variable values are be shown in plots.

You can inspect equations by opening an example model, select one of the blocks with you mouse pointer and select "Go Down "from the right mouse menu. If you repeat this you will always see an equation model at the lowest level.

**Variables**
Variables can change value during a simulation. You can inspect the current value of a variables in the Variable Chooser.

**Parameters**
Parameters have a fixed value that you can change before a simulation in the Parameters/Initial Values Editor.

**Constants**
Constants are symbolic representations of numerical quantities that do not change during or in between simulation runs.

**Initial Values**
Some functions like an integral or a hold have an initial value. These initial values can be entered in the equation model (see int-function with a zero initial value in the example above: \( v = (1/m)*\text{int}(Fm, 0) \)) or be changed before a simulation in the the Parameters/Initial Values Editor.

### 6.3 Hierarchy

Any *main model* (or system) in 20-sim may be described as a composition of lower level *submodels*. These submodels themselves may again be described as a composition of lower level submodels etc. The lowest level consists of elementary submodels, which do not consist of submodels themselves.
hierarchic model. The lowest model in the hierarchy is always an equation model.

You can inspect this in the Editor. If you click the Model tab at the left of the Editor, the Model Browser shows complete model hierarchy: a tree like structure showing all the submodels that are used in the model. If you open the example model Examples\Control \Standard Control\FluidLevelControl the tree will look like:

The Model Browser at the left of the Editor shows the complete model hierarchy.
Tip

- To travel through the hierarchy, click any model in the tree and press **ENTER** to go down. Press **Backspace** to go up.

- You can also select a submodel in the *Graphical Editor* and click **Go Up** or **Go Down** from the *Model* menu.

- When a model is very large you may want to use the **Go Back** or **Go Forward** buttons from the *Model* menu to travel back and forth between branches in the hierarchy.

6.4 Language

You can set the language of the 20-sim menus: Settings - Language. Only the 20-sim tool language will change, not the help files.
7  Editor

7.1  Introduction

7.1.1  Editor

20-sim consists of two main windows and many tools. The first window is the Editor and the second is the Simulator. The Editor is used to enter and edit models. The Editor opens automatically when you start 20-sim:

![The 20-sim Editor.](image)

The Editor consists of four parts:

- **Model tab / Library tab**: The Model tab shows the model hierarchy, i.e. the composition of all the elements of the model. The Library tab shows the 20-sim library.

- **Graphical Editor / Equation Editor**: At the lowest level of the hierarchy this editor will show the model equations. In the higher levels this editor will show the graphical parts of your model.

- **Output tab / Process tab / Find tab**: The Output tab shows the files that are opened and stored. The Process tab shows the compiler messages. The Find tab shows the search results.

- **Interface tab / Icon tab / Globals tab**: The Interface tab shows the interface (inputs, outputs, ports) of a selected model. Double clicking it will open the Interface Editor. The Icon tab shows the icon of a selected model. Double clicking it will open the Icon Editor. The Globals tab will show the global parameters and variables of your model. Double clicking it will open the Global Relations Editor.

**Using the Editor**
The best way to find your way around the Editor is to read the Getting Started manual. It contains a number of topics that will explain the basics of entering equation models, graphical models and run a simulation.

### 7.1.2 Equation Editor

Equations models are the models at the lowest level in the model hierarchy. A model without an interface (inputs, output, ports), will have no hierarchy and is thus automatically an equation model. If you have opened an equation model, the right part of the Editor shows the Equation Editor. In the Equation Editor you can enter and edit equation models.

Use
Put your mouse in the Equation Editor and start typing. If you click on the buttons of the taskbar, sample code is inserted. Read the language reference section to find out more.

**Color Syntax Highlighting**

Functions, Variables etc. are given special colors to distinguish them from the other text.

**Auto Indent**

If a line is indented (using the tab), the next line will start at the same indentation. You can remove indentation by clicking the Backspace button.

**Multi-Line Tabbing**

You can give multiple lines of code a new indentation by clicking the tab button. Select all the lines and click Shift-tab to remove.

**Variables Pane**

The Variables pane at the right side of the Equation Editor shows the actual variable and parameter values of a model.
7.1.3 Equation Editor Taskbar

When you select an equation model, the corresponding equations are show in the Equation Editor. A special button bar, called the taskbar, is part of the Equation Editor. The taskbar helps you to enter functions, statements, templates etc.

![The taskbar of the Equation Editor.](image)

- **Statements**: click on this button to insert if-then-else expressions and more.
- **Functions**: click on this button to insert functions.
- **Specials**: click on this button to insert special functions.
- **Operators**: click on this button to insert operators.
- **Units**: click on this button to insert quantities and units.
- **Declarations**: click on this button to insert declarations of parameters, variables and more.
- **Constants**: click on this button to insert predefined constants.
7.1.4 **Graphical Editor**

If you have opened a graphical model, the right part of the Editor shows the **Graphical Editor**. In the **Graphical Editor** you can enter and edit block diagram models, iconic diagram models and bond graphs.

![Graphical model with the Graphical Editor (right part).](image)

**Use**
- Select models from the *Model Library* and drag them to the **Graphical Editor**.
- You can use the buttons of the taskbar, to connect the models and change their position.
- Drag and drop image files (bitmaps, svg images,..) to enhance the appearance of your model.
- Use the buttons of the taskbar, to create your own drawings.
7.1.5 Graphical Editor Taskbar

Taskbar
When you view or enter a graphical model in 20-sim it is shown in the Graphical Editor. A special button bar, called the taskbar, is part of the Graphical Editor. The taskbar helps you to select models, connect them and manipulate them. You can also use the taskbar to enter drawing objects. The taskbar is also part of the Icon Editor.

The taskbar of the Graphical Editor.

Selection Mode: Click this button to select models and objects
Insert Terminals: (Icon Editor only) Click this button to insert terminals.
Connection Mode: (Graphical Editor only) Click this button create connections between models.
Line: Click this button to draw lines.
Spline: click this button to draw splines.
Rectangle: click this button to draw rectangles.
Ellipse: click this button to draw ellipses.
Text: click this button insert text.
Bitmap: click this button insert bitmaps and images in svg format.
Line Color: click this button to set the line color of a selected object.
Fill Color: click this button to set the fill color of a selected object.
Rotate and Mirror: click this button to rotate or mirror a selected object.
Arrange and Group: click this button to group objects, put them to the front etc.
Line Styles: click this button to select the line style of selected objects.
Zoom: click this button to select the zoom factor. You can also click Ctrl + mouse wheel to zoom in and out.

View Menu
- **Choose Colors**: Choose the line color, text color and shadow color of selected items in the model.
- **Show Name**: Show the submodel name right, left, top down or hide.
- **Port Names**: Show the port names of the submodels.
- **Causality Info**: Show the causality of the iconic diagram and bond graph connections.
- **Orientation Info**: Show the orientation of the connections.
- **Show Terminals**: Show the terminals of the models. With the Show Terminals option selected, you can change the location and properties of the terminals directly in the Editor (no need to open the Icon Editor).

### 7.1.6 Search

If you make the Editor wide enough, you will see at the top right a Search box. You can enter terms here and search them throughout the model. The results are displayed in the Find tab at the bottom of the Editor.

1. In the search box, **type** the item you want to search and click **ENTER**.
2. In the list with found items in the Find tab, click on the item that you were searching for.

Now 20-sim will jump to the submodel where the searched item was listed.

- **Scope**: The search scope depends on which level of the model you are in. Only the current submodel and all submodels below are searched. Select the top element in the Model Browser (Model tab at the left of the Editor) to search the whole model.
- **Library**: The 20-sim Library is always searched.
- **Help Files**: The 20-sim Help Files are always searched.
- **Jump**: The Find tab shows the found items with a blue hyperlink. Click on the hyperlink to quickly jump to the corresponding model.
- **Find again (F3)**: Click the F3 button to quickly jump through the found items in the Find tab.
• **Menu**: You can also start a search from the menu: Click *Edit - Find.*

## 7.1.7 Library

In 20-sim, creating models only takes you just a few mouse clicks. By *dragging* an element from the library and *dropping* it in the graphical editor, your model is actually built the same way as you would draw an engineering scheme. 20-sim supports various model representations, such as block diagrams and iconic diagrams. These representations may be combined in one model.

The library contains a various sections:

- **Bond Graph**: bond graph elements
- **Iconic Diagrams**: Physical components
- **Signal**: Block diagram elements
- **Examples**: Example models that show you how you can use models for various physical domains and applications.
- **Tutorial**: Example models that show you how to perform various tasks in 20-sim
- **Getting Started**: all the models that you need in the lessons of the Getting Started manual.

You can find the library at the left of the Editor.
Custom libraries
You can create your own model libraries in 20-sim:
1. From the Tools menu click Options - Folders - Library Folders.
2. Add your folder.
3. Give it a useful name by clicking Edit Label.
4. Click OK to close the dialog.

Then you can add your own library models to the library:
1. Select the submodel that you want to store in your library.
2. From the File menu select Save Submodel.
3. Store the submodel in your library folder.

The next time you start up 20-sim, the library will show the new submodel.

7.1.8 Options
The general properties of 20-sim models are shown in the Options dialog.
- From the Settings menu choose the Options command.
- From the Tools menu choose the Options command.

Editor
- Fonts: Enter the default fonts used in graphical models (Editor) and equation models (Equation Editor).
- Syntax Highlighting Threshold: Select the number of characters that should be submitted for color syntax highlighting. If this number is too large, the editor may become very slow.
- Undo Buffer Memory Size: Increase the amount of memory used for the undo buffer if you want to store more undo actions.
- Submodel Colors: Check this option to turn Gradient Fill on. This option will apply a slight vertical gradient to all blocks with a background color.

Plots
You can choose the default settings for a simulation plot in this tab.
- Default Line Thickness: Enter the default plot line thickness.

Folders
You can choose the location of libraries and files in the Folders tab.
- Library Folders: Enter the library paths and corresponding library names here. The libraries are shown in the Library tab.
- **C-code Folders**: C-code can be generated for various targets. For each target a file targets.ini defines how the C-code should be generated. You can enter the locations of ini-files here.

- **Matlab-Code folders**: 20-sim models can be exported to Matlab. Similar to C-code generation, a file targets.ini defines how the code should be generated. You can enter the locations of ini-files here.

- **Model Template Folders**: You can enter the location of model templates.

- **DLL Search Folders**: If a 20-sim model is using a DLL-function that is stored on a different location from the model itself, you can enter the location here.

**Scripting Server**

20-sim uses the XML-RPC protocol to communicate with external software and run scripts. By default, 20-sim will only accept scripting connections from your local computer (*Localhost only* option is enabled by default). In most cases the default settings should be fine. However, for each of these protocols, settings may be changed. Ask your system administrator for details.

**Scripting Client**

You can configure specific settings for scripting with Matlab and Octave.

**Matlab Session Type**

20-sim can communicate with MATLAB through scripts and dedicated functions (tomatlab, domatlab, frommatlab). The MATLAB session type determines how MATLAB is started as an automation server:

- **Shared session**: A shared session will open one running version of MATLAB (minimized window), that can be shared with multiple running versions of 20-sim.

- **Shared desktop session**: A shared desktop session will open one running version of MATLAB (full desktop session), that can be shared with multiple running versions of 20-sim.

- **Dedicated session**: A dedicated session will open a new running version of MATLAB for every running versions of 20-sim.

**Remark**: Note that although the shared desktop session will open MATLAB in desktop mode, it will not be able to use an existing Matlab session started by the user. If you want 20-sim to connect to your existing running MATLAB session, enable the MATLAB Automation Server using the following MATLAB call:

```matlab
enableservice('AutomationServer',true)
```

**Octave Folder**

Enter or select the path where Octave is installed.
7.2 Using Models

7.2.1 Open Models

Models in 20-sim are stored with the extension .emx. You can open an existing model in several ways:

1. From the File menu, select Open.
2. Click the Library tab and from the Library drag and drop your model to the Graphical Editor.
3. Open a Windows Explorer. Drag and drop your model to the Graphical Editor.

You can open Packed Files with the Open dialog by selecting a file with the extension .emz.

7.2.2 Save Models

Models in 20-sim are stored with the extension .emx. You can save an existing model in several ways.

Main Models

1. From the File menu, select Save: This will save the complete model. If no file name is known a Save dialog is opened.
2. From the File menu, select Save As: This is essentially the same as the Save command but now the Save dialog is opened even if a file name is known.
3. From the File menu, select Save a copy As: This is similar to Save As but now a copy of the file is saved instead. This allows the user to keep on working on the model while saving intermediate experiments.

During Save As and Save copy As you can choose various formats to store models:

1. emx: The standard format for 20-sim models
2. emp: The processed format for 20-sim model
3. emz: The packed format. This is a zip file that contains all external files that may be required to run a model.

Submodels

1. From the File menu, select Save Submodel: This will save the submodel that is selected in your Graphical Editor.

Encrypted

1. From the File menu, select Save Encrypted: This will allow you to store a model using encryption. If a submodel was selected, a menu is opened asking you to store the submodel or the complete model.
Encrypted models are useful if you want others to use your 20-sim model, without seeing the underlying equations. If an encrypted model is loaded in 20-sim, the Go Down command does not work on that model. The encrypted model is shown with a lock in the model hierarchy.

**Note:** You can also encrypt or decrypt models using the Edit menu.

**Warning:** Once a model is encrypted, you can not decrypt it anymore! So keep cautious that you always store a non-encrypted original.

**Processed**

1. From the **File menu**, select **Save Encrypted**: This will allow you to store a model using encryption. If a submodel was selected, a menu is opened asking you to store the submodel or the complete model.

Encrypted models are useful if you want others to use your 20-sim model, without seeing the underlying equations. If an encrypted model is loaded in 20-sim, the Go Down command does not work on that model. The encrypted model is shown with a lock in the model hierarchy.

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### 7.2.3 Packed Files

To get a simulation running in 20-sim, the data stored in various files may be needed:

- .emx: model files
- .txt: data files (fileinput)
- .bmp: bitmap files (for use in 3D Animation)
- .dll: external dll-files (user defined external functions)
- etc.

You can pack all these files into one zip-file, using the **Pack** command from the **File** menu. With this command 20-sim will check all the files that are used and store them into a single zip-file. This option is useful for archiving and sending models by e-mail.

**Pack**

1. When the **Pack** command is clicked, a **Save As dialog** appears asking you to enter a name. Always save with the default extension .emxz because 20-sim uses this extension to recognize packed files.
After the Save As dialog, a 20-sim Pack dialog appears, showing the collected files. In this dialog you can select the files that should be packed.

2. **Select** the files that should be packed and click the **OK** button.

**Unpack**

You can open Packed Files using the Unpack command from the File menu.

1. When the **Unpack** command is clicked, an Open dialog appears asking you to open a file. Open a file with the extension .emxz because 20-sim uses this extension to recognize packed files.

After the Open dialog, a 20-sim Unpack dialog appears. In this dialog you can see the file that you have selected to unpack and you can choose the method of unpacking.

2. If you want to unpack all files and put them in their original location, select the option Unpack with full path.
3. If you want to unpack all files and to a specific directory, select the option Unpack to directory.
4. Select Keep Relative Paths if you want to keep the original folder structure.

### 7.2.4 Processed Files

Before a model can be simulated it has to be processed / compiled. For large models this can take a while. You can prevent this by saving a model as a processed model:

1. In the Editor From the File menu, select **Save As**.
2. Choose the extension Processed Model File .emp.

Now the model is stored in its compile form and you can directly open the simulator.

**Note:** You cannot edit processed models, so make sure that you always store models using the standard .emx extension.
7.2.5 Insert Models

You can insert submodels from a library using the built in Library tab:

1. Click the Library tab to open the library.

2. Select the submodel that you want to insert and drag and drop it in the Graphical Editor.

You can also use a file browser:

1. In the Editor From the File menu, select Open Browser. The File Explorer appears.
2. Select the submodel of interest and drag and drop it in the Graphical Editor.

You can also use a the Insert menu:

1. In the Editor From the Insert menu, select a submodel to insert.

Tips and Tricks

- Scroll up and down using you Mouse Wheel.
- You can zoom in (F4) and out (F6) by pressing the CtrI-Key and using your Mouse Wheel.
- Use a finer grid by zooming in.
- Select multiple objects by keeping the CtrI-Key pressed.

7.2.6 Connecting Models

In 20-sim, submodels can be connected using the mouse. When a connection is created it will be displayed using straight lines. When a connection has been made you can change it into a smooth line using the right mouse menu. You can change the color of a connection using the colorbar at the bottom of the Editor. 20-sim supports two types of mouse use. "Tapping Mode" and "Pressing Mode". In the Tapping Mode you click the mouse button (do not keep it pressed but quickly "tap" the button) while making a connection. In the Pressing Mode you keep the mouse button pressed while making a connection.

Tapping Mode

To connect two submodels using straight lines, you have to:

1. In the toolbar, click to change to connection mode.
2. Put the mouse pointer on top of the first submodel and click the left mouse button (do not keep it pressed but quickly "tap" the button).
3. Drag the mouse pointer towards the second submodel (you will see a connection drawn from the first submodel towards the mouse pointer).
4. Put the mouse pointer on top of the second submodel and click the left mouse button again (do not keep it pressed but quickly "tap" the button).
5. While dragging from the first submodel to the second, you can click the left mouse button (do not keep it pressed but quickly "tap" the button) to create **intermediate points**.

**Pressing Mode**

To connect two submodels using straight lines, you have to:

1. In the toolbar, click to change to **connection mode**.
2. Put the **mouse pointer** on top of the **first submodel** and press **left mouse button** (keep it pressed).
3. Drag the **mouse pointer** towards the second submodel (you will see a connection drawn from the first submodel towards the mouse pointer).
4. Put the mouse pointer on top of the **second submodel** and release the left mouse button.
5. While dragging from the first submodel to the second, you can click the right mouse button to create **intermediate points**.

**Smooth Line**

To connect two submodels using a smooth line, you have to:

1. Make a **straight line** connection with **intermediate points**.
2. In the toolbar, click to change to **selection mode**.
3. Select the connection that was created.
4. From the **right mouse** menu select "**smooth line**".

**Show Terminals**

The connections between models start and end at terminals. When you are in connection mode ( ), these terminals are shown. You can explicitly show them by clicking View - Show Terminals. The way connections behave, depend on the terminals being fixed or not fixed.

**Tips & Tricks**

- 20-sim will automatically detect which connection has to be made: a signals, a bond or an iconic diagram connection.
- Depending on the physical domain, every connection will have a specific color. You can change these colors in the Units Editor.
- You can toggle between connection mode and selection mode by pressing the space bar.
- Connections on a submodel can have a fixed position, or move around the border of the submodel. This property can be set in the Icon Editor, or by showing the terminals.
7.2.7 Change Models

You can change (sub)models by selecting them with your mouse. Here are some tips:

**General**
- Use selection mode (click in the toolbar) to select models, connections etc.
- Use connection mode (click in the toolbar) to create connections between submodels.
- Switch between selection mode and connection mode with the space bar.

**Submodels**
- Change submodel name: Select submodel - Right mouse menu - Properties - Name
- Delete submodel: Select submodel - click Delete key.
- Replace submodel: Select new submodel from the library and drag onto the existing submodel until it highlights.
- Change ports/connections: Select submodel - Right mouse menu - Edit Interface
- Change submodel icon: Select submodel - Right mouse menu - Edit Icon

**Connections**
- New connection: Editor in connection Mode -
- Change connection: Select connection - Right mouse menu - Add point
- Delete connections: Select connection - click Delete key.
- Insert submodel into a connection: Select new submodel from the library and drag onto the existing connection until it highlights.

**Various**
- Add summation: Editor in connection Mode - Click on submodel to start a new connection - click on existing connection to end new connection - Plus minus.
- Add multiply/divide: Editor in connection Mode - Click on submodel to start a new connection - click on existing connection to end new connection - MultiplyDivide.

7.2.8 Implode / Explode

Using the **Implode** command of the **Editor** menu you can quickly create a new submodel out of a set of select submodels.

1. In the toolbar, click to change to selection mode.
2. Select the the submodels.
3. From the **Edit** menu, click the **Implode** command.

Using the **Explode** command of the **Editor** menu you can quickly open the contents of a selected submodel in the current model layer.

1. In the toolbar, click to change to selection mode.
2. Select a submodel.
3. From the **Edit** menu, click the **Explode** command.

### 7.2.9 Dissolve

If you want to delete a submodel from a signal path, but keep the signals/ports intact, you can use the Dissolve command. The Dissolve command will delete the submodel and connects the input signal directly to the output.

1. In the taskbar click the **Selection Mode** button.
2. **Select** the submodel that you want to delete.
3. From the **Edit menu**, select **Dissolve**: This will delete the selected submodel and move the signals/ports to the next submodel.

### 7.2.10 Simplify Models

Use the **Simplify Model** command to simplify graphical models according to the following rules:

#### Block Diagrams

1. Combining splitters.
2. Combining of multiplications and/or divisions.

#### Bond Graphs

1. Eliminating junctions.
2. Melt equal junctions.
3. Eliminating double differences.

#### Iconic Diagrams

1. Eliminating nodes.

To simplify a (sub)model, you have to:

1. Select the complete model or submodel of which you want to simplify.
2. From the **Model** menu select the **Simplify Model** command.
7.2.11 Navigate Models

Model Hierarchy

If you click the Model tab at the left of the Editor, the Model Browser shows complete model hierarchy: a tree like structure showing all the submodels that are used in the model.

The Model Browser at the left of the Editor shows the complete model hierarchy.

1. You can travel through the hierarchy, click any model in the tree and press ENTER to go down. Press Backspace to go up.

2. You can also select a submodel in the Graphical Editor and click Go Up or Go Down from the Model menu.

3. When a model is very large you may want to use the Go Back or Go Forward buttons from the Model menu to travel back and forth between branches in the hierarchy.

Where Am I?

In large model with many levels in the hierarchy, it may be difficults to quickly see where you are.

1. If you want to see in which submodel you are, click Go Up to jump one level higher in the hierarchy.

The submodel that was selected will now be displayed with orange thick orange outlines.
**7. Editor**

**Zooming**

1. In the Editor from the **View** menu you can select **Zoom** to zoom in and out to see details or the overview of a model.

2. You can also use the Ctrl-key with the mouse wheel to zoom in and out.

**Scrolling**

1. Use the **scroll bars** to navigate from top to bottom or from the left to the right.

2. Use the Home, End, PgUp, and PgDown keys for scrolling large models easily.
7.2.12 Add Variable To

When you hover your mouse above a connection or on top of a variable, you can use your right mouse menu to quickly add variables to a plot or copy values to the clipboard.

1. Hover your mouse above the connection or variable.
2. Click the right mouse button.
3. From the menu choose: "Add xxxx to" and select your option.

The following options are available:

- Plot in Simulator: add the variable to a simulator plot.
- Favorites: Make this variable a favorite.
- Input Probes: Use this variable as an input probe for linearization.
- Output Probes: Use this variable as an output probe for linearization.
- Copy: copy the value and unit to clipboard.

7.2.13 Check Models

To check a complete model, you have to:

1. From the Model menu select the Check Complete Model command. Now the complete model will be checked.

If any warnings or errors are found, they are displayed in Process tab of the Editor.
In the Process tab the compiler messages are displayed.

2. Put your **mouse** on top of an **error message** and click.

20-sim will jump to the part where the error was caused. You can try to solve the error and check again.

### 7.2.14 Model Properties

The properties of 20-sim models are shown in the *Model Properties* dialog. You can open the *Model Properties* in various ways.

- Select the proper model in the Model Browser and then click **Properties** from the **Right Mouse** menu.
- Select the model in the Graphical Editor and then click **Properties** from the **Right Mouse** menu.
- From the **File menu** choose the **Properties** command.
- From the **Settings menu** choose the **Model** command.
- From the **Settings menu** choose the **Submodel** command.

Depending if a *submodel* was selected or a *main model*, various tabs are visible:
Description

In this tab you can enter the name of the submodel and enter various fields to classify a model. The most important elements are:

- **Name**: Enter a unique name for the model.
- **Help Page**: Enter the location of a help page that should be displayed when you click F1 or Help.
- **Version**: The version number of the model. The version number can be displayed in the background and is included if you generate C-code from the model.

Library

In this tab you can find information on location of the model and some important properties.

- **Version**: The version of 20-sim that was used to create the model.
- **Library Path**: If the model was stored in a known library, the path is shown.
- **Library File**: The relative location of the submodel in the library or the absolute location of the model submodel on your computer.
- **Created**: The date of creation.
- **Main Model / Submodel**: Shows if the model is a main model or submodel.
- **Allow model updates**: Allow the Check for Model Updates command to check if there is an update available for this model.
- **Replace parameters when this model is used to update another model**: If you drag and drop a model from the library on top of an existing model, it will be replaced. Select this option if you want the original parameters to be replaced as well.
Background Image
In this tab you can specify a background image for the model. If the model is a graphical model, in the background the image is shown.

- **None**: default, no image shown.
- **Inherit From Parent**: Use the background that was defined one model higher in the model hierarchy.
- **Static Bitmap**: Specify the bitmap file to be used.
- **Script File**: You can specify a script file if you want to use a dynamic background.
- **Scaling**: Scaling of the background image.

Processing
This tab is only available for main models. 20-sim can operate in two modes: *Debug Mode* and *Fast Mode*. In this tab you can define settings for both modes.

Warnings/Errors

- **Model contains algebraic variables**: See the section on algebraic loops.
- **Model contains algebraic loops**: See the section on algebraic loops.
- **Algebraic variables solved**: See the section on algebraic loops.
- **Model contains constraint variables**: See the section on constraints.
- **Constraint variables solved**: See the section on constraints.
- **Model contains dependent states**: The model contains differential equations which could not be solved.
- **Dependent states are transformed**: The model contains differential equations which were solved.
- **Output is not used**: Output signals that are not used for connections to other models.
- **Input is not used**: Input signals that are not used for connections to other models (to make such models simulate, a zero input value is applied to all not-connected inputs).
- **Port is not used**: Ports that are not connected.
- **Parameter is not used**: Parameters that are defined but not used.
- **Matrix is assigned a scalar**: A matrix is assigned to a scalar.
- **Variable is not used**: Variables that are defined but not used.
- **Variable Multiple set**: Variables that are assigned a value more than once.
- **Variable is never given a value**: Variables that are never assigned a value.
- **Variable is set but not used**: The variable is assigned a value but never used.
- **Unit Conversion when SI disabled**: Not relevant yet.
- **Unit Conversion when SI enabled**: A unit conversion was found.
- **Unit missing for variable when SI disabled**: Not relevant yet.
- **Quantities Mismatch**: Variables with different quantities are compared.
- **Unit is unknown**: A unit has been used that is not available in the Quantities and Units file.
- **Equations interpreted as code**: Equations can only be valid when interpreted as sequential code. For example when variables are assigned more than once.
7. Editor

- *Possible loss of data at type conversion:* A type conversion has been found that may lead to loss of precision digits.
- *Type conversion found:* A type conversion has been found.
- *Conversion of booleans found:* A type conversion involving booleans has been found.

**Model optimization**

- *Transform Dependent States:* Try to solve differential equations.
- *Solve algebraic variables:* Try to analytically solve algebraic loops.
- *Remove Redundant Equations:* Try to remove equations that do not influence model behavior.
- *Optimize Equation Structure:* Try to separate equations into an input section, a dynamic section and an output section.
- *Optimize Static Expressions:* Move expressions with constant output throughout the simulation to the static part of the model equations.
- *Optimize Duplicate Expressions:* Calculate an expression only once and use the result everywhere.
- *Optimize Divisions:* Rewrite divisions as multiplications whenever possible.

**Simulator**

This tab is only available for main models. You can set the simulator properties here.

- *Initialize variables at start of simulation:* You can choose to set any variable that was not given a proper value, to zero at the start of a simulation. You can also choose to set the value to NaN to make detection more easy.
- *Calculate Hold Instruction During Initialization:* Calculate an output for hold functions during the initialization of a simulation.
- *Preferred CPU Architecture:* In Fast Mode, 20-sim uses the fastest instruction set available on the CPU. The list presented here shows from top to bottom the instruction sets that are available on your CPU. The fastest set is listed at the bottom of the list and selected by default. You can override this selection by choosing another instruction set. Changing this setting is only recommended for expert users!

### 7.2.15 General Properties

The general properties of 20-sim models are shown in the *Options* dialog.

- From the **Settings menu** choose the *Options* command.
- From the **Tools menu** choose the *Options* command.

**Editor**

- **Fonts:** Enter the default fonts used in graphical models (Editor) and equation models (Equation Editor).
• **Syntax Highlighting Threshold**: Select the number of characters that should be submitted for color syntax highlighting. If this number is too large, the editor may become very slow.

• **Undo Buffer Memory Size**: Increase the amount of memory used for the undo buffer if you want to store more undo actions.

• **Submodel Colors**: Check this option to turn Gradient Fill on. This option will apply a slight vertical gradient to all blocks with a background color.

**Plots**

You can choose the default settings for a simulation plot in this tab.

• **Default Line Thickness**: Enter the default plot line thickness.

**Folders**

You can choose the location of libraries and files in the *Folders tab*.

• **Library Folders**: Enter the library paths and corresponding library names here. The libraries are shown in the Library tab.

• **C-code Folders**: C-code can be generated for various targets. For each target a file targets.ini defines how the C-code should be generated. You can enter the locations of ini-files here.

• **Matlab-Code folders**: 20-sim models can be exported to Matlab. Similar to C-code generation, a file targets.ini defines how the code should be generated. You can enter the locations of ini-files here.

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• **Shared desktop session**: A shared desktop session will open one running version of MATLAB (full desktop session), that can be shared with multiple running versions of 20-sim.

• **Dedicated session**: A dedicated session will open a new running version of MATLAB for every running versions of 20-sim.
Remark: Note that although the shared desktop session will open MATLAB in desktop mode, it will not be able to use an existing Matlab session started by the user. If you want 20-sim to connect to your existing running MATLAB session, enable the MATLAB Automation Server using the following MATLAB call:

```matlab
enableservice('AutomationServer',true)
```

Octave Folder
Enter or select the path where Octave is installed.

### 7.2.16 Check Energetic Behavior

If you select the **Check Energetic Behaviour** command of the **Model** menu, 20-sim will check the complete model and generate additional variables. The additional variables will only be generated for submodels with powerports:

- power for every power port.
- the net power that flows into the submodel (total sum of all the powers).
- the net energy of the submodel (integrated net power)

This command is the same as Check Complete Model command but will generate extra variables:

- `Sumodelname\port.power`: the net power flow of the port.
- `Sumodelname\summated_port_power`: the net power flow into the model.
- `Sumodelname\summated_port_energy`: the net energy of the model.

You can inspect these variables during simulation in the Variable Chooser.

### 7.2.17 Analyze Causality

Causal analysis is the procedure to get the model equations correct form. For Bond Graph models this means that the direction of the efforts and flows of the bonds have to be determined. The result of the analysis is displayed by causal strokes (denoted by I). For Iconic Diagrams this means that the direction of the across and through variables of the connections have to be determined. The result of the analysis is displayed by causal arrows (denoted by -> ).

To perform causal analysis you have to:

1. From the **Model** menu select the **Analyze Causality** command. Now causality will be assigned in the complete model.

**Bond Graphs**

- Causal strokes are shown in Bond Graphs automatically.
• Setting Causality can also be done by hand. Just select a bond and choose Properties from the right mouse menu. A menu pops up in which you can set causality by hand. The corresponding causal stroke is displayed in green (denoted by |).

```
R ← 1 ─────── R
```

*User defined causality (denoted by |).*

• If 20-sim fails to perform a causal analysis of the model (a **causal conflict**), the corresponding bond is displayed red.

```
Se ← 1 ─────── Se
```

*A causal conflict (denoted by the red bond).*

• Some submodels have a preferred causality. If assignment of the preferred causality is not possible (because of other constraints), the corresponding causal stroke is displayed in orange (denoted by |).

```
Se ← 1 ─────── C
```

*Preferred causality not assigned (denoted by |).*

• To see the order in which automatic causality assignment has been performed, choose **Causality Info** from the **View** menu.

**Iconic Diagrams**

• Causality in Iconic Diagrams is only shown when you select the **Causality Info** command of the **View Menu**.

```
Causal Information shown by arrows.
```

• If 20-sim fails to perform a causal analysis of the model (a **causal conflict**), the corresponding connection is displayed red.
7.2.18 **Show Terminals**

The connections between models start and end at terminals. In the Graph Editor you can view these terminals by clicking View - Show Terminals.

1. Put the **mouse pointer** on a **terminal** to see its name in the tooltip.

1. With the **mouse pointer** on a **terminal** click the **left mouse button and keep it pressed** to change the location of the terminal.

2. With the **mouse pointer** on a **terminal** click the **right mouse button** to open the right mouse menu.

3. From the **right mouse** menu click **Delete** to **delete** the **Submodel**.

4. From the **right mouse** menu click **Properties** to select the **Terminal Properties**.

This will open the **Terminal Properties** showing the name of the input, output or port and the option to fixate the position. With a fixed position, the connections will start or end exactly at the position of the terminal. Without a fixed position, the connections will point to the center of the icon and start or end at the border of the icon.
Fixed and Not-Fixed Terminals

The way connections behave, depends on the terminals having a fixed position or non-fixed position. This is illustrated in the next figure.

1. Not-fixed terminals (at the left in the figure): The connections point from the middle of one model to the middle of the other model. If more than one connection is used, these connections are drawn on top of each other. If one of the models is moved, the connections are drawn with horizontal or vertical lines as long as possible.

2. Not-fixed terminals (in the middle of the figure) with intermediate points: You can separate the connections from being drawn on top of each other. Insert an intermediate points and drag the connection away. If one of the models is moved, the connections are drawn separately, with horizontal or vertical lines as long as possible.

3. Fixed terminals connected to not-fixed terminals (at the right of the figure): If one of the models has fixed terminals, these prevail. If one of the models is moved, the connections are drawn with horizontal or vertical lines as long as possible.
Tip
You can change the terminals and icon in more detail, using the Icon Editor.

7.2.19 Implementations
A model may have various implementations. It means that you can combine several versions of a submodel and store them in one block. If you drag and drop a submodel with implementations, 20-sim will ask which one to use.

Using Implementation
A fine example of a model with various implementations is the model `MachineDynamics.emx` from the `Examples\1D mechanics` library. This example model has several submodels with implementations:

- SpringDampers: frameflex and motorflex
- SignalGenerator-Sweep: sweep

You can see this in the Model browser at the left of the Editor. The models with implementations have show the implementation that is currently selected between brackets.

The selected implementation is shown between brackets in the Model Browser.

You can change the implementation:

1. **Select** the submodel.
2. From the right mouse menu choose **Edit Implementation** and **select** the implementation that you want to change.
3. Make the **changes** that you want in the submodel.

4. **Store** the submodel using the **Save Submodel** command of the **File** menu.

**Inserting Submodels with Implementations**

When you drag and drop a model with implementation into the **Graphical Editor** you will be asked which implementation to use. In the Model browser, the chosen implementation is shown between brackets (*Default* and *ZeroMean* in the picture above). If you hover the mouse above a submodel with an implementation, you also see the chosen implementation between brackets.

**Building Submodels with Implementations**

You can make submodels with implementations yourself:

1. **Select** a submodel.
2. From the **right mouse** menu choose **Edit Implementation** and **Add New**.
3. Enter the **name** of the implementation and click **OK**.
4. **Store** the submodel using the **Save Submodel** command of the **File** menu.

**Changing Implementations**

If you change one of the implementations, the other implementations will not be affected. This may sometimes be annoying. You can circumvent this by:

**Updating the Interfaces**

1. **Select** a submodel with an implementation.
2. From the **right mouse** menu choose **Edit Implementation** and **Update Interfaces**.

This will make the interfaces of all implementations equal to the current one.

**Updating the Icons**

3. **Select** a submodel with an implementation.
4. From the **right mouse** menu choose **Edit Implementation** and **Update Icons**.

This will make the icons of all implementations equal to the current one.
Continuous-Time and Discrete-Time Models

In 20-sim you can model continuous-time systems, discrete-time systems and combinations of continuous-time systems and discrete-time systems (hybrid) systems. By default, models in 20-sim are continuous-time, and simulated using continuous-time integration methods. However, the program will automatically identify discrete-time parts in a model and simulate them at a fixed rate.

Continuous-Time

Continuous-time models describe real-world processes. To simulate a continuous-time model, the model will be calculated many steps per second to get a result that is a good representation of the real-world process. If you model a car suspension system, about 100 steps per second might be sufficient to give a good representation of the behaviour of the car. If you model an electronics circuit, 100,000 steps per second might be required. The default integration method in 20-sim will automatically choose the required steps per second.

Discrete-Time

Discrete-time models describe processes that run on computers at a fixed rate. To simulated a discrete-time model, you only have to indicate the rate at which the model should be calculated. This is called the sample rate or sample frequency. The sample rate of a discrete-time part can be set in the Simulator.

Mixed Models

In 20-sim you can model in continuous-time and discrete-time. Mixed models containing discrete-time parts and continuous time parts are supported as well. The example below shows a continuous time model of a PI-controlled system at the top. At the bottom the same system is shown with a discrete time controller and a continuous-time system. The discrete-time part is indicated by green input and output lines.

Identification of Discrete-Time Parts

In 20-sim every model is continuous-time by default. Discrete-time parts of a model are identified by the occurrence of special functions:
Normally these functions are hidden in the equations that describe a submodel, but 20-sim will automatically recognize that the input or output of such a function should be discrete-time. If the output is discrete-time it is propagated to the next function, which output is then also "tagged" as discrete-time, and so on until the whole discrete-time part of a model is identified. A discrete time part of a model is indicated by green inputs and outputs (see previous picture).

**Connection**

Continuous-time parts of a model can be connected to discrete-time parts, by using the functions:
- **sample**: The sample function has a continuous-time input and a discrete-time output.
- **hold**: The hold function has a discrete-time input and continuous-time output.

You can find these functions for example in the following library models:
- DA.emx (Discrete to Analog Converter)
- AD.emx (Analog to Digital Converter)
- Encoder.emx (Optical Encode)

**Forbidden Functions**

In a discrete part of a model, certain functions are not allowed, because they are specifically meant for the use in continuous-time models:
- **algebraic**
- **constraint**
- **ddt**
- **dly**
- **event**
- **eventdown**
- **eventup**
- **frequencyevent**
- **int**
- **limint**
- **tdelay**
- **timeevent**

If you use a library model that contains such a function in a discrete-time part, an error message will be given.
7.2.21 Masked Models

In 20-sim there are special models which can only be editor by special editors. These models are called masked models. Masked models are indicated by an pink shadow with the word *mask*. If you select a masked model and select *Go Down* to inspect the contents, a special editor will be opened. In this editor you can make the desired edits and update the model. Once the model has been updated successfully the pink background disappears.

Some examples of masked models.

7.2.22 Working with Multi-Dimensional Models

Multi-Dimensional models are models that have connections which are of a size \([n,m]\) with either \(n\) or \(m\) larger than one. Here \(n\) is the numbers of rows and \(m\) is the numbers of columns. More information on this matrix notation can be found in the topic on matrices and vectors.

The advantage of multidimensional models is shown in the example below. On top two submodels are connected by three (single) signals. The same submodels are also shown below, connected by one multi-dimensional signal of size \([3,1]\). If these submodels have to be used a lot, multi-dimensional signals or multi-signals, are easier to use. Multi-dimensional signals, bonds and connections are shown in 20-sim by double lines.
The Secret: Multi-Dimensional Ports

The secret of multi-dimensional models is hidden in the model interface. If you open the Interface Editor to inspect an interface, you will notice that each port (signal, iconic diagram or bond graph) has a default size (dimension) of 1 (1 Row, 1 Column). By increasing the number of rows and/or columns this size can be increased.

Definition of Multi-ports: increase the number of rows or columns.
The Trick: Automatic Connection

When two submodels are connected, 20-sim will automatically check for the port-sizes and create a connection:

1. If the port-sizes are unequal, an error message will be generated.
2. If both ports have size one, a single signal, bond or connection will be drawn.
3. If both ports have a size larger than one, a multi-signal, multi-bond or multi-connection will be drawn.

The Finishing Touch: Matrices and Vectors

Behind each multi-dimensional submodel, there are equations in the end. To combine multi-dimensional ports with equations, you can use matrices and vectors. 20-sim has a large connection of matrix and vector functions and operators, to help you define any possible matrix equation. For example the gain model in the picture on top, could have been described as shown below.

![Use the matrix and vector notation to define the model equations.](image)

7.2.23 Exporting Models

There are several methods to export 20-sim models.

Export to previous versions of 20-sim
You can save a model file using the **Save** command or the **Save As** command from the **File** menu. If you want to save part of your model, use the **Save Submodel** command of the **File** menu. A **Save** dialog will be opened in which you can enter the model name and location. At the bottom of the dialog, you can use the **Save As Type** box to select the file type:

- **Model files (*.emx)** Standard 20-sim 4.x format
- **Packed files (*.emz)** Zipped file including all linked files (e.g. datafiles, dll's, bitmaps etc.)
- **Sidops text files** Save model as text file. (*.txt)

**Export to zip file**

You can save a model and all externally linked files into one zip-file, using the **Pack** command of the **File** menu. With the **Unpack** command of the **File** menu, you can open these zip-files.

**Export to Clipboard**

From the **File** menu click **Export** and **To File** to export a selected model as a drawing to the clipboard (**Windows Enhanced Metafile** format).

**Export to File**

From the **File** menu click **Export** and **To File** to export a selected model as a drawing to a file (**Windows Enhanced Metafile** format).

**Export to HTML**

From the **File** menu click **Export** and **To HTML** to export the model, simulations etc. to an HTML file for the use in a word processor.

**Export to Bitmap**

From the **File** menu click **Export** and **To Bitmap** to export a selected model as a drawing to a file (**png** format).

**Export to Matlab (m-file)**

To export 20-sim models to Matlab, from the **Editor** you have to select the **File** menu and then click **Export to Matlab/Simulink** command. This will open a **Matlab-Code Generation** dialog. You can choose to export a complete model or a submodel. In both cases, three m-files are generated:

- **ModelName.m**: A file containing the model equations and special 20-sim functions. The model equations are directly translated from the equations that are shown with the Show Equations command of the Model menu.
- **ModelName_run.m**: An example file showing you how to run a simulation with the exported model in 20-sim.
- **ModelName_print.m**: This file contains a function that is used in the run file.

**Export to Simulink (m-file)**
20-sim models can be exported to Simulink S-functions. S-functions are block diagram elements of which the internal description can be an *m-file* or a *dll-file*. 20-sim can export both types. M-files can be opened from within Matlab and are therefore more accessible. *Dll-files* are compiled out of C-code, which makes them inaccessible, but a lot faster. Simulink does not support powerports. Therefore the powerports in a 20-sim model are translated to input and output ports.

To export 20-sim models to Simulink with an *m-file* description, from the *Editor* select the *File* menu and then click the *Export to Matlab/Simulink* command. This will open a *Matlab-Code Generation* dialog. You can choose to export a complete model or a submodel. In both cases, two files are generated:

- **FileName_.mdl**: The exported 20-sim model based on an *m-file* that describes the model.
- **FileName.m**: An *m-file* that contains the model equations and special 20-sim functions. The model equations are directly translated from the equations that are shown with the Show Equations command of the *Model* menu.

**Export to Simulink (dll-file)**

To export 20-sim models to Simulink with an *dll-file* description, from the *Simulator* you have to select the *Tools* menu and then click the *C-code generation* command. This will open the *C-code Generation* dialog where you can choose to export to a Simulink S-function.

If you select the *OK* button, ANSI C-Code will be generated and compiled into a dll-function. Some files will be generated of which two are needed in Simulink:

- **FileName_.mdl**: The exported 20-sim model based on a dll-file that describes the model.
- **FileName.dll**: A dll-file that contains the model equations and special 20-sim functions. The model equations are directly translated from the equations that are shown with the Show Equations command of the *Model* menu.

**Export as Functional Mockup Unit (FMU-file)**

20-sim supports the FMI standard. See FMI Support for the details. In 20-sim, you can export several types of *Co-Simulation* FMUs. See the FMU Export page for the required steps.

**7.2.24 Encrypt Models**

You can encrypt submodels to prevent others to inspect the contents.

1. In the Editor **select a submodel**.
2. From the *Editor menu* select *Encrypt model*.
Now you will be asked to enter a password. Please take care to store the password in a safe location, so you can decrypt it later.

3. Enter a **password**.

Now you will get a question whether the user is allowed to generate C-code for this encrypted submodel? If you want the users of this model to generate C-code choose yes. If you want to disclose the code of the submodel and prevent C-code generation, choose no.

Note: You can also encrypt a complete model using the **Save Encrypted** command.

### 7.2.25 Decrypt Models

You can remove the encryption of model with the **Decrypt Models** command:

1. In the Editor **select the submodel** that is **encrypted**. You can recognize it from the lock symbol.
7. Editor

The lock symbol in the model menu shows that a submodel is encrypted.

2. From the Editor menu select Decrypt Model.

You can remove an encryption by selecting Decrypt Model.

Now you will be asked to enter a password. This is the password that has been used to previously encrypt it. Enter the password and the encryption is removed.

7.2.26 Documentation Editor

The Documentation Editor can be open from the File menu in the 20-sim Editor by clicking Document. The Document Editor can be used to generate an html document that can be used for Word Processors and Presentation software.

The Document Editor will generate an html document that is fully hyperlinked. From a table of contents you can click to go to the desired part of the document. You can also click in pictures to go to the desired submodels.
General Items

- **File**: Select the output file.
- **Source**: Select the whole model or parts of it.
- **Submodel**: If documentation of a part of the model should be documented, select the desired submodel.

Model

- **Table of Contents**: Select this option to start the document with a table of contents.
- **Information**: Information on the creation date, user, file location etc.
- **Structure**: The model hierarchy (list of all submodels, their submodels etc.).

SubModel

- **Information**: Information on the creation date, user, file location etc.
- **Icon**: The picture of the submodel icon.
- **Interface**: The inputs, outputs and ports.
- **Implementation**: The model implementation with equations at the lowest level.

Simulation

- **Constants**: List of the constants that are used in the model.
- **Parameters**: List of the parameters that are used in the model.
- **Initial Values**: List of the starting values of the states of the model.
- **Plots**: Show pictures of the plots.
- **Plot Properties**: Show the plot settings.
- **Frequency Response**: Show the frequency responses.
- **Favorite Parameters**: List of the favorite parameters that are used in the model.
- **Favorite Variables**: List of the favorite variables.
7. Editor

- **Variables**: List of the variables.
- **Run**: list of the run settings.
- **Multiple Run**: List of the multiple run settings.

### 7.2.27 Check for Model Updates

Most 20-sim models will be built using predefined submodels from a library. You can use the **Check for Model Updates** command of the **Models** menu to see if there are updates of these submodels. A window will open, showing you all the predefined library submodels.

![Update From Library](image)

**Items**

- **Library Paths**: This part shows the libraries that are included in the search for predefined submodels. You can select or deselect these libraries. You can add your own libraries in the **General Properties** window.
- **Models**: This part shows all the submodels of which a match has been found in the libraries.
  - **Model Name**: The local name of the submodel.
  - **Status**: Shows if the match is **older**, **equal** or **newer**.
  - **Original Filename**: Original name of the submodel file.
  - **Original Directory**: Original location of the submodel file.
  - **Model Time Stamp**: Time when the used model was saved.
  - **Library Time Stamp**: Time when the library model was saved.

**Note**

- The **Check for Model Updates** command will only check the time stamp of a model. If you have changed a submodel, without saving it, the time stamp is not altered.
To prevent models from being included in the updates check, switch off the Allow model updates option of the Model properties.

If you are not sure if a submodel should be changed, open the new library submodel in a separate Editor first.

7.2.28 Backgrounds

Graphical models may be shown with a background picture. In the Editor from the Settings menu choose the Model command to define the settings.

Static Backgrounds

Static backgrounds are just bitmap files that you can define.

Dynamic Backgrounds

Dynamic Background are .svg files in which you can enter 20-sim tokens (e.g. the model name, date, creator etc.). The tokens are replaced by 20-sim and then the .svg file has to be converted into a bitmap image. 20-sim uses the open source software Inkscape (http://inkscape.org) to make this conversion.

To get a clear understanding of this mechanism, have a look at the example model Examples\Tips and Tricks\Background images\BackgroundImage.emx. You can open it from the model library. In this model backgrounds are explained.

- In the same folder where the model is stored, a background image named background.svg can be found. This an image file which contains 20-sim specific tokens like %SUBMODELNAME% and %DESCRIPTION%. These tokens will be automatically replaced by 20-sim. Have a look at the example model to see the list of available tokens.
- In the same folder where the model is stored, an .xml file named inkscape_background.xml can be found. This is a script file that replaces the tokens and converts the .svg file into a png bitmap, using inkscape.

To create your own dynamic backgrounds:

1. Create an .svg image with the tokens that you want to use. Store it in the folder where your model is located.

2. Copy the .xml file inkscape_background.xml to your own .xml file and make it refer to the new .svg file. Store it in the folder where your model is located.

3. In the 20-sim model open the Model Properties. In the Background Image tab, select Script File and enter the name of your .xml file.

7.2.29 Naming Conventions

In 20-sim the following naming conventions are used:

Files

All files in 20-sim follow the standard windows naming conventions for filenames.

- 20-sim model files (*.emx)
• 3D animation scenery files (*.scn)
• 3D Mechanics model files (*.3dm)

**Equations**

All elements in 20-sim that will become part of the model equations should follow these naming conventions:

- A name may consist of characters (abcdefghijklmnopqrstuvwxyzABCDEFGHIJKLMNOPQRSTUVWXYZ), numbers (1234567890) or corresponding Unicode foreign language characters and numbers.
- A name may not start with a number.
- Names are case sensitive
- Spaces are not allowed

Not allowed:
- Reserved words
- Mathematical symbols (±, etc.)
- Drawing symbols and other symbols (§, #, °, etc.)

Examples of these elements are:

- Model names: models in 20-sim have a name that can be changed in the Model Properties.
- Constant names can be entered in the Equation Editor.
- Parameter names can be entered in the Equation Editor.
- Variable names can be entered in the Equation Editor.
- Port names can be entered in the Interface Editor.

**3D Mechanics Editor**

All name in the 20-sim 3D Mechanics Editor should follow these conventions:

- A name may consist of characters (abcdefghijklmnopqrstuvwxyzABCDEFGHIJKLMNOPQRSTUVWXYZ) and/or numbers (1234567890) and/or underscore (_)
- A name should start with a character.

**Plots, Labels Etc.**

Elements that will not end up in the model equations can have any name.

### 7.2.30 Keyboard Shortcuts

This is a list of keyboard shortcuts in the graph editor.

**File**

<table>
<thead>
<tr>
<th>Command</th>
<th>Shortcut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open File</td>
<td>Ctrl + O</td>
</tr>
<tr>
<td>Print</td>
<td>Ctrl + P</td>
</tr>
<tr>
<td>Save File</td>
<td>Ctrl + S</td>
</tr>
</tbody>
</table>

**Current Page**

<table>
<thead>
<tr>
<th>Command</th>
<th>Shortcut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zoom in</td>
<td>F4</td>
</tr>
</tbody>
</table>
7. Editor

Zoom reset  F5
Zoom out  F6
Zoom to fit  F7

**Editing**

<table>
<thead>
<tr>
<th>Command</th>
<th>Shortcut</th>
</tr>
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<tbody>
<tr>
<td>Undo</td>
<td>Ctrl + Z</td>
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<tr>
<td>Redo</td>
<td>Ctrl + Y</td>
</tr>
<tr>
<td>Cut</td>
<td>Ctrl + X</td>
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<tr>
<td>Copy</td>
<td>Ctrl + C</td>
</tr>
<tr>
<td>Paste</td>
<td>Ctrl + V</td>
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<tr>
<td>Duplicate</td>
<td>Ctrl + D</td>
</tr>
<tr>
<td>Delete</td>
<td>Del</td>
</tr>
<tr>
<td>Dissolve</td>
<td>Ctrl + Del</td>
</tr>
<tr>
<td>Select All</td>
<td>Ctrl + A</td>
</tr>
<tr>
<td>Send to Front</td>
<td>Alt + Shift + F</td>
</tr>
<tr>
<td>Send to Back</td>
<td>Alt + Shift + B</td>
</tr>
<tr>
<td>Group (drawing elements only)</td>
<td>Ctrl + G</td>
</tr>
<tr>
<td>Ungroup (drawing elements only)</td>
<td>Ctrl + U</td>
</tr>
<tr>
<td>Rotate Left</td>
<td>Alt + Shift + L</td>
</tr>
<tr>
<td>Rotate Left</td>
<td>Alt + Shift + R</td>
</tr>
<tr>
<td>Rotate Left</td>
<td>Alt + Shift + H</td>
</tr>
<tr>
<td>Mirror Vertical</td>
<td>Alt + Shift + V</td>
</tr>
<tr>
<td>Edit / Rename Submodel</td>
<td>F2</td>
</tr>
<tr>
<td>Toggle selection / connect mode</td>
<td>Space</td>
</tr>
<tr>
<td>Toggle Show Terminals</td>
<td>Ctrl + T</td>
</tr>
</tbody>
</table>

**Navigation**

<table>
<thead>
<tr>
<th>Command</th>
<th>Shortcut</th>
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<tbody>
<tr>
<td>Go Back</td>
<td>Alt + Left</td>
</tr>
<tr>
<td>Go Up</td>
<td>Alt + Up</td>
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<tr>
<td>Go Down</td>
<td>Alt + Down</td>
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<tr>
<td>Go Forward</td>
<td>Alt + Right</td>
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</tbody>
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**Actions**

<table>
<thead>
<tr>
<th>Command</th>
<th>Shortcut</th>
</tr>
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<tbody>
<tr>
<td>Start Simulator</td>
<td>Ctrl + R</td>
</tr>
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</table>

**Search**

<table>
<thead>
<tr>
<th>Command</th>
<th>Shortcut</th>
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<tbody>
<tr>
<td>Find</td>
<td>Ctrl + F</td>
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<tr>
<td>Find Again</td>
<td>F3</td>
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**Help**

<table>
<thead>
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<th>Command</th>
<th>Shortcut</th>
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<tbody>
<tr>
<td>Current Selected Item</td>
<td>F1</td>
</tr>
</tbody>
</table>
7.3 Compiling

7.3.1 Compiling Models

When you enter a model and open the Simulator or when you select the Check Complete Model command of the Model menu, the model will be compiled. During compilation, 20-sim will perform a number of tasks.

Error Checking

- **Type checking**: 20-sim will search for illegal type conversion and possible loss of data.
- **Unit Checking**: Many models in 20-sim use units and quantities. 20-sim will check for a proper use of these units and quantities.

Optimizing Model Structure

- **Analyze causality**: determine the causal order of equations.
- **Integral Form**: Equations are changed to integral form as much as possible.
- **Solving differential equations**: Differential equations are solved directly if possible.
- **Solving Algebraic Loops**: Algebraic loops are solved to their analytical solution, where possible.
- **Optimizing Equation Structure**: Some equations have to be calculated only once during each simulation step, because they do not influence the model dynamics. Depending on their relation to the model dynamics (needed for or a result of) these equations are calculated before the model dynamics (input equations) or after the model dynamics (output equations).
- **Remove redundant equations**: A lot of model equations are just assignments like \( \text{var1} = \text{var2} \), where one variable is already known. 20-sim reduces these equations from the model and maps the unknown variables to known variables.

After these tasks a complete equation model is created, which can be inspected using the Show Equations command of the Model menu. After the complete equation model has been created the following tasks are applied:

Compiling

- **Find the correct order of execution**: All equations will split up into their most simple form and rewritten into the correct order of execution.
- **Interpreter Code**: Create interpreter like code out of the equations. This is low level code that can be understood by the simulation algorithms.
- **Machine Code**: When you have the Built-In compiler option selected, the interpreter code is compiled into platform specific 32-bit machine code. This code uses the full power of native Pentium and 486 instructions. The result is a dramatic increase of simulation speed: 100% to 400%, depending on the kind of model used!

**Simulation Code**

The resulting code, either interpreter code or machine code, is used in the Simulator to perform simulation runs with and therefore also know as simulation code. As we have learned, the simulation code can be quite different from the original model equations. To denote the function of each original model variable in the simulation code, 20-sim uses the following names:

- independent rate
- independent state
- dependent rate
- dependent state
- algebraic loop in
- algebraic loop out
- interesting variable
- hidden variable

### 7.3.2 Causal Form

Equations within 20-sim may be entered in random form. During compilation, 20-sim will automatically try to rewrite equations into a causal form and set them in a correct order. I.e. a form where all output variables are written as function of input variables. Consider for example the following model:

```plaintext
variables
    real u,z;

equations
    u = sin(time);
    u = cos(z);
```

Here the (input) variable u is given by the equation $u = \sin(time)$. Consequently the (output) variable z should be written as a function of u. This is exactly what 20-sim will try to do while compiling the model into simulation code. I.e. the function $\cos$ will be inverted and the model will be rewritten to:

```plaintext
variables
    real u,z;

equations
    u = sin(time);
    z = arccos(u);
```

Some functions cannot be inverted. Consequently not all equations can be rewritten. 20-sim will report this to the user, during model checking.
**Fixed Causality**
For some models there is only one causal form. For example a simple iconic diagram model that describes coulomb friction can be written as:

\[
\begin{align*}
\text{parameters} \\
\quad \text{real } R_c; \\
\text{equations} \\
\quad p.F &= R_c*\text{abs}(p.v);
\end{align*}
\]

Here \( p.F \) denotes the force and \( p.v \) denotes the velocity of the powerport \( p \). The equation cannot be rewritten to a form where \( p.F \) is the input. This can be explicitly stated, by giving the powerport \( p \) a fixed causality. During compilation 20-sim will try to keep the model in this fixed form. If this is not possible an error message will be generated.

Fixed causality has the highest priority for assigning causality. During compilation 20-sim will first assign all models with a fixed causality, then all models with a preferred causality, then all models with a likes causality and then all models with an indifferent causality.

**Preferred Causality**
For some models there is a preferred causal form. For example the iconic diagram model that describes a spring can be written as:

\[
\begin{align*}
\text{parameters} \\
\quad \text{real } k; \\
\text{equations} \\
\quad p.F &= (1/k)*\text{int}(p.v);
\end{align*}
\]

Here \( p.F \) denotes the force and \( p.v \) denotes the velocity of the powerport \( p \). The equation is written in integral form which is preferred. Consequently the preferred input is the velocity. Should the force be the input, the equation must be rewritten to a differential form, which is leads to less efficient simulation. This can be explicitly stated, by giving the powerport \( p \) an preferred causality. During compilation 20-sim will try to keep the model in this preferred form. If this is not possible the equations will be rewritten to the less preferred form.

Preferred causality has a lower priority than fixed causality. During compilation 20-sim will first assign all models with a fixed causality and then all models with a preferred, likes and indifferent causality.

**Likes Causality**
For some models there is a causal form which is liked more than the other. For example the iconic diagram model that describes a parasitic volume can be written as:

\[
\begin{align*}
\text{effort in causality}(p) \text{ then} \\
\quad p.phi &= 0; \\
\text{else} \\
\quad \text{volume ratio} &= \text{int}(p.phi/V); \\
\quad p.p &= B * \text{volume ratio} + p_{\text{initial}}; \\
\text{end};
\end{align*}
\]
Here $p\.phi$ denotes the volume flow and $p\.p$ denotes the pressure of the powerport $p$. The equation is written in integral form which is liked. Consequently the preferred output is the pressure. Should the pressure be the input, the equation gives a zero flow as output. During compilation 20-sim will first try to keep all models the liked form. If this is not possible the equations will be rewritten to the other form.

Likes causality has a lower priority than preferred causality. During compilation 20-sim will first assign all models with a fixed causality and then all models with a preferred, likes and indifferent causality.

**Indifferent Causality**

For some models the causal form is not known beforehand. For example the iconic diagram model that describes a damper can be written as:

\[
\begin{align*}
\text{parameters} \\
\text{real } d; \\
\text{equations} \\
p.F = d*p.v;
\end{align*}
\]

Here $p.F$ denotes the force and $p.v$ denotes the velocity of the powerport $p$. There is no preferred input (force or velocity). This can be explicitly stated, by giving the powerport $p$ an indifferent causality. During compilation 20-sim will determine whether $p.F$ or $p.v$ is the input variable and consequently rewrite the equations.

indifferent causality has a lower priority than likes causality. During compilation 20-sim will first assign all models with a fixed causality and then all models with a preferred, likes and indifferent causality.

**Setting Causality**

For some models, the equations are too complex to analyze causality. To help 20-sim, using the right causality, you can set causality for every port in the Interface Editor.

### 7.3.3 Integral Form

Consider the following first order linear model:

![Diagram](image)

This model can be described by the dynamic equation:

\[
\text{output} = \int (\text{input} - K*\text{output} )
\]

Now look at the following model:
This model can be described by the dynamic equation:

\[
output = \frac{input - ddt(output)}{K}
\]

Note that we can rewrite this equation as:

\[
ddt(output) = input - K*output
\]

or

\[
output = \text{int}(input - K*output)
\]

This is the same equation as the previous model! Apparently, both models are the same! Both models can therefore be described by the dynamic equations:

\[
\begin{align*}
ddt(output) &= input - K*output \\
output &= \text{int}(input - K*output)
\end{align*}
\]

We call the first equation the **differential form** (no integrals). The second equation is called the **integral form** (no derivatives). In 20-sim, models can be entered in integral form as well as the differential form.

### Solving Differential Equations

During compilation, 20-sim will automatically try to rewrite equations into the integral form, since this leads to more efficient simulation. Sometimes an integral form cannot be found. Then algorithms will be applied to solve the differential directly. For example an equation like:

\[
output = ddt(sin(a*time))
\]

will be replaced by the following equation (applying the chain rule and using the known derivative for the sine function):

\[
output = a*cos(a*time)
\]

Sometimes a differential cannot be solved directly. Then only the Backward-Differentiation Methods can be used for simulation.

### Simulation Code

After compilation simulation code is generated. The equation in integral form:

\[
output = \text{int}(input - K*output)
\]

will be written as:
and can be handled by all integration methods. The equation in differential form:

\[ ddt(output) = input - K*output \]

will be written as:

\[ dependent rate = input - K*output \]
\[ dependent state = output \]

and can only be handled by the Backward-Differentiation Methods.

### 7.3.4 Algebraic Loops

An algebraic loop in a model is a loop consisting of elements without "memory like" functions. To calculate the variables in this loop, the variable values themselves are needed. Consider the following example of an algebraic loop in an amplifier with negative feedback:

\[ x = K*(u-x) \]

The variable \( x \) depends on its own value and must be solved by iteration. In 20-sim every simulation algorithm is accompanied by an iteration routine. Fortunately 20-sim is able to solve many algebraic loops at equation level. For this model this leads to the analytic solution the system:

\[ x = K*u/(1+K) \]

**Simulating algebraic loops**

Although 20-sim contains a sophisticated algorithms to find analytic solutions, the occurrence of unbreakable loops can not always be prevented. The occurrence of algebraic loops may lead to an increase of simulation time, or even stop simulation when iteration fails.

The best solution for these problems is to have a critical look at the model and change the order of calculations in a model. Possible solutions are:

- Algebraic Loops occur when the order of calculations is arbitrary. When an algebraic loop occurs in an equation model or in a set of equation models, you may change the order of calculation by rewriting the equations. The calculation order in bond graph models can be changed by introducing hand-defined causality.
• Introduce ‘parasitic’ energy storage elements (e.g. a small mass, a small capacitor etc.) to break an algebraic loop. These elements introduce however, large poles in the state equations, which might increase the simulation time considerably.

• Delete elements in the algebraic loop which are not relevant for the model’s simulation output (e.g. small dampers, very stiff springs etc.). Care should however be taken, since correct deletions are not always possible and require considerable modeling skill and intuition.

• Combine dual elements. Sometimes elements of the same type can be combined by adding the parameter values (e.g. combining a mass m1 and a mass m2 to a mass m1 + m2). This will in most cases decrease the amount of algebraic loops.

7.3.5 Order of Execution

Equations within 20-sim may be entered in random form. During compilation, 20-sim will automatically try to rewrite equations into a correct order of execution. I.e. a form where all output variables are written as function of input variables and output variables of previous lines. Consider for example the following equations:

```plaintext
variables
    real u,z;
equations
    z = sin(u);
    u = cos(time);
```

Here the (input) variable $z$ is given as a function of $u$. Consequently $u$ should be calculated first. This is exactly what 20-sim will try to do while compiling the model into simulation code. I.e. the equations will be executed as:

```plaintext
u = cos(time);
z = sin(u);
```

Code Blocks

Equations in a code block are not reordered. A code block is a set of equations inside a statement. Suppose we have the following equations:

```plaintext
if condition then
    code block 1
    ...
else
    code block 2
    ...
end;
```

To prevent incorrect executions of the if-statement, the equations of the code blocks will not be separated. Inside a code-block, equations can are not rewritten into an new order of execution. E.g. the following equations:
\[
\text{if } \text{time} > 10 \text{ then} \\
\quad z = \sin(u); \\
\quad a = z^2; \\
\quad u = \cos(\text{time}); \\
\text{end;}
\]

Will be not be reordered and therefore not correctly executed! To get correct code, enter code blocks in a correct order, e.g.:

\[
\text{if } \text{time} > 10 \text{ then} \\
\quad u = \cos(\text{time}); \\
\quad z = \sin(u); \\
\quad a = z^2; \\
\text{end;}
\]

**Prevent Order Changes**

To make all equations a code block you can use the code section. E.g.

```plaintext
parameters
    real y = 8;
variables
    real x1, x2, x3;

code
    x1 = time; \\
    x2 = sin(time); \\
    x3 = y*x1;
```

**Integration Steps**

Some integration algorithms do more calculations before generating the next output value. These calculations are called minor steps, the output generation is called a major step. During a minor step, all model equations are executed. In most cases you will not notice this because only the results of the major step are shown in the simulator. There are however, exceptions. The next topic will discuss this in more detail.

### 7.3.6 Integration Steps

Some integration methods do more calculations before generating the next output value. These calculations are called **minor steps**, the output generation is called a **major step**.

<table>
<thead>
<tr>
<th>integration method</th>
<th>minor steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euler</td>
<td>0</td>
</tr>
<tr>
<td>Backward Euler</td>
<td>variable</td>
</tr>
<tr>
<td>Adams-Bashford 2</td>
<td>0</td>
</tr>
<tr>
<td>Runge Kutta 2</td>
<td>1</td>
</tr>
</tbody>
</table>
Execution of Equations

During a minor step, all model equations are executed. In most cases you will not notice this because only the results of the major step are shown in the simulator. There is one exception. If you use equations like

```
variables
    real y;
initialequations
    y = 0;
equations
    y = y + 1;
```

you will find that the value of \(y\) depends on the integration method that is used. The reason is obvious once you realize that the equations are executed during minor steps. If you use a Runge Kutta 2 integration method, there is one minor step during which \(y\) is increased and one major step during which \(y\) is increased again!

**Major**

To prevent an equation from being calculated during minor steps, you can use the predefined variable `major`. This variable will return the boolean `false` when calculations are performed for a minor step and will return `true` when calculations are performed during a major step. The `major` variable is used for example in the library model `Amplitude Sensor`: 
parameters  
real initial = 0.0;
variables  
real prev, peak;
initialequations  
peak = initial;
prev = 0;
output = initial;
code  
if major then
  peak = max((abs(input), peak));
  if (input > 0 and prev < 0) or (input < 0 and prev > 0) then
    output = peak;
    peak = 0;
  end;
  prev = input;
end;

Note that the initial values are set in the initialequations section, because we do no want the variables to be set to zero at every integration step. Instead of an equations section, a code section is used to prevent 20-sim from rewriting the equations in a different order.

7.3.7 Show Equations

During processing a complete set of equations is generated of each model. To inspect these equations or copy them for use in other programs, you have to:

1. From the Model menu select the Check Complete Model command.
2. From the Model menu select the Show Equations command.

Now a window is popped up showing all the model equations.

The model equations after compiling.
7.4 Icon Editor

7.4.1 Icon Editor

The Icon Editor is a vector oriented drawing editor that can be used to create custom made icons for any 20-sim model. You can also use the Icon Editor to change the appearance of existing models.

Open

1. In the Editor select the model that you want to give a new appearance.
2. From the Tools menu select Icon Editor,
3. or from the right mouse menu select Edit Icon,
4. or at the bottom left of the Editor click the Icon tab and in the Icon tab double click.
Use

1. Use the **taskbar buttons** or the menu commands to insert objects and edit these objects.
2. If you are satisfied with the icon, insert the **terminals**.
3. From the Icon Editor **menu**, select **File** and **Update**.
4. **Close** the Icon Editor.

Grid

When you move objects, a grid is applied. A finer grid is obtained when you zoom in using the mouse wheel

**Tips and Tricks**

- Scroll up and down using your **Mouse Wheel**.
- You can zoom in (F4) and out (F6) by pressing the **Crtl-Key** and using your **Mouse Wheel**.
- Use a finer grid by zooming in.
- Select multiple objects by keeping the **Crtl-Key** pressed.

### 7.4.2 Terminals

Most submodels will contain ports (i.e an input signal, an output signal or a power port). If you are creating submodel icons, you want to indicate the connection points of these ports. These connection points are called **terminals**. In the Icon Editor you can define the position of the terminals.

1. In the taskbar click the **Terminal button**
2. Click with the **mouse** pointer on the position where you want to **insert a terminal**.

If you have multiple inputs, outputs or ports, a menu will open to ask you which input, output or port should be selected.
The inputs, outputs and ports are indicated by rectangles.

The terminals are visible in the drawing as small rectangles.

3. You can **select a terminal** and from the right mouse menu click **Properties**.

This will open the *Terminal Properties* showing the name of the input, output or port and the option to fixate the position. With a fixed position, the connections will start or end exactly at the position of the terminal. Without a fixed position, the connections will point to the center of the icon and start or end at the border of the icon.

![20-sim Terminal Properties](image)

*You can give a terminal a fixed position.*
Tip
1. You can see the terminals of a model in the Editor. Go to the View menu and select Show Terminals.
2. With the Show Terminals option selected, you can change the location and properties of the terminals directly in the Editor (no need to open the Icon Editor).

7.5 Global Parameters and Variables

7.5.1 Introduction
If you want to share parameter values or variable values between submodels, you can use signals from one submodel to the others. This is not always desired and it will increase the effort that you have to make in connecting submodels.

Using globals is an alternative for sharing values. By defining a parameter or variable global, we can instruct 20-sim that a parameter or variable value is shared between submodels.

Using Globals
If you want to share parameters or variables between submodels, you have to:
1. Add the keyword global to definition of the parameter or variable.
2. Define the scope of the globals, i.e. which models share the same parameters and variables?

7.5.2 Global Parameters and Variables
By adding the keyword global to a parameter or variable in the Equation Editor, its value is shared all over the model. It means that various submodels can use the same parameter or variable, but you only have to assign the value once. In equation models, the keyword global is added after the definition of the data type:

```plaintext
parameters
  real global par1 = 100 {Hz};
  real global par2;
variables
  real global var1;
  real global var2;
..```

Parameters can only be assigned a value once. The same goes for variables. In only one submodel the global variable can be assigned a value using an equation. If parameters or variables are assigned more than once, 20-sim will generate an error.

Scope
By default, global parameters and variables and valid in the entire model. However, the scope can be limited to a certain branch in your model tree.
Changing Global Parameters Values
You can change the value of a global parameter in the Parameters/Initial Values Editor. By default, global parameters and variables are valid in the entire model. In the Parameters/Initial Values Editor, you will find the parameters at the top level of the hierarchy. If the parameter has a scope, you will find it in the specific branch of the model hierarchy.

7.5.3 Scope
By adding the keyword global to a parameter or variable in the Equation Editor, its value is shared all over the model. For certain models, this is not wanted. You may want the parameter or variables only to be shared in a certain branch of the model hierarchy. This is known as limiting the scope of a global parameter or variable to a branch.

Example
Suppose we have model "RaceCar.emx" with a model hierarchy that consists of front wheels, rear wheels, and a car body. The front wheels may consist of a left and a right wheel, and each wheel has a tire, a rim, and a suspension. In the picture below, you can see the model hierarchy in the tree at the left of the Editor.

Suppose the tire and the rim models share the same parameter diameter. We can make this parameter global, so we have to specify the value only once. However, for a racecar, the diameter of the front wheels may be different from the diameter of the rear wheels. In that case, we can limit the scope of the global parameter diameter to the branch FrontWheels. This is done in the Global Relations Editor at the left bottom of the Editor as shown in the picture above.

Global Relations Editor
You can limit the scope by using the Global Relations Editor. In this editor, you can enter parameters or variables. All global parameters or variables in the same branch of the model hierarchy will share the same value.
**OneUp**
You can limit the scope by using the keyword oneup. This will allow you to define the values of a global parameter or global variable in a submodel.

**Whole Model**
If no parameter or variable is defined using the Global Relations Editor, the scope is the whole model. I.e. global parameters and variables are shared across the whole model.

### 7.5.4 Global Relations Editor
The *Global Relations Editor* is used to restrict the scope of global parameters and variables. You can find the *Global Relations Editor* at the lower left of the *Editor* by selecting the Globals tab.

1. In the *Editor*, go to the *Model Hierarchy* at the left and select the *submodel*, you want to add global parameters or variables for.
2. Select the *Globals tab* at the lower left of the Editor.

![Image](image_url)

*Select the Globals tab, put your mouse pointer on top and click Edit Global Relations.*

3. Put your **mouse pointer** in the middle of the tab. From the **right mouse menu** select **Edit Global Relations**.

This will open the Global Relations Editor. You can use this editor to enter parameters, variables and equations.
Use the Global Relations Editor to enter parameters, variables and equations.

You can enter parameters, variables and equations here just like in the Equations Editor.

4. **Do not add the keyword global!**

In the Global Relations Editor, you should not add the keyword global. If you do, the scope is not limited anymore.

**Errors**

If you have made errors in the Global Relations Editor:

1. Click Check Complete Model. Any error will be then be displayed in the Process tab.
2. Click on the error in the Process tab and you will see it highlighted in the Global Relations Editor.
7.6 Interface Editor

7.6.1 Interface Editor

The Interface Editor can be used to define the interface, i.e. the input signals, output signals and power ports of a submodel.

Open

1. In the Editor select the model of which you want to change the interface.
2. From the Tools menu select Interface Editor,
3. or from the right mouse menu select Edit Interface,
4. or at the bottom right of the Editor click the Interface tab and in the Interface tab double click.

Use

1. Use the Edit menu to add ports to the list.
2. Select a port from the list and change its properties (make it an input signal, output signals and power ports etc.)
3. From the Interface Editor menu, select File and Update.
4. **Close** the Interface Editor.

**Tips**

1. Use the **Move Up** and **Move Down** buttons to order the list of ports.

### 7.6.2 Port Properties

From the *Edit* menu select *Add Port*. A new port will now be added to the list. If you select the port in the list you can change its properties

- **Name**: Enter the name of the port.
- **Type**: Select the port-type: Signal, Iconic Diagram or Bond Graph.

**Signal**

- **Size**: If the signal is multi-dimensional, enter the number of rows and columns.
- **Orientation**: Choose input signal or output signal.
- **Quantity**: If the signal represents a physical quantity, you can choose the quantity from a predefined list.
- **Unit**: If the signal represents a physical quantity, you can choose the corresponding unit from a predefined list.
- **Type**: The default type of a signal is a real number. Choose out of *real*, *integer* or *boolean*.

**Iconic Diagram**

- **Size**: If the port is multi-dimensional, enter the number of rows and columns.
- **Orientation**: Choose an input or output orientation for the port.
- **Domain**: Choose the physical domain of the port. The most general domain is power. Depending on your choice you will see the two variables (Across and Through) associated with the port.
- **Causality**: Select the causality of the port.
- **Separate High/Low Terminals**: You may choose this option for models with a velocity difference, voltage difference etc.
- **Any Number of Terminals**: You may choose this option for models with a variable number of connections.

**Bond Graph Port**

- **Size**: If the port is multi-dimensional, enter the number of rows and columns.
- **Orientation**: Choose an input or output orientation for the port.
- **Domain**: Choose the physical domain of the port. The most general domain is power. Depending on your choice you will see the two variables (Effort and Flow) associated with the port.
7. Editor

- **Causality**: Select the causality of the port.

### 7.6.3 Orientation

In the *Interface Editor* you can set the orientation of a port. In the *Editor* this orientation can be made visible by setting the Orientation Info command from the *View* menu. Depending on the type of port the orientation has a different meaning.

- **Signals**: For signals the orientation indicates the direction of the associated variable: input or output.
- **Bond Graphs**: The orientation of a bond graph port is the direction of the half arrow at the end of a bond. It indicates the direction of the positive power flow.
- **Iconic Diagrams**: The orientation of an iconic diagram port also indicates the direction of the positive power flow.

If you select the top of the list in the Interface Editor, you can choose the *Port Relations* tab to set multiple port relations:

- **Equal / Not equal**: The equal and not equal restrictions can be used to specify that a port p1 must have the same or opposite orientation as port p2.

### 7.6.4 Causality

A powerport is always characterized by two variables. One of these variables should be an input and one of these variables should be an output. The choice of input and output variable is called causality. In the *Interface Editor* you can set the causality of the ports of a submodel. The following causal forms can be chosen:

1. **Fixed out**: One of the two variables is always an output variable.
2. **Preferred out**: One of the two variables is preferably an output variable.
3. **Likes**: Same as preferred out but with lower priority: one of the two variables is preferably an output variable.
4. **Indifferent**: A powerport with an indifferent causality restriction can have both variables as output.

During processing, the assignment of the causal forms goes with the rank in the list. First all elements with a *fixed out* assignment are set, then the elements with a preferred out assignment, then with a likes assignment and finally with an indifferent assignment.

If you select the top of the list in the *Interface Editor*, you can choose the *Port Relations* tab to set multiple port restrictions:

- **Equal / Not equal**: The equal and not equal restrictions can be used to specify that a powerport p1 must have the same or opposite causality as powerport p2. This is denoted as p1 equal p2 and p1 not equal p2 respectively.
- **One_out**: The restriction One_out should only be used for bond graph ports. It is used to indicate that at a one or zero junction, only one bond may have an effort out causality.
7. Editor

- **One_in**: The constraint restriction One_in should only be used for bond graph ports. It is used to indicate that at a one or zero junction, only one bond may have an effort in causality.

In the Editor this causality can be made visible by setting the Causality Info command from the View menu.

### 7.6.5 Ports with more than one Terminal

By default, an iconic diagram port is a port where power can be exchanged between a component and its environment in terms of an across variable and a through variable. Such a port is represented by one terminal (connection point). However, there are two special cases where it is desirable to define an iconic diagram port that has more than one terminal.

#### Separate High / Low Terminals

Consider, as an example, a mechanical spring. The power that flows into such a component is uniquely determined by the velocity difference between the two terminals of the component and the common force that acts upon both ends. Because of this one could say that there is one port, whose power is determined by one across value (the velocity difference) and one through value (the common force), but is represented by two terminals. To support this, 20-sim allows you to define a special type of iconic diagram port by indicating that is has **Separate High / Low Terminals**. The two terminals of the connection are named **high** and **low**. If the port is named \( p \), the formal equations are:

**fixed in orientation:**

\[
\begin{align*}
p.F &= p\text{\_high}.F = p\text{\_low}.F \\
p.v &= p\text{\_high}.v - p\text{\_low}.v
\end{align*}
\]

**fixed out orientation:**

\[
\begin{align*}
p.F &= p\text{\_high}.F = p\text{\_low}.F \\
p.v &= -p\text{\_high}.v + p\text{\_low}.v
\end{align*}
\]

In 20-sim these equations are automatically derived.

#### Any Number of Terminals

Consider, as an example, a mass. A characteristic of this component is that you can connect many springs and dampers to it. Implicitly, one expects that the net force (i.e., the summation of the forces applied by the connected components) will be applied to the mass, and that it will have a single velocity. To support this, 20-sim allows you to define a special type of iconic diagram port by indicating the kind to be **Any Number of Terminals**. The terminals of the connection are named \( 1, 2, 3 \) etc.. If the port is named \( p \), the formal equations are:

**fixed in orientation:**

\[
\begin{align*}
p.v &= p1.v = p2.v = p3.v = \ldots \\
p.F &= \text{sign1}\cdot p1.F + \text{sign1}\cdot p2.F + \text{sign1}\cdot p3.F + \ldots
\end{align*}
\]

**fixed out orientation:**


\[ p.v = p1.v = p2.v = p3.v = ... \]
\[ p.F = -\text{sign1}*p1.F - \text{sign1}*p2.F - \text{sign1}*p3.F - ... \]

with

\text{sign} = 1 \text{ when } p1 \text{ has a fixed in orientation etc.}
\text{sign} = -1 \text{ when } p2 \text{ has a fixed out orientation etc.}

In 20-sim these equations are automatically derived.

### 7.7 Domains, Quantities and Units

#### 7.7.1 Domains, Quantities and Units Editor

At various modeling levels you can use information on physical domains, quantities and units. This information is stored in the file \textit{QuantitiesAndUnits.ini} in the 20-sim bin directory. To edit this information you can use the \textit{Domains, Quantities and Units Editor}. When opened, the editor automatically reads the file \textit{QuantitiesAndUnits.ini}. When closed the editor asks you where to store the file. Note that any changes made become effective after 20-sim has been restarted.

![The Domains, Quantities and Units Editor.](image)

You can start the \textit{Domains, Quantities and Units Editor} by selecting the \textit{Units Editor} command from the \textit{Tools} menu. In the editor a tree-like structure is shown indicating the available Domains, Quantities and Units.

1. You can select every items in the tree for editing.
2. Use the **Add** or **Delete** button to add new items or delete existing item.

3. Use the **Find button** to find items in the tree.

### 7.7.2 Domains

In the Interface Editor every powertport (Iconic Diagram or Bond Graph) can be assigned a physical domain. 20-sim will use this information to prevent that ports of different physical domains may be connected. More popular: in this way you can never connect a translation model to an electric component.

![Interface Editor](image)

*Use the Interface Editor to assign a physical domain to a port.*

In the *Interface Editor* you can select the physical domain that you want to assign to a port. The editor will show the corresponding port variables and the notation that should be used in the model equations.

The tables below show the available domains and their respective port variables.

<table>
<thead>
<tr>
<th>power domain</th>
<th>across</th>
<th>through</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>across</td>
<td>through</td>
</tr>
<tr>
<td>Mechanical</td>
<td>velocity</td>
<td>force</td>
</tr>
</tbody>
</table>
Translation | velocity | force
Rotation | angular velocity | torque
Pneumatic | pressure | air flow
Thermal | temperature | entropy flow
Electric | voltage | current
Hydraulic | pressure | volume flow
Magnetic | magnetomotoric force | magnetic flux

For the power domains the variables multiply to **power**. There are also some domains defined where the variables do not multiply to power. These are called **pseudo domains**. The following pseudo domains are defined.

**pseudo domain** | across | through
--- | --- | ---
Pseudo Pneumatic | pressure | mass flow
PseudoThermal | temperature | heat flow
PseudoThermalH | temperature | enthalpy flow
PseudoHydraulic | pressure | mass flow

You can enter new (pseudo) domains in the Domains, Quantities and Units Editor. If the port is defined as a bond graph port, effort and flow are used to indicate the domain variables. The corresponding tables are shown below.

**power domain** | effort | flow
--- | --- | ---
Power | effort | flow
Mechanical | force | velocity
Translation | force | velocity
Rotation | torque | angular velocity
Pneumatic | pressure | air flow
Thermal | temperature | entropy flow
Electric | voltage | current
Hydraulic | pressure | volume flow
Magnetic | magnetomotoric force | magnetic flux

**pseudo domain** | effort | flow
--- | --- | ---
Pseudo Pneumatic | pressure | mass flow
PseudoThermal | temperature | heat flow
PseudoThermalH | temperature | enthalpy flow
PseudoHydraulic | pressure | mass flow
7.7.3 Quantities and Units

In 20-sim, to every constant, parameter and variable a quantity may be assigned. Well known quantities are for example position, velocity, time and energy. 20-sim will use these quantities to check the validity of (basic) equations. The value of a quantity can be expressed in a specific unit. The quantity time can for example be expressed in the unit second or in the unit minute:

<table>
<thead>
<tr>
<th>quantity</th>
<th>unit</th>
<th>multiplication to SI unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>second (SI unit)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>minute</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>hour</td>
<td>3600</td>
</tr>
<tr>
<td></td>
<td>day</td>
<td>86400</td>
</tr>
<tr>
<td></td>
<td>year</td>
<td>31556926</td>
</tr>
<tr>
<td>Position</td>
<td>meter (SI unit)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>foot</td>
<td>0.3048</td>
</tr>
<tr>
<td></td>
<td>inch</td>
<td>0.0254</td>
</tr>
<tr>
<td></td>
<td>yard</td>
<td>0.9144</td>
</tr>
</tbody>
</table>

In 20-sim a quantity can be expressed in every desired unit. To prevent conversion problems, internal calculations are always performed in standard SI-units. Therefore non-SI units are stored with a multiplication factor. When a variable has a unit, the unit can also have common engineering prefixes. For example, a parameter \( m \) \{kg\} with a value of 0.1 can be selected in the Parameters / Initial Values Editor. If you click on the unit, you can select other units to enter the mass.

You can use the units in the Parameters / Initial Values Editor to select a desired unit.

You can enter new quantities and units in the Domains, Quantities and Units Editor.
7. Editor

7.7.4 Editing Domains

You can edit existing domains or add new domains in the Domains, Quantities and Units Editor. In the Domains section you can add new domains or edit existing domains. Each domain has several edit fields:

- Domain name: If you click on a selected domain in the tree, you can edit the name.
- Description: Enter a description of the domain.
- Quantities: You can enter quantities of these variables in the quantities section.
- Mechanical Domain: Select this button if your domain is part of the mechanical domain.
- Pseudo Domain: Select this button if your domain is a pseudo domain.
- Color: Double-click the color box to change the color of a domain.

In some domains the integrated effort/flow variables and differentiated effort/flow variables are of a specific quantity. You can enter these quantities in the according edit fields. For some domains these values have no meaning and you can leave the edit fields blank.

7.7.5 Editing Quantities

You can edit existing quantities or add new quantities in the Domains, Quantities and Units Editor. In the Quantities section you can add new quantities or edit existing quantities. Each quantity has several edit fields:

- Quantity name: If you click on a selected quantity in the tree, you can edit the name.
- Description: Enter a description of the quantity.
- Variable name: This name is used for display purposes. For example if one of the variables of a port p has the quantity length it will be denoted as p.x.
- SI Symbol: Enter the official SI-symbol here. Enter combinations as nominator/denominator (e.g. Electric Resistance: kg.m2/A2.s3)
- Units: Every quantity can be expressed in several unique units (i.e. a unit can be assigned to one quantity only). You can enter new units here or edit existing units that belong to the selected quantity.
- Unit Symbol: For display purposes every unit has a specific symbol. It is shown here in a read-only field.

A quantity can have an alias name. Enter this alias as a subentry of the main quantity. This alias name refers to the main quantity and therefore to the same associated units.
7.7.6 Editing Units

You can edit existing units or add new units in the Domains, Quantities and Units Editor. In the Units section you can add new units or edit existing units. Each unit has several edit fields:

- **Unit name**: If you click on a selected unit in the tree, you can edit the name.
- **Description**: Enter a description of the unit.
- **Quantity**: Choose the quantity to which the unit should be associated. A unit can be associated to one quantity only.
- **Symbol**: For display purposes every unit has a specific symbol.
- **Multiplications**: A quantity can be expressed in several units. To prevent conversion problems, internal calculations are always performed in standard SI-units. Therefore non-SI units are stored with a multiplication factor. You can enter the multiplication factor here.
- **Allow Symbol Prefixes**: Some units can be expressed with symbol prefixes. Select the check box to allow the use of prefixes. 20-sim supports the following prefixes:

<table>
<thead>
<tr>
<th>prefix</th>
<th>symbol</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>femto</td>
<td>f</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>pico</td>
<td>p</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>nano</td>
<td>n</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>micro</td>
<td>u</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>milli</td>
<td>m</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>centi</td>
<td>c</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>deci</td>
<td>d</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>hecto</td>
<td>h</td>
<td>$10^{2}$</td>
</tr>
<tr>
<td>kilo</td>
<td>k</td>
<td>$10^{3}$</td>
</tr>
<tr>
<td>mega</td>
<td>M</td>
<td>$10^{6}$</td>
</tr>
<tr>
<td>giga</td>
<td>G</td>
<td>$10^{9}$</td>
</tr>
<tr>
<td>tera</td>
<td>T</td>
<td>$10^{12}$</td>
</tr>
</tbody>
</table>

**Example**

```plaintext
parameters
real mylength = 1 {cm}; // equal to: 0.01 {m}
```


7.8 FMI Support

7.8.1 FMI Standard

**FMI Standard**

20-sim supports the *Functional Mock-up Interface (FMI)* standard (http://fmi-standard.org/) for tool independent exchange of simulation models. The FMI defines an interface to be implemented by an executable called **FMU** (*Functional Mock-up Unit*). The FMI functions are called by a simulation environment to create one or more instances of the FMU and to simulate them, typically together with other models. An FMU may either have its own solvers (FMI for *Co-Simulation*) or require the simulation environment to perform numerical integration (FMI for *Model Exchange*). The FMI standard has currently two versions FMI 1.0 and FMI 2.0.

A simulation tool that can import and simulate one or more FMUs is a FMI master. The FMU is a FMI slave.

**FMI Support in 20-sim**

20-sim implements the FMI 2.0 interface for *Co-Simulation*. 20-sim supports both importing and exporting FMUs. You can import an FMU in 20-sim as a special submodel and you can export a 20-sim submodel as an FMU. 20-sim implements an FMI master algorithm to run an FMU inserted into your model.

20-sim 5.1 supports:

**Import**

- FMI 2.0 Co-Simulation FMU

**Export**

- FMI 1.0 Co-Simulation FMU (Standalone)
- FMI 2.0 Co-Simulation FMU (Standalone)
- FMI 2.0 Co-Simulation FMU (Tool-wrapper)

with:

- **Standalone**: This FMU can be exported from a 20-sim submodel using C-code generation. It does not depend on the original 20-sim model or your 20-sim license and can be used standalone. However, this type of FMU can only be exported if the submodel is exportable as C-code.

- **Tool-wrapper**: This FMU can be exported from a 20-sim model with a Co-simulation Interface. A tool-wrapper FMU is a communication FMU that opens the original model in the modelling tool and takes care of remotely executing the co-simulation steps inside 20-sim. It uses the 20-sim Scripting Toolbox to communicate with 20-sim to exchange inputs/outputs and parameters.
7.8.2 Co-simulation Interface

The 20-sim tool-wrapper FMU uses 20-sim and its simulator to simulate the model. To exchange input and output signals between 20-sim and the FMI master (co-simulator), you will need to extend your model with special variables that can be set or read by the FMI master. These variables are the co-simulation inputs and outputs. They can be defined in the model in an equation section called `externals`:

```plaintext
externals
    real global export mycosimOutput;
    real global import mycosimInput;
```

To make it possible to set or read a parameter by the co-simulation engine, it should be marked as `'shared'`:

```plaintext
parameters
    // shared design parameters
    real mycosimParameter ('shared') = 1.0;
```

The next step is to export a tool-wrapper FMU for the prepared model. See FMU Export for the details.

7.8.3 FMU Import

You can import an FMU directly in 20-sim for co-simulation within 20-sim itself. Presently 20-sim can only import FMI 2.0 co-simulation FMUs. Follow these steps to import an FMU in 20-sim:

1. Copy/move the FMU to the same folder as your model. This is not required but recommended to prevent embedding hardcoded paths in your model.

2. Using Windows Explorer, drag the FMU file on your 20-sim model (see the Figure below). Alternatively, you can use the menu option `Insert, Submodel, FMI 2.0 Co-simulation Import` to import an FMU.
This creates a new submodel with a blue icon that acts as an FMU wrapper. FMU inputs and outputs are translated into 20-sim submodel inputs and outputs. FMU parameters (scalar variables with causality “parameter”) are also available in 20-sim. This means that you can alter the default values of these FMU parameters in 20-sim. The altered FMU parameters are transferred to the FMU during the initialization mode phase of the FMU.

### 7.8.4 FMU Export

20-sim can export two types of FMUs:

**Standalone FMU**

This FMU can be exported from a 20-sim submodel using C-code generation. It does not depend on the original 20-sim model or your 20-sim license and can be used standalone. However, this type of FMU can only be exported if the submodel is exportable as C-code.

To export a **Standalone FMU**:

1. Select a submodel
2. Select the *File* menu
3. Select *Export*
4. Select the option *FMI 1.0 Co-Simulation FMU Export (standalone)* or *FMI 2.0 Co-Simulation FMU Export (standalone)*
5. This will ask for a Folder in which your FMU will be generated

**Limitations:**

The following 20-sim language features that are not supported, (or are only partly supported) for standalone FMU export, are:

- **Hybrid models**: Models that contain both discrete- and continuous time sections cannot be generated at once. However, it is possible to export the continuous and discrete blocks separate.
- **File I/O**: The 20-sim “Table2D” block is supported; the “datafromfile” block is not yet supported.
- **External code**: Calls to external code are not supported. Examples are: DLL(), DLLDynamic() and the MATLAB functions.
- **Variable delays**: The tdelay() function is not supported due to the requirement for dynamic memory allocation.
- **Event functions**: Timeevent(), frequencyevent() statements are ignored in the generated FMU.
- **Fixed-step integration methods**: Euler, Runge-Kutta 2 and Runge-Kutta 4 are supported.
- **Variable-step integration methods**: Only Vode-Adams is supported.
- **Implicit models**: Models that contain unsolved algebraic loops are not supported.
**Tool-wrapper FMU**

This FMU can be exported from a 20-sim model with a Co-simulation Interface. A tool-wrapper FMU is a communication FMU that opens the original model in the modelling tool and takes care of remotely executing the co-simulation steps inside 20-sim. It uses the 20-sim Scripting Toolbox to communicate with 20-sim to exchange inputs/outputs and parameters.

To export a **Tool-wrapper FMU** for your 20-sim model:

1. Extend the model with a *co-simulation interface*. See the page Co-simulation Interface for the details.
2. Select the *File* menu
3. Select *Export*
4. Select the option *FMI 2.0 Co-Simulation FMU Export (Toolwrapper)*
8 Simulator

8.1 Introduction

8.1.1 Simulator

20-sim consists of two main windows and many tools. The first window is the \textit{Editor} and the second is the \textit{Simulator}. The \textit{Editor} is used to enter and edit models. The \textit{Simulator} is used to simulate and analyze the models. The Simulator is opened in the \textit{Editor} by clicking the \textit{Start Simulator} button from the \textit{Model} menu.

\begin{center}
\includegraphics[width=0.7\textwidth]{simulator.png}
\end{center}

\textit{The Simulator is used to carry out simulations, show the results and analyze them.}

The \textit{Simulator} consists of three parts:

- \textit{Simulator Tree}: This is the tree at the left. Here plots and plot windows can be added.
- \textit{Simulation Plot}: This is the graph in the middle. Here the simulation results are shown.
- \textit{Output tab}: The \textit{Output tab} shows warnings and messages.

\textbf{Settings}

After the model has been successfully entered, it must be checked and compiled to generate simulation code. This is done in 20-sim automatically when you open the \textit{Simulator} or when you check a model. In some cases the model contains errors which have to be solved by adapting the model. Errors in 20-sim are presented in the \textit{Process tab} at the bottom of the \textit{Editor}. After a successful compilation of a model that is created in the Editor you can open the Simulator. In the Simulator you have to enter specific settings:

- Parameters / Initial Values.
- Run Properties.
8. Simulator

- Plot Properties.

**Running**
After the settings have been entered you can run the simulation.

**Plotting**
Simulation results can be shown in 20-sim as:
- Numerical Plots:
  - Time Domain (default)
  - Frequency Domain (FFT Analysis & Linearization)
- Animation in a Graphical Model
- 3D Animation

**Debugging**
If you experience problems during simulation you have to resolve them in a debugging session.

**Analysis**
After a successful simulation you can analyze your model using various tools:
- Parameter Sweeps
- Curve Fitting
- Optimization
- Sensitivity Analysis
- Monte Carlo Analysis
- Variation Analysis
- FFT Analysis
- Linearization

**Message Log**
The bottom of the Simulator shows a tab named *Output*. This tab contains the *Message Log* which shows all the messages, warnings and errors, that are generated during a simulation.


8. Simulator

8.2 Running a Simulation

8.2.1 Parameters and Initial Values

The Parameters/Initial Values Editor is used to edit the constants, parameters and initial values of a model. Parameters and initial values can be changed during simulation, constants cannot be changed. To open the Parameters/Initial Values Editor, you have to:

1. In the Simulator, choose Properties - Parameters or in the Editor, choose Model - Show Parameters.

The Parameters/Initial Values Editor.

The parameter items (Name, Value, Quantity, Unit, Description, Kind, Arithmetic Type, Attributes, Value) of the parameters and initial values are listed in right part of the window. The list of parameters and initial values that is displayed depends on the selected submodel in the left part of this window.

Items

- **Model Hierarchy**: The left part displays the complete model hierarchy. At each level of the hierarchy, submodels can be selected. The right part of the window then shows the parameters and initial values of that submodel. To see all parameters and initial values, select the top level of the hierarchy, i.e. the main model listed on top.

- **Parameters and Initial Values**: The order of the parameters or initial values in the list depends on the order in which the submodels were originally entered in the Editor. Click on the name box to make the order to alphabetical. Drag the name box to change the width of the parameters list.
8. Simulator

- **Value**: You can change the default value of a parameter or initial value in the value list. Select the parameter or initial value (mouse) and enter the desired value. Use the Enter key to quickly run through a list of parameters.

- **Unit**: If available, select the desired Unit from the drop down list.

- **Attributes**: Parameter may be limited in range or made read only. If so, these limits are listed in the Attributes.

- **From Matlab / To Matlab**: Use the buttons to import or exports parameter values from or to Matlab.

- **Expand Vectors/Matrices**: Select this option to see the individual members of matrices and vectors.

- **Show Hidden**: Hidden parameters are by default not visible. Select this option to show hidden parameters.

- **Import**: Use this button to import the parameter values from another model.

**Commands**

If you select a model or submodel in the hierarchy tree several command are available using the right mouse menu:

- **Copy Parameters (for parameters or Constants)**: Of the selected (sub)model, copy the parameter name, value and other properties to clipboard for use in a spreadsheet or file.

- **Copy Initials (for Initial Values)**: Of the selected (sub)model, copy the initial value name and other properties to clipboard for use in a spreadsheet or file.

- **Initials to Zero**: Of the selected (sub)model, set the initial values to zero.

If you select a parameter, initial value or several command are available using the right mouse menu:

- **Copy Value**: Copy the value to clipboard.

- **Copy with Unit**: Copy the value and unit to clipboard.

- **Copy Specified**: Specify what to copy to the clipboard.

**Note**

- All equations in 20-sim are calculated using standard SI-units. You can however enter parameters, using whatever Unit you like. In the Parameters/Initial Values Editor, you can change the unit using the little drop down list next to the Value box.

- The description of a parameter can be specified in the parameters part of the equation description of a model.

- To see a global parameter, select the top level of the hierarchy, i.e. the main model listed on top.
8.2.2 Run Properties

The Run Properties Editor can be used to choose the integration method used for simulation. An integration method is the algorithm that calculates the model equations during each simulation and generates the output values for the simulation plots. The default integration method is the Backward Differentiation Formula (BDF).

The most important properties that you can set are:

1. Start: the start time of the run.
2. Finish: the finish time of the run.
3. Integration Method: The integration method that is used.
4. Step Size: If you click the Set Properties button, you can set the (maximum) step size.
5. Accuracy: If you click the Set Properties button, you can set the absolute and relative error.

To open the Run Properties Editor, you have to:

1. From the Properties menu select the Run command.

The Run Properties Editor.

Initially, the fields in the Run Properties Editor contain default values if no experiment was loaded. Two or more tabs can be selected:

- **Simulator**: This tab shows the general simulation settings.
8. Simulator

- **Discrete Systems**: This tab is only visible when discrete systems are part of your model. It contains the settings for the sample frequency.
- **Algebraic Relations Solver**: This tab is only visible when your model contains algebraic loops that could not be solved during processing.
- **Integration Method**: The last tab contains the specific settings for the selected integration method.

**More / Less**

Using the **More** button you can set advanced settings:

**Event handling**

**Realtime Simulation**

Realtime simulation is useful when you want a simulation to run as fast as the real time. E.g for 20-sim models that are used for training simulators or models which are coupled to external devices that run in real time.

- **Attempting Realtime Simulation**: Section the **On** option, to run a simulation as fast as the real time or a multiple that you can set with the **Speed Factor**.
- **Maximum Allowed Lost Time**: With variable step simulation, a large model may not always run fast enough to run real time during the whole simulation. You can set the number of ms delay that is allowed.

**Finish**

**8.2.3 Plots**

The simulation plots are shown in the **simulator tree** at the left of the simulator window.

![Simulation Plots](image)

You can open additional plots in 20-sim.
You can expand the simulator tree to see the plot windows. A plot window can contain one or more plots. A plot contains one or more curves. The curves show the simulated values of a chosen variable or parameter.

**Plot Windows**

A plot window contains the simulator tree and one or more plots. In the simulators tree, using the right mouse menu you can add or delete plot windows. You can also open a new plot window using the View menu of the Simulator.

**Plot**

You can add plots to a plot window. 20-sim supports the following plots:

1. Plot: a standard plot showing one or more variables.
2. 3D Animation: a 3D Animation showing objects in 3D.
3. FFT Plot: a plot showing the FFT transform.

Using the right mouse menu you can quickly:

- **Add, delete, cut, copy** and **paste** plots.
- Change the appearance of a plot by selecting Plot Properties.
- **Hide** and **Show** plots.
- **Disable** and **Enable** plots.
- **Move** plots **Up** and **Down**.
- **Rename** plots

**Note**: With hide plot, the plot information is still calculated during simulation. If you use a large amount of plots this will affect memory space. With disable plot, the information is not calculated during simulation. This will save memory.

**Curve**

Each plot may contain one or more curves. Using the right mouse menu you can quickly:

- Add, delete, copy and paste curves.
- **Move** curves **Up** and **Down**.
- Change the variable by selecting Curve Properties.
8.2.4 Plot Properties

The Plot Properties Editor can be used to enter the plot specifications. To open the Plot Properties Editor, you have to:

1. From the Properties menu select the Plot command.

The editor shows three tabs which can be used to set the properties of the plot and the x and y variables.

**Plot Properties Tab**

The Plot Properties Tab shows the general settings that accompany a plot. A preview is shown in the lower part of the tab.

- **Plot Title**: Select this option to add a title to the plot. In the text box you can type the desired title. Use the radio buttons to display the title to the left, in the middle or to the right of the plot.
- **Color Themes**: Use this option to select a different theme for the plot.
- **Colors**: Click the drop down list and choose the colors for the various plot options.
- **Grid**: Select this option to show the grid.
- **Background**
  - **Windows Default**: Select this option to get the default Windows background.
8. Simulator

- **3D Look**: Select this option to get a plot with 3D Look (sunken edges).
- **Axes**:
  - Select the options *Logarithmic X* and *Logarithmic Y* to show logarithmic plots.
  - *Show X-Values*: Use this option to show or hide the X-axis values.
  - *Show Legend*: Use this option to show or hide a legend.
- **Fonts**: Click the *Title*, *Values* and *Labels* buttons to select the font options for the title, values and labels.
- **Apply To**: You can select here to apply the changes to: 1) All plots in the model, 2) All plots in the window, 3) only this plot or 4) Set it as default for all future plots.

**X-Axis Tab**

The *X-Axis Tab* can be used to specify the variable plotted along the X-axis.

![The X-Axis tab of the Plot Properties Editor.](image)

- **Variable Name**: The time, a variable or a parameter can be chosen as the X-axis variable. Click the button on the right (Choose) to open the Variable Chooser and select the desired variable or parameter. You can also type the variable name directly.
- **Label**: Enter the label that should be printed below the X-axis.
- **Show Unit**: Select this option to display the unit of the chosen variable.
• **Scaling**
  
  • *Manual*: Fix the scale of the X-axis by selecting a minimum and maximum value in the From and To boxes.
  
  • *Post*: During the simulation run, the scale for the variable along the axis is fixed. When the run is finished or has been interrupted by the user, the minimal and maximal scale values are automatically updated and the plot is redrawn to make sure all calculated points are displayed.
  
  • *Automatic*: When a variable reaches the end of the scale, during simulation, the minimal and maximal scale values are automatically updated and the plot is redrawn to make sure all calculated points are displayed.
  
  • *Clip to Bounds*: When a variable reaches the end of the scale, during simulation, the minimal and maximal scale values are automatically updated and the plot is redrawn to make sure all calculated points are displayed. When the run is finished or has been interrupted by the user, the minimal and maximal scale values are automatically updated to show the plot at maximum scope.
  
  • *Show Values*: Use this option to show or hide the X-axis values.

**Y-Axis Tab**

The Y-Axis Tab is used to specify the curves that should be shown in the plot. For each selected curve, a tab is shown, displaying the settings of that curve.
The Y-Axis tab of the Plot Properties Editor.

Curves

- **Add Curve**: Add a new tab to specify a new curve to be displayed in the plot.
- **Delete Curve**: Delete the selected tab. As a result, the curve specified in the tab will not be displayed in the plot, and the settings are lost.
- **Variable Name**: Use this box to connect a variable to a curve. One of the dynamic variables of the model can be selected or a parameter. Click the button on the right (Choose) to open the Variable Chooser and select the desired variable or parameter. You can also type the variable name directly.

- **Label**: Enter the name of the curve. This label is also printed next to the Y-axis.
- **Show Unit**: Select this option to display the unit of the chosen variable.
- **Line Properties**
  - **Line Style**: Select the desired line style of the curve.
  - **Thickness**: Select the desired line thickness of the curve. You can set the default line thickness in the General Properties dialog.
  - **Color**: Select the desired line color of the curve.
• **Order**: In the plot a line is drawn from plot point to plot point. You can choose the line to be of two orders of interpolation:
  - Zero: the line consists only of horizontal and vertical parts.
  - First: the line consists of straight parts.

• **Tick Style Properties**
  - **Tick Style**: Each calculated point of a curve, can be displayed by a special marker. Select here the desired marker.
  - **Min. Distance (pixels)**: To prevent markers from being drawn on top of each other, you can set the minimum distance between markers. Points that are to close to a previous marker are not drawn with a marker.
  - **Color**: Select the marker.

• **Multiplication/Offset**: add an optional scaling and offset to the selected variable before displaying in the plot
  - m: scale (multiply) the selected variable with this value before plotting.
  - a: Y-axis offset before scaling
  - b: Y-axis offset after scaling

• **Scaling**: Scaling can be selected for each curve individually or combined for all curves.
  - **Shared Y Axes**: Select this option to use one Y-axis scale for all curves.
  - **Manual**: Fix the scale of the variable by selecting a minimum and maximum value in the From and To boxes.
  - **Post**: During the simulation run, the scale for the variable along the axis is fixed. When the run is finished or has been interrupted by the user, the minimal and maximal scale values are automatically updated and the plot is redrawn to make sure all calculated points are displayed.
  - **Automatic**: When a variable reaches the end of the scale, during simulation, the minimal and maximal scale values are automatically updated and the plot is redrawn to make sure all calculated points are displayed.
  - **Clip to Bounds**: When a variable reaches the end of the scale, during simulation, the the minimal and maximal scale values are automatically updated and the plot is redrawn to make sure all calculated points are displayed. When the run is finished or has been interrupted by the user, the minimal and maximal scale values are automatically updated to show the plot at maximum scope.
  - **Show Values**: Select or de-select this option to show or hide the name and scale of a curve.
  - **Separate X-Axis**: If you want another x-axis than specified in the X-axis tab, click the Choose button to select the desired variable.
8.2.5 Running a Simulation

After specification of the Parameters/Initial Values, the Run Properties and Plot Properties you can start a simulation run by choosing the appropriate command from the Simulation menu.

- **Run**: Select the Run command to start or continue a simulation run. Once a run is started, the Stop command becomes active. The run can be interrupted by selecting this command.

- **Stop**: Use the Stop command to interrupt a simulation. Once a simulation has stopped it can be continued by selecting the Start Simulation command.

- **Clear**
  - **All Runs**: Select the Clear All Runs command to clear all runs that were performed, from the graphical screen and from the computer memory.
  - **Last Run**: Select the Clear Last Run command to clear the run that was performed last, from the graphical screen and from memory.
  - **Previous Runs**: Select the Clear Previous Runs command to clear all runs, but the last, from the graphical screen and from memory.

- **One Step**: Use the One Step command to calculate one new simulation point. Using this command repeatedly, allows you to run a simulation step by step.

- **Brute Force**: Using the Brute Force command, curves are displayed after complete calculation of a simulation run. This saves time (re)drawing curves during calculations and therefore considerably speeds up simulation.

- **Multiple Run**: Select the Multiple Run command to start multiple runs needed for the **Time Domain Toolbox**. Runs can be interrupted by selecting the Stop command.

- **Replay**
  - **3D Animation**: Any 3D Animation that was performed during a simulation run, can be quickly replayed using this option.
  - **Real Time 3D Animation**: Any 3D animation that was performed during a simulation run, can be replayed in real time (i.e. frames are skipped if necessary) using this option.
  - **Read Datafile**: Use the Read Data File command to read previously stored simulation runs from file.

- **Copy States**: With the Copy States command the current independent state variables can be imported as new initial values. Current state variables are the state variables at the end of a simulation run or at the point where a simulation run was interrupted.
8.2.6 Numerical Values

In every simulation plot you can inspect the numerical values by selecting the Numerical Values command of the View menu. The Numerical Values window, can also be popped up by double clicking the left mouse button, while pointing the mouse at a curve in the plot.

The Numerical Values window will pop up and display the numerical values of all plotted variables as a function of time. The last variable shown is always the X-axis variable (usually time).

- **Run Number**: The run number indicates the run of which the numerical values are shown. The highest number indicates the last run simulated. Lower numbers are used for previous runs. To select another run number, type in the number of interest or point in the plot at the curve of interest. In the simulation plot, previous runs are shown with fading colors.
8. Simulator

- **List**: The list shows all variables that are shown in the plot and their corresponding X-values and Y-values. The variable that is currently selected is pointed out by an arrow in the plot.
- **Scroll-bar**: Use the scroll-bar to change the selected x-axis variable value (usually time).
- **Find**: With the Find button, the global maximum etc. of the selected variable can be found. The following functions can be selected:
  - Global Maximum
  - Global Minimum
  - Next Local Maximum
  - Next Local Minimum
  - Previous Local Maximum
  - Previous Local Minimum
- **Mark**: Click the Mark button to store the set of numerical values. If you drag the scroll-bar to find a new set of values, the relative changes will be displayed as well as a first order derivative.

### 8.2.7 Variable Chooser

The Variable Chooser can be used to select and inspect any dynamic variable of the loaded model. The names, kinds, types, values, quantities, units and descriptions of the variables of the loaded model are listed in right part of the window. The list of dynamic variables displayed, depends on the selected (sub)model in the left part of this window. The left part displays the complete model hierarchy.

![Variable Chooser](image)

The Variable Chooser shows all variables of a model.
Items

- **Model Hierarchy**: The model hierarchy shows several keys:
  - **Model**: At each level of the hierarchy, submodels can be selected and inspected. The right part of the window then shows the variables that are part of that submodel. To see all variables including time, select the top level of the hierarchy, i.e. the main model listed on top. Click on one of the variable items (Name, Value, Quantity, Unit, Description, Kind, Arithmetic Type, Value) to order the variables alphabetically.
  - **Input Probes/Output Probes**: In the Frequency Response dialog pairs of input variables and output variables can be selected for linearization. If input variables have been selected they are shown under the input probes key. If output variables have been selected they are shown under the output probes key.
  - **Favorites**: variables that are used a lot can be added to the favorites key for easy use.
  - **Variables**: Select the desired variable from the list (use your mouse pointer), select the desired Unit from the drop down list and click OK to close the window.

- **Minimum and Maximum values**: If you run a simulation in Debug Mode, the minimum and maximum value of every variable is shown.

- **Unit Selection**: If a quantity was assigned to the selected variable with multiple units (e.g. position -> m, mm, inch, etc.) you can switch units by the unit selection at the bottom of the variable list.

- **Attributes**: Variables may be limited in range or made read only. If so, these limits are listed in the Attributes.

- **Expand Vectors/Matrices**: Select complete vectors and matrices or only their elements.

- **To Matlab**: Use the button to export a variable value to Matlab. You will be asked to enter a Matlab variable. Data will be exchanged between this Matlab variable and the variable that is selected in 20-sim.

- **Show Variables**: Select the specific kind of variables (Variables, States/Rates, Alias Variables, Dependent/Algebraic, Hidden Variables, Knots) that should be displayed in the Variables list.

Actions

If you select a variable in the list and use the right mouse menu several actions can be performed:

- **Add to Favorites**: add the selected variable to the favorites list.
- **Add to Input Probes**: Add the variable to the list of inputs for linearization. This list is used in the Frequency Response dialog.
- **Add to Output Probes**: Add the variable to the list of outputs for linearization. This list is used in the Frequency Response dialog.
- **Copy**: copy the variable value to clipboard.
8. Simulator

- **Copy with Unit:** copy the variable value and corresponding value to clipboard.
- **Copy Specified:** Specify the items that should be copied and then copy to clipboard.

**Tips**

1. All equations in 20-sim are calculated using standard SI-units. You can however display the results, using whatever Unit you like. In the Variable Chooser, you can change the unit using the little drop down list just above the Show Variables section.

2. To see global variables, select the top level of the hierarchy, i.e. the main model listed on top.

3. To quickly find some variables out of the list, add the keyword interesting in the equation description. In the Variables list, de-select States, Rates, Algebraic Loops, Dependent States and Dependent Rates. Then only the interesting variables are shown.

4. When using large models, opening the Variable Chooser may take some time. Use the General Properties window to set the maximum number of variables that should be shown.

5. To hide variables from the list, add the keyword hidden in the equation description. Hidden variables are not visible in the Variable Chooser.

6. When you open the Variables Chooser from a plot, it will also show the parameters of a model or submodel, to allow parameters to be plotted.
8.2.8 Debugging

20-sim has various tool to help you to pinpoint and resolve problems that may occur during a simulation.

- **Switch to Debug Mode**: 20-sim is operating in *Debug Mode* when you see the `Debug Mode button`. If your *Simulator* or *Editor* is in *Fast Mode* click on the button to change to *Debug Mode*.

- **Recompile your model**: In the editor select *Check Complete Model* from the *Model* menu. This will recompile your model in *Debug* mode and show a maximum of warnings. If any warning looks suspicious, solve this first.

- **Breakpoints**: Set breakpoints to monitor time or conditions between variables.

- **Run to the breakpoint**: Use the *Run* command from the *Simulation* menu to run the simulation to a breakpoint. As soon as the breakpoint has been reached, the simulation will halt. The *Output tab* at the bottom of the Simulator will display which breakpoint was active.

- **Simulate Step-by-Step**: Use the command One Step from the *Simulation* menu to simulate do one simulation step for the complete model.

- **Inspect the Results**: After each step, open the Variable Chooser to inspect the various variables of the model. You can also switch to the *Editor* to inspect results at model level:
  - **Submodels**: Select a specific submodel and choose *parameters* or *variables* to inspect the parameters and variables of that submodel.
  - **Equation submodels**: Put the mouse pointer on top of an equation and point to a variable or parameter of interest. A box will appear, showing the numerical value associated with that variable or parameter.

```plaintext
parameters
  real initial = 0;

equations
  output := hold (input, initial);
  135.156

Use the mouse pointer to inspect numerical values.
```

- **Graphical submodels**: Put the mouse pointer on top of a signal, bond or connection. A box will appear, showing the numerical value associated with that signal, bond or connection.
8. Simulator

8.2.9 Breakpoints

20-sim allows you define stops in a simulation called breakpoints. You can set breakpoints using the Breakpoint Editor. This editor can be opened by selecting the Breakpoints command from the Properties menu in the Simulator.

![Breakpoint Editor](image)

Setting Breakpoints.

You can run a simulation from breakpoint to breakpoint, using the Continue command from the Simulation menu.

Breakpoints are useful when problems occur during simulation. By defining an appropriate breakpoint and using the Run command, you can run a simulation until the point where the problem occurs. You can continue the simulation using single steps or just running it again.

Use the mouse pointer to inspect numerical values.
Items

- **Add/Delete**: Use the Add and Delete buttons to add or delete breakpoints. When you add a breakpoint, an editor will be opened to enter the breakpoint conditions.
- **Breakpoints**: The Breakpoints list shows the entered breakpoints.
- **Enter the ... skip before stopping**: A breakpoint may occur more than once before it should stop the simulation run. Enter here the number of times to skip the breakpoint.
- **When**: A breakpoint may occur more than once during a simulation run. With this option you can select the breakpoint to be active only once or always.
- **Active**: Use this option to make a breakpoint effective or not.
- **Edit Condition**: When a breakpoint is selected in the breakpoints list, you can edit it, using the Edit Condition button. This will open an editor which helps you to enter the breakpoint condition.
- **Import**: Import breakpoints from another model.

Note

Breakpoints are only active when 20-sim is operating in *Debug Mode!*

8.2.10 **New Simulation Plot**

You can open additional plots by selecting the *New Plot Window* command from the *View* menu of the simulator. Or hover your mouse on top of the *Plot Windows* item in the *Simulator tree* and use your *right mouse menu*.

![New Simulation Plot](image)

You can open additional plots in 20-sim.

Every plot will have a menu bar and buttons to allow you to enter the settings for the plot and running a simulation.
8.2.11 New 3D Animation Plot

You can open additional 3D Animations by selecting the *New 3D Animation Window* command from the *View* menu of the simulator.

Every 3D Animation will have a menu bar and buttons to allow you to enter the settings for the plot and running a simulation. More information on 3D animation can be found in the 3D Animation Toolbox.

8.2.12 Arrange Plots

A *Plot Window* can contain multiple plots with multiple curves. It can also contain a mix of curve plots and 3D animation plots.

Change the plot window layout

By default, 20-sim will auto-arrange plots row-wise, then column-wise. It is possible to change the tile options to:

- Tile Horizontal
- Tile Vertical
- Strip Chart

*Strip Chart* is a special version of *Tile Vertical* with a common X-axis for all plots.

To change the tile options, right-click on the plot window in the *Plot Windows* tree and select the menu *Tile Plots.*
8. Simulator

Change the plot tile options

**Reorder plots and curves**

To change the order of plots within a plot window, you can drag-drop plots in the tree. It is also possible to move a plot from one plot window to another in this way. Moving curves within plots and between plots is also possible via drag-drop.
8.2.13 Resample Curves

Select the Resample Curves command from the View menu to sample a simulation run with a fixed sample time. This is useful if you want to use your simulation results in other programs that need data with a fixed time step. An example is given below where a curve (red dots) is shown that is simulated with a variable step integration method. Resampling with a sample time of 0.1 s will result in a curve with only the blue dots.

![Resample Curves](image)

Use the Resample Curves command to get equidistant timing in the plot.

Selection of the Resample Curves command of the View menu pops up the Resample Curves dialog. You can enter the amount of data that you want to resample and the sample time or frequency.
8. Simulator

The Resample Curves dialog.

Note
To get simulation data with a fixed time step, using a fixed step integration method is not enough, because this data may contain additional steps generated by time or state events. Only the Resample Curves command will guarantee fixed time step data!

8.2.14 Copy States

To get the same model behavior, compared to the end of the previous run, we have to copy the states of a model to the initial values.

When you use the Copy States command of the Simulation menu, 20-sim overwrites the initial values of the functions ddt, int, limint and resint with their current output states. This can be done at the end of a simulation run or at any point where a simulation run was interrupted.

Tip 1

You can reset the initial values to zero by using the Reset Initials command from the Simulation menu.

Tip 2

For some models, behavior at some operating point or "steady state" is of interest. Use the Copy States command to create simulation that directly starts at working level:
1. Run a simulation from \( t = 0 \) [s] until the operating point is reached. Use the **Copy States** command to store the states as new initial values. Now save the experiment using some special name.

2. Now each time you open this experiment, simulations directly start at operating point.

**States**

Consider the following first order linear model:

\[
\text{output} = \text{int}(0) + \text{int}(\ f(\text{input},\text{output}) )
\]

with:

\[
\text{int}(0) = \text{the initial value of the integral} \\
\text{f(input,output)} = \text{input} - K*\text{output}
\]

In more general terms this equation can also be described as:

\[
\text{state} = \text{int}(0) + \text{int} (\text{rate}) \\
\text{rate} = f(\text{input}, \text{state})
\]

When we start to simulate this model at \( t = 0 \) [s] the value of the integral is zero. The state is therefore equal to the initial value \text{int}(0):

\[
\text{state}(0) = \text{int}(0)
\]

At the end of a simulation, the integral may be unequal to zero. The state is therefore equal to:

\[
\text{state}(end) = \text{int}(0) + \text{int}(\text{rate}(end))
\]

In other words, the value of the state is **characteristic** for the behavior of the model. To start a new simulation with the same behavior, we have to change the initial value to:

\[
\text{int}(0) = \text{state}(end)
\]

This is valid for all dynamic models: The states of a model are characteristic for its behavior. To get the same behavior, compared to the end of a previous run, we have to copy the states to the initial values.
8.2.15 Reset Initial Values

Initial Values define the starting point of any simulation. You can reset the initial values to zero by using the **Reset Initials** command from the **Simulation** menu.

8.2.16 Speeding Up Simulations

Debug Mode and Fast Mode

By default, 20-sim models are simulated in the debug mode, which is indicated by the **Debug Mode** button at the left top of the Simulator. In the Debug Mode the Simulator checks on divisions by zero and all other kinds of problems and gives proper warnings when something goes wrong. This is very help for debugging a model but slow down the speed of the Simulator considerably.

If your model runs fine you can change the **Debug Mode button** to Fast Mode. Now 20-sim will use all tricks to give you the highest simulation speed possible.

**Settings**

- In the Editor you can click **Settings - Model - Processing** to open the General Properties and see the checks and settings for the Debug Mode and Fast Mode. Changing these settings is only recommended for expert users!
- In the Editor you can click **Settings - Model - Simulator** to change the instruction set used by the CPU during simulation in Fast Mode. Changing this setting is only recommended for expert users!

8.2.17 Exporting Simulations

There are several methods to export simulation results:

1. Export Plot to Clipboard or File.
2. Export Experiment To Clipboard.
3. Export Data to File.

**Export to Clipboard or File**

From the **File** menu, you can choose **Export Plot to MetaFile** or **Export Plot to Clipboard** to export a drawing of the simulation plot.

**Export High Resolution Plot to Clipboard or File**

Simulation plots can be very dense. To limit the file size, by default not all details are exported to clipboard or to file. If you need a detailed plot, from the **File** menu, you can choose **Export High Resolution Plot to Clipboard or Bitmap**. Another option is to use the right mouse menu, when the mouse on top of a plot and select **High Resolution Export**.
Export Experiment To Clipboard.
From the File menu, you can choose Export Experiment to Clipboard to export all plot settings. A dialog will be opened asking you to specify the settings that should be copied. You can select:
- Parameters
- Initial Values
- Plot Specifications
- Run Specifications
- Multiple Run Specifications
- Export Data Specifications
- BreakPoints

Export Data to File
From the File menu, you can choose Save Data To File to export the plotted values to a data file. A file dialog window will pop up asking you to enter a filename. You can choose from the following file formats:
- Comma Separated File (*.csv): This is the default format and can be used for exporting data to spreadsheet programs such as Microsoft Excel or Open Office Calc.
- 20-sim data file (*.n): This is the standard 20-sim format.
- Data Files (*.dat): The standard ANSI format for data files.

Tip
You can use the Export Data To File command to store simulation results of time consuming simulations. For later use you can use the Import From Data File command to read the result from file.

8.2.18 Importing Simulations
There are several methods to import simulation results:

1. Import experiment.
2. Import simulation data.

Export Plot Settings
From the File menu, you can choose Import Experiment to import the simulation settings from another model. The setting contain all the necessary information that you need to define a simulation:
- parameters
- run properties
- plot properties
- ...

Import Data File
From the File menu, you can choose Import Data From File to import a previously saved simulation plot. A window will pop up allowing you to specify the filename and variables that should be plotted.
If the file contains a header describing the variables inside, they will be shown in the variables dialog.

- **Filename**: You can select an existing filename using the browse button or type one. Data can be read as text file or as binary format.
- **Read Header**: Select this button if you want extra information (variable names etc.) to be read from the data file.
- **Variables**: The variables box shows the number of columns that were found in the data file. Each column must be matched with a variable that is shown in the plot. Click with the mouse on a column number to select it. Then click the Match Variable button. This opens a Variable Chooser in which you can select a variable. When a header was used when storing the data file, this matching is done automatically.
- **Match Variable**: Use this button to select a matching variable for each column in the variables box.
- **Plot Variables**: Use the Delete button to delete a selected variable
- **Plot Variables**: Use this button to put the same variables as shown in the plot into the columns of the variables box.
- **Up/Down**: Use the Up and Down buttons to change the order of the variables shown in the list.
**Tip**
You can use the *Export Data To File* command to store simulation results of time consuming simulations. For later use you can use the *Import From Data File* command to read the result from file.

### 8.2.19 Full Screen Mode
You can show simulation plots and 3D Animations in full screen mode.

1. Put your mouse on top of a plot or animation.
2. From the **right mouse menu**, select **Toggle Full Screen**.

To remove the full screen mode:

1. From the **right mouse menu**, select **Toggle Full Screen** or press the **Escape** key.

### 8.2.20 Keyboard Shortcuts
This is a list of keyboard shortcuts in simulator.

#### Navigation

<table>
<thead>
<tr>
<th>Command</th>
<th>Shortcut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Save 20-sim project</td>
<td>Ctrl + S</td>
</tr>
</tbody>
</table>

#### Current Page

<table>
<thead>
<tr>
<th>Command</th>
<th>Shortcut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zoom in</td>
<td>F4</td>
</tr>
<tr>
<td>Zoom normal</td>
<td>F5</td>
</tr>
<tr>
<td>Zoom out</td>
<td>F6</td>
</tr>
<tr>
<td>Zoom to fit</td>
<td>F7</td>
</tr>
</tbody>
</table>

#### Control

<table>
<thead>
<tr>
<th>Command</th>
<th>Shortcut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Simulation</td>
<td>Ctrl + E</td>
</tr>
<tr>
<td>Next Camera</td>
<td>Ctrl + A</td>
</tr>
<tr>
<td>Process Frequency Response</td>
<td>Ctrl + F</td>
</tr>
<tr>
<td>Replay Simulation</td>
<td>Ctrl + Q</td>
</tr>
<tr>
<td>Replay Datafile</td>
<td>Ctrl + D</td>
</tr>
<tr>
<td>Run Simulation</td>
<td>Ctrl + R</td>
</tr>
<tr>
<td>Stop Simulation</td>
<td>Ctrl + T</td>
</tr>
<tr>
<td>One Step Simulation</td>
<td>Ctrl + W</td>
</tr>
<tr>
<td>Brute Force Simulation</td>
<td>Ctrl + Shift + R</td>
</tr>
<tr>
<td>Dynamic Error Budgetting</td>
<td>Ctrl + B</td>
</tr>
</tbody>
</table>
8.2.21 Training Simulators

Training simulators are simulation models that run real-time and can be used to train people. 20-sim has some features that allow you to turn 20-sim into a training simulator. The example model KnuckleBoomCraneKeyboard will show you how it works:

1. Go to the Examples Library and look into the 3D Mechanics folder or in the search bar enter KnuckleBoomCraneKeyboard. The Find tab will show the results. Click on the link to jump to the model.
2. Drag and drop the model to the editor. The keyboard inputs are shown in the model.
3. Run a simulation and use the keyboard inputs to move the crane.

Developing your own training simulator is not difficult. All you have to do is:

1. Develop a model, that will mimic your training system.
2. Allow manual inputs, by keyboard or joystick. The library of 20-sim contains special blocks for keyboard input or joystick input which you can use.
3. Run the simulation in real-time.
4. Use 3D animations to show views of your system.
5. Run the 3D-Animations in full screen.

Tips

- Use transparency to show or hide parts of your 3D animation.
8.3 Run Properties

8.3.1 Simulator Tab

The Simulator tab is the first tab of the Run Properties Editor. This tab shows the general simulation settings:

![The 20-sim Run Properties.](image)

**Items**

- **Timing (seconds):**
  - *Start:* the start time of a simulation run (default: 0)
  - *Finish:* the finish time of a simulation run (default: 10)
  - *Event delta:* the accuracy for spotting state events. This option can only be selected if a model contains state events.
- **Integration Methods**: 8 numerical integration methods are available, each with its own parameters. The parameters can be changed by clicking the Set Properties button or selecting the tab on top of the editor.
  
  - Euler
  - Backward Euler
  - Adams-Bashford 2
  - Runge Kutta 2
  - Runge-Kutta 4
  - Runge Kutta Dormand Prince 8
  - Runge-Kutta-Fehlberg
  - Vode Adams
  - Backward Differentiation Formula (BDF)
  - Modified Backward Differentiation Formula (MBDF)

- **Output After Each**: This is the plot interval. Use this option to generate output only after each equidistant time interval has passed. For each interval, the exact simulation point is used (if available) or the nearest point is used (if not available, for example when using variable step algorithms).

- **Related Options**
  
  - **BreakPoints**: Click this button to open the Breakpoints Editor.
  - **General Properties**: Click this button to open the General Properties Editor.
  - **More**: Click this button to set advanced options:
    - **Endless**: Select this option if you do not want the simulation to stop.
    - **Attempting Real-Time simulation**: Select this option if you want the simulation to run as fast as the real time. You can choose the option *Catch up with lost time* and set the *Maximum allowed lost time*.

**Tips**

- Use **Attempting Real-Time simulation** when you have keyboard input or joystick input in your model.
8.3.2 Discrete System Tab

The Run Properties Editor can be used to edit the sample frequency of a discrete-time system in the model. 20-sim automatically detects the existence of discrete systems in a model. For each discrete system, one extra tab (Discrete System) is shown in the Run Properties Editor.

![Discrete Systems tab](image.png)

**The Discrete Systems tab.**

**Items**

- **Identified with:** Each discrete system in a model is assigned a unique identifier. 20-sim detects discrete systems by looking for discrete functions and variables:

  1. sample
  2. hold
  3. next
  4. previous
  5. samptime

When a function has been found, the elements of the corresponding discrete system are identified by propagation of the equations. In order of appearance in the model, the discrete system is assigned a unique identifier:

  1. sample -> the variable that is assigned to the output of the sample function.
  2. hold -> the variable that is assigned to the output of the hold function.
  3. previous -> the discrete state corresponding with the previous function.
4. next -> the discrete state corresponding with the next function.
5. sampletime -> the variable that is equal to the sampletime.

- **Timing (Standard)**: Each discrete system has a default sample frequency of 1 Hz. You can change this frequency to any desired value:
  - *Discrete Time Interval (s)*: The sample interval (in s) of the discrete system
  - *Frequency (Hz)*: The sample frequency (in Hz) of the discrete system.

- **Timing (Advanced)**: For discrete-time control loops that interact with physical continuous-time systems through sensors (analog to digital) and actuators (digital to analog) the specific timing is important. Click the Advanced button to specify this timing.

### 8.3.3 Advanced Discrete System Settings

The **Advanced Discrete System Settings** dialog can be used to set the timing for discrete-time control loops that interact with physical continuous-time systems through sensors (analog to digital) and actuators (digital to analog). You can open the dialog by:

1. In the Simulator from the **Properties** menu, click **Run** to open the Run Properties Editor.
2. Select the **Discrete System tab** and click the **Advanced Settings** button.

In the **Advanced Discrete System Settings** dialog you can specify the timing of control loops with a fixed sampletime (click **Global Time**) and control loops with a variable sampletime (click **Previous Sample Event Time**).

**Fixed Sampletime**

When you click the **Global Time** option the following window appears.
The window shows the timing diagram for a fixed sample time control loop. The loops start with an clock interrupt from a timer. It will take some time before the interrupt is handled and generally some calculations are performed before the sensor signals (sample) are read. This delay is represented by the sample delay which is divided in a fixed time and a variable time part. The control loop will proceed and perform the necessary calculations to generate the actuator output (hold). These calculations will take some time, which is represented by the fixed time hold delay. After this action the control loops will come to a halt until the next clock interrupt is generated.

If the control loops is properly designed it will know the task it is performing when a clock interrupt is getting in. E.g. if it is still calculating the actuator outputs when clock interrupt is getting in, an error will be generated, specifying that the sampletime is too small to perform all necessary calculations.

**Items**

- **Sample Delay**:
  - **Fixed**: Enter the fixed sample delay here.
  - **Variable**: Enter the variable delay here. You can chose from two distributions:
    - **Uniform**: The delay is uniformly distributed between the given minimum and maximum.
    - **Gaussian**: The delay has a given mean and standard deviation.

- **Hold Delay**: Enter the fixed hold delay here.

- **Action on Sample Missed**: An error will be generated when the total delay is larger than the sampletime or when the total delay is negative.
Variable Sampletime

When you click the **Previous Sample Event Time** option the following window appears.

The window above shows the timing diagram for a variable sampletime control loop. It performs the same tasks as a fixed sampletime control loop, but will start the next loop as soon as the previous loop was finished. The variable sampletime control loop does not use a clock interrupt!

**Items**

- **Sample Delay**:
  - **Fixed**: Enter the fixed sample delay here.
  - **Variable**: Enter the variable delay here. You can chose from two distributions:
    - **Uniform**: The delay is uniformly distributed between the given minimum and maximum.
    - **Gaussian**: The delay has a given mean and standard deviation.
- **Hold Delay**: Enter the fixed hold delay here.
- **Action on Sample Missed**: Only an error will be generated when the total delay is negative.
8.3.4 **Algebraic Relations Solver Tab**

The *Algebraic Relations Solver tab* of the Run Properties Editor is visible when your model contains algebraic loops that could not be solved during processing. In the tab, you can specify the tolerance of the algebraic solver algorithm. For each model evaluation, this solver tries to solve the algebraic loop relations, while standard integration algorithms, such as Euler, can be used to evaluate the model equations.

![The Algebraic Relations Solver tab.](image)

8.3.5 **Euler**

This is the explicit Euler method. It is a single-step explicit method, which needs one model calculation per time step. The size of the time step is fixed. This simulation algorithm requires 1 parameter to be specified:

- **Step Size**: the step time of the integration algorithm (default: 0.01).

8.3.6 **Backward Euler**

This is a combination of the implicit Backward Euler method and the explicit Forward Euler method. It is a single-step implicit method, which needs one model calculation per time step. With the parameter alpha the combination is defined:

<table>
<thead>
<tr>
<th>alpha</th>
<th>combination</th>
<th>explicit/implicit</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>100% Forward Euler</td>
<td>explicit</td>
</tr>
<tr>
<td>0</td>
<td>50% Forward Euler, 50% Backward Euler</td>
<td>explicit</td>
</tr>
<tr>
<td>1</td>
<td>100% Backward Euler</td>
<td>implicit</td>
</tr>
</tbody>
</table>
- **Step Size**: the step time of the integration algorithm (default: 0.01).
- **Relative Tolerance**: Relative tolerance for the rootfinding in the Backward Euler method.
- **Alpha**: Choose between Forward Euler (alpha = -1), Trapezoidal (alpha = 0) and Backward Euler (alpha = 1).

### 8.3.7 Adams-Bashford

This is the trapezoidal rule. It is a single-step explicit method, which needs only two model calculations per time step. The size of the time step is fixed. This simulation algorithm requires 1 parameter to be specified:
- **Step Size**: the step time of the integration algorithm (default: 0.1).

### 8.3.8 Runge Kutta 2

This is an explicit single-step second-order derivatives method which needs 2 model calculations per time step. It is the simple form of the classical Runge-Kutta method. The size of the time step is fixed. This simulation algorithm requires 1 parameter to be specified:
- **Step Size**: the step time of the integration algorithm (default: 0.01).

### 8.3.9 Runge-Kutta 4

This is an explicit single-step fourth-order derivatives method which needs 4 model calculations per time step. It is the classical Runge-Kutta method. The size of the time step is fixed. This simulation algorithm requires 1 parameter to be specified:
- **Step Size**: the step time of the integration algorithm (default: 0.01).

### 8.3.10 Runge-Kutta-Fehlberg

This is an explicit variable-step 4/5-order derivatives method, primarily designed to solve non-stiff and mildly stiff differential equations. Because the method has very low overhead costs, it will usually result in the least expensive integration when solving problems requiring a modest amount of accuracy and having equations that are not costly to evaluate. This simulation algorithm has 4 parameters:
- **Integration Error** (required)
  - **Absolute**: The absolute integration error, valid for every state variable (default: 1e-6).
  - **Relative**: The relative integration error, valid for every state variable (default: 1e-6).
- **Step Size** (not required)
  - **Initial**: The step size for the first simulation step (default: 0.01).
  - **Maximum**: The maximum size of a simulation step (default: 1).
8.3.11 Runge Kutta Dormand Prince 8

This is an explicit variable-step 8-order derivatives method, primarily designed to solve non-stiff and stiff differential equations. This simulation algorithm has 4 parameters:

- **Integration Error** (required)
  - **Absolute**: The absolute integration error, valid for every state variable (default: 1e-6).
  - **Relative**: The relative integration error, valid for every state variable (default: 1e-6).
- **Step Size** (not required)
  - **Initial**: The step size for the first simulation step (default: 0.01).
  - **Maximum**: The maximum size of a simulation step (default: 1).

8.3.12 Vode Adams

This is the explicit variable-step stiff integration algorithm of Cohen and Hindmarsh. This method is specially suited for explicit models that combine high and low frequency vibrations with little damping (so called "stiff" models). This simulation algorithm has 4 parameters:

- **Integration Error** (required)
  - **Absolute**: The absolute integration error, valid for every state variable (default: 1e-6).
  - **Relative**: The relative integration error, valid for every state variable (default: 1e-6).
- **Maximum Step Size** (not required): The maximum size of a simulation step (default: 1).
- **Multistep Method** (required): The variable step integration method that is used. A BDF method is default and best suited for stiff systems.
- **Iteration Type** (required): The method used for iteration loops (algebraic relations). The Newton method is default and best suited for stiff systems.

8.3.13 Backward Differentiation Formula (BDF)

This is an implicit multi-step variable-order first-order derivatives method. It is Gear's backward differentiation formula, which is up to fifth order, so 1 to 5 model calculations are needed per time step. The code of the Dassl library is used. It is suitable for models having derivative causalities and/or algebraic loops. This simulation algorithm has 4 parameters:

- **Integration Error** (required)
  - **Absolute**: The absolute integration error, valid for every state variable (default: 1e-5).
  - **Relative**: The relative integration error, valid for every state variable (default: 1e-5).
8. Simulator

- **Step Size** (not required)
  - Initial: The step size for the first simulation step (default: 0.1).
  - Maximum: The maximum size of a simulation step (default: 1).

Note

- Undamped models are not simulated properly with this method.
- The default values are suitable for problems with time constants of order of magnitude of 0.1 to 1. Initial Step Size and Maximal Step Size influence the behavior of the method and should be tuned with care.

8.3.14 Modified Backward Differentiation Formula (MBDF)

This is an implicit multi-step variable-order first-order derivatives method. It is Gear's backward differentiation formula, which is up to fifth order, so 1 to 5 model calculations are needed per time step. The code of the Dassl library is used. It is suitable for models having derivative causalities and/or algebraic loops. The MBDF allows the use of constraint variables when proper initial values are used.

This simulation algorithm has 4 parameters:

- **Integration Error** (required)
  - Absolute: The absolute integration error, valid for every state variable (default: 1e-5).
  - Relative: The relative integration error, valid for every state variable (default: 1e-5).

- **Step Size** (not required)
  - Initial: The step size for the first simulation step (default: 0.1).
  - Maximum: The maximum size of a simulation step (default: 1).

Note

- This is the only method that supports the use of the constraint function.
- The MeBDFi method cannot handle contraints that do not influence the model. Therefore 20-sim will check at the beginning of the simulation if contraints have been properly defined. The contraints that do not influence the model are set to zero automatically. If you do not want to use this check, deselect the **Smart Contraint Solving** option.
- Undamped models are not simulated properly with this method.
- The default values are suitable for problems with time constants of order of magnitude of 0.1 to 1. Initial Step Size and Maximal Step Size influence the behavior of the method and should be tuned with care.
9 Language Reference

9.1 Introduction

9.1.1 Language Reference

Every (sub)model has an implementation. This can be a composition of lower level submodels, which themselves are composed of lower level submodels etc. At the bottom of this hierarchy the submodels consist of a set of mathematical equations (equation submodel). These submodels are therefore known as equation submodels.

All equations used in 20-sim are described in the language SIDOPS+. A simple equation model written in SIDOPS+ is shown below:
You will find out that in most cases the SIDOPS+ language is equal to standard mathematical notation. Regardless of your modeling background, you can learn quickly to build your own equation models. 20-sim comes with over 80 built-in functions that do most of the work for you. To learn more about equation models, have a look at the following sections:

1. Model Layout
2. Keywords ( Constants, Parameters, Variables, Equations )
3. Data Types
4. Operators
5. Functions
6. Statements

### 9.1.2 Equation Model Layout

The general layout of an equation model is:

```plaintext
constants
    // enter your constants here, for a description see constants
parameters
    // enter your parameters here, for a description see parameters
variables
```

A simple equation model in 20-sim.
At least one `equations` or one `code` section is required. The other sections are optional.

### 9.1.3 Equations

The body of an equation model consists of the keywords `initialequations`, `code`, `equations` and `finalequations`, each followed by one or more equations. Equations are relations between variables indicated by an equal (=) sign:

```plaintext
y = x + 1;
z + y = sin(time*2*pi*f);
g = ddt(g + z, g_initial);
```

An equation can be combination of operators, functions, power-port variables, inputs and outputs (port names), constants, parameters and variables. Equations in 20-sim follow the standard mathematical notation.

#### Rules

The following rules must be obeyed when specifying equations:

1. An equation may span more than one line but must always be finished by a semicolon (;).
2. Parentheses () may be used to indicate grouping as in ordinary mathematical notation, e.g.
   ```plaintext
   u = sin(time*2*3.1415 + (a + b)/c);
   ```
3. Extensions like .e or .f are used to indicate the effort and the flow variables of powerports. These extensions are not allowed for any other type of identifier (i.e. inputs, outputs, constants, parameters or variables).
4. 20-sim has some predefined variables which have a special meaning.
5. Each variable must be assigned a value exactly once.
6. Errors are shown automatically after checking in the Process tab. Double clicking on the error text will make 20-sim jump to the error, which is then colored red.

#### Execution Order

1. Equations within 20-sim may be entered in random order. During compilation, 20-sim will automatically try to rewrite equations into a correct order of execution.
9.1.4 Equation Sections

In 20-sim equations can be divided in four sections: initialequations, equations, code and finalequations.

Initialequations

The initialequations section should contain all equations that should calculated before the simulation run. The equations are calculated once. The equations in this section form a code block, i.e. the equations themselves and the order of the equations are not rewritten during compilation and executed sequentially. The results of the initialequations section are not shown in the simulator plots and can therefore not be inspected in the Numerical Values window!

Example

The initialequations section is used in the library model Spring Damper (stiffness):

```plaintext
parameters
    real k = 10.0 {N/m};
    real m = 1.0 {kg};
    real b = 0.05 {};
variables
    real x {m};
    real d {damping,N.s/m};
initialequations
    d = 2*b*sqrt(k*m);
equations
    x = int (p.v);
    p.F = k * x + d*p.v;
```

As you can see in the initialequations section the damping d is calculated out of the relative damping b, mass m and stiffness k.

Equations

The equations section contains all standard equations. They do not have to be entered in a sequential form. They are rewritten during compilation to get the correct order of execution. The resulting code is calculated every simulation step. You can see the use of the equations section in the example above.

Code

The code section contains a code block. A code block contains all equations that must be calculated sequentially, i.e. the equations themselves and the order of the equations are not rewritten during compilation. The resulting sequential code is calculated every simulation step.

Example

The code section is used in the library model Spring Damper (stiffness):
parameters
    real initial = 0.0;
variables
    real prev, peak;
initialequations
    peak = initial;
    prev = 0;
    output = initial;
code
    if major then
        peak = max(abs(input), peak);
        if (input > 0 and prev < 0) or (input < 0 and prev > 0) then
            output = peak;
            peak = 0;
        end;
        prev = input;
    end;
Finalequations
The finalequations section should contain all equations that should be calculated after a
simulation run. The equations are calculated once. The equations in this section form a
code block, i.e. the equations themselves and the order of the equations are not
rewritten during compilation and executed sequentially. The results of the finalequations
section are not shown in the simulator plots and can therefore not be inspected in the
Numerical Values window!

Example
The finalequations section is used in the library model DoMatlab-Final:

    parameters
        string command = "";
    finalequations
        // send the command to the workspace
        doMatlab (command);

As you see you can give the parameter command any value, which is then exported to
Matlab at the end of the simulation run.

9.1.5 Using Port Names
To use port variables in equations, you must use the port names that are defined in the
Interface Editor.

Signal Ports
For signal ports, you can directly use the port names. The example below, shows the
library model Differentiate-SVF.emx. In the Interface Editor, two ports are defined with
the names input and output. In the equations these names are used.
The Interface tab shows the contents of the Interface Editor.

**Power ports**

Power ports describe the flow of power and are always characterized by two variables: the *power-port variables*. For bond graph ports the extensions `.e` and `.f` are used to indicate these variables. For iconic diagram ports many aliases are known, for example `.u` and `.i` for the electric domain. You can use these power-port variables in equations by typing the port name followed by a dot and the extension.

You can always find the correct extensions by opening the *Interface Editor* and selecting a port. The example below, shows the library model *Friction.emx*. In the Interface Editor, one power port is defined with the name `p`. As shown, the correct description of both variables is `p.v` and `p.F`.

Double clicking in the Interface tab will open the Interface Editor.

The equation description of this model (see below) shows the use of the variables `p.v` and `p.F`. 

---

```plaintext
parameters
real N = 10.0; // Derivative gain
real initial = 0.0; // Initial output variables
real hidden rate;
real hidden initial_input;
boolean hidden initialized;

equations
if not initialized then
    initial_input = input;
    initialized = true;
end;
rate = - N * output;
```

---
In the equations the port variables p.F and p.v are used.

9.1.6 Reserved Words

While entering equations, the 20-sim Editor will automatically detect reserved words. You can recognize reserved words, because they will be shown with a different color:

<table>
<thead>
<tr>
<th>element</th>
<th>color</th>
</tr>
</thead>
<tbody>
<tr>
<td>keywords</td>
<td>black</td>
</tr>
<tr>
<td>data types</td>
<td>black</td>
</tr>
<tr>
<td>functions</td>
<td>blue</td>
</tr>
<tr>
<td>statements</td>
<td>black</td>
</tr>
<tr>
<td>predefined variables</td>
<td>blue</td>
</tr>
</tbody>
</table>

20-sim knows the following reserved words:
9.1.7 White Space

Like C and other programming languages, 20-sim does not recognize white space (spaces and tabs, carriage returns) except in a string. We recommend that you use white space to make your model easier to follow. For example, the following model is dense and difficult to read:

```plaintext
variables
    real y,u;
equations
    y = step(1);
    u = -step(1);
    if time > 5 then y = -ramp(1); u = ramp(1);
    else y = ramp(1); u = -ramp(1); end;
```

Adding white space with indentation makes the same code much easier to read:

```plaintext
variables
    real y;
    real u;
equations
    y = step(1);
    u = -step(1);
    if time > 5 then
        y = -ramp(1);
        u = ramp(1);
    else
        y = ramp(1);
        u = -ramp(1);
    end;
```
9.1.8 Writing Comments

20-sim gives you several options to create comments in a model. You can use each option to add explanatory text to your model or to exclude ("comment out") certain parts of your model for testing and debugging purposes.

Block Quotes ("...")
You can enclose a block of text between quotes ("). This method makes it easy to write a comment over multiple lines:

"This is a line of sample code that shows you how to use the 20-sim comments"

Programming /*...*/
You can enclose a block of text between the constructs /* and */. This method is used often in programming and also allows to write a comment over multiple lines:

/*This is a line of sample code that shows you how to use the 20-sim comments*/

Single Line Comment (//...)
A option often used in programming is to insert // into a line. The compiler ignores everything to the right of the double slashes on that line only.

// This is a line of sample code showing the 20-sim comments.

You can begin comments anywhere in a model. 20-sim will automatically recognize comments and color it green.

9.1.9 State and Time Events

Normally an integration algorithm uses a fixed time step or a variable step, depending only on the model dynamics. In some cases, the algorithm is forced to perform calculations at a specific time.

Time Events
The most simple form of forced calculation is calculation at a specific time. This is called a time event. The following functions cause time events.

<table>
<thead>
<tr>
<th>function</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>timeevent</td>
<td>Forces the integration algorithm perform a calculation at a specific time.</td>
</tr>
<tr>
<td>frequencyevent</td>
<td>Forces the integration algorithm perform a calculation at a specific frequency.</td>
</tr>
<tr>
<td>sample, hold, next, previous</td>
<td>These functions introduce a discrete system in a model. A discrete system forces the integration algorithm to perform calculations every sampletime.</td>
</tr>
</tbody>
</table>
9. Language Reference

State Events
Sometimes the integration algorithm must iterate to find the next calculation step. This is
called a state event. The following functions cause state events.

<table>
<thead>
<tr>
<th>function</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>event</td>
<td>Forces the integration algorithm to find the exact point where the input crosses zero.</td>
</tr>
<tr>
<td>eventup</td>
<td>Forces the integration algorithm to find the exact point where the input crosses zero from a negative to a positive value.</td>
</tr>
<tr>
<td>eventdown</td>
<td>Forces the integration algorithm to find the exact point where the input crosses zero from a positive to a negative value.</td>
</tr>
<tr>
<td>limint</td>
<td>Forces the integration algorithm to find the exact point where the output become larger or smaller than the minimum and maximum parameters.</td>
</tr>
<tr>
<td>resint</td>
<td>Forces the integration algorithm to find the exact point where the input becomes zero.</td>
</tr>
</tbody>
</table>

To find the exact point where simulation should be performed iteration is used. The accuracy of the iteration can be set by the event delta parameter in the Run Properties window.

9.1.10 Using Brackets and Newlines

You can use brackets and newlines in various ways to create order in your equations.

Parenthesis ()

Parentheses may be used to indicate grouping as in ordinary mathematical notation, e.g.:

\[ u = \sin(time*f*2*3.1415 + (a + b)/c ); \]

If a lot of parenthesis are used, it may be hard to see the grouping. You can always put your mouse pointer next to a parenthesis and have the group highlighted.

Square Brackets []

Square Brackets are used to indicated matrix sizes and matrix elements:
parameters
    integer \( p[6,6] \) = [1,0,0,0,0;0,2,0,0,0,0;0,0,2,0,0,0;0,0,0,5,0,0;0,1,0,0,5,0;0,1,0,0,0,6];
variables
    real \( v[3] \);
equations
    v = p[4:6,6];

Newlines
Newlines, tabs and white spaces can be used to make your equations more readable. E.g for the parameter example from above we could also write:

    parameters
        integer \( p[6,6] \) = [
            1,0,0,0,0,0;
            0,2,0,0,0,0;
            0,0,2,0,0,0;
            0,0,0,5,0,0;
            0,1,0,0,5,0;
            0,1,0,0,0,6
        ];

9.2 Keywords

9.2.1 Keywords
Before the actual equations, three sections can be entered denoted by the keywords \textit{constants}, \textit{parameters} and \textit{variables}. This is shown in the example below:

    constants
        real basefrequency = 60;
        real \( \pi = 3.14159265 \);
    parameters
        real amplitude = 1;
    variables
        real \( plot \);
equations
    \( plot = \text{amplitude} * \sin (\text{basefrequency} * 2 * \pi * \text{time}); \)

9.2.2 Constants
Constants are symbolic representations of numerical quantities that do not change during or in between simulation runs. Constants must be defined in 20-sim, using the \textit{constants} keyword. After the keyword, lines with constant declarations can be entered. Every line must be finished by a semicolon (;). An example is given below:

    constants
        real \( V = 1 \{ \text{volume, m3} \}; \) // the volume of barrel 1
        real hidden \( D = 0.5 \{ \text{length, m} \}; \) // the length of part 1
...
Types
20-sim currently supports four types of constants: boolean, integer, real and string. These types must be specified explicitly. The use of the type real is shown in the example above.

Hidden
To prevent users from inspecting constants, the keyword hidden can be applied. This keyword should follow the data type.

Constant names
Constant names can consist of characters and underscores. A constant name must always start with a character. Constant names are case-sensitive. No reserved words may be used for constants. If a reserved word is used, an error message will pop-up while checking the model. In the example above the names V and D are used.

Constant Values
It is advised to assign every constant a value. Otherwise 20-sim will assign a default value (0, false or an empty string), which can easily lead to misinterpretations. Unlike parameter values, constant values cannot be overridden in the Simulator.

Quantity and Unit
If a constant is known to represent a physical value, you can define the corresponding quantity and unit. 20-sim will use this information to do a unit check on equations. The use of quantities and units is optional. In the example above the quantities volume and length are used with the units m3 and m.

Example
```plaintext
constants
    real pi = 3.14159265359;
    real two pi = 6.28318530718;
    integer i = 10 {length,m}; // vehicle length
    integer j = 1 {time,s};

constants
    string filename = 'data.txt';
    integer i = 1;
    real state = 0.0;
    boolean t = true, f = false;
```

Tip
- You can easily enter constants by using the Add button in the Equation Editor Taskbar.
- You can easily select quantities and units by using the Units button of the Equation Editor Taskbar.
- Use the 20-sim naming convention for constant names.
9.2.3 Predefined Constants

Some constants in 20-sim have a predefined value. These constants do not have to be declared in the constants section of a model. You can add your own predefined constants in the file Constants.ini in the 20-sim bin-directory.

**Standard**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi)</td>
<td>3.1415926535897932384626433832795</td>
<td>Standard acceleration of gravity</td>
</tr>
<tr>
<td>exp1</td>
<td>2.71828182845904523536028747135266</td>
<td>Standard acceleration of gravity</td>
</tr>
<tr>
<td>twopi</td>
<td>6.28318530717958647692528676655901</td>
<td>Standard acceleration of gravity</td>
</tr>
<tr>
<td>sqrt2</td>
<td>1.41421356237309504880168872420969</td>
<td>Standard acceleration of gravity</td>
</tr>
<tr>
<td>log2</td>
<td>0.693147180559453094172321214581766</td>
<td>Standard acceleration of gravity</td>
</tr>
</tbody>
</table>

**Physics**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g_n)</td>
<td>9.80665 {m/s^2}</td>
<td>Standard acceleration of gravity</td>
</tr>
<tr>
<td>G</td>
<td>66.7259e-12 {N.m/kg^2}</td>
<td>Newtonian constant of gravitation</td>
</tr>
<tr>
<td>(c_0)</td>
<td>299.792458e6 {m/s}</td>
<td>Speed of light (vacuum)</td>
</tr>
<tr>
<td>(\mu_0)</td>
<td>1.25663706143591795385057 {H/m}</td>
<td>Permeability (vacuum)</td>
</tr>
<tr>
<td>epsilon_0</td>
<td>8.854188e-12 {F/m}</td>
<td>Permittivity (vacuum)</td>
</tr>
<tr>
<td>(h)</td>
<td>6.6260755e-34 {J.s}</td>
<td>Planck constant</td>
</tr>
<tr>
<td>(m_p)</td>
<td>2.17671e-08 {kg}</td>
<td>Planck mass</td>
</tr>
<tr>
<td>(l_p)</td>
<td>1.61605e-35 {m}</td>
<td>Planck length</td>
</tr>
<tr>
<td>(t_p)</td>
<td>5.39056e-44 {s}</td>
<td>Planck time</td>
</tr>
<tr>
<td>(e)</td>
<td>1.60217733e-19 {C}</td>
<td>Elementary charge</td>
</tr>
<tr>
<td>(R_H)</td>
<td>25812.8056 {Ohm}</td>
<td>Quantized Hall resistance</td>
</tr>
<tr>
<td>(\mu_B)</td>
<td>9.2740154e-24 {J/T}</td>
<td>Bohr magneton</td>
</tr>
<tr>
<td>(\mu_N)</td>
<td>5.0507866e-27 {J/T}</td>
<td>Nuclear magneton</td>
</tr>
<tr>
<td>(R_y)</td>
<td>10973731.534 {1/m}</td>
<td>Rydberg constant</td>
</tr>
<tr>
<td>(a_0)</td>
<td>5.29177249e-11 {m}</td>
<td>Bohr radius</td>
</tr>
<tr>
<td>(N_A)</td>
<td>6.0221367e+23 {1/mol}</td>
<td>Avogadro constant</td>
</tr>
<tr>
<td>(m_u)</td>
<td>1.6605402e-27 {kg}</td>
<td>Atomic mass constant</td>
</tr>
<tr>
<td>(F)</td>
<td>96485.309 {C/mol}</td>
<td>Faraday constant</td>
</tr>
<tr>
<td>(k)</td>
<td>1.380658e-23 {J/K}</td>
<td>Boltzmann constant</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>5.67051e-08 {W/m2.K4}</td>
<td>Stefan-Boltzmann constant</td>
</tr>
<tr>
<td>(b)</td>
<td>0.002897756 {m.K}</td>
<td>Wien constant</td>
</tr>
<tr>
<td>(R)</td>
<td>8.31451 {J/mol.K}</td>
<td>Molar gas constant</td>
</tr>
<tr>
<td>(V_m)</td>
<td>0.0224141 {m3/mol}</td>
<td>Molar volume (ideal gas)</td>
</tr>
<tr>
<td>(n_0)</td>
<td>2.686763e+25 {1/m3}</td>
<td>Loschmidt constant</td>
</tr>
</tbody>
</table>

**m_e** | 9.1093897e-31 \{kg\}                   | Electron mass                         |
**m_p** | 1.6726231e-27 \{kg\}                   | Proton mass                           |
**m_n** | 1.6749286e-27 \{kg\}                   | Neutron mass                          |
9.2.4 Parameters

Parameters are symbolic representations of numerical quantities which can only be changed after simulation has been stopped. They can therefore be changed in between of simulation runs, or after the user has (temporarily) stopped the simulation.

Parameters must be defined in 20-sim, using the parameters keyword. After the keyword, lines with parameter declarations can be entered. Every line must be finished by a semicolon (;) and may be followed by comment with a description of the parameter. An example is given below:

```
parameters
  real V = 1 {volume, m3}; // the volume of barrel 1
  real hidden D = 0.5 {length, m}; // the length of part 1
  real x (range=<-1,1>) = 0.1 {m}; // the position of part x with a min-max range
  real global L = 3.1 {m}; // A global parameter, can be used in other models, but should be assigned a value only once
  real favorite P = 1.1 {V}; // A parameter, that is made favorite: it will appear in the favorites list for quick selection
...
```

Change Parameter Values

Parameters can be assigned default values. These values can be changed in the code. However, a quicker way to change parameter values is to open the Parameters/Initial Values Editor. This editor will allow you to quickly changes parameter values and run a simulation.

Types

20-sim currently supports four types of parameters: boolean, integer, real and string. These types must be specified explicitly. The use of the type real is shown in the example above.

Hidden

To prevent users from inspecting parameters or decreasing the list of parameters, the keyword hidden can be applied. This keyword should follow the data type.

Global

To use the same parameter in other submodels, the keyword global can be applied. This keyword should follow the data type. Note that the keywords oneup and global are mutually exclusive. Only one can be used.
OneUp
The keyword oneup should be used after the type (real, boolean, integer) and keyword hidden and before the name of the parameter. It is used to limit the scope of a parameter. Note that the keywords oneup and global are mutually exclusive. Only one can be used.

Favorite
To quickly find a parameter in the Parameters/Initial Values Editor the keyword favorite can be applied. This keyword should follow the data type.

Parameter Names
Parameter names can consist of characters and underscores. A parameter name must always start with a character. Parameter names are case-sensitive. No reserved words may be used for parameters. If a reserved word is used, an error message will pop-up while checking the model. In the example above the names V and D are used.

Ranges
Right after a parameter name you can enter annotations for the minimum value, range etc. Examples:

```plaintext
parameters
    real V (min=0.1) = 1 {volume, m3}; // the volume of barrel 1, minimum volume = 0.1 m3
    real R (max=100) = 20 {ohm}; // the resistance, maximum value = 100 ohm
    real x (range=<-10,10>) = 0.5 {length, m}; // the position of part x, range from -10 to 10 m
    real D (readonly=true) = 0.1 {m}; // the diameter of the tube, readonly
```

Quantity and Unit
If a parameter is known to represent a physical value, you can define the corresponding quantity and unit. 20-sim will use this information to do a unit check on equations. The use of quantities and units is optional. In the example above the quantities volume and length are used with the units m3 and m.

Comment
If comment is added at the end of the parameter declaration, it is shown in the Variable Chooser to facilitate the selection between variables.
Example

parameters
real p1 = 12, p2, state = 1.1;
ishort i = 10 {length,m}; // vehicle length
integer j = 1 {time,s};

parameters
string filename = 'data.txt'; // This comment appears as a description in
the Parameters/Initial values editor.
integer i = 1; // Just a parameter
real state; // Initial velocity [m/s]
boolean t = true; // T = true

Tip

- You can easily enter parameters by using the Add button in the Equation Editor Taskbar.
- You can easily select quantities and units by using the Units button of the Equation Editor Taskbar.
- Use the 20-sim naming convention for parameter names.

9.2.5 Annotations

Introduction
Annotations are properties that can be applied to parameters and variables. They have to be entered between brackets, separated by commas, right after the parameter or variable name.

Readonly
The readonly property can only be applied to parameters. You can use it to prevent a parameter value to be changed in the Parameters Editor.

real y (readonly=true) = 20 {kg}; // the mass y, cannot be changed value in the parameters editor

Ranges
Parameters and Variables can be limited in range or restricted by annotations.

real x (range=<-1,1>) = 0.1 {m}; // the position of part x with a min-max range

Annotations start ( and end with a bracket ). Various elements can be included inside the brackets, separated by semicolons. Annotation have to be placed right after the parameter name. The following annotations are supported:

- min=0
- max=10,1
- range=<-17,2.345>
- range = [0,1]
• $\text{range} = <,0>$

Brackets mean "equal or". So

$\text{range} = [0,1]$  
means equal or larger than zero and smaller or equal to 1. If one of the element of a range is omitted, this means infinity. So

$\text{range} = [0,]$  
means equal to zero or larger. Larger than or smaller can also be used. So:

$\text{range} = <0,1>$  
means larger than zero and smaller than 1. And

$\text{range} = <0,>$  
means larger than zero.

**View**

Integers can be entered using a decimal, hexadecimal or binary notation. They are by default, displayed using their decimal notation. You can use the annotations to show an integer in their hexadecimal or binary notation.

```plaintext
integer x ('view=hex') = 0xE2F3; // the integer is entered in hexadecimal notation
integer y ('view=hexadecimal');
integer z ('view=binary') = 0b11011;
```

**Note**

- The ranges are only checked in debug mode.
- No spaces are allowed between the brackets.
- Readonly does only apply for parameters.

### 9.2.6 Variables

Variables are symbolic representations of numerical quantities that may change during simulation runs. Variables must be defined in 20-sim, using the variables keyword. After the keyword, lines with variable declarations can be entered. Every line must be finished by a semicolon (;). An example is given below:
variables
    real interesting V {volume, m3}; // the volume of barrel 1
    real hidden D {length, m}; // the length of part 1
    real x (min=0.0) {m}; // the position of part x with a
    minimum value of 0.0
...

Types

20-sim currently supports four types of variables: boolean, integer, real and string. These types must be specified explicitly. The use of the type real is shown in the example above.

Interesting

By adding the keyword interesting after the variable type, a variable will be given special focus in the Variable Chooser. The Variable Chooser shows the complete list of variables of a model and is used to select variables for plotting. The keyword interesting is shown in the variable list, making it easier to find variables of special interest.

Hidden

To prevent users from inspecting variables or decreasing the list of variables, the keyword hidden can be applied. This keyword should follow the data type.

Global

To use the same variable in other submodels, the keyword global can be applied. This keyword should follow the data type. Note that the keywords oneup and global are mutually exclusive. Only one can be used.

OneUp

The keyword oneup should be used after the type (real, boolean, integer) and keyword hidden and before the name of the variable. It is used to limit the scope of a variable. Note that the keywords oneup and global are mutually exclusive. Only one can be used.

Favorite

To quickly find a variable in the Variable Chooser the keyword favorite can be applied. This keyword should follow the data type.

Variable Names

Variable names can consist of characters and underscores. A variable name must always start with a character. Variable names are case-sensitive. No reserved words may be used for variables. If a reserved word is used, an error message will pop-up while checking the model.

Annotations

Right after a variable name you can enter annotations for the minimum value, range etc.

Variable Values

Variables cannot be assigned default values.

Quantity and Unit

If a variable is known to represent a physical value, you can define the corresponding quantity and unit. 20-sim will use this information to do a unit check on equations. The use of quantities and units is optional. In the example above the quantities volume and length are used with the units m3 and m.
Comment
If comment is added at the end of the variable declaration, it is shown in the Variable Chooser to facilitate the selection between variables.

Predefined Variables
20-sim has some predefined variables which have a special meaning.

Example
```plaintext
variables
  real interesting p1,p2,state;
  integer i;
  integer j;

variables
  string filename;
  integer interesting i;
  real interesting state;
  boolean t,f;
```

Tip
- Use the 20-sim naming convention for variable names.

9.2.7 Predefined Variables
Some variables in 20-sim have a predefined value. These variables do not have to be declared in the variables section of a model.

time
The variable time is equal to the simulated time. It can for example be used in functions such as:

```plaintext
u = sin(time*f*2*3.1415);
```

starttime
The variable starttime is equal to the Start value of the Simulator Run Properties (typically 0.0 {s}).

finishtime
The variable finishtime is equal to the Finish value of the Simulator Run Properties (e.g. 10.0 {s}). It can be used for example to execute some actions just before finishing the simulation:

```plaintext
if (time >= finishtime - 1.0) then
  // do some action
end;
```

realtime
The variable realtime contains the elapsed wall-clock time (in seconds) from the start of the simulation. It can be used to monitor if the simulation runs slower, equally fast or faster than real time.

```plaintext
if (time >= realtime) then
```
// simulation is realtime or faster than realtime
else
    // simulation is slower that real time
end;

**sampletime**
The variable *sampletime* is equal to the sampletime. It is only meaningful when it is used in an equation model that is part of a discrete loop in your model. 20-sim will automatically detect, which loop the model belongs to and assign the proper value to the variable sampletime.

**stepsize**
The variable *stepsize* contains the actual stepsize of the integration routine. It can be used to monitor the variable step sizes of methods like BDF and Vode Adams.

**random**
The variable *random* will yield a random variable uniformly distributed in the interval $[-1,1]$. E.g.:

$$ u = \text{random}; $$

**true**
The variable *true* will return the boolean value true.

**false**
The variable *false* will return the boolean value false.

**major**
Some integration algorithms, will perform model calculations at one or more intermediate points before calculating the next output value. To prevent equations being calculated, at these intermediate steps, you can use the variable *major*. This variable will return the boolean *false* when calculations are performed for an intermediate step and will return *true* when calculations are performed for the output values.

**Example**

```plaintext
....
if major then
    sim_steps = sim_steps + 1;  // this equation is not evaluated at intermediate points
end;
....
```

### 9.2.8  Global Parameters and Variables

By adding the keyword *global* to a parameter or variable in the Equation Editor, its value is shared all over the model. It means that various submodels can use the same parameter or variable, but you only have to assign the value once. In equation models, the keyword *global* is added after the definition of the data type:
9. Language Reference

```plaintext
parameters
  real global par1 = 100 {Hz};
  real global par2 ;
variables
  real global var1;
  real global var2;
  ..
  ..
```

Parameters can only be assigned a value once. The same goes for variables. In only one submodel the global variable can be assigned a value using an equation. If parameters or variables are assigned more than once, 20-sim will generate an error.

**Scope**

By default, global parameters and variables and valid in the entire model. However, the scope can be limited to a certain branch in your model tree.

**Changing Global Parameters Values**

You can change the value of a global parameter in the Parameters/Initial Values Editor. By default, global parameters and variables and valid in the entire model. In the Parameters/Initial Values Editor you will find the parameters at the top level of the hierarchy. If the parameter has a scope, you will find it in the specific branch of the model hierarchy.

### 9.2.9 OneUp

The keyword Oneup is used to restrict the scope of global parameters and variables. It allows you to use submodels to define the values of global parameters or global variables as an alternative to the Globals Relations Editor.

**Example**

In the example model Accumulator Test (type Accumulator Test in the search box to find it in the Examples library) four hydraulic circuits are used. All models in the circuits share the same parameters for the fluid properties such as density, bulk modulus etc. This is done by making them global.
The blue submodel *Fluid Properties*, defines the values of these global parameters. The model internally used the **OneUp** keyword. The equations of the submodel are:

```plaintext
parameters
    real oneup kin_viscosity (range= <0,>) = 2.7e-5 {m2/s};
    real oneup rho (range= <0,>) = 865.0 {kg/m3};
    real oneup B (range= <0,>) = 1.6e9 {Pa};
    real oneup p_vapour (range= <-1e5,>) = -99900.0 {Pa};
```

The keyword OneUp limits the scope of a global parameter or variable to the branch that shares contains the submodel where it is defined. In this example this is the model layer that contains the *Fluid Properties* model and all of the hydraulic circuits that you see.

**OneUp**
The keyword oneup should be used after the type (real, boolean, integer) and before the name of the parameter or variable.

**Note**
The keywords oneup and global are mutually exclusive. Only one can be used.

### 9.3 Types

#### 9.3.1 Data Types

For all parameters, variables, initial conditions etc. 20-sim supports the following data types:

1. Boolean
2. Integer
3. Real
4. String

The declaration of data types can be done in the *constants, parameters* and *variables* sections of the model. E.g.:
parameters
  real a = 1;
  integer B[2,2];
variables
  string c;
  boolean yesno;

Declaration of data types in equations is not allowed. E.g.:
  real v = sin(t*a + b); // This is not allowed!

Hidden
To prevent users from inspecting variables, parameters or constants (e.g. for encrypted models) or decreasing the list of parameters and variables, the keyword hidden can be applied. This keyword should follow the data type. For example:

parameters
  real hidden a = 1;
  integer hidden B[2,2];
variables
  string hidden c;
  boolean hidden yesno;

Interesting
To allow for a quick selection of variables in the Variable Chooser, the keyword interesting can be applied for variables. This keyword should follow the data type. For example:

parameters
  real a = 1;
  integer B[2,2];
variables
  string interesting c;
  boolean interesting yesno;

Interesting variables are shown, even when all options are deselected in the Variable Chooser. This makes it possible to quickly select variables out of a large list.

9.3.2 Boolean
Either true (1) or false (0). Variables of this type should not be used to store any other values. Like C++, 20-sim evaluates non-zero values as true; only the value of zero is evaluated as false. Normally, the value of one is used to indicate true.

Examples
  boolean a;
  boolean b = true;
  boolean c = false;
  boolean D[2,2] = [true,true;false;false];
  a = b and c;
Limitations
When used in standard functions, booleans are treated as reals with value 0 or 1. An equation like:

```plaintext
boolean a = true;
real c;
c = sin(a);
```

would yield c equal to 0.8415. Try to avoid these constructions, since they lead to confusions.

9.3.3 Integer
Signed four-byte integer. It can hold any decimal value between \(-2^{31}\) and \(+2^{31}-1\). Integer is the recommended data type for the control of program loops (e.g. in for-next loops) and element numbering.

Notations
Integer values can be entered using the following notation:

- Decimal: any combination using the symbols 0,1,2,3,4,5,6,7,8 and 9.
- Binary: starting with "0b" followed by any combination using the symbols 0 and 1.
- Hexadecimal: starting with "0x" followed by any combination using the symbols 0,1,2,3,4,5,6,7,8,9,A,B,C,D,E and F.

Annotations
The value of an integer is displayed by default (e.g. in the Parameters Editor) in the decimal notation. You can use Annotations to display integers in their hexadecimal or binary notation.

Example
```plaintext
parameters
  integer i = 1, j = 2;
  integer B[2,2] = [1,2;3,4];
  integer x ('view=hexadecimal') = 0xE2F4;
  integer y ('view=binary') = -0b111011;
variables
  integer b;
equations
  b = B[i,j] * x * y;
```

Limitations
When used in standard functions, integers are treated as reals. An equation like:

```plaintext
parameters
  integer c;
equations
  c = 10*sin(time);
```

would yield c equal to 0.8415. Try to avoid these constructions, since they lead to confusions. Use the round function instead:
parameters
  integer c;
equations
  c = round(10*sin(time));

9.3.4  Real

Signed 64 bit floating point number. The maximum representable number is 1.7976931348623158e+308. The minimum positive value unequal to zero is 2.2250738585072014e-308. If reals exceed this range during simulation, the numerical values window will display the values 1.#INF (positive infinite) or -1.#INF (negative infinite).

Example
  real a = 0.0;
  real b = 1.04e-31, c = -3198.023e-64;
  real B[2,2] = [1.2, 22.4; 3.0e3, -4.023e-6];

Limitations
In practice, during simulation, real should not exceed 1e-100 .. 1e100 to prevent instability in the integration algorithms.

9.3.5  String

A string is an array of characters. There is no limit to the amount of characters a String may contain. Simple string concatenation (e.g. concatenation that can be done during processing) is allowed. Strings must always be entered between single quotes ('). A single quote can be escaped with a second quote, so if a single quote should be part of the string, it needs to be typed twice.

Example
  parameters
    string c = 'C:\data.txt';
    string b = 'This is a string with a " single quote';
  variables
    real d;
    string name;
equations
    if time > 10 then stopsimulation (b); end;
    d = table(c,1);
    name = c + ' // file';
    toMatlab (d, name)

Limitations
Strings may only be used as input for some special functions (e.g. table).
9.3.6 Typecasting

Type casting is a way to convert a variable from one data type to another data type. For example from real to boolean or from real to integer. Typecasting can be done in equations using the data type between parentheses:

```plaintext
variables
    real t;
    boolean b;

equations
    t = if time > 10 then 1.33 else 0 end;
    b = (boolean) t;
```

In the example above the real variable \( s \) is converted to the boolean variable \( b \). In 20-sim the C-code style type casting is used. An integer or real value of 0 is converted to True and a non zero value is converted to false.

Typecasting is done automatically in 20-sim, but when the data type is not given a warning will be generated:

```plaintext
variables
    real s;
    boolean b;

equations
    s = if time > 10 then 1.33 else 0 end;
    b = s;
```

In the example above the warning "Possible loss of data when converting from real to boolean in equation \( b = s \);" will be given. To prevent this warning, use typecasting with parenthesis as shown in the top example.
9.4 Functions

9.4.1 Functions

In 20-sim you can use all kind of functions to describe your equations. They are classified according to the list below.

1. Arithmetic
2. Discrete
3. Event
4. Expansion
5. Extern
6. Matrix
7. Port
8. Source
9. Trigonometric

9.4.2 Arithmetic

abs

Syntax

\[ Y = \text{abs}(X); \]

Description

Returns the absolute value of X or the elements of X.

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>abs(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>-2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>-1e-102</td>
<td>1e-102</td>
</tr>
<tr>
<td>[1.1,2.7;-3.6,-4]</td>
<td>[1.1,2.7;3.6,4]</td>
</tr>
</tbody>
</table>

Limitations

- X and Y must have the same size.
- For scalars, the abs function can also be written as: \( Y = |X|; \)
algebraic

Syntax

\[ y = \text{algebraic}(x); \]

Description

\( y \) becomes equal to \( x \). This function forces the integration algorithm to find a solution by using the algebraic loop solver. Normally when algebraic loops occur in a model, 20-sim will itself will break the algebraic loop using the algebraic loop solver internally. You can use this function to break an algebraic loop at a user-defined position.

Examples

\[ u = \sin(time); \]
\[ a = \text{algebraic}(y); \]
\[ y = K*(u - a); \]

Note

Be very careful with this function. In most cases the symbolic engine of 20-sim will find and exact solution which will lead to much faster simulation!

ceil

Syntax

\[ Y = \text{ceil}(X); \]

Description

Rounds \( X \) or the elements of \( X \) to the nearest integers greater than or equal to \( X \).

Examples

<table>
<thead>
<tr>
<th>( X )</th>
<th>( \text{ceil}(X) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.1</td>
<td>3</td>
</tr>
<tr>
<td>-2.6</td>
<td>-2</td>
</tr>
<tr>
<td>3.4</td>
<td>4</td>
</tr>
<tr>
<td>[1.1,-2.7;3.5,-4.1]</td>
<td>[2,-2;4,-4]</td>
</tr>
</tbody>
</table>

Limitations

\( X \) and \( Y \) must have the same size.

constraint

Syntax

\[ y = \text{constraint}(x); \]

Description
This function iteratively assigns a value to y such that x approaches zero within a given error margin. It only works in combination with the MBDF simulation method! The function is very useful for entering constraints in physical systems and inverse dynamics.

**Examples**

This example makes a velocity \( v_m \) equal to a reference velocity \( v_s \):

\[
\begin{align*}
\text{vs} &= \sin(\text{time}); & // \text{reference velocity} \\
\text{v} &= \text{vm} - \text{vs}; & // \text{If v = 0 then the mass follows the reference velocity} \\
\text{F} &= \text{constraint(v)}; & // \text{Make F have a value that yields a zero velocity v} \\
\text{vm} &= (1/m) \cdot \text{int(F)}; & // \text{mass}
\end{align*}
\]

**ddt**

**Syntax**

\[
y = \text{ddt}(x,\text{init});
\]

**Description**

Returns the derivative value of x with respect to the time. The initial value of y is equal to the value of init.

**Method**

20-sim will always try to rewrite equations in such a way that only integrals are used (integral form). This is done automatically and means all integration methods can be applied. Sometimes an integral form cannot be found. Then only the Backward-Differentiation Method can be used for simulation.

**Examples**

<table>
<thead>
<tr>
<th>equation</th>
<th>integral form</th>
<th>integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{ddt(x,0)} = u - k*x; )</td>
<td>( x = \text{int(u - k*x)}; )</td>
<td>All methods</td>
</tr>
<tr>
<td>( x = \text{ddt(sin(time),0)}; )</td>
<td>not possible!</td>
<td>Only BDF</td>
</tr>
</tbody>
</table>

**Limitations**

When no integral form can be found, the use of the derivative function can introduce noisy signals or may even cause signals to exceed the data range.

**derivative**

**Syntax**

\[
y = \text{derivative}(x,\text{base});
\]

**Description**

Returns the derivative value of x with respect to base. E.g:
variables
    real x, y, z;
equations
    x = sin (time);
    y = derivative (x, time);
    z = derivative (x^2, x);

Limitations
20-sim will use its symbolic engine to solve the derivative and rewrite it to a closed form. If no solution is found, an error message is generated.

dly

Syntax
    y = dly(x, init);

Description
y is equal to the value of x, one simulation-time step delayed. The initial value of y is equal to init

Example
    x = sin(time*0.3);
    y = dly(x, 1.0);

Limitations
x, y and init must be scalars.

energyfunction

Syntax
    H = energyfunction(x, v, F, E);

Description
Returns the partial derivative of an energy function and the derivative of the energy variable. Used for port hamiltonian functions.

F = d(E)/dx
v = ddt(x) or x = int(v);

x and v have a causal relation: one of them should be an input and one of them should be an output.

Example
In this example the potential energy of a spring is given by the variable E. E is defined as a function of the variable x.
parameters
   real k = 1000 {N/m};
variables
   real H {J};       // spring energy (potential)
   real x {m};
   real v {m/s};
   real F {N};
   real E {J};
equations
   v = sin (time);
   E = 0.5*k*x^2;
   H = energyfunction ( x , v, F , E );

20-sim will (symbolically) solve this to:

F = d(E)/dx = 0.5 * k * 2 * x

and

x = int(v)

Limitations
- The partial derivative of the energy function should exist and will be symbolically
  solved by 20-sim.
- If the variable x is an input for the function, the time derivative to yield the variable
  v will be symbolically solved if possible.
- The function only accepts scalar inputs.

exp

Syntax
   \( Y = \exp(X); \)

Description
Returns the exponential function of X or the elements of X.

   \( y = e^x; \)

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>( \exp(x) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.718282 ( (= e^1) )</td>
</tr>
<tr>
<td>2.1</td>
<td>8.166170 ( (= e^{2.1}) )</td>
</tr>
<tr>
<td>-2.6</td>
<td>0.074274 ( (= e^{-2.6}) )</td>
</tr>
<tr>
<td>[1,2.1;-2.6,1]</td>
<td>[2.718282,8.166170;0.074274,2.7 18282] ( (= [e^1,e^{2.1},e^{-2.6},e^1]) )</td>
</tr>
</tbody>
</table>
Limitations
X and Y must have the same size.

exp10

Syntax
Y = exp10(X);

Description
Returns the exponential function (base 10) of X or the elements of X.

\[ y = 10^x; \]

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>exp10(x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 ( = 10^1 )</td>
</tr>
<tr>
<td>2.1</td>
<td>125.89 ( = 10^{2.1} )</td>
</tr>
<tr>
<td>-2.6</td>
<td>0.00251 ( = 10^{-2.6} )</td>
</tr>
<tr>
<td>[1,2.1;-2.6,1]</td>
<td>[10,125.89;0.00251,10]</td>
</tr>
<tr>
<td></td>
<td>( = [10^1,10^{2.1};10^{-2.6},10^1] )</td>
</tr>
</tbody>
</table>

Limitations
X and Y must have the same size.

exp2

Syntax
Y = exp2(X);

Description
Returns the exponential function (base 2) of X or the elements of X.

\[ y = 2^x; \]

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>exp2(x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 ( = 2^1 )</td>
</tr>
<tr>
<td>2.1</td>
<td>4.8709 ( = 2^{2.1} )</td>
</tr>
</tbody>
</table>

Limitations
X and Y must have the same size.
-2.6 \quad 0.16494 (= 2^{-2.6})

\[1,2.1;-2.6,1\] \quad [2,4.8709;0.16494,2] 
\quad ( = [2^1,2^{2.1};2^{-2.6},2^1] )

Limitations
X and Y must have the same size.

**floor**

Syntax
\[ Y = \text{floor}(X); \]

Description
Rounds X or the elements of X to the nearest integers less than or equal to X.

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>floor(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.1</td>
<td>2</td>
</tr>
<tr>
<td>-2.6</td>
<td>-3</td>
</tr>
<tr>
<td>3.4</td>
<td>3</td>
</tr>
<tr>
<td>[1.1,-2.7;3.5,-4.1]</td>
<td>[1,-3;3,-5]</td>
</tr>
</tbody>
</table>

Limitations
X and Y must have the same size.

**initialvalue**

Syntax
\[ Y = \text{initialvalue}(X); \]

Description
Returns the initial value of X or the elements of X. Value should be assigned to X first.

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>initialvalue(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>sin(time)</td>
<td>0</td>
</tr>
<tr>
<td>[cos(time); sin(time)]</td>
<td>[1;0]</td>
</tr>
</tbody>
</table>

Limitations
X and Y must have the same size.
**int**

**Syntax**

\[ y = \text{int}(x, \text{init}) \]

**Description**

Returns the integral of \( x \) with respect to the time. The initial value of \( y \) is equal to the value of \( \text{init} \). This initial value is optional. If no value is entered, a default initial value of 0 is used.

**Examples**

\[
\begin{align*}
  y &= \text{int}(x, 0); \\
  z &= \text{int}(\sin(time*w + p) - \cos(time*x + z), b);
\end{align*}
\]

**limint**

**Syntax**

\[ y = \text{limint}(x, \text{min}, \text{max}, \text{init}) \]

**Description**

Returns the integral of \( x \) with respect to the time. The initial value of \( y \) is equal to the value of \( \text{init} \). The output of this integral is limited between a maximum and minimum bound given by the parameters \( \text{min} \) and \( \text{max} \).

This function forces the integration algorithm to find the exact point where the gets saturated. If the integral is in saturated condition and the input changes sign, the output wanders away from the bounds immediately.

The limitedIntegrator block is used for the prevention of wind-up in PI and PID controllers in control applications. It is also used in kinematics, electrical circuits, process control, and fluid dynamics.

**Examples**

\[
\begin{align*}
  x &= 10 \times \sin(time*10); \\
  y &= \text{limint}(x, -1, 1, 0);
\end{align*}
\]

**limit**

**Syntax**

\[ y = \text{limit}(x, a, b) \]

**Description**

This function limits the signal \( x \) between a minimum of \( a \) and a maximum of \( b \).
Examples

\[ x = 10 \times \sin(\text{time}); \]
\[ y = \text{limit}(x, -5, 5); \]

Limitations

a, b, x and y must be scalars. a must be smaller than b.

log

Syntax

\[ y = \log(x); \]

Description

Returns the natural logarithm of X or the elements of X.

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>log(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2.1</td>
<td>0.6931</td>
</tr>
<tr>
<td>4</td>
<td>1.3863</td>
</tr>
<tr>
<td>[1, 2.1; 4, 1]</td>
<td>[0, 0.6931; 1.3863, 0]</td>
</tr>
<tr>
<td>-2.6</td>
<td>not allowed!</td>
</tr>
</tbody>
</table>
Limitations
X and Y must have the same size. X or the elements of X must be larger than zero.

log10

Syntax
   \( Y = \log_{10}(X); \)

Description
Returns the base 10 logarithm of X or the elements of X.

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>log10(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>1.6990</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>[1,50;100,1]</td>
<td>[0,1.6990;2,0]</td>
</tr>
<tr>
<td>-2.6</td>
<td>not allowed!</td>
</tr>
</tbody>
</table>

Limitations
X and Y must have the same size. X or the elements of X must be larger than zero.

log2

Syntax
   \( Y = \log_{2}(X); \)

Description
Returns the base 2 logarithm of X or the elements of X.

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>log2(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2.1</td>
<td>1.0704</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>[1,2.1;4,1]</td>
<td>[0,1.0704;2,0]</td>
</tr>
<tr>
<td>-2.6</td>
<td>not allowed!</td>
</tr>
</tbody>
</table>

Limitations
X and Y must have the same size. X or the elements of X must be larger than zero.
**resint**

**Syntax**

\[
  y = \text{resint}(x,\text{newoutp},\text{reset},\text{init});
\]

**Description**

Returns the integral of \( x \) with respect to the time. The initial value of \( y \) is equal to the value of \( \text{init} \). The output of this integral is reset to the value of \( \text{newoutp} \) when the Boolean argument \( \text{reset} \) is \( \text{TRUE} \).

**Examples**

\[
x = 1;
reset = \text{event}(\sin(\text{time}));
y = \text{resint}(x,0,\text{reset},0);
\]

or

\[
x = 1;
reset = \text{if } y > 10 \text{ then true else false end};
y = \text{resint}(x,0,\text{reset},0);
\]

---

**round**

**Syntax**

\[
Y = \text{round}(X);
\]

**Description**

Rounds \( X \) or the elements of \( X \) to the nearest integer.

**Examples**

<table>
<thead>
<tr>
<th>( X )</th>
<th>( \text{round}(X) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.1</td>
<td>2</td>
</tr>
<tr>
<td>-2.6</td>
<td>-3</td>
</tr>
<tr>
<td>3.7</td>
<td>4</td>
</tr>
<tr>
<td>[1.1,-2.7;3.5,-4.1]</td>
<td>[1,-3;4,-4]</td>
</tr>
</tbody>
</table>

**Limitations**

\( X \) and \( Y \) must have the same size.
sign

Syntax

\[ Y = \text{sign}(X); \]

Description

Returns the sign of \( X \) or the elements of \( X \).

\[ X < 0: Y = -1 \]
\[ X = 0: Y = 0 \]
\[ X > 0: Y = 1 \]

Examples

<table>
<thead>
<tr>
<th>( X )</th>
<th>( \text{sign}(X) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.1</td>
<td>1</td>
</tr>
<tr>
<td>-2.6</td>
<td>-1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>[1,2.1;-2.6,0]</td>
<td>[1,1;-1,0]</td>
</tr>
</tbody>
</table>

Limitations

\( X \) and \( Y \) must have the same size.

square

Syntax

\[ Y = \text{sqr}(X); \]

Description

Returns the square of \( X \) or the elements of \( X \).

Examples

<table>
<thead>
<tr>
<th>( X )</th>
<th>( \text{sqr}(X) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 ((= 1^2))</td>
</tr>
<tr>
<td>2.1</td>
<td>4.41 ((= 2.1^2))</td>
</tr>
<tr>
<td>-2.6</td>
<td>6.76 ((=-2.6^2))</td>
</tr>
<tr>
<td>0</td>
<td>0 ((= 0^2))</td>
</tr>
<tr>
<td>[1,2.1;-2.6,0]</td>
<td>[1,4.41;6.76,0]</td>
</tr>
<tr>
<td></td>
<td>((= [1^2,2.1^2,-2.6^2,0^2]))</td>
</tr>
</tbody>
</table>
Limitations
x and y must be scalars.

sqrt

Syntax

\[ X = \sqrt{Y}; \]

Description
Returns the square root of X or the elements of X.

Examples

<table>
<thead>
<tr>
<th>X</th>
<th>sqrt(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.1</td>
<td>1.44913</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>[1,2.1;4,1]</td>
<td>[1,1.44913;2,1]</td>
</tr>
<tr>
<td>-1</td>
<td>not allowed!</td>
</tr>
</tbody>
</table>

Limitations
X and Y must have the same size. X or the elements of X must be larger than or equal to zero.

tdelay

Syntax

\[ y = \text{tdelay}(x,\text{delaytime}); \]

Description
Returns the (continuous) signal \(x\) delayed for an absolute time (given by \(\text{delaytime}\)). The initial value of \(y\) for \(time = 0\) to \(\text{delaytime}\) is equal to zero. This block is intended to model a continuous delay in a continuous simulation. Use the Unit Delay block to model a digital delay.

Examples

\[
\begin{align*}
x &= 10*\sin(time*10); \\
y &= \text{tdelay}(x,2);
\end{align*}
\]

Limitations
\(x,y\) and \(\text{delaytime}\) must be scalars. delaytime must be a positive constant value.
9. Language Reference

**trunc**

**Syntax**

\[ Y = \text{trunc}(X); \]

**Description**

Rounds \( X \) or the elements of \( X \) towards zero (i.e. the function \( \text{trunc} \) removes the fraction).

**Examples**

<table>
<thead>
<tr>
<th>( X )</th>
<th>( \text{trunc}(X) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.1</td>
<td>2</td>
</tr>
<tr>
<td>-2.6</td>
<td>-2</td>
</tr>
<tr>
<td>3.4</td>
<td>3</td>
</tr>
<tr>
<td>[1.1, -2.7; 3.5, -4.1]</td>
<td>[1, -2; 3, -4]</td>
</tr>
</tbody>
</table>

**Limitations**

\( X \) and \( Y \) must have the same size.

9.4.3 Discrete

**hold**

**Syntax**

\[ y = \text{hold}(x,\text{init}); \]

**Description**

The \( \text{hold} \) function implements a zero order hold function operating at a specified sampling rate. It provides a mechanism for creating a continuous output signal \( y \) out of a discrete input signal \( x \). The initial value of \( y \) is equal to the value of \( \text{init} \).
Examples

\[ x = \sin(\text{time} \times 0.3); \]
\[ y = \text{sample}(x); \]
\[ z = \text{previous}(y); \]
\[ u = \text{hold}(z,-1); \]

Limitations

\(x\) and \(y\) must be scalars. \(x\) be a discrete signal. \(y\) is a continuous signal. 20-sim will automatically detect the existence of discrete signals. Each chain of discrete signals will be assigned a specific sample time. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).

next

Syntax

\[ y = \text{next}(x,\text{init}); \]

Description

The next function allows you to make constructs like:

\[ x(k+1) = x(k) - 0.1 + u(k) \]

where \(k\) is the \(k^{th}\) sample. Using the next function, this can be entered in 20-sim as:

\[ \text{next}(x,0) = x - 0.1 + u; \]

Limitations

\(x\) and \(y\) will become discrete signals. 20-sim will automatically detect the existence of discrete signals. Each chain of discrete signals will be assigned a specific sample time. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).
### previous

**Syntax**

\[ y = \text{previous}(x, \text{init}); \]

**Description**

The previous function delays the input signal \( x \) and holds it for one sample interval. It is equivalent to the \( z^-1 \) discrete time operator. The \( \text{init} \) argument is the first value for \( y \) at \( t=0 \) s.

![Graph of previous function](image)

**Examples**

\[ x = \sin(\text{time}*0.3); \]
\[ y = \text{sample}(x); \]
\[ z = \text{previous}(y); \]
\[ u = \text{hold}(z); \]

**Limitations**

\( x \) and \( y \) will become discrete signals. 20-sim will automatically detect the existence of discrete signals. Each chain of discrete signals will be assigned a specific sample time. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).

### sample

**Syntax**

\[ y = \text{sample}(x, \text{init}); \]

**Description**
The sample function implements a sample and hold function operating at a specified sampling rate. It provides a mechanism for discretizing a continuous input signal. The initial value of y is equal to the value of init. This initial value is optional. If no value is entered, a default initial value of 0 is used.

### Examples

\[
x = \sin(time \times 0.3);
y = \text{sample}(x);
z = \text{previous}(y);
u = \text{hold}(z);
\]

### Limitations

- x and y must be scalars. x represents a continuous signal and y represents a discrete signal.
- y will become a discrete signals. 20-sim will automatically detect the existence of discrete signals. Each chain of discrete signals will be assigned a specific sample time. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).
9.4.4 Event

**event**

**Syntax**

\[ y = \text{event}(x); \]

**Description**

\( y \) becomes true when \( x \) is zero. This function forces the integration algorithm to find the exact point where the input crosses zero. This is called a state event.

**Examples**

\[ x = \sin(time*\omega + \phi); \]
\[ y = \text{event}(x); \]

**Limitations**

\( y \) must be a boolean, \( x \) must be an expression yielding a scalar.

**eventdown**

**Syntax**

\[ y = \text{eventdown}(x); \]

**Description**

\( y \) becomes true when \( x \) is zero. This function forces the integration algorithm to find the exact point where the input crosses zero from a positive to a negative value. This is called a state event.

**Examples**

\[ x = \sin(time*\omega + \phi); \]
\[ y = \text{eventdown}(x); \]

**Limitations**

\( y \) must be a boolean, \( x \) must be an expression yielding a scalar.

**eventup**

**Syntax**

\[ y = \text{event}(x); \]

**Description**

\( y \) becomes true when \( x \) is zero. This function forces the integration algorithm to find the exact point where the input crosses zero from a negative to a positive value. This is called a state event.
Examples
\[
\begin{align*}
x &= \sin(\text{time} \cdot \omega + \phi); \\
y &= \text{eventup}(x);
\end{align*}
\]

Limitations
\(y\) must be a boolean, \(x\) must be an expression yielding a scalar.

---

**frequencyevent**

Syntax
\[
y = \text{frequencyevent}(p,o);
\]

Description
\(y\) becomes true every time when \(p\) [s] have passed. The function starts after an offset of \(o\) [s]. The offset parameter is optional. This function is a time event function.

Examples
\[
\begin{align*}
\text{parameters} & \\
  \text{real period} &= 0.1 \text{ s}; \\
  \text{real offset} &= 0.005 \text{ s}; \\
\text{variables} & \\
  \text{boolean } y,z; \\
\text{equations} & \\
  y &= \text{frequencyevent}(1); & // y = \text{true every second} \\
  z &= \text{frequencyevent}(\text{period,offset}); & // z = \text{true at 0.005 s, 0.105 s, 0.205 s etc.}
\end{align*}
\]

Limitations
\(y\) must be a boolean, \(p\) and \(o\) must be a parameter or a constant.

---

**timeevent**

Syntax
\[
y = \text{timeevent}(x);
\]

Description
\(y\) becomes true when time is equal to \(x\). This function forces the integration algorithm to do a calculation when time \(y\) becomes true. This is a time event function.

Examples
The example code below forces the integration algorithm, to do a calculation at the start of the step:
\[
\begin{align*}
x &= \text{step}(\text{start\_time}); \\
y &= \text{timeevent}(\text{start\_time});
\end{align*}
\]

Limitations
\(y\) must be a boolean, \(x\) must be an expression yielding a scalar.
9.4.5 Expansion

**equal**

**Syntax**

```plaintext
equal([x1,x2, ...,xn]);
```

**Description**

This function is used to make all elements of a matrix equal. It returns the equations \( x_2 = x_1, x_3 = x_1, \ldots, x_n = x_1 \). During processing the equations will be automatically reshaped into a proper causal form. This function is created for use in library models that use a matrix with unknown size which results from the collect function.

**Examples**

Suppose we have \( m \) bonds connected to a submodel, collected in a port \( p \). We could then use the function:

```plaintext
collect(p.e);
```

During processing this equation will be expanded as:

```plaintext
[p.e1;p.e2;...;p.n];
```

If we use the equal function:

```plaintext
equal(collect(p.e));
```

this results in:

```plaintext
equal([p.e1;p.e2;...;p.n]);
```

which will be expanded in:

```plaintext
p.e2 = p.e1;
p.e3 = p.e1;
..  
p.en = p.e1
```

**Limitations**

This function is designed for a special class of models and should be used by experienced users only!
mul

Syntax

\[ y = \text{mul}([x_1, x_2, \ldots, x_n]); \]

Description

This function is used for multiplication of variables of which one may be unknown. It returns the equation \( y = x_1 \times x_2 \times \ldots \times x_n \). During processing this equation will be automatically reshaped into a causal form.

This function is created for use in library models that have unknown inputs such as MultiplyDivide model. Try to avoid the use of this function!

Examples

equations                  after reshaping (processing)
\[ x_1 = 1; \]              \[ x_1 = 1; \]
\[ x_2 = 2; \]              \[ x_2 = 2; \]
\[ 1 = \text{mul}([x_1, x_2, x_3]); \]  \[ x_3 = (1/x_1)/x_2; \]

\[ y = \sin(\text{time}); \]
\[ x_2 = 2; \]
\[ y = \text{mul}([x_1, x_2]); \]

Limitations

This function is designed for a special class of models and should be used by experienced users only! \( y, x_1, x_2, \ldots, x_n \) must be scalars. \( n \) may be 1 or higher.

sum

Syntax

\[ y = \text{sum}([x_1, x_2, \ldots, x_n]); \]

Description

This function is used for summation of variables of which one may be unknown. It returns the equation \( y = x_1 + x_2 + \ldots + x_n \). During processing this equation will be automatically reshaped into a causal form.

This function is created for use in library models that have unknown inputs such as PlusMinus model. Try to avoid the use of this function!

Examples

equations                  after reshaping (processing)
\[ x_1 = 1; \]              \[ x_1 = 1; \]
\[ x_2 = 2; \]              \[ x_2 = 2; \]
\[ 0 = \text{sum}(x_1, x_2, x_3); \]  \[ x_3 = x_1 + x_2; \]
\( y = \sin(time); \)

\( x2 = 2; \)

\( y = \text{sum}(x1, x2); \)

Limitations

- This function is designed for a special class of models and should be used by experienced users only! \( y, x1, x2, \ldots, x_n \) must be scalars. \( n \) may be 1 or higher.

- Use the function \text{msum} if you want to use a standard summation of multiple variables.

9.4.6 External data

Syntax

\[
y = \text{data}(\text{filename}, \text{column});
\]

with:

- \text{filename}: the filename of the data file
- \text{column}: the column number starting with 0 for the first column (time)

Description

This function generates an output by linear interpolation of data read from file. The data on file is stored in columns. The first column contains the time values (\( t \)) and the second column contains the corresponding output values (\( y \)).

- The time data of the first column needs to be monotonically increasing.
- Discontinuities are allowed, by providing the same time point twice in the table.
- Values outside of the range are computed by linear extrapolation of the last two points.

The first argument (\text{filename}) of this function must be a parameter of the type string and is used as a reference to a filename. This reference can be specified using the complete path or relative to the model directory. The second argument (\text{column}) of this function must be a parameter of the type integer denoting a whole number. It is used to denote the column number.
The input file must be an ASCII (text) file or a Comma Separated Values (.csv) file and should consist at least two columns of data. The first column (number 0) should always contain the time values. The other columns (number 1, 2, 3, etc.) should contain the corresponding data values. The parameter `column` is used to specify which column is used for as output data.

The various values must be separated by a space, a tab or a comma. Each new set of time and data values must start on a new line. No comment or other text may be part of the file. The filename of the input file can be specified using the complete path (e.g. `c:\data\data.tbl`). When no path is given, the file is assumed to be in the same directory as your model.

The first row may contain names for the columns. Names should be indicated by quotation marks (").

**Example**

```plaintext
parameters
    string filename = 'data.txt';
    integer col = 2;
variables
    real y;
equations
    y = data(filename,col);
```

Example data.txt file with header:

```
"time","x","y"
0.0, 1, 2
0.1, 5, 10
0.2, 6, 11
```

**Limitations**

`y` must be a scalar. `from_file` must be string parameter. `x` must be an integer parameter.
dll

Syntax

\[
y = dll(filename, functionname, x);
\]

Description

Given a function (\textit{functionname}) of a dll (\textit{filename}), the dll function returns the output values (\textit{y}) for a given input (\textit{x}).

Users can write their own source code using a native compiler such as Visual C++ or Borland C++. With these compilers it is possible to create DLLs with user defined functions that have an input- output relation which can be embedded in simulation code.

Example

\begin{verbatim}
parameters
  string filename = 'example.dll';
  string function = 'myFunction';
variables
  real x[2], y[2];
equations
  x = [ramp(1); ramp(2)];
  y = dll(filename, function, x);
\end{verbatim}

Limitations

\textit{filename} and \textit{functionname} must be string parameters. Note that the size of \textit{Y} and \textit{X} (scalars or matrices) must correspond with the size that is expected for the given dll-function.

Search Order

20-sim uses the following search order for the dll-file:

1. The bin directory of 20-sim (usually C:\Program Files\20-sim 5.1\bin).
2. The current directory.
3. A directory that is entered in list of paths in the General Properties dialog (choose Tools - Options - Folders - DLL Search Paths). Use this option to store DLL's in a central location.
4. The Windows system directory.
5. The Windows directory.
6. The directories that are listed in the \textit{PATH} environment variable.

The simplest place to put the DLL-file is the bin directory, but it is always possible to give a complete path for the DLL filename.

Code generation notice

20-sim allows for code generation of the 20-sim model. In case of a DLL call, 20-sim cannot generate the complete code for a DLL call since it only knows the DLL file name, function name and arguments and not the internal DLL code.
Therefore, in the generated code, the \texttt{dll(dll\_name, function\_name, in)} will be generated as:

\begin{verbatim}
%dll\_name\%_%function\_name\%(double *inarr, int inputs, double *outarr, int outputs, int major)
\end{verbatim}

Where \texttt{%dll\_name\%} and \texttt{%function\_name\%} are replaced with the actual DLL and function name. You have to add the C-code implementation of this function yourself to the generated code before you can compile it.

### Writing Static DLL's

Almost every compiler that can build Windows applications, can also build dll-files containing dll-functions. For two compilers an example will be given how to build the \texttt{static dll's} (i.e. dll functions that do not contain internal model states) in combination with 20-sim. The two compilers are: Visual C++ and Borland C++.

When the simulator has to call the user defined dll for the first time the dll is linked and the appropriate function is called. At the end of the simulation run the dll will be disconnected from the simulator. In general the dll-function called by the simulator has the following syntax in 20-sim:

\begin{verbatim}
Y = dll(filename, functionname, X);
\end{verbatim}

For example (equation model):

\begin{verbatim}
parameters
    string dll\_name = 'example.dll';
    string function\_name = 'myFunction';
variables
    real in[2], out[2];
equations
    in = [ramp(1), ramp(2)];
    out = dll(dll\_name, function\_name, in);
\end{verbatim}

The name of the function is the actual name which was given to the corresponding string parameter. The return value of the function determines whether the function was successful or not. A return value of 0 means success, every other value error. When a nonzero value is returned the simulation stops after finishing its current simulation step. The parameters given to the function correspond directly to the 20-sim parameters: double pointers for the inputs and outputs point to an array of doubles.

### Function arguments

The user-function in the dll must have certain arguments. The function prototype is like this:

\begin{verbatim}
int myFunction(double *inarr, int inputs, double *outarr, int outputs, int major)
\end{verbatim}
where

- \textit{inarr}: pointer to an input array of doubles. The size of this array is given by the second argument.
- \textit{inputs}: size of the input array of doubles.
- \textit{outarr}: pointer to an output array of doubles. The size of this array is given by the fourth argument.
- \textit{outputs}: size of the output array of doubles.
- \textit{major}: boolean which is 1 if the integration method is performing a major integration step, and 0 in the other cases. For example Runge-Kutta 4 method only has one in four model evaluations a major step.

\textbf{Initializing the DLL-file}

When the dll is linked to the simulator it is often useful to perform some initializations. There are several ways to perform these initializations.

\textbf{Method 1}

When the simulator has attached the dll-file it automatically searches for a function with the name 'int Initialize()'. If this function is found it is called. The return value is checked for success, 1 means success, 0 means error. At the end of the simulation run just before the dll-file is detached the simulator searches for a function called 'int Terminate()'. In this function the necessary termination action can be performed like cleaning up allocated memory.

At the start of every run the simulator also searches a function with the name 'int InitializeRun()'. If it is found it is called the same way the Initialize function was called. At the end the same happens with the function 'int TerminateRun()'. This is very useful in multiple run simulations, in this case the dll-file is linked only once with the simulator, and only once the Initialize and Terminate functions are called. But for every subsequent run the InitializeRun and TerminateRun functions are called so every run can be initialized and terminated gracefully. In this case in the Terminate function collection of multiple run data could be collected and saved for example.

So suppose you have a multiple run with 2 runs, the following functions (if they exist) will be called in the dll-file in this order:

\begin{verbatim}
Initialize()
InitializeRun()
TerminateRun()
Terminate()
\end{verbatim}

\textbf{Method 2}

Using the DLLEntryPoint function. This function is automatically called when the library is linked or detached. Both in Visual C++ and in Borland C++ this function has the same syntax. However when using visual C++ as the compiler, our simulator which is build with Visual C++ does not seem to be able to call this function. So the framework as given below only works with a Borland C++ dll.

\begin{verbatim}
// Every dll has an entry point LibMain || DllEntryPoint
\end{verbatim}
// and an exit point WEP (windows exit point).
BOOL WINAPI DllEntryPoint(HINSTANCE hinstDll, DWORD fdwRreason, LPVOID plvReserved)
{
    if (fdwRreason == DLL_PROCESS_ATTACH)
    {
        return 1; // Indicate that the dll was linked successfully.
    }
    if (fdwRreason == DLL_PROCESS_DETACH)
    {
        return 1; // Indicate that the dll was detached successfully.
    }
    return 0;
}

Method 3
When using an object oriented language it is possible to have a global variable which is
an instance of a class. When linking the dll-file to the simulator the constructor function
of this global variable will be called automatically. In this constructor the initialization can
be performed. When the dll-file is detached the destructor of the global variable is
called. Some care should be taken with this method of terminating. E.g. if the user is
asked for a filename using a FileDialog this sometimes causes the complete application
to crash. The reason for this is that some of the dll-files contents was already destructed
and that some functionality may not work anymore resulting in an application error. The
solution for this problem is to use method 1 of initialization and destruction.

Frame work for a Visual C++ dll-file implementation.
#include <windows.h>
#define DllExport __declspec( dllexport )
extern "C"
{
    DllExport int myFunction(double *inarr, int inputs, double *outarr,
int outputs, int major)
    {
        ... // function body
        return 0; // return successful
    }
    DllExport int Initialize()
    {
        ... // do some initializations here.
        return 0; // Indicate that the dll was initialized successfully.
    }
    DllExport int Terminate()
    {
        ... // do some cleaning here
        return 0; // Indicate that the dll was terminated successfully.
    }
}

Frame work for a Borland C++ dll-file implementation.
#include <windows.h>
extern "C"
{
    int _export myFunction(double *inarr, int inputs, double *outarr, int outputs, int major)
    {
        ... // function body
        return 0; // return successful
    }
    int _export Initialize()
    {
        ... // do some initializations here.
        return 0; // Indicate that the dll was initialized successfully.
    }
    int _export Terminate()
    {
        ... // do some cleaning here
        return 0; // Indicate that the dll was terminated successfully.
    }
}

// Every dll has an entry point LibMain || DllEntryPoint
// and an exit point WEP.
BOOL WINAPI DllEntryPoint(HINSTANCE hinstDll, DWORD fdwReason, LPVOID plvReserved)
{
    if (fdwReason == DLL_PROCESS_ATTACH)
    {
        ... // do some initializations here.
        return 1; // Indicate that the dll was initialized successfully.
    }
    if (fdwReason == DLL_PROCESS_DETACH)
    {
        ... // do some cleaning here
        return 1; // Indicate that the dll was initialized successfully.
    }
    return 0;
}

**Note**

Make sure that Borland C++ does not generate underscores in front of the exported function names! This can probably be found in the compiler settings.

**Working example**

Here is a complete working example of how to use a dll-function from within the simulator. This code will compile with Visual C++ or gcc. See the Borland C++ framework how to write this code in Borland C++.

/* Example C++ DLL for 20-sim */
#include <windows.h>
#include <math.h>
#include <fstream>
#include <stdio.h>

#define DLLEXPORT __declspec( dllexport )

using namespace std;

ofstream outputStream;

#ifdef _MSC_VER
#define snprintf _snprintf
#endif

extern "C"
{
    char g_lasterrormessage[255]; /* Used to store a DLL error message for transfer to 20-sim */

    const char* g_modelpath;

/**
 * This is an example of a function that can be called in your 20-sim model using the dll() Sidops call
 *
 * @param inarr   This double array contains all inputs that will be send from 20-sim to the other side
 * @param inputs  20-sim tells the dll how many elements inarr[] contains.
 * @param outarr  Result from this dll function that will be returned to 20-sim
 * @param outputs 20-sim tells the dll how many elements it expects (and allocated) in outarr.
 * @param major   1=major integration step, 0=minor step (e.g. an intermediate integration method step in Runge Kutta 4)
 **/

DLLEXPORT int myFunction(double *inarr, int inputs, double *outarr, int outputs, int major)
{
    // Check the sizes of our input and output arrays
    if (inputs != outputs)
    {
        snprintf(g_lasterrormessage, 255, "%s: expects that the number of inputs is equal to the number of outputs.", __FUNCTION__);  
        return 0; // Failure
    }

    for (int i = 0; i < inputs; i++)
    {
        outarr[i] = cos(inarr[i]);
        outputStream << inarr[i] << " " << outarr[i] << " ";
    }
}

20-sim 5.1 Reference Manual 190
9. Language Reference

}  
outputStream << endl;  
return 1; // Success  
}  

/****** Initialization and cleanup ******/

/**
 * Note 1:
 * The Initialize(), InitializeRun(), Terminate() and TerminateRun()  
 * functions are optional.
 * Implement them when you need to initialize something before the  
 * actual experiment is started and to cleanup/reset your DLL  
 * functionality for a next run.
 * Note 2:
 * When these functions are implemented, the "continue run"  
 * functionality in 20-sim is disabled.
 */

/**
 * Initialize() [optional]
 * This function is called by the 20-sim simulator BEFORE starting the  
 * simulation experiment (and only once in a multiple run experiment)  
 * to initialize the dll properly.
 */

DLLEXPORT int Initialize()
{
    outputStream.open("c:\temp\data.log");
    return 0; // Indicate that the dll was initialized successfully.
}

/**
 * InitializeRun() [optional]
 * This function is called by the 20-sim simulator BEFORE starting the  
 * simulation experiment (and only once in a multiple run experiment)  
 * to initialize the dll properly.
 */

DLLEXPORT int InitializeRun()
{
    /* Clear lasterrormessage before every run. */
    snprintf(g_lasterrormessage, 255, "");

    return 0; /* Indicate that the dll was initialized successfully. */
}

/**
 * TerminateRun() [optional]
 * This function is called by 20-sim after each finished run
 */
Usage within 20-sim
Suppose the dll has been created as "example.dll". With the following code this model can be tested:
parameters
  string dll_name = 'example.dll';
  string function_name = 'myFunction';
variables
  real in[2], out[2];
equations
  in = [ramp(1), ramp(2)];
  out = dll(dll_name, function_name, in);

Note that the general function "dll" is used. The arguments of this function, dll_name and function_name, are parameters which are used to denote the dll that should be used and the function of that dll that should be called. You can load this model from the Demonstration Models Library:

1. Open the Editor.
2. From the demo library open the model DllFunction.emx (choose File and Open)
3. Start the simulator (Model menu and Start Simulator).
4. Start a simulation run (select Run from the Simulation menu).

Code generation notice
20-sim allows for code generation of the 20-sim model. In case of a DLL call 20-sim cannot generate the complete code for a DLL call since it only knows the DLL file name, function name and arguments and not the internal DLL code.

Therefore, in the generated code, the dll(dll_name, function_name, in) will be generated as:

%dll_name%_%function_name % (double *inarr, int inputs, double *outarr, int outputs, int major)

Where %dll_name% and %function_name% are replaced with the actual DLL and function name. You have to add the C-code implementation of this function yourself to the generated code before you can compile it.

dlldynamic

Syntax
  y = dlldynamic(filename, functionname, x);

Description
Given a function (functionname) of a dll (filename), the dll function returns the output values (X) for a given input (Y).

Users can write their own source code using a native compiler such as Visual C++ or Borland C++. With these compilers it is possible to create DLL’s with user defined functions that have an input- output relation which can be embedded in simulation code.

Examples
  parameters
string dllName = 'demoDynamicDll.dll';
string functionName = 'SFunctionCalculate';
variables
  real x[2], y[2];
equations
  x = [ramp(1);ramp(2)];
  y = dlldynamic(dllName, functionName, x);

Limitations

The *filename* and *functionname* must be string parameters. Note that the size of Y and X (scalars or matrices) must correspond with the size that is expected for the given dll-function.

Search Order

20-sim uses the following search order for the dll-file:

1. The bin directory of 20-sim (usually C:\Program Files\20-sim 5.1\bin).
2. The current directory.
3. A directory that is entered in list of paths in the General Properties dialog (choose Tools - Options - Folders - DLL Search Paths). Use this option to store DLL's in a central location.
4. The Windows system directory.
5. The Windows directory.
6. The directories that are listed in the PATH environment variable.

The simplest place to put the dlldynamic-file is the bin directory, but it is always possible to give a complete path for the dll filename.

Code generation notice

This function is not supported in Matlab M-code or C-code generation.

Writing Dynamic DLL's

Almost every compiler that can build Windows applications, can also build dll-files containing dll-functions. For the Visual C++ compiler an example will be given how to build the dynamic dll's (i.e. dll functions that may contain internal model states) in combination with 20-sim.

The functions in the DLL are called in a specific sequence. For communication with the functions and the Simulator Kernel information is passed in a structure. This structure looks like this:
struct SimulatorSFunctionStruct
{
    double versionNumber;
    int nrInputs;
    int nrOutputs;
    int nrIndepStates;
    int nrDepStates;
    int nrAlgLoops;
    double simulationStartTime;
    double simulationFinishTime;
    double simulationCurrentTime;
    BOOL major;
    BOOL initialOutputCalculation;
};

1. Initialize
At the start of the simulation the function

    int Initialize()

is called. When this function is not present it is not called. Any initializations of data
structures can be performed here.

2. SFunctionInit
During initialization of the Simulator Kernel the function

    int SFunctionInit(SimulatorSFunctionStruct *s)

is called. Return value is 0 means error. every other value succes Argument is a pointer
to the simstructure. On initialization the following fields should be filed in:

    nrIndepStates
    nrDepStates
    nrAlgLoop

The following fields already have valid values:

    simulationStartTime giving the start time of the simulation
    simulationFinishTime giving the finish time of the simulation
    simulationCurrentTime giving the current time (actually the start time at
                              the moment of initialization)
3. Initial values for the states

```c
int SFunctionGetInitialStates(double *initialIndepStates,
                              double *initialDepRates,
                              double *initialAlgloopIn,
                              SimulatorSFunctionStruct *simStruct);
```

Return value is 0 means error. every other value succes. The initial value for the independent states, dependent rates and algebraic loop variables can be specified by the DLL in this function. It is just called before the initial output calculation function in step 3. If all the initial values are zero, nothing has to be specified.

4. Initial Output Calculation

It is possible that the DLL-function can give an initial output. A separate function is called so that the DLL can calculate it's initial output values. The boolean initialOutputCalculation in the simulatorSFunction structure is used. Just the sFunction is called. as in point 5.

5. SFunction calling

Here all the fields of the SimulatorSFunctionStruct are input for the function. The inputArray, stateArray, outputArray and rateArray are always given as arguments of the function. Dependent on the number of dependent states and algebraic loop variables more arguments can be given as shown in the functions below (sFunctionName is the name defined by the parameter name specified by the user):

Return value is 0 means error. every other value succes

**case: no dependent states, no algebraic loop variables**

```c
int sFunctionName(double *inputArray,
                   double *stateArray,
                   double *outputArray,
                   double *rateArray,
                   SimulatorSFunctionStruct *simStruct);
```

**case: dependent states, no algebraic loop variables**

```c
int sFunctionName(double *inputArray,
                   double *stateArray,
                   double *dependentRateArray,
                   double *outputArray,
                   double *rateArray,
                   double *dependentStateArray,
                   SimulatorSFunctionStruct *simStruct);
```
**case: no dependent states, algebraic loop variables**

```c
int sFunctionName(double *inputArray,
                    double *stateArray,
                    double *algLoopInArray,
                    double *outputArray,
                    double *rateArray,
                    double *algLoopOutrray,
                    SimulatorSFunctionStruct *simStruct);
```

**case: dependent states, algebraic loop variables**

```c
int sFunctionName(double *inputArray,
                    double *stateArray,
                    double *dependentRateArray,
                    double *algLoopInArray,
                    double *outputArray,
                    double *rateArray,
                    double *dependentStateArray,
                    double *algLoopOutrray,
                    SimulatorSFunctionStruct *simStruct);
```

the boolean major in the SimulatorSFunctionStruct determines whether the evaluation of the model is done at the time output is generated (major == TRUE ) or that the model is evaluated because of determining model characteristics. For example Runge-Kutta4 integration method uses three minor steps before taking a major step where output is generated. Higher order methods can have different number of minor steps before a major step is taken.

**6. Termination**

At the end of the simulation the function:

```c
int Terminate()
```

is called. When this function is not present it is not called. Any terminations of data structures can be performed here.


```c
#include <windows.h>
#define DllExport __declspec( dllexport )
extern "C"
{
    DllExport int dllfunction(double *inarr, int inputs,
                               double *outarr, int outputs, int major)
```
Framework for a Borland C++ dll-file implementation.

```c
#include <windows.h>
extern "C"
{
    int _export dllfunction(double *inarr, int inputs, double *outarr, int outputs, int major)
    {
        ... // function body
        return 0; // return successful
    }
    int _export Initialize()
    {
        ... // do some initializations here.
        return 0; // Indicate that the dll was initialized successfully.
    }
    int _export Terminate()
    {
        ... // do some cleaning here
        return 0; // Indicate that the dll was terminated successfully.
    }
}
```

```c
DllExport int Initialize()
{
    ... // do some initializations here.
    return 0; // Indicate that the dll was initialized successfully.
}
DllExport int Terminate()
{
    ... // do some cleaning here
    return 0; // Indicate that the dll was terminated successfully.
}
```
// Every dll has an entry point LibMain || DllEntryPoint
// and an exit point WEP.
BOOL WINAPI DllEntryPoint(HINSTANCE hinstDll, DWORD fdwRreason, LPVOID plvReserved)
{
    if (fdwRreason == DLL_PROCESS_ATTACH)
    {
        ... // do some initializations here.
        return 1; // Indicate that the dll was initialized successfully.
    }
    if (fdwRreason == DLL_PROCESS_DETACH)
    {
        ... // do some cleaning here
        return 1; // Indicate that the dll was initialized successfully.
    }
    return 0;
}

Working example
Here is a complete working example of how to use a dll-function from within the simulator. This code will compile with Visual C++. See the Borland C++ framework how to write this code in Borland C++.

#include <windows.h>
#include "SimulatorSFuncti onStruct.h"

/ ************************************************************************
*******
* in this source file we are gonna describe a linear system which is defined by
* the following transfer function description:

34
Y = ---------------- * U
s^2 + 6s + 34

or A, B, C, D system:

A = [ 0, -3.4;
    10, -6];
B = [ -3.4;
    0];
C = [0, -1];
D = 0
which has two poles on (-3 + 5i) and (-3 - 5i)

steady state = 1

******************************************************************************
********/
#define DllExport __declspec( dllexport )

extern "C"
{

    // called at begin of the simulation run
    DllExport int Initialize()
    {
        // you can perform your own initialization here.

        // success
        return 0;
    }

    // called at end of the simulation run
    DllExport int Terminate()
    {
        // do some cleaning here

        // success
        return 0;
    }

    DllExport int SFunctionInit(SimulatorSFunctionStruct *s)
    {
        // tell our caller what kind of dll we are
        s->nrIndepStates = 2;
        s->nrDepStates = 0;
        s->nrAlgLoops = 0;

        // dubious information, since 20-sim itself does not check
        and need this info
        s->nrInputs = 1;
        s->nrOutputs = 1;

        // return 1, which means TRUE
        return 1;
}
DllExport int SFunctionGetInitialStates(double *x0, double *xd0, double *xa0, SimulatorSFunctionStruct *s)
{
    // fill in the x0 array here. Since we specified no
    // Dependent states, and No algebraic loop variables
    // the xd0 and xa0 may not be used.
    // initial value is zero.
    x0[0] = 0;
    x0[1] = 0;

    // return 1, which means TRUE
    return 1;
}

DllExport int SFunctionCalculate(double *u, double *x, double *y, double *dx, SimulatorSFunctionStruct *s)
{
    // we could check the SimulatorSFunctionStruct here if we
    // are in an initialization state and/or we are
    // in a major integration step.
    #if 0
    if (s->initialialOutputCalculation)
        ; // do something
    // possibly do some explicit action when we are in a
    major step.
    if (s->major == TRUE)
        ; // do something
    #endif
    dx[0] = -3.4 * x[1] - 3.4 * u[0];
    dx[1] = 10 * x[0] - 6 * x[1];

    y[0] = -x[1];

    // return 1, which means TRUE
    return 1;
}

// extern "C"
BOOL APIENTRY DllMain(HANDLE hModule,
    DWORD ul_reason_for_call,
Use within 20-sim
Suppose the dll has been created as "demoDynamicDll.dll". With the following code this model can be tested:

```plaintext
class LPVOID lpReserved
{
    return TRUE;
}
```

parameters
```plaintext
string dllName = 'demoDynamicDll.dll';
string functionName = 'SFunctionCalculate';
equations
    output = dlldynamic (dllName, functionName, input);
```

Note that the general function "dlldynamic" is used. The arguments of this function, dllName and functionName, are parameters which are used to denote the dll that should be used and the function of that dll that should be called. You can load this model from the Demonstration Models Library:

1. Open the Editor.
2. From the demo library open the model DllFunction.emx (choose File and Open)
3. Start the simulator (Model menu and Start Simulator).
4. Start a simulation run (select Run from the Simulation menu).

settoolsetting

Syntax
```plaintext
status = settoolsetting('key', value)
```

Description
The settoolsetting() function can be used to change simulator settings from your model.

The following values for key are possible:
```plaintext
    modelname
    modelfilename
    modelexperimentname
    fastmode
    simulationmode
    endless
    integrationmethod
    starttime
    finishtime
```
eventdelta
outputaftereach
instructionset
integrationmethod.Euler.stepsize
integrationmethod.BackwardEuler.alpha
integrationmethod.BackwardEuler.stepsize
integrationmethod.BackwardEuler.absolutetolerance
integrationmethod.BackwardEuler.relativetolerance
integrationmethod.AdamsBashforth.stepsize
integrationmethod.RungeKutta2.stepsize
integrationmethod.RungeKutta4.stepsize
integrationmethod.RungeKutta8.absolutetolerance
integrationmethod.RungeKutta8.relativetolerance
integrationmethod.RungeKutta8.initialstepsize
integrationmethod.RungeKutta8.maximumstepsize
integrationmethod.RungeKuttaFehlberg.absolutetolerance
integrationmethod.RungeKuttaFehlberg.relativetolerance
integrationmethod.RungeKuttaFehlberg.initialstepsize
integrationmethod.RungeKuttaFehlberg.maximumstepsize
integrationmethod.VodeAdams.absolutetolerance
integrationmethod.VodeAdams.relativetolerance
integrationmethod.VodeAdams.initialstepsize
integrationmethod.VodeAdams.maximumstepsize
integrationmethod.BDFMethod.initialstepsize
integrationmethod.BDFMethod.maximumstepsize
integrationmethod.BDFMethod.absolutetolerance
integrationmethod.BDFMethod.relativetolerance
integrationmethod.MeBDFiMethod.initialstepsize
integrationmethod.MeBDFiMethod.maximumstepsize
integrationmethod.MeBDFiMethod.absolutetolerance
integrationmethod.MeBDFiMethod.relativetolerance

Example
variables
  real x, y, dummy;
code
  y = int (x);
  x = sin (time);

  if time > 7 then
    dummy = settoolsetting ('integrationmethod.Euler.stepsize', 0.1);
  else
    if time > 6 then
      dummy = settoolsetting ('integrationmethod.Euler.stepsize', 0.01);
    else
      if time > 5 then
        dummy = settoolsetting ('integrationmethod.Euler.stepsize', 1);
      end;
  end;
**table**

**Syntax**

```plaintext
y = table(file_name, x);
```

**Description**

This model uses a one-dimensional table with data points to calculate the output \( y = f(x) \) as a function of the input \( x \). The output \( y \) is calculated using linear interpolation between the table data points.

- The input data \( x \) of the first column needs to be monotonically increasing.
- Discontinuities are allowed, by providing the same input point twice in the table.
- Values outside of the table range, are computed by linear extrapolation of the last two points.

The first argument (*file_name*) of this function must be a parameter of the type string and is used as a reference to a filename. This reference can be specified using the complete path or relative to the model directory. The second argument (*x*) should be a real variable.

### (example):

<table>
<thead>
<tr>
<th>( x )</th>
<th>( y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>-2</td>
<td>-1</td>
</tr>
<tr>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>4.0</td>
</tr>
</tbody>
</table>

A table must be stored as an ASCII (text) file or a Comma Separated Values (.csv) file and should consist two columns of data. The first column consists of the \( x \)-values and the second column of the corresponding \( y \)-values. Each line of the file may only contain one \( x \)- and one corresponding \( y \)-value. The two values must be separated by a space or a tab. Each new set of \( x \)- and \( y \)-values must start on a new line. No comment or other text may be part of the table-file.
Example

```plaintext
parameters
    string filename = 'data.txt';
variables
    real y;
    real x;
equations
    x = ramp(1);
    y = table(filename, x);
```

Example data.txt format:

```
-2.5, -0.5
-2.0, -1.0
0.0, -1.0
1.0, 0.0
2.0, 2.0
3.0, 3.0
5.0, 4.0
6.0, 4.0
```

Limitations
x and y must be scalars. from_file must be string parameter.

9.4.7 Matrix

adjoint

Syntax

```plaintext
Y = adjoint(T);
Y = adjoint(W,V);
```

Description
Returns the adjoint matrix [6,6] of a twist or wrench vector T [6,1]:

```plaintext
Y = adjoint(T);
Y = adjoint(W,V);
```
or returns the adjoint matrix $[6,6]$ of an angular velocity vector $W [3,1]$ and a velocity vector $V [3,1]$:

$$ W = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}, \quad V = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \rightarrow$$

$$ \text{adjoint}(W,V) = \begin{bmatrix} \text{skew}(W) & 0 \\ \text{skew}(V) & \text{skew}(W) \end{bmatrix} = \begin{bmatrix} 0 & -\omega_3 & \omega_2 & 0 & 0 & 0 \\ \omega_3 & 0 & -\omega_1 & 0 & 0 & 0 \\ -\omega_2 & \omega_1 & 0 & 0 & 0 & 0 \\ 0 & -\nu_3 & \nu_2 & 0 & -\omega_3 & \omega_2 \\ \nu_3 & 0 & \nu_1 & \omega_3 & 0 & -\omega_1 \\ -\nu_2 & \nu_1 & 0 & -\omega_2 & \omega_1 & 0 \end{bmatrix} $$

The adjoint function is useful for dynamics described by twists and wrenches.

**Examples**

$$ W = [w1 ; w2 ; w3]; $$
$$ V = [v1 ; v2 ; v3]; $$
$$ Y = \text{adjoint}(W,V); $$

**Limitations**

$Y$ must be of size $[6,6]$, $W$ must always be of size $[3,1]$, $V$ must have the size $[3,1]$ and $T$ must have size $[6,1]$. 

9. Language Reference

20-sim 5.1 Reference Manual 206
Adjoint

Syntax

\[ A = \text{Adjoint}(H); \]
\[ A = \text{Adjoint}(R,P); \]

Description

Returns the adjoint matrix \([6,6]\) of a homogeneous matrix \([4,4]\):

\[
H = \begin{bmatrix}
    r_{11} & r_{12} & r_{13} & p_1 \\
    r_{21} & r_{22} & r_{23} & p_2 \\
    r_{31} & r_{32} & r_{33} & p_3 \\
    0 & 0 & 0 & 1
\end{bmatrix} = \begin{bmatrix} R & P \\ 0 & 1 \end{bmatrix} \rightarrow
\]

\[
\text{Adjoint}(H) = \begin{bmatrix}
    R & 0 \\
    \text{skew}(P) \times R & R
\end{bmatrix} = \begin{bmatrix}
    r_{11} & r_{12} & r_{13} & 0 & 0 & 0 \\
    r_{21} & r_{22} & r_{23} & 0 & 0 & 0 \\
    r_{31} & r_{32} & r_{33} & 0 & 0 & 0 \\
    -p_3 \cdot r_{31} + p_2 \cdot r_{32} + p_1 \cdot r_{33} & -p_3 \cdot r_{32} + p_2 \cdot r_{33} & -p_3 \cdot r_{33} - p_2 \cdot r_{32} & r_1 & r_2 & r_3 \\
    -p_3 \cdot r_{11} - p_2 \cdot r_{12} & -p_3 \cdot r_{12} - p_1 \cdot r_{13} & -p_3 \cdot r_{13} - p_2 \cdot r_{12} & r_{21} & r_{22} & r_{23} \\
    -p_3 \cdot r_{11} + p_1 \cdot r_{13} & -p_2 \cdot r_{12} - p_1 \cdot r_{13} & -p_2 \cdot r_{13} & r_{31} & r_{32} & r_{33}
\end{bmatrix}
\]

or returns the adjoint matrix \([6,6]\) of a rotation matrix \([3,3]\) and position vector \([3]\):

\[
R = \begin{bmatrix}
    r_{11} & r_{12} & r_{13} \\
    r_{21} & r_{22} & r_{23} \\
    r_{31} & r_{32} & r_{33}
\end{bmatrix}, \quad P = \begin{bmatrix}
    p_1 \\
    p_2 \\
    p_3
\end{bmatrix} \rightarrow
\]

\[
\text{Adjoint}(R, p) = \begin{bmatrix}
    R & 0 \\
    \text{skew}(P) \times R & R
\end{bmatrix} = \begin{bmatrix}
    r_{11} & r_{12} & r_{13} & 0 & 0 & 0 \\
    r_{21} & r_{22} & r_{23} & 0 & 0 & 0 \\
    r_{31} & r_{32} & r_{33} & 0 & 0 & 0 \\
    -p_3 \cdot r_{31} + p_2 \cdot r_{32} + p_1 \cdot r_{33} & -p_3 \cdot r_{32} + p_2 \cdot r_{33} & -p_3 \cdot r_{33} - p_2 \cdot r_{32} & r_1 & r_2 & r_3 \\
    -p_3 \cdot r_{11} - p_2 \cdot r_{12} & -p_3 \cdot r_{12} - p_1 \cdot r_{13} & -p_3 \cdot r_{13} - p_2 \cdot r_{12} & r_{21} & r_{22} & r_{23} \\
    -p_3 \cdot r_{11} + p_1 \cdot r_{13} & -p_2 \cdot r_{12} - p_1 \cdot r_{13} & -p_2 \cdot r_{13} & r_{31} & r_{32} & r_{33}
\end{bmatrix}
\]

The Adjoint function is useful for dynamics described by twists and wrenches.

Examples

\[
R = [\cos(\alpha), -\sin(\alpha), 0; \sin(\alpha), \cos(\alpha), 0; 0, 0, 0];
\]
\[
P = [p_1; p_2; p_3];
\]
\[
A = \text{Adjoint}(R, P);
\]

Limitations

H must be of size \([4,4]\), R must always be of size \([3,3]\), P must have the size \([3,1]\) and A must have size \([6,6]\).
antisym

Syntax

\[ y = antisym(A); \]

Description

Returns an anti-symmetric matrix. This function is equal to:
\[ y = (A - transpose(A))/2; \]

Examples

\[ A = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}; \]
\[ Y = antisym(A); \]

Limitations

A must be a square matrix. Y and A must be of the same size.

columns

Syntax

\[ y = columns(A); \]

Description

Returns the number of columns of A.

Examples

\[ A = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}; \]
\[ y = columns(A); \]

Limitations

y must be a scalar.

cross

Syntax

\[ Y = cross(A,B); \]

Description

This functions returns the vector cross product of the vectors A and B. That is \[ Y = A \times B \] or:

Examples
parameters
    real A[3] = [1;2;3];
    real B[3] = [4;5;6];
variables
    real Y[3];
equations
    Y = Cross(A,B); // Y = [-3;6;-3]

Limitations
Y, A and B must be column vectors of size 3.

det

Syntax
    y = det(A);
or
    Y = |A|;

Description
Returns the determinant of the square matrix A.

Examples
    A = [1,2;3,ramp(1)];
    y = det(A);

Limitations
A must be a square matrix, y must be a scalar.

diag

Syntax
    Y = diag(x);

Description
Fills the diagonal elements of the matrix Y with the elements of the column vector x.

Example
variables
    real x[3];
    real Y[3,3];
equations
    x = [1;2;3];
    Y = diag(x);

Limitations
Y must be a matrix of size [n,n]. x must be a column vector of size n.
eye

Syntax

\[ Y = \text{eye}(n); \]

Description

Returns the the n-by-n identity matrix.

Example

\[ Y = \text{eye}(3); \]

Limitations

Y must be a matrix of size \([n,n]\). n must be an integer value.

homogeneous

Syntax

\[ H = \text{homogeneous}(R,P); \]

Description

Returns the homogenous matrix \([4,4]\) of a rotation matrix \(R[3,3]\) and position vector \(P[3]\):

\[
\begin{bmatrix}
  r_{11} & r_{12} & r_{13} \\
  r_{21} & r_{22} & r_{23} \\
  r_{31} & r_{32} & r_{33}
\end{bmatrix}, \quad
\begin{bmatrix}
  P_1 \\
  P_2 \\
  P_3
\end{bmatrix}
\rightarrow
\begin{bmatrix}
  r_{11} & r_{12} & r_{13} & P_1 \\
  r_{21} & r_{22} & r_{23} & P_2 \\
  r_{31} & r_{32} & r_{33} & P_2 \\
  0 & 0 & 0 & 1
\end{bmatrix}
\]

The homogenous matrix gives a full coordinate transformation from one reference frame to another. It can be used for 3D dynamics.

Examples

\[
R = \begin{bmatrix}
\cos(\alpha) & -\sin(\alpha) & 0 \\
\sin(\alpha) & \cos(\alpha) & 0 \\
0 & 0 & 0
\end{bmatrix}; \\
P = \begin{bmatrix}
p_1 \\
p_2 \\
p_3
\end{bmatrix}; \\
H = \text{homogeneous}(R,P);
\]

Limitations

R must always be of size \([3,3]\), P must have the size \([3,1]\) and H must have size \([4,4]\).

inner

Syntax

\[ y = \text{inner}(A,B); \]

Description
Returns the scalar product of the column vectors A and B. A and B must be vectors of the same length. Inner(A,B) is the same as transpose(A)*B.

**Example**

```
A[3] = [1;2;3];
B[3,1] = [4;5;6];
y = inner(A,B); 
```

**Limitations**

A and B must be vectors of the same size [n,1] or [n]. y must be a scalar.

---

### inverse

**Syntax**

```
Y = inverse(A); 
```

**Description**

Returns the inverse of square non-singular matrix A.

**Examples**

```
A = [1,0;0,1+ramp(1)];
Y = inverse(A); 
```

**Limitations**

A must be a non-singular square matrix. Y must have the same size as A.

---

### inverseH

**Syntax**

```
Y = inverseH(H);
Y = inverseH(R,P); 
```

**Description**

Returns the inverse of a homogeneous matrix H [4,4]. The homogeneous matrix can be entered directly or by a rotation matrix R[3,3] and position vector P [3,1]. The size of the inverse Y is also [4,4].

This function uses the special nature of a homogeneous matrix. I.e the inverse can be computed directly instead of the numerical approach of the standard inverse function.

**Examples**

```
H = [cos(alpha),-sin(alpha),0,p1 ; sin(alpha),cos(alpha),0,p2 ; 0,0,0,p3 ; 0,0,0,1];
Y = inverseH(H); 
```

```
R = [cos(alpha),-sin(alpha),0 ; sin(alpha),cos(alpha),0 ; 0,0,0];
P = [p1 ; p2 ; p3];
Y = inverseH(R,P); 
```

**Limitations**

H must be a homogeneous matrix of size [4,4], R must always be of size[3,3] , P must have the size [3,1] and Y must have size [4,4].
linsolve

Syntax

\[ x = \text{linsolve}(A,b [,\text{method}]); \]

Description

This function solves the equation
\[ A*x = b; \]
Where \( A \) is a square matrix of arbitrary size \( n \) and \( x \) and \( b \) are vectors of size \( n \).

Returns the inverse of square non-singular matrix \( A \).

The last argument is a string that specifies the desired method to use.

<table>
<thead>
<tr>
<th>method</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lu</td>
<td>LU decomposition (default method)</td>
</tr>
<tr>
<td>qr</td>
<td>QR factorization</td>
</tr>
<tr>
<td>cholesky</td>
<td>Cholesky factorization</td>
</tr>
<tr>
<td>gmres</td>
<td>Generalized Minimum Residual</td>
</tr>
</tbody>
</table>

The \( \text{gmres} \) method allows further steering of the method by specifying method parameters:

<table>
<thead>
<tr>
<th>method parameter</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>tol</td>
<td>Set the desired tolerance to use</td>
</tr>
<tr>
<td>maxiter</td>
<td>Set the maximum number of iterations to use</td>
</tr>
<tr>
<td>ortho</td>
<td>Set the method of Gramm-Schmidt orthogonalization:</td>
</tr>
<tr>
<td></td>
<td>1 modified Gramm-Schmidt</td>
</tr>
<tr>
<td></td>
<td>2 iterative Gramm-Schmidt</td>
</tr>
<tr>
<td></td>
<td>3 classical Gramm-Schmidt</td>
</tr>
<tr>
<td></td>
<td>4 iterative classical Gramm-Schmidt</td>
</tr>
</tbody>
</table>

The \( \text{lu}, \text{qr} \) and \( \text{gmres} \) methods allow a non-square matrix \( A \) to be entered yielding a pseudoinverse.

Examples

\[
A = [1,2;0,1+ramp(1)];
\]
\[
b = [1;5];
\]
\[
x = \text{linsolve}(A,b);
\]
\[
x2 = \text{linsolve}(A,b,'qr');
\]
\[
x3 = \text{linsolve}(A,b,'gmres tol=1e-8 ortho=4');
\]

Limitations

A must be a non-singular square matrix.

Note

The following equations
\[
A*x = b;
\]
\[
x = \text{inverse}(A)*b;
\]
\[
x = (A^{-1})*b;
\]
all lead in the calculation of the inverse of \( A \) and will give the same result as
For the inverse calculation, Cramers rule is used. This is a method which is fast for small matrix sizes. The linsolve function with the gmres method is superior to Cramers rule for larger matrix sizes.

max

Syntax
\[ y = \text{max}(A); \]

Description
Returns the value of the largest matrix element of A.

Examples
\[
A = [1,2;3,ramp(1)];
\]
\[ y = \text{max}(A); \]

Limitations
y must be a scalar.

min

Syntax
\[ y = \text{min}(A); \]

Description
Returns the value of the smallest matrix element of A.

Examples
\[
A = [1,2;3,ramp(1)];
\]
\[ y = \text{min}(A); \]

Limitations
y must be a scalar.

msum

Syntax
\[ y = \text{msum}(A); \]

Description
Returns the sum of the matrix elements of A.

Examples
\[
A = [1,2;3,4;5,6];
\]
\[ y = \text{msum}(A); \]

Limitations
y must be a scalar.
multiplyH

Syntax

$$C = \text{multiplyH}(A,B);$$

Description


Examples

parameters

real $D[4,4] = [1,0,0,1; 0,1,0,0; 0,0,1,0; 0,0,0,1]$;
real $E[4,4] = [1,0,0,2; 0,1,0,3; 0,0,1,0; 0,0,0,1]$;
real $F[4,1] = [1,1,1,1]$;

variables

real $G[4,4]$;
real $H[4,1]$;

equations

$G = \text{multiplyH}(D,E)$;
$H = \text{multiplyH}(D,F)$;

Limitations

When $A$ and $B$ are homogeneous matrices $[4,4]$ then $C$ must be a homogenous matrix $[4,4]$. When $A$ is a homogenous matrix $[4,4]$ and $B$ is a homogenous position vector $[4,1]$ then $C$ must also be a position vector $[4,1]$.

norm

Syntax

$$y = \text{norm}(A);$$
$$Y = ||A||;$$

Description

Returns the square root of the sum of the squared matrix elements of $A$: 
9. Language Reference

\[ y = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{m} A[i,j]^2} \]

**Examples**

\[ A = \begin{bmatrix} 1,2;3,ramp(1) \end{bmatrix}; \]
\[ y = \text{norm}(A); \]

**Limitations**

y must be a scalar.

---

**norminf**

**Syntax**

\[ y = \text{norminf}(A); \]

**Description**

Returns the largest row sum of the absolute values of the matrix A:

\[ \max \left\{ \sum_{j=1}^{m} |a_{ij}|, 1 \leq i \leq m \right\} \]

**Examples**

\[ A = \begin{bmatrix} 1,2;3,ramp(1) \end{bmatrix}; \]
\[ y = \text{norminf}(A); \]

**Limitations**

y must be a scalar.

---

**rows**

**Syntax**

\[ y = \text{rows}(A); \]

**Description**

Returns the number of rows of A.

**Examples**

\[ A = \begin{bmatrix} 1,2;3,4;5,6 \end{bmatrix}; \]
\[ y = \text{rows}(A); \]

**Limitations**

y must be a scalar.
skew

**Syntax**

\[ Y = \text{skew}(X); \]

**Description**

Returns the vector product:

\[
\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3
\end{bmatrix} \rightarrow
\begin{bmatrix}
  0 & -x_3 & x_2 \\
  x_3 & 0 & -x_1 \\
  -x_2 & x_1 & 0
\end{bmatrix}
\]

**Examples**

\[
\begin{bmatrix}
  1 \\
  2 \\
  3
\end{bmatrix} \rightarrow
\begin{bmatrix}
  0 & -3 & 2 \\
  3 & 0 & -1 \\
  -2 & 1 & 0
\end{bmatrix}
\]

**Limitations**

\( X \) must be a vector of size \( n \). \( Y \) must be a matrix of size \([n,n]\).

sym

**Syntax**

\[ y = \text{sym}(A); \]

**Description**

Returns a symmetric matrix. This function is equal to:

\[ y = (A + \text{transpose}(A))/2; \]

**Examples**

\[
A = [1,2;3,4];
Y = \text{sym}(A);
\]

**Limitations**

\( A \) must be a square matrix. \( Y \) and \( A \) must be of the same size.

tilde

**Syntax**

\[
H = \text{tilde}(T);
H = \text{tilde}(W,V);
\]

**Description**

Returns the twist matrix \([4,4]\) of a twist or wrench vector \( T \) \([6,1]\):
Or returns the twist matrix \([4,4]\) of an angular velocity vector \(W\ [3,1]\) and a velocity vector \(V\ [3,1]\):

\[
\begin{bmatrix}
\omega_1 \\
\omega_2 \\
\omega_3 \\
v_1 \\
v_2 \\
v_3
\end{bmatrix}, \quad \rightarrow \quad \tilde{s}(T) = \begin{bmatrix} 0 & -\omega_3 & \omega_2 & v_1 \\
\omega_3 & 0 & -\omega_1 & v_2 \\
-\omega_2 & \omega_1 & 0 & v_3 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

The tilde function is useful for dynamics described by twists and wrenches.

**Examples**

\[
W = \begin{bmatrix} w_1 \\
w_2 \\
w_3 \end{bmatrix}, \quad V = \begin{bmatrix} v_1 \\
v_2 \\
v_3 \end{bmatrix}, \quad \rightarrow \quad \tilde{s}(W,V) = \begin{bmatrix} 0 & -\omega_3 & \omega_2 & v_1 \\
\omega_3 & 0 & -\omega_1 & v_2 \\
-\omega_2 & \omega_1 & 0 & v_3 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

**trace**

**Syntax**

\[
y = \text{trace}(A);
\]

**Description**

Returns the sum of the diagonal elements of the matrix \(A\).

**Examples**

\[
A = \begin{bmatrix} 1,2,3;4,ramp(1),6 \end{bmatrix};
\quad y = \text{trace}(A);
\]

**Limitations**

\(y\) must be a scalar.
9. Language Reference

transpose

Syntax

\[ Y = \text{transpose}(A); \]

Description

Returns the transpose of the matrix A.

Examples

\[ A = \begin{bmatrix} 1, & 2; 3, & \text{ramp}(1) \end{bmatrix}; \]
\[ Y = \text{transpose}(A); \]

Limitations

With the A matrix of size \([n,m]\), Y must have the size \([m,n]\).

9.4.8 Port

collect

Syntax

\[ y = \text{collect}(p.e); \]
\[ y = \text{collect}(p.f); \]
\[ y = \text{collect}(m); \]

(with p.e and p.f powerportvariables and m a signal)

Description

Some models in 20-sim can have an unknown amount of signals or bonds connected. They are treated as an array with unknown length.

For example the PlusMinus model can have \(n\) signals that must be added and \(m\) signals that must be subtracted. 20-sim treats them as an array plus and an array minus with:

\[ \text{plus} = [\text{plus1}; \text{plus2}; \ldots; \text{plusn}] \text{ and minus} = [\text{minus1}; \text{minus2}; \ldots; \text{minusm}] \]

To assign an array of unknown length, the collect function is used. It creates an array with port variables or signals. This function is created for use in library models that have an unknown amount of bonds or signals connected. Try to avoid the use of this function!

Examples

Suppose we have \(m\) bonds connected to a submodel, collected in a port \(p\). We could then use the equation:

\[ Y = \text{collect}(p.e); \]

During processing, this equation will be rewritten as:

\[ Y = [p.e1; p.e2; \ldots; p.n]; \]
Suppose we have a submodel with \( n \) input signals connected. We could then write the equation:

\[
y = \text{sum}(\text{collect}(\text{input}));
\]

During processing, this equation will be rewritten as:

\[
y = \text{sum}([\text{output}_1; \text{output}_2; \ldots; \text{output}_n]);
\]

which is of course equal to:

\[
y = \text{output}_1 + \text{output}_2 + \ldots + \text{output}_n;
\]

**Limitations**

This function is designed for a special class of models and should be used by experienced users only! The function is only valid when used in a submodel.

---

**direct**

**Syntax**

\[
y = \text{direct}(p.e);
\]

\[
y = \text{direct}(p.f);
\]

(with \( p.e \) and \( p.f \) powerportvariables)

**Description**

This function is equal to the collect function, but utilizes the direction of the bonds connected to the submodel to sign the powerportvariables. This function is created specially for the bond graph submodels `OneJunction.emx` and `ZeroJunction.emx`. Try to avoid the use of this function!

**Examples**

Suppose we have 4 bonds connected to a 0-junction, collected in a port \( p \). \( p_1 \) and \( p_4 \) are pointing towards the junction and \( p_2 \) and \( p_3 \) are pointing from the 0-junction. We could then use the equation:

\[
Y = \text{direct}(p.f);
\]

During processing, this equation will be rewritten as:

\[
Y = \{p.f_1; -p.f_2; -p.f_3; p.f_4\};
\]

Which can of course be used in combination with the sum function:

\[
\text{sum}(Y) = 0;
\]

To get the 0-junction equation:
\[ p.f1 - p.f2 - p.f3 + p.f4 = 0; \]

**Limitations**
This function is designed for a special class of models and should be used by experienced users only! The function is only valid when used in a submodel.

### first

**Syntax**

\[
y = \text{first}(p.e); \\
y = \text{first}(p.f); \\
y = \text{first}(m); 
\]

(with p.e and p.f powerportvariables and m a signal)

**Description**
Some models in 20-sim can have an unknown amount of signals or bonds connected. They are treated as an array with unknown length. For example the PlusMinus model can have \( n \) signals that must be added and \( m \) signals that must be subtracted. 20-sim treats them as an array \( \text{plus} \) and an array \( \text{minus} \) with:

\[
\text{plus} = [\text{plus1};\text{plus2};..;\text{plusn}] \quad \text{and} \quad \text{minus} = [\text{minus1};\text{minus2};..;\text{minusm}] 
\]

The function \( \text{first} \) returns the value of the first element of an array of unknown length. This function is created for use in library models that have an unknown amount of bonds or signals connected. **Try to avoid the use of this function!**

**Examples**
Suppose we have \( m \) bonds connected to a submodel, collected in a port \( p \). We could then use the equation:

\[
y = \text{first}(p.e); 
\]

During processing, this equation will be rewritten as:

\[
y = p.e1; 
\]

**Limitations**
This function is designed for a special class of models and should be used by experienced users only! The function is only valid when used in a submodel.
9.4.9 Source

**gauss**

**Syntax**

\[ y = gauss(x,s); \]

**Description**

Returns gaussian noise with a variance \( x \) and seed \( s \). The seed parameter is optional. When omitted, the default value (0) is used.

**Examples**

\[
\begin{align*}
x &= 20; \\
y &= gauss(x); \\
z &= gauss(x,450);
\end{align*}
\]

**Limitations**

\( x \) and \( y \) must be scalars. The seed \( s \) must be a number in the region \( <0,65535> \).

**impulse**

**Syntax**

\[ y = impulse(x,w); \]

**Description**

Returns a pulse signal with start time \( x \), width \( w \) and height \( 1/w \):

- \( time < x: y = 0 \)
- \( time >= x \) and \( < x+w: y = 1/w \)
- \( time >= x+w: y = 0 \)

Note: The integral (i.e. the area) of an impulse is always 1. If \( w \) is chosen small, the amplitude of the impulse will be high.

**Examples**

\[
\begin{align*}
x &= 20, w = 0.01; \\
y &= impulse(x,w);
\end{align*}
\]

**Limitations**

\( x \) and \( w \) must be scalars, \( w > 0 \).

**ramp**

**Syntax**

\[ y = ramp(x); \]

**Description**

Returns a ramp signal with start time \( x \):
\textit{time} < x: \quad y = 0 \\
\textit{time} \geq x: \quad y = \text{time} - x

\textbf{Examples}
\begin{align*}
x &= 20, \quad \text{amplitude} = 10; \\
y &= \text{amplitude} \times \text{ramp}(x);
\end{align*}

\textbf{Limitations}
x and y must be scalars.

\textbf{ran}

\textbf{Syntax}
\begin{equation*}
y = \text{ran}(x,s);
\end{equation*}

\textbf{Description}
Returns uniformly distributed noise in the interval \([-x,x]\) with seed s. The seed parameter is optional. When omitted, the default value (0) is used.

\textbf{Examples}
\begin{align*}
x &= 20; \\
y &= \text{ran}(x); \\
z &= \text{ran}(x,450);
\end{align*}

\textbf{Limitations}
x and y must be scalars. The seed s must be a number in the region \(<0,65000>\).

\textbf{Random Seed}
20-sim generates a sequence of random numbers for each simulation differently depending upon the value of the seed parameter. The random noise function and gaussian noise function are affected by this. The default value of the seed is 0. The maximum value is 65535.

\textit{default value} (0)
When the seed value is 0 (default value), 20-sim generates a new sequence of random numbers for each simulation and for each new random function. E.g. when two random functions with default seed value (0) are used in one model, they will generate different sequences of random numbers during a simulation.

\textit{other values} (>0)
When the seed value is chosen larger than zero, 20-sim generates the same sequence of random numbers for each simulation. Moreover 20-sim will generate the same sequence of random numbers for each random function that uses the same seed parameter (>0). E.g. when two random functions with seed value 50, are used in one model, they will generate the same sequence of random numbers during a simulation.
step

Syntax

\[ y = \text{step}(x); \]

Description

Returns a step signal with start time \( x \):

- \( \text{time} < x \): \( y = 0 \)
- \( \text{time} \geq x \): \( y = 1 \)

Examples

- \( x = 20, \text{amplitude} = 10; \)
- \( y = \text{amplitude*step}(x); \)

Limitations

\( x \) and \( y \) must be scalars.

9.4.10 Trigonometric

arcsin

Syntax

\[ Y = \text{arcsin}(X); \]

Description

Returns the arcsine of the elements of \( X \).

Examples

- \( b = \cos(\text{time}); \)
- \( a = \text{arcsin}(b); \)
- \( X = [0.5*\cos(\text{time});0.75*\cos(\text{time})]; \)
- \( Y = \text{arcsin}(X); \)

Limitations

\( Y \) and \( X \) must have the same size. The elements of \( X \) must be in the range \([ -1 , 1] \).
arccos

Syntax

\[ Y = \text{arccos}(X); \]

Description

Returns the arccosine of the elements of \( X \).

Examples

\[
\begin{align*}
  b &= \sin(\text{time}); \\
  a &= \text{arccos}(b); \\
  X &= [0.5\sin(\text{time}); 0.75\sin(\text{time})]; \\
  Y &= \text{arccos}(X);
\end{align*}
\]

Limitations

\( Y \) and \( X \) must have the same size. The elements of \( X \) must be in the range \([-1, 1]\).
### arccosh

**Syntax**

\[ Y = \text{arccosh}(X); \]

**Description**

Returns the hyperbolic arccosine of the elements of \( X \).

**Examples**

\[ y = \text{arccosh}(\text{time} + 1.0); \]

**Limitations**

\( Y \) and \( X \) must have the same size. The elements of \( X \) must be 1 or bigger.
arcsinh

Syntax

\[ Y = \text{arcsinh}(X); \]

Description

Returns the hyperbolic arcsine of the elements of \( X \).

Examples

\[
\begin{align*}
a &= \text{arcsinh}(\text{time}); \\
X &= [0.5*\cos(\text{time}); 0.75*\cos(\text{time})]; \\
Y &= \text{arcsinh}(X);
\end{align*}
\]

Limitations

\( Y \) and \( X \) must have the same size.

---

arctan

Syntax

\[ Y = \text{arctan}(X); \]

Description

Returns the arctangent of the elements of \( X \).

Examples

\[
\begin{align*}
a &= \text{arctan}(\text{time}); \\
X &= [\text{ramp}(1); -0.5*\text{ramp}(9)]; \\
Y &= \text{arctan}(X);
\end{align*}
\]

Limitations

\( Y \) and \( X \) must have the same size.
arctanh

Syntax

\[ Y = \text{arctanh}(X); \]

Description

Returns the hyperbolic arctangent of the elements of X.

Examples

\[
\begin{align*}
    b &= \sin(time); \\
    a &= \text{arctan}(b); \\
    X &= [\sin(time); -0.5\cos(time)]; \\
    Y &= \text{arctanh}(X);
\end{align*}
\]

Limitations

Y and X must have the same size. The elements of X must be in the range \([-1, 1]\).
atan2

Syntax

\[ R = \text{atan2}(Y, X); \]

Description

This is the four quadrant arctangent of the elements of Y and X. Unlike arctangent function, atan2 does distinguish between diametrically opposite directions.

Examples

\[
\begin{array}{ccc}
X, Y & \text{arctan}(Y/X); & \text{atan2}(Y, X); \\
1,1 & n/4 & n/4 \\
-1,-1 & n/4 & -3n/4 \\
0,1 & - & n/2 \\
0,0 & - & \text{set to 0 instead of undefined.}
\end{array}
\]

\[
\begin{align*}
y &= \sin(\text{time}); \\
x &= \cos(\text{time}); \\
r &= \text{atan2}(y, x);
\end{align*}
\]

\[
\begin{align*}
X &= \text{ramp}(0)\text{;}\text{ramp}(1)); \\
Y &= [1;1]; \\
R &= \text{atan2}(Y,X);
\end{align*}
\]

Limitations

r, x and y must have the same size. It produces results in the range \((-n, n]\). Atan2(0, 0) is defined as 0 instead of undefined.
cos

Syntax

\[ Y = \cos(X); \]

Description

Returns the cosine of the elements of \( X \).

Examples

\[
\begin{align*}
  b &= \text{ramp}(2.5); \\
  a &= \cos(b); \\
  X &= [\text{ramp}(0);\text{ramp}(1)]; \\
  Y &= \cos(X);
\end{align*}
\]

Limitations

\( Y \) and \( X \) must have the same size.

![Graph of cos function](image)

cosh

Syntax

\[ Y = \cosh(X); \]

Description

Returns the hyperbolic cosine of the elements of \( X \).

Examples

\[
\begin{align*}
  b &= \text{ramp}(2.5); \\
  a &= \cosh(b); \\
  X &= [\text{ramp}(0);\text{ramp}(1)]; \\
  Y &= \cosh(X);
\end{align*}
\]

Limitations

\( Y \) and \( X \) must have the same size.
**sin**

**Syntax**

\[ Y = \sin(X); \]

**Description**

Returns the sine of the elements of \( X \).

**Examples**

\[
\begin{align*}
  b &= \text{ramp}(2.5); \\
  a &= \sin(b); \\
  X &= [\text{ramp}(0); \text{ramp}(1)]; \\
  Y &= \sin(X);
\end{align*}
\]

**Limitations**

\( Y \) and \( X \) must have the same size.
sinh

Syntax

\[ Y = \sinh(X); \]

Description

Returns the hyperbolic sine of the elements of X.

Examples

\[
\begin{align*}
    b &= \text{ramp}(2.5); \\
    a &= \sinh(b); \\
    X &= [\text{ramp}(0); \text{ramp}(1)]; \\
    Y &= \sinh(X);
\end{align*}
\]

Limitations

Y and X must have the same size.
sincos

Syntax

\[ Y = \text{sincos}(x); \]

Description

Returns both the sine and cosine of \( x \).

Example

```
variables
    real Y[1,2];
equations
    Y = sincos(time);
```

Limitations

\( Y \) is a vector of 2 and \( X \) is a scalar.
tanh

Syntax

\[ Y = \tanh(X); \]

Description

Returns the hyperbolic tangent of the elements of \( X \).

Examples

\begin{align*}
  b &= \text{ramp}(2.5); \\
  a &= \tan(b); \\
  X &= [\text{ramp}(0);\text{ramp}(1)]; \\
  Y &= \tanh(X);
\end{align*}

Limitations

\( Y \) and \( X \) must have the same size.

\begin{center}
\includegraphics[width=\textwidth]{tanh_graph.png}
\end{center}

\begin{center}
Y = \tanh(X)
\end{center}

-4 -2 0 2 4

\text{Tanh}

0.5 1

0 0

-0.5 0

-1

\text{X (rad)}

\text{Y = tanh(X)}

\tan

Syntax

\[ Y = \tan(X); \]

Description

Returns the tangent of the elements of \( X \).

Examples

\begin{align*}
  b &= \text{ramp}(2.5); \\
  a &= \tan(b); \\
  X &= [\text{ramp}(0);\text{ramp}(1)]; \\
  Y &= \tan(X);
\end{align*}

Limitations

\( Y \) and \( X \) must have the same size.
9.5 Operators

9.5.1 Operators

In 20-sim you can use the following operators in equations:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>Multiplication</td>
</tr>
<tr>
<td>+</td>
<td>Addition</td>
</tr>
<tr>
<td>-</td>
<td>Subtraction</td>
</tr>
<tr>
<td>.*</td>
<td>ArrayMultiplication</td>
</tr>
<tr>
<td>./</td>
<td>ArrayDivision</td>
</tr>
<tr>
<td>.^</td>
<td>ArrayPower</td>
</tr>
<tr>
<td>/</td>
<td>Division</td>
</tr>
<tr>
<td>div</td>
<td>Integer division</td>
</tr>
<tr>
<td>mod</td>
<td>Modulus operator</td>
</tr>
<tr>
<td>^</td>
<td>Power</td>
</tr>
<tr>
<td>and</td>
<td>Boolean and</td>
</tr>
<tr>
<td>or</td>
<td>Boolean or</td>
</tr>
<tr>
<td>xor</td>
<td>Boolean exclusive or</td>
</tr>
<tr>
<td>&lt;</td>
<td>Less than</td>
</tr>
<tr>
<td>&lt;=</td>
<td>Less than or equal</td>
</tr>
<tr>
<td>&lt;&gt;</td>
<td>Not equal</td>
</tr>
<tr>
<td>==</td>
<td>Equal</td>
</tr>
<tr>
<td>&gt;=</td>
<td>Larger than or equal</td>
</tr>
</tbody>
</table>
> Larger than
- Prefix Minus Sign
+ Prefix Plus Sign
not Prefix Boolean Not
| .. | Absolute / Determinant / Norm
(data type) Type casting operator
bitand Bitwise AND
bitor Bitwise OR
bitxor Bitwise XOR
bitcmp Bitwise complement
bitset Bitwise set
bitget Bitwise get
swapbytes Swap bytes
bitclear Bitwise clear
bitinv Bitwise invert
bitshift Bitwise shift (left)
bitshiftright Bitwise shift (right)

### 9.5.2 Arithmetic

#### Absolute

Absolute / Determinant / Norm ( |..| )

**Syntax**

|A| or ||A||

**Description**

The upright stroke (|) is not a real operator. Depending on what's between the strokes, the following functions are applied:

- | scalar | -> abs(scalar)
- | matrix | -> det(matrix)
- | vector | -> abs(vector)
- || matrix || -> norm(matrix)

#### Multiplication

**Syntax**

A * B

**Description**
A * B multiplies A with B. For nonscalar A and B, the number of columns of A must equal the number of rows of B. If C = A*B then the elements of C can be calculated out of the matrix elements of A and B as:

\[ C[1, j] = \sum_{k=1}^{n} A[1, k] B[k, j] \]

A scalar can be multiplied with a matrix of any size.

**Examples**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>A * B</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>-4.5</td>
<td>5.4</td>
<td>-24.3</td>
</tr>
<tr>
<td>2</td>
<td>[1,2;3,4]</td>
<td>[2,4;6,8]</td>
</tr>
<tr>
<td>[1,-2;-3,4]</td>
<td>4</td>
<td>[4,-8;-12,16]</td>
</tr>
<tr>
<td>[1,2,3;4,5,6]</td>
<td>[1,2,3,4;5,6]</td>
<td>[22,28;49,64]</td>
</tr>
<tr>
<td>[1,2;3,4;5,6]</td>
<td>[1,2,3;4,5,6]</td>
<td>not allowed!</td>
</tr>
</tbody>
</table>

**Limitations**
For nonscalar A and B, the number of columns of A must equal the number of rows of B.

**Addition**

**Syntax**

\[ A + B \]

**Description**
A + B adds A and B. A and B must have the same size, unless one is a scalar. A scalar can be added to a matrix of any size.

**Examples**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>A + B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>2.1</td>
<td>-3.2</td>
<td>-1.1</td>
</tr>
<tr>
<td>[1,2;3,4]</td>
<td>[1,1;5,5]</td>
<td>[2,3;8,9]</td>
</tr>
<tr>
<td>2</td>
<td>[1,2;3,4]</td>
<td>[3,4;5,6]</td>
</tr>
<tr>
<td>[1,2;3,4]</td>
<td>4</td>
<td>[5,6;7,8]</td>
</tr>
<tr>
<td>[1,2;3,4]</td>
<td>[5,6;7,8;9,10]</td>
<td>not allowed!</td>
</tr>
</tbody>
</table>

**Limitations**
If A and B are matrices, they must have the same size.
Subtraction

Syntax

\[ A - B \]

Description

A - B subtracts B from A. A and B must have the same size, unless one is a scalar. A scalar can be subtracted from a matrix of any size.

Examples

\[
\begin{array}{c|c|c}
A & B & A - B \\
\hline
5 & 3 & 2 \\
-4.2 & 5.5 & -9.7 \\
[4, 5; 6, 7] & [1, 1; 5, 5] & [3, 4; 1, 2] \\
[4, 5; 6, 7] & 4 & [0, 1; 2, 3] \\
4 & [4, 5; 6, 7] & [0, -1; -2, -3] \\
\end{array}
\]

Array Multiplication

Syntax

\[ A .* B \]

Description

A .* B multiplies the elements of A by the elements of B. A.*B is the array or matrix with elements A(i,j)*B(i,j).

Examples

\[
\begin{array}{c|c|c}
A & B & A .* B \\
\hline
[1,-2,-4,2] & [1,2,1,4] & [1,-4,-4,8] \\
[2,0;0,2] & [1,2;3,4] & [2,0,0,8] \\
[2,0;0,2] & 1 & not allowed! \\
\end{array}
\]

Limitations

A and B must have the same size.
Array Division

Syntax

\[ A ./ B \]

Description

A ./ B divides the elements of A by the elements of B. A./B is the matrix with elements \( A(i,j)/B(i,j) \).

Examples

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>A ./ B</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1,-2,-4,2]</td>
<td>[1,2,1,4]</td>
<td>[1,-1,-4,0.5]</td>
</tr>
<tr>
<td>[2,0;0,2]</td>
<td>[1,2;3,4]</td>
<td>[2,0,0,0.5]</td>
</tr>
<tr>
<td>[2,0;0,2]</td>
<td>1</td>
<td>not allowed!</td>
</tr>
</tbody>
</table>

Limitations

A and B must have the same size.

Array Power

Syntax

\[ A .^ B \]

A .^ b

Description

A .^ B raises the elements of A to the power of the elements of B (B is a matrix). A.^B is the matrix with elements \( A(i,j)^{B(i,j)} \).

A .^ b raises the elements of A to the power of b (b is a scalar). A.^b is the matrix with elements \( A(i,j)^{b} \).

Examples

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>A .^ B</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1,-2,-4,2]</td>
<td>[1,2,1,4]</td>
<td>[1,4,-4,16]</td>
</tr>
<tr>
<td>[2,2;3,2]</td>
<td>[1,0;3,4]</td>
<td>[2,1;27,16]</td>
</tr>
</tbody>
</table>

A               | b                | A .^ b              |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>[1, 2; 3, 4]</td>
<td>2</td>
<td>[1, 4; 9, 16]</td>
</tr>
<tr>
<td>[16, 4]</td>
<td>0.5</td>
<td>[4, 2]</td>
</tr>
</tbody>
</table>

Limitations

The A and B matrices must have the same size or \( b \) should be a scalar.
Division

Syntax

\[ A / B \]

Description

A / B divides A by B. For a nonscalar B, A/B equals A*\text{inverse}(B). For a nonscalar A, each element of A is divided by the scalar B.

Examples

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>A / B</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>-40.5</td>
<td>5</td>
<td>-8.1</td>
</tr>
<tr>
<td>2</td>
<td>[1,2;3,4]</td>
<td>[-4,2;3,-1]</td>
</tr>
<tr>
<td>[1,-2;-3,4]</td>
<td>4</td>
<td>[0.25,-0.5;0.75,1]</td>
</tr>
<tr>
<td>[2,0;0,2]</td>
<td>[1,2;3,4]</td>
<td>[-4,2,3,-1]</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>not allowed!</td>
</tr>
<tr>
<td>1</td>
<td>[1,2,3;4,5,6]</td>
<td>not allowed!</td>
</tr>
</tbody>
</table>

Limitations

If A and B are matrices, they must have the same size. If B is a matrix and it becomes singular, simulation is stopped.

Integer Division

Syntax

\[ a \ div \ b \]

Description

a div b divides the scalar a by the scalar b and rounds the output toward zero.

Examples

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>a div b</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>9.9</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>-8</td>
<td>2</td>
<td>-4</td>
</tr>
<tr>
<td>-7.9</td>
<td>2</td>
<td>-3</td>
</tr>
</tbody>
</table>
-7.9  -2  3

Limitations
a and b must be scalars.

Modulus Operator

Syntax
\text{a mod b}

Description
a \text{ mod } b \text{ returns the signed remainder after division: } 
\text{a mod b} = \text{a} - \text{trunc(}\text{a / b}) \text{ *b}

Examples

\begin{array}{ccc}
\text{a} & \text{b} & \text{a mod b} \\
10 & 5 & 0 \\
9.9 & 5 & 4.9 \\
-8 & 2 & 0 \\
-7.9 & 2 & -1.9 \\
-7.9 & -2 & -1.9 \\
\end{array}

Limitations
a and b must be scalars.

Power

Syntax
\text{A ^ b}

Description
\text{A ^ b} \text{ raises } \text{A} \text{ to the power } \text{b}. \text{ For a nonscalar A and integer b, A^b is computed by repeated multiplication of A. If b is negative A is inverted first. If b is zero, A^b is the identity matrix. For other values of b, it is rounded to its nearest integer value. Making b a nonscalar is not allowed.}

Examples

\begin{array}{ccc}
\text{A} & \text{b} & \text{A ^ b} \\
5 & 3 & 125 \\
4 & -2.1 & 0.054409 \\
\end{array}
Limitations
- b must be a scalar. b is rounded downward to the nearest integer value.
- A should be a scalar value or a square matrix.

9.5.3 Binary

bitand

Syntax
\[ y = a \text{ bitand } b \]

Description
\( a \text{ bitand } b \) performs a bitwise AND between \( a \) and \( b \). Both \( a \) and \( b \) are treated as 32-bit (4-byte) integer values, so an eventual fraction will be ignored.

Example
In 20-sim, all bitwise function arguments are treated as 32-bit integers. Thus the binary representation of 30 (ignoring leading zeroes) is equal to 11110 as shown in the figure below. Similarly, the binary representation of 9 is 1001. The binary value of \( 30 \text{ bitand } 9 \) is equal to 01000, which corresponds with decimal value of 8.
Limitations
a and b must be integers.

bitclear

Syntax
\[ y = a \text{ bitclear } b \]

Description
\( a \text{ bitclear } b \) clears the \( b^{th} \) bit of \( a \). Both \( a \) and \( b \) are treated as 32-bit (4-byte) integer values, so an eventual fraction will be ignored.

Example
In 20-sim, all bitwise function arguments are treated as 32-bit integers. Thus the binary representation of 30 (ignoring leading zeroes) is equal to 11110 as shown in the figure below. The operation 30 \( \text{bitclear} \) 3 clears the 3\(^{rd} \) bit of 11110 which gives 11010. This binary value has a decimal value of 26.
9. Language Reference

**Limitations**
a and b must be integers.

**bitcmp**

**Syntax**

\[ y = a \text{ bitcmp} b \]

**Description**
a bitcmp b performs the b bit complement of a. Both a and b are treated as 32-bit (4-byte) integer values, so an eventual fraction will be ignored.

**Example**

In 20-sim, all bitwise function arguments are treated as 32-bit integers. Thus the binary representation of 30 (ignoring leading zeroes) is equal to 11110 as shown in the figure below. The operator 30 bitcmp 9 performs the 9 bit complement of 30. This gives the binary value 111100001 which corresponds with the decimal value 481.
9. Language Reference

Limitations
a and b must be integers.

**bitget**

**Syntax**

\[ y = a \text{ bitget } b \]

**Description**

\( a \text{ bitget } b \) gets the \( b^{th} \) bit of \( a \). Both \( a \) and \( b \) are treated as 32-bit (4-byte) integer values, so an eventual fraction will be ignored.

**Example**

In 20-sim, all bitwise function arguments are treated as 32-bit integers. Thus the binary representation of 30 (ignoring leading zeroes) is equal to 11110 as shown in the figure below. The operation \( 30 \text{ bitget } 5 \) gets the 5\(^{th} \) bit of 11110 which is 1.
9. Language Reference

Limitations
a and b must be integers.

**bitinv**

**Syntax**

\[ y = \text{bitinv} \ a \]

**Description**

\( \text{bitinv} \ a \) inverts all bits of \( a \). \( a \) is treated as 32-bit (4-byte) signed integer values, so an eventual fraction will be ignored. All one bits are changed to zero and all zero bits are changed to one.

**Example**

In 20-sim all variables are stored as doubles. This means a decimal value of 30 is 4 bytes as shown in the figure below. Because the binary representation of 30 is equal to 11110, only the last byte is filled with non zero bits. The operation \( \text{bitinv} \ 30 \) inverts the bits of "00000000 00000000 00000000 00011110" (30) to "11111111 11111111 11111111 1110001" which is -31 (as signed integer).
Limitations

a and b must be integers. B should be in the range: [-31..31]

bitor

Syntax

\[ y = a \ bitor \ b \]

Description

a bitor b performs a bitwise OR between a and b. Both a and b are treated as 32-bit (4-byte) integer values, so an eventual fraction will be ignored.

Example

In 20-sim, all bitwise function arguments are treated as 32-bit integers. Thus the binary representation of 30 (ignoring leading zeroes) is equal to 11110 as shown in the figure below. Similarly, the binary representation of 9 is 1001. The binary value of 30 bitor 9 is equal to 11111, which corresponds with a decimal value of 31.
9. Language Reference

**Limitations**
a and b must be integers.

**bitset**

**Syntax**

\[ y = a \text{ bitset } b \]

**Description**

*a bitset b* sets the \( b^{th} \) bit of \( a \). Both \( a \) and \( b \) are treated as 32-bit (4-byte) integer values, so an eventual fraction will be ignored.

**Example**

In 20-sim, all bitwise function arguments are treated as 32-bit integers. Thus the binary representation of 30 (ignoring leading zeroes) is equal to 11110 as shown in the figure below. The operation 30 bitset 1 sets the last bit of 11110 to one which gives 11111. This binary value corresponds with a decimal value of 31.
9. Language Reference

Limitations

a and b must be integers.

bitshift

Syntax

\[ y = a \ bitshift b \]

Description

a \ bitshift b \ shifts the bits of \ a \ with \ b \ places. Both \ a \ and \ b \ are treated as 32-bit (4-byte) integer values, so an eventual fraction will be ignored. A positive value of \ b \ shifts the bits to the left and a negative value shifts the bits to the right.

Example

In 20-sim all variables are stored as doubles. This means a decimal value of 30 is 4 bytes as shown in the figure below. Because the binary representation of 30 is equal to 11110, only the last byte is filled with non zero bits. The operation \( 30 \ bitshift \ 1 \) shifts the bits of 11110 with one place which gives 111100. This number has a decimal value of 60.
Limitations

a and b must be integers. B should be in the range: [-31..31]

**bitshiftright**

**Syntax**

\[ y = a \text{ bitshiftright } b \]

**Description**

A *bitshiftright* operation shifts the bits of *a* with *b* places. Both *a* and *b* are treated as 32-bit (4-byte) integer values, so an eventual fraction will be ignored.

A positive value of *b* shifts the bits to the right and a negative value shifts the bits to the left.

**Example**

In 20-sim all variables are stored as doubles. This means a decimal value of 30 is 4 bytes as shown in the figure below. Because the binary representation of 30 is equal to 11110, only the last byte is filled with non-zero bits. The operation 30 *bitshiftright* 1 shifts the bits of 11110 with one place which gives 1111. This number has a decimal value of 60.
Limitations
a and b must be integers. B should be in the range: [-31..31]

bitxor

Syntax
\[ y = a \text{ bitxor } b \]

Description
a bitxor b performs a bitwise XOR between a and b. Both a and b are treated as 32-bit (4-byte) integer values, so an eventual fraction will be ignored.

Example
In 20-sim, all bitwise function arguments are treated as 32-bit integers. Thus the binary representation of 30 (ignoring leading zeroes) is equal to 11110 as shown in the figure below. Similarly, the binary representation of 9 is 1001. The binary value of 30 bitxor 9 is equal to 10111, which corresponds with a decimal value of 23.
Limitations
a and b must be integers.

swapbytes

Syntax
   swapbytes a

Description
swapbytes a swaps the bytes of a.

Example
In 20-sim all variables are stored as doubles. This means a decimal value of 30 is 4 bytes as shown in the figure below. Because the binary representation of 30 is equal to 11110, only the last byte is filled with non zero bits. The operation swapbytes 30 swaps byte D to A, C to B, B to C and A to D (see figure below) which gives a decimal value of 503316480.
9. Language Reference

5.1 Reference Manual

Limitations
a and b must be integers.

9.5.4 Boolean

and

Syntax
a and b

Description
a and b performs a logical AND between a and b. If a or b are not a boolean, 0 represents a logical false and any nonzero value represents a logical true. The truth table for this operator is shown below.

Table

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>a and b</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>true</td>
</tr>
</tbody>
</table>

Limitations
a and b must be scalars.
**or**

**Syntax**

\[ a \text{ or } b \]

**Description**

\( a \text{ or } b \) performs a logical OR between \( a \) and \( b \). If \( a \) or \( b \) are not booleans, 0 represents a logical false and any nonzero value represents a logical true. The truth table for this operator is shown below.

**Table**

<table>
<thead>
<tr>
<th>( a )</th>
<th>( b )</th>
<th>( a \text{ or } b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>true</td>
</tr>
</tbody>
</table>

**Limitations**

\( a \) and \( b \) must be scalars.

**xor**

**Syntax**

\[ a \text{ xor } b \]

**Description**

\( a \text{ xor } b \) performs a logical Exclusive OR between \( a \) and \( b \). If \( a \) or \( b \) are not booleans, 0 represents a logical false and any nonzero value represents a logical true. The truth table for this operator is shown below.

**Table**

<table>
<thead>
<tr>
<th>( a )</th>
<th>( b )</th>
<th>( a \text{ xor } b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>

**Limitations**

\( a \) and \( b \) must be scalars.
9.5.5 Comparison

Less than

Syntax
   \[ a < b \]

Description
The \(<\) operator compares two arguments and yields a boolean. If \(a\) is less than \(b\), then \(a < b\) yields true. If \(a\) is equal or larger than \(b\), then \(a < b\) yields false.

Example

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>a &lt; b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>true</td>
</tr>
<tr>
<td>1.01e2</td>
<td>101.0</td>
<td>false</td>
</tr>
<tr>
<td>31</td>
<td>1</td>
<td>false</td>
</tr>
<tr>
<td>-12</td>
<td>-11</td>
<td>true</td>
</tr>
</tbody>
</table>

Limitations
\(a\) and \(b\) must be scalars.

Less than or Equal

Syntax
   \[ a \leq b \]

Description
The \(\leq\) operator compares two arguments and yields a boolean. If \(a\) is less than or equal to \(b\), then \(a \leq b\) yields true. If \(a\) is larger than \(b\), then \(a \leq b\) yields false.

Example

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>a &lt; b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>true</td>
</tr>
<tr>
<td>1.01e2</td>
<td>101.0</td>
<td>true</td>
</tr>
<tr>
<td>31</td>
<td>1</td>
<td>false</td>
</tr>
<tr>
<td>-12</td>
<td>-11</td>
<td>true</td>
</tr>
</tbody>
</table>

Limitations
\(a\) and \(b\) must be scalars.
### Not Equal

#### Syntax

\[ a \not= b \]

#### Description

The \( \not= \) operator compares two arguments and yields a boolean. If \( a \) is equal to \( b \), then \( a \not= b \) yields false. If \( a \) is not equal to \( b \), then \( a \not= b \) yields true.

#### Example

<table>
<thead>
<tr>
<th>( a )</th>
<th>( b )</th>
<th>( a \not= b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>false</td>
</tr>
<tr>
<td>1.01e2</td>
<td>101.0</td>
<td>false</td>
</tr>
<tr>
<td>31</td>
<td>1</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
</tbody>
</table>

#### Limitations

\( a \) and \( b \) must be scalars.

### Equal

#### Syntax

\[ a == b \]

#### Description

The \( == \) operator compares two arguments and yields a boolean. If \( a \) is equal to \( b \), then \( a == b \) yields true. If \( a \) is not equal to \( b \), then \( a == b \) yields false. It is typically used in an if-statement.

#### Example

<table>
<thead>
<tr>
<th>( a )</th>
<th>( b )</th>
<th>( a == b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>true</td>
</tr>
<tr>
<td>1.01e2</td>
<td>101.0</td>
<td>true</td>
</tr>
<tr>
<td>31</td>
<td>1</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>false</td>
</tr>
</tbody>
</table>

#### Note

The normal equal sign (\( = \)) should only be used for equations. The equal sign (\( = \)) makes the left side of an equation equal to the right side. This is different to the equal statement (\( == \)) which compares two arguments and yields a boolean.
Larger Than

Syntax

\[ a > b \]

Description

The > operator compares two arguments and yields a boolean. If a is less than or equal to b, then \( a > b \) yields false. If a larger than b, then \( a > b \) yields false.

Example

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>a &gt; b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>false</td>
</tr>
<tr>
<td>1.01e2</td>
<td>101.0</td>
<td>false</td>
</tr>
<tr>
<td>31</td>
<td>1</td>
<td>true</td>
</tr>
<tr>
<td>-12</td>
<td>-11</td>
<td>false</td>
</tr>
</tbody>
</table>

Limitations

a and b must be scalars.

Larger Than or Equal

Syntax

\[ a >= b \]

Description

The >= operator compares two arguments and yields a boolean. If a is less than b, then \( a > b \) yields false. If a larger than or equal to b, then \( a > b \) yields true.

Example

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>a &gt;= b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>false</td>
</tr>
<tr>
<td>1.01e2</td>
<td>101.0</td>
<td>true</td>
</tr>
<tr>
<td>31</td>
<td>1</td>
<td>true</td>
</tr>
<tr>
<td>-12</td>
<td>-11</td>
<td>false</td>
</tr>
</tbody>
</table>

Limitations

a and b must be scalars.
9.5.6 Prefix

Prefix Plus Sign

Syntax

\[ Y = +A \]

Description
The plus sign may be used as a prefix for scalars, vectors and matrices.

Examples

\[
\begin{align*}
A & & +A \\
5 & & 5 \\
[4, 5; -6, 7.1] & & [4, 5; -6, 7.1] \\
\end{align*}
\]

Prefix Minus Sign

Syntax

\[ Y = -B \]

Description
The minus sign may be used as a prefix for scalars, vectors and matrices.

Examples

\[
\begin{align*}
A & & -A \\
5 & & -5 \\
[4, 5; -6, 7.1] & & [-4; -5; 6; -7.1] \\
\end{align*}
\]

Boolean Not

Syntax

\[ y = \text{not } a \]

Description
The boolean prefix not performs an inversion of a.

Table

<table>
<thead>
<tr>
<th>a</th>
<th>not a</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-5</td>
</tr>
<tr>
<td>[4, 5; -6, 7.1]</td>
<td>[-4; -5; 6; -7.1]</td>
</tr>
</tbody>
</table>
9. Language Reference

false true
true false

Limitations
a must be a boolean.

9.6 Statements

9.6.1 Statements

Statements are important to guide the flow of information in equation models. 20-sim supports the following statements:

1. For to Do
2. If Then
3. If Then Else
4. If Then Else (expression)
5. Repeat Until
6. Switch Case
7. StopSimulation
8. Warning
9. While Do
10. toMatlab
11. fromMatlab
12. doMatlab
13. EffortInCausality
14. FlowInCausality

9.6.2 If Then

Syntax

if condition then
equation;
....
end;

Description

The simplest if statement evaluates a condition and performs the specified equation(s) if the condition is true. If the condition is not true, 20-sim ignores the equation(s).
Examples

```plaintext
b = false;
y = ramp(1);
u = -ramp(1);
if time > 5 then
    y = -ramp(1); // equations to be executed if condition is true,
    u = ramp(1); // these are not executed if condition is false
end;
if time == 10 then // note the use of the equal operator ==
    b = true; // equations to be executed if condition is true,
end;
```

Limitations

1. The output of the condition must be a boolean.

Note

1. Take care when using an event functions in if-then-else statements. In if-then-else statements only the equations of the true parts are evaluated, so event functions may not always be triggered!

2. There is also an if-then-else statement.

3. Equations within an if statement have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially.

9.6.3 If Then Else

Syntax

```plaintext
if condition then
    equation;
else
    equation;
end;
```

Description

The if-then-else statement evaluates a condition and performs the first set of equation(s) if the condition is true and the second set of equation(s) if the condition is false. If the condition is true, 20-sim ignores the second set of equation(s). If the condition is false, 20-sim ignores the first set of equation(s).

Nesting

If-then-else statements may be nested as many times as desired. Do not forget to included the word "end;" to finish every nested statement!

Examples

```plaintext
y = step(1);
u = -step(1);
if time > 5 then
```
y = -ramp(1); // equations to be executed if condition is true,
    u = ramp(1); // these are not executed if condition is false
else
    y = ramp(1); // equations to be executed if condition is false,
    u = -ramp(1); // these are not executed if condition is true
end;

//Nesting
if time < 5 then
    a = 1;
    b = sin(time*1);
else
    if time == 5 then
        a = 2;
        b = sin(time*2);
    else
        a = 3
        b=sin(time*3);
    end;
end;

Limitations

1. The output of the condition must be a boolean.

Note

1. Take care when using an event functions in if-then-else statements. In if-then-else statements only the equations of the true parts are evaluated, so event functions may not always be triggered!

2. There is also an if-then-else expression.

3. Equations within an if statement have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially.
### 9.6.4 If Then Elsif

**Syntax**

```
if condition then
  equation;
...
elsif condition then
  equation;
...
elsif condition then
  equation;
...
else
  equation;
...
end;
```

**Description**

The if-then-elsif-else statement is a variant of the if-then-else statement. It makes nested conditions easier to write. It evaluates a condition and performs the first set of equation(s) if the condition is true, otherwise it evaluates the second condition and performs the second set of equation(s) if that condition is true and so on. If the first condition is true, 20-sim ignores the other sets of equation(s). If the first condition is false, 20-sim ignores the first set of equation(s) and jumps to the second condition etc.

**Examples**

```plaintext
x = (integer) time;
if x < 4 then
  y = 1;
elsif x < 6 then
  y = 3;
elsif x < 8 then
  y = 5;
else
  y = 0;
end;
```

**Limitations**

1. The output of the condition must be a boolean.

**Note**

1. Take care when using an event functions in if-then-else statements. In if-then-else statements only the equations of the true parts are evaluated, so event functions may not always be triggered!

2. Equations within an if statement have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially.
9.6.5 If Then Else (expression)

Syntax

\[ y = \text{if condition then expression else expression end; } \]

Description

The if-then-else expression evaluates a condition and makes \( y \) equal to the first expression if the condition is true and makes \( y \) equal to the second expression if the condition is false. If the condition is true, 20-sim ignores the second expression. If the condition is false, 20-sim ignores the first expression. Because the complete construct forms one expression, only one semicolon is used at the end.

Nesting

If-then-else expression may be nested. Take care that no semicolons are used, because no matter how large the construct is, it is still one expression!

Examples

\[ y = \text{if time > 5 then -ramp(1) else ramp(1) end; } \]

// Nesting:
\[ x = \text{if time < 1 then 1 else if time < 2 then 2 else if time == 2 then 1 else 0 end end; } \]

Limitations

1. The output of the condition must be a boolean.
2. If needed, always use the equal operator (==) in the condition.

Note
1. Take care when using event functions in if-then-else expressions. In if-then-else expressions only the equations of the true parts are evaluated, so event functions may not always be triggered!

2. There is also an if-then-else statement.

3. Equations within an if statement have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially.

9.6.6 For To Do

Syntax

```
for variable = start to stop by step do
  equation;
  equation;
  ....
end;
```

Description

The for statement is designed to execute equation(s) a fixed number of times. It begins with the keyword `for` and an expression that specifies the number of times the equations within the for statement should be executed. The for statement ends with the keyword `end`. The default increment in a for statement is one (1), but you can use the keyword `by` to adjust the increment.

The equations within the for statement are always executed once. The for statement stops when the variable has exceeded the stop value.

Examples

```
variables
  real i,y[10];

equations
  for i = 1 to 2 do
    // executed 2 times: y[1] and y[2]
    y[i] = ran (1);
  end;
  for i = 2 to 4.1 by 2 do
    // executed 3 times: y[2], y[4] and y[6]
    y[i] = ran (1);
  end;
```

Limitations

1. The start, stop and step values must be scalars. The step value is optional. There are no limitations to the number of equations that can be used within the for statement.

2. Equations within an for statement have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially.
9.6.7 While Do

Syntax

code

\[
\text{while condition do}
\]
\[
\text{equation;}
\]
\[
\text{equation;}
\]
\[
\text{....}
\]
\[
\text{end;}
\]

Description

The while statement is designed to execute equation(s) repeatedly, as long as the condition is true. The condition is evaluated before the equations are executed.

It is the user’s responsibility to guarantee that the execution of the while statement finishes by making the condition become false at a certain time.

Example

variables

\[
\text{real } i, y[3];
\]

initial equations

\[
y = 0;
\]

code // Use code to ensure sequential execution

\[
i = 1;
\]

while \( i \leq \text{rows}(y) \) do

\[
\text{// executed 3 times for each model calculate:}
\]
\[
\text{// } y[1] \text{ and } y[2] \text{ and } y[3] \text{ are filled}
\]
\[
y[i] = \sin(\text{time}) \times i;
\]
\[
\text{// } i \text{ is incremented to guarantee a stop of the loop}
\]
\[
i = i + 1;
\]

end;

Limitations

1. The output of the condition must be a boolean. If the boolean does not become false, the loop never ends! There are no limitations to the number of equations that can be used within the while statement.

2. Equations within an while statement have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially.
9.6.8 Repeat Until

Syntax

\begin{verbatim}
   code
   repeat
       equation;
       equation;
       ....
   until condition;
\end{verbatim}

Description

The repeat statement is designed to execute equation(s) repeatedly, as long as the condition is true. The condition is evaluated after the equations are executed.

It is the user's responsibility to guarantee that the execution of the repeat statement finishes by making the condition become false at a certain time.

Examples

\begin{verbatim}
variables
   real i,z[4];
initial equations
   z = 0;
code // Use code to ensure sequential execution
   i = 1;
   repeat
       // executed 4 times:
       z[i] = cos(time) * i;
       // i is incremented to guarantee a stop of the loop
       i = i + 1;
   until (i > rows(z));
\end{verbatim}

Limitations

1. The output of the condition must be a boolean. If the boolean does not become false, the loop never ends! There are no limitations to the number of equations that can be used within the repeat statement.

2. If needed, always use the equal operator (==) in the condition.

3. Equations within an repeat statement have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially.
9.6.9 Switch Case

Syntax

```
switch variable
  case variable1 do
    equations;
  case variable2 do
    equations;
  default do
    equations;
end;
```

Example

```
equations
  z = 4;
  i = floor(time);
  switch i
    case 1 do
      y = 1;
    case 2 do
      y = 2;
    case 3 do
      y = 3;
    case z do
      y = 4;
    default do
      y = 5;
  end;
```

Description

The switch case statement is designed to execute equation(s) based on the value of a variable. Only the equations of the valid branch are executed. If none of the branches is valid, the equations of the default branch are executed.

Limitations

1. The switch variable should not be changed inside one of the branches.
2. Equations within a switch case statement have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially. Therefore it is advised only to use this statement in a code section.

Tips

1. Keep the condition variables (variable1, variable2) constant during simulation to prevent confusion.
2. Make sure that the switch variable has the right value to execute the branch. In the example, the time variable changes value every time step. The floor function is used to keep it at a constant value long enough to see the branches in action.
9.6.10 Stopsimulation

Syntax

```
stopsimulation ('string');
```

Description

The stopsimulation function stops the simulation as soon as it comes to action. It is useful when used in combination with an if statement. As soon as the simulation stops, the log window will appear showing the string that is used in the function.

- **Normal stop**: If the string starts with 'Error', the Simulator will stop and the Editor will jump to the the model containing the stopsimulation function.
- **Silent stop**: If the string does not start with 'Error' the Simulation will jump to the **finalequations** section, execute them and stop the simulation.

Examples

In the example below the Simulator will stop the simulation at time > 6 and show a message 'time > 6' in the output tab. The **finalequations** are evaluated and number has a value of 2:

```
variables
  integer number;
initialequations
  number = 1;
equations
  if time > 6 then
    stopsimulation ('time > 6');
  end;
finalequations
  number = 2;
```

In the example below the Simulator will stop the simulation at time > 6 and show a message 'time > 6' in the output tab. The Editor will jump to this model showing an error message. The **finalequations** are not evaluated and number has a value of 1:

```
variables
  integer number;
initialequations
  number = 1;
equations
  if time > 6 then
    stopsimulation ('Error time > 6');
  end;
finalequations
  number = 2;
```
9.6.11  Warning

Syntax

    warning ('string',boolean);

Description

The warning function displays a message in the the log window. You can choose to display the string once (boolean = true) or every simulation step (boolean = false). It is advised to use the warning function in combination with an if-then statement or event-function.

Examples

    warning('this message will be displayed every simulationstep!',false);
    if time > 1
        warning('this message will be displayed every simulationstep after time > 1!',false);
    end;
    if x > 100 then
        warning('this message will be displayed only once after x > 100',true);
    end;
    if event(y) then
        warning('this message will be displayed when y is exactly 0',false);
    end;

9.6.12  toMatlab

Syntax

    toMatlab(<20-sim variable>)
    toMatlab(<20-sim variable>, 'matlab variable name')

Description

The toMatlab statement allows you to pass a variable from 20-sim to Matlab.

The first argument is the name of the 20-sim variable to send to Matlab (source). This 20-sim variable can be a scalar variable, a vector or a matrix. The second (optional) argument 'matlab variable name' is the name of the corresponding matlab variable (destination).

When the 'matlab variable name' argument is omitted, 20-sim will use the full hierarchical name of the 20-sim variable. A 20-sim variable named Controller\x becomes in Matlab: Controller_x

The corresponding fromMatlab statement allows you to retrieve a variable from Matlab.

Example

    // this example shows how a variable can be transferred to matlab and from matlab during simulation
    variables
        real x;
        real y;
        real vector[2];
        real matrix[2,2];
// at the start of the simulation
initialequations
  // create an empty array a
  doMatlab ('a = []; ');
  // create a variable
  doMatlab ('b=0; ');
  // create a vector
  doMatlab ('vector=[1 2];');
  // create a matrix
  doMatlab ('matrix=[1 2; 3 4];');

// during simulation
equations
  // calculate x
  x = sin (time);
  // send it to Matlab
  toMatlab (x,'x');
  // and add it to array a
  doMatlab ('a = [ a x ]; ');
  // in Matlab add 2 to x
  doMatlab ('b = x + 2;');
  // read matlab 'b' into 20-sim variable 'y'
  fromMatlab(y, 'b');
  // read matlab 'vector' into 20-sim variable 'vector'
  fromMatlab(vector, 'vector');
  // read matlab 'matrix' into 20-sim variable 'matrix'
  fromMatlab(matrix, 'matrix');

// at the end of the simulation
finalequations
  // plot the resulting array in Matlab
  doMatlab (' plot (a); ');
// create an empty array a
doMatlab ('a = []; ');

// create a variable
doMatlab ('b=0; ');

// create a vector
doMatlab ('vector=[1 2];');

// create a matrix
doMatlab ('matrix=[1 2; 3 4];');

// during simulation
equations
// calculate x
x = sin (time);

// send it to Matlab
toMatlab (x,'x');

// and add it to array a
doMatlab ('a = [ a x ]; ');   // in Matlab add 2 to x
doMatlab ('b = x + 2;');

// read matlab 'b' into 20-sim variable 'y'
fromMatlab(y, 'b');

// read matlab 'vector' into 20-sim variable 'vector'
fromMatlab(vector, 'vector');

// read matlab 'matrix' into 20-sim variable 'matrix'
fromMatlab(matrix, 'matrix');

// at the end of the simulation
finalequations
// plot the resulting array in Matlab
doMatlab (' plot (a); ');

9.6.14 fromMatlab

**Syntax**

```
fromMatlab(<20-sim variable>)
fromMatlab(<20-sim variable>, 'matlab variable name')
```

**Description**

The `fromMatlab` statement allows you to retrieve a variable from Matlab and store it into a 20-sim variable. The first argument is the name of the 20-sim variable to use as storage (destination). This 20-sim variable can be a scalar variable, a vector or a matrix and should match the size used at the Matlab side. The second (optional) argument `matlab variable name` is the name of the Matlab variable to retrieve (source).

When the `matlab variable name` argument is omitted, 20-sim will use the full hierarchical name of the 20-sim variable.
A 20-sim variable named `Controller\x` requests from Matlab: `Controller_x`

The corresponding `toMatlab` statement allows you to pass a variable from 20-sim to Matlab.
Example

// this example shows how a variable can be transferred to matlab and from matlab
during simulation

variables
    real x;
    real y;
    real vector[2];
    real matrix[2,2];

// at the start of the simulation
initialequations
    // create an empty array a
    doMatlab ('a = []; '); 
    // create a variable
    doMatlab ('b=0; '); 
    // create a vector
    doMatlab ('vector=[1 2];');
    // create a matrix
    doMatlab ('matrix=[1 2; 3 4];');

// during simulation

equations
    // calculate x
    x = sin (time);
    // send it to Matlab
    toMatlab (x,'x');
    // and add it to array a
    doMatlab ('a = [ a x ]; ');
    // in Matlab add 2 to x
    doMatlab ('b = x + 2;');
    // read matlab 'b' into 20-sim variable 'y'
    fromMatlab(y, 'b');
    // read matlab 'vector' into 20-sim variable 'vector'
    fromMatlab(vector, 'vector');
    // read matlab 'matrix' into 20-sim variable 'matrix'
    fromMatlab(matrix, 'matrix');

// at the end of the simulation
finalequations
    // plot the resulting array in Matlab
    doMatlab (' plot (a); ');
### 9.6.15 Effortincausality

**Syntax**

```plaintext
effortincausality (portname) then
    equation;
    equation;
    ...
else
    equation;
    equation;
    ...
end;
```

**Description**

The effortincausality statement evaluates if a port has causality effort in and performs the first set of equation(s) if the condition is true and the second set of equation(s) if the condition is false. If the condition is true, 20-sim ignores the second set of equation(s). If the condition is false, 20-sim ignores the first set of equation(s).

Depending on the domain you are working in, effort and flow correspond to particular variables. The table below shows the variables for the domains that are currently supported in 20-sim.

<table>
<thead>
<tr>
<th>Domain</th>
<th>effort (e)</th>
<th>flow (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>power</td>
<td>effort $e$</td>
<td>flow $f$</td>
</tr>
<tr>
<td>mechanical (trans)</td>
<td>force $F$ [N]</td>
<td>velocity $v$ [m/s]</td>
</tr>
<tr>
<td>mechanical (rot)</td>
<td>torque $T$ [Nm]</td>
<td>angular velocity $\omega$ [rad/s]</td>
</tr>
<tr>
<td>pneumatic</td>
<td>pressure $p$ [Pa]</td>
<td>volume flow $\phi$ [m$^3$/s]</td>
</tr>
<tr>
<td>thermal</td>
<td>temperature $T$ [K]</td>
<td>entropy flow $dS$ [J/Ks]</td>
</tr>
<tr>
<td>electric</td>
<td>voltage $u$ [V]</td>
<td>current $i$ [A]</td>
</tr>
<tr>
<td>hydraulic</td>
<td>pressure $p$ [Pa]</td>
<td>volume flow $\phi$ [m$^3$/s]</td>
</tr>
<tr>
<td>magnetic</td>
<td>current $i$ [A]</td>
<td>voltage $u$ [V]</td>
</tr>
<tr>
<td>pseudothermal</td>
<td>temperature $T$ [K]</td>
<td>heat flow $dQ$ [W]</td>
</tr>
</tbody>
</table>
Examples

effortincausality p then
    R = if p.u > 0 then Ron else Roff end; // executed if causality of port p is effort (u) in
    else
        R = if p.i > 0 then Ron else Roff end; // executed if causality of port p is flow (i) in
    end;
    p.i = p.u/R;

Note

1. Take care when using event functions in effortincausality statements. In this statement only the equations of the true parts are evaluated, so event functions may not always be triggered!

2. There is also a flowincausality statement.

3. Equations within an effortincausality have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially.

9.6.16 Flowincausality

Syntax

    flowincausality (portname) then
        equation;
        equation;
        ...
    else
        equation;
        equation;
        ...
    end;

Description

The effortincausality statement evaluates if a port has causality flow in and performs the first set of equation(s) if the condition is true and the second set of equation(s) if the condition is false. If the condition is true, 20-sim ignores the second set of equation(s) if the condition is false, 20-sim ignores the first set of equation(s).

Depending on the domain you are working in, effort and flow correspond to particular variables. The table below shows the variables for the domains that are currently supported in 20-sim.

<table>
<thead>
<tr>
<th>Domain</th>
<th>effort (e)</th>
<th>flow (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>power</td>
<td>effort e</td>
<td>flow f</td>
</tr>
<tr>
<td>mechanical</td>
<td>force F [N]</td>
<td>velocity v [m/s]</td>
</tr>
<tr>
<td>(translation)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 9. Language Reference

#### 9.7 Matrices and Vectors

##### 9.7.1 Declaration

Matrices and column vectors are declared in the `constants`, `parameters` and `variables` sections of a model. Declaration of matrices and column vectors is equal to the declaration of scalars, the size however has to be specified explicitly using square brackets `[ ]`. For example:

```plaintext
parameters
    real A[3,3], B[3,3];
    integer C[2,2] = [1,3;5,7];
    real K[4] = [1;2;3;4];
variables
    real K[4], L[4], D[4,5];
    integer M[2,2], N[2,2];
```

Matrices and Vectors can only be of the datatype real or integer.

<table>
<thead>
<tr>
<th>Physical Quantity</th>
<th>Mathematical Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical (rotation)</td>
<td>torque</td>
<td>$T$ [Nm]</td>
</tr>
<tr>
<td></td>
<td>angular velocity</td>
<td>$\omega$ [rad/s]</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>pressure</td>
<td>$p$ [Pa]</td>
</tr>
<tr>
<td></td>
<td>volume flow</td>
<td>$\phi$ [m$^3$/s]</td>
</tr>
<tr>
<td>Thermal</td>
<td>temperature</td>
<td>$T$ [K]</td>
</tr>
<tr>
<td></td>
<td>entropy flow</td>
<td>$dS$ [J/Ks]</td>
</tr>
<tr>
<td>Electric</td>
<td>voltage</td>
<td>$u$ [V]</td>
</tr>
<tr>
<td></td>
<td>current</td>
<td>$i$ [A]</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>pressure</td>
<td>$p$ [Pa]</td>
</tr>
<tr>
<td></td>
<td>volume flow</td>
<td>$\phi$ [m$^3$/s]</td>
</tr>
<tr>
<td>Magnetic</td>
<td>current</td>
<td>$i$ [A]</td>
</tr>
<tr>
<td></td>
<td>voltage</td>
<td>$u$ [V]</td>
</tr>
<tr>
<td>Pseudothermal</td>
<td>temperature</td>
<td>$T$ [K]</td>
</tr>
<tr>
<td></td>
<td>heat flow</td>
<td>$dQ$ [W]</td>
</tr>
</tbody>
</table>

**Examples**

```plaintext
flowincausality p then
R = if p.i > 0 then Ron else Roff end; // executed if causality of port p is flow (i) in
else
R = if p.u > 0 then Ron else Roff end; // executed if causality of port p is effort (u) in
end;
p.u = p.i*R;
```

**Note**

1. Take care when using event functions in effortincausality statements. In this statement only the equations of the true parts are evaluated, so event functions may not always be triggered!

2. There is also an effortincausality statement.

3. Equations within an effortincausality have to be written in the correct order of execution, i.e. they are not rewritten into a causal form but executed sequentially.
### 9.7.2 Notation

Matrix sizes in 20-sim are always denoted by \([n,m]\) where \(n\) is the number of rows and \(m\) is the number of columns. Elements can separately be denoted with commas (,) distinguishing between row elements and semicolons (;) distinguishing between rows.

<table>
<thead>
<tr>
<th>matrix size</th>
<th>matrix form</th>
<th>20-sim notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4,1]</td>
<td>1 3 5 7</td>
<td>[1;3;5;7]</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>[1,4]</td>
<td>1 3 5 7</td>
<td>[1,3,5,7]</td>
</tr>
<tr>
<td>[2,3]</td>
<td>1 2 3 4 5 6</td>
<td>[1,2,3;4,5,6]</td>
</tr>
<tr>
<td>[3,2]</td>
<td>1 2 3 4 5 6</td>
<td>[1,2;3,4;5,6]</td>
</tr>
</tbody>
</table>

Column vectors are matrices with only one column. Consequently the column size may be omitted in the notation.

<table>
<thead>
<tr>
<th>column size</th>
<th>column form</th>
<th>20-sim notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4]</td>
<td>1 3 5 7</td>
<td>[1;3;5;7]</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>
9.7.3 Use

Matrices and Vectors can be used in equations just like scalars. If possible, the element notation can be left out. **If equations get ambiguous, element notation must be used!**

**Whole matrix or vector**

\[
K = 1; \quad // \text{Make all elements of } K \text{ equal to } 1.
\]

\[
M = C; \quad // \text{Make matrix } M \text{ equal to matrix } C \text{ (sizes have to be equal)}.
\]

\[
N = D*\text{inverse}(L); \quad // \text{Make matrix } N \text{ equal to the matrix product of } D \text{ and the inverse of } L \text{ (sizes of } N, D \text{ and } L \text{ have to be equal)}.
\]

**Matrix and vector elements**

\[
N = [\sin(time),\cos(time);\cos(time),-\sin(time)]; \quad // \text{Make elements of } N \text{ equal to functions}.
\]

\[
L[4] = time; \quad // \text{Make element 4 of columned } L \text{ equal to time}.
\]

\[
D[2,5] = A[2,2]*B[1,1]; \quad // \text{Declare one element}
\]

**Multiple elements (ranges)**

To prevent multiple equations for assigning matrix elements, ranges can be assigned using a colon. E.g. 1:5 means element 1 to 5, 7:8 means element 7 and 8. Backward counting ranges (like 10:1) are not allowed!

\[
\]

**variables**

\[
\text{real } v[3], p[6,6];
\]

**equations**

\[
\]

**Operators**

Some scalar operators can also be used for matrices and vectors. Depending on the specific operator, the meaning may differ for scalars, vectors and matrices.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>Multiplication</td>
</tr>
<tr>
<td>+</td>
<td>Addition</td>
</tr>
<tr>
<td>-</td>
<td>Subtraction</td>
</tr>
<tr>
<td>.*</td>
<td>ArrayMultiplication</td>
</tr>
<tr>
<td>./</td>
<td>ArrayDivision</td>
</tr>
<tr>
<td>.^</td>
<td>ArrayPower</td>
</tr>
<tr>
<td>/</td>
<td>Division</td>
</tr>
<tr>
<td>^</td>
<td>Power</td>
</tr>
<tr>
<td>-</td>
<td>Prefix Minus Sign</td>
</tr>
<tr>
<td>+</td>
<td>Prefix Plus Sign</td>
</tr>
<tr>
<td></td>
<td>..</td>
</tr>
</tbody>
</table>
### Functions
A lot of special matrix and vector functions are supported in 20-sim:

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjoint</td>
<td></td>
</tr>
<tr>
<td>adjoint</td>
<td></td>
</tr>
<tr>
<td>Antisym</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td></td>
</tr>
<tr>
<td>Cross</td>
<td></td>
</tr>
<tr>
<td>Determinant</td>
<td></td>
</tr>
<tr>
<td>Diag</td>
<td></td>
</tr>
<tr>
<td>Eye</td>
<td></td>
</tr>
<tr>
<td>Homogeneous</td>
<td></td>
</tr>
<tr>
<td>Inner</td>
<td></td>
</tr>
<tr>
<td>Inverse</td>
<td></td>
</tr>
<tr>
<td>InverseH</td>
<td></td>
</tr>
<tr>
<td>Linsolve</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td></td>
</tr>
<tr>
<td>Msum</td>
<td></td>
</tr>
<tr>
<td>Norm</td>
<td></td>
</tr>
<tr>
<td>Norminf</td>
<td></td>
</tr>
<tr>
<td>Rows</td>
<td></td>
</tr>
<tr>
<td>Skew</td>
<td></td>
</tr>
<tr>
<td>Sym</td>
<td></td>
</tr>
<tr>
<td>Tilde</td>
<td></td>
</tr>
<tr>
<td>Trace</td>
<td></td>
</tr>
<tr>
<td>Transpose</td>
<td></td>
</tr>
</tbody>
</table>
9.8 Advanced Topics

9.8.1 Algebraic Loops

An algebraic loop in a model is a loop consisting of elements without "memory like" functions. To calculate the variables in this loop, the variable values themselves are needed. Consider the following example of an algebraic loop in an amplifier with negative feedback:

Standard derivation of a simulation model would yield:

\[ x = K(u-x) \]

The variable \( x \) depends on its own value and must be solved by iteration. In 20-sim every simulation algorithm is accompanied by an iteration routine. Fortunately 20-sim is able to solve many algebraic loops at equation level. For this model this leads to the analytic solution the system:

\[ x = \frac{Ku}{1+K} \]

Simulating algebraic loops

Although 20-sim contains a sophisticated algorithms to find analytic solutions, the occurrence of unbreakable loops can not always be prevented. The occurrence of algebraic loops may lead to an increase of simulation time, or even stop simulation when iteration fails.

The best solution for these problems is to have a critical look at the model and change the order of calculations in a model. Possible solutions are:

- Algebraic Loops occur when the order of calculations is arbitrary. When an algebraic loop occurs in an equation model or in a set of equation models, you may change the order of calculation by rewriting the equations. The calculation order in bond graph models can be changed by introducing hand-defined causality.

- Introduce 'parasitic' energy storage elements (e.g. a small mass, a small capacitor etc.) to break an algebraic loop. These elements introduce however, large poles in the state equations, which might increase the simulation time considerably.

- Delete elements in the algebraic loop which are not relevant for the model's simulation output (e.g. small dampers, very stiff springs etc.). Care should however be taken, since correct deletions are not always possible and require considerable modeling skill and intuition.

- Combine dual elements. Sometimes elements of the same type can be combined by adding the parameter values (e.g. combining a mass \( m_1 \) and a mass \( m_2 \) to a mass \( m_1 + m_2 \)). This will in most cases decrease the amount of algebraic loops.
9.8.2 Causal Form

Equations within 20-sim may be entered in random form. During compilation, 20-sim will automatically try to rewrite equations into a causal form and set them in a correct order. I.e. a form where all output variables are written as function of input variables. Consider for example the following model:

```plaintext
variables
  real u,z;
equations
  u = sin(time);
  u = cos(z);
```

Here the (input) variable u is given by the equation $u = \sin(time)$. Consequently the (output) variable z should be written as a function of u. This is exactly what 20-sim will try to do while compiling the model into simulation code. I.e. the function cos will be inverted and the model will be rewritten to:

```plaintext
variables
  real u,z;
equations
  u = sin(time);
  z = arccos(u);
```

Some functions cannot be inverted. Consequently not all equations can be rewritten. 20-sim will report this to the user, during model checking.

Fixed Causality

For some models there is only one causal form. For example a simple iconic diagram model that describes coulomb friction can be written as:

```plaintext
parameters
  real Rc;
equations
  p.F = Rc*abs(p.v);
```

Here $p.F$ denotes the force and $p.v$ denotes the velocity of the powerport $p$. The equation cannot be rewritten to a form where $p.F$ is the input. This can be explicitly stated, by giving the powerport $p$ a fixed causality. During compilation 20-sim will try to keep the model in this fixed form. If this is not possible an error message will be generated.

Fixed causality has the highest priority for assigning causality. During compilation 20-sim will first assign all models with a fixed causality, then all models with a preferred causality, then all models with a likes causality and then all models with an indifferent causality.

Preferred Causality

For some models there is a preferred causal form. For example the iconic diagram model that describes a spring can be written as:
\begin{verbatim}
parameters
  real k;

equations
  p.F = (1/k)*int(p.v);
\end{verbatim}

Here \( p.F \) denotes the force and \( p.v \) denotes the velocity of the powerport \( p \). The equation is written in integral form which is preferred. Consequently the preferred input is the velocity. Should the force be the input, the equation must be rewritten to a differential form, which is leads to less efficient simulation. This can be explicitly stated, by giving the powerport \( p \) an preferred causality. During compilation 20-sim will try to keep the model in this preferred form. If this is not possible the equations will be rewritten to the less preferred form.

Preferred causality has a lower priority than fixed causality. During compilation 20-sim will first assign all models with a fixed causality and then all models with a preferred, likes and indifferent causality.

**Likes Causality**

For some models there is a causal form which is liked more than the other. For example the iconic diagram model that describes a parasitic volume can be written as:

\begin{verbatim}
effortincausality(p) then
  p.phi = 0;
else
  volume_ratio = int(p.phi/V);
  p.p = B * volume_ratio + p_initial;
end;
\end{verbatim}

Here \( p.phi \) denotes the volume flow and \( p.p \) denotes the pressure of the powerport \( p \). The equation is written in integral form which is liked. Consequently the preferred output is the pressure. Should the pressure be the input, the equation gives a zero flow as output. During compilation 20-sim will first try to keep all models the liked form. If this is not possible the equations will be rewritten to the other form.

Likes causality has a lower priority than preferred causality. During compilation 20-sim will first assign all models with a fixed causality and then all models with a preferred, likes and indifferent causality.

**Indifferent Causality**

For some models the causal form is not known beforehand. For example the iconic diagram model that describes a damper can be written as:

\begin{verbatim}
parameters
  real d;

equations
  p.F = d*p.v;
\end{verbatim}

Here \( p.F \) denotes the force and \( p.v \) denotes the velocity of the powerport \( p \). There is no preferred input (force or velocity). This can be explicitly stated, by giving the powerport \( p \) an indifferent causality. During compilation 20-sim will determine whether \( p.F \) or \( p.v \) is the input variable and consequently rewrite the equations.
indifferent causality has a lower priority than likes causality. During compilation 20-sim will first assign all models with a fixed causality and then all models with a preferred, likes and indifferent causality.

**Setting Causality**
For some models, the equations are too complex to analyze causality. To help 20-sim, using the right causality, you can set causality for every port in the Interface Editor.

### 9.8.3 Integral Form
Consider the following first order linear model:

![Diagram of first order linear model]

This model can be described by the dynamic equation:

\[ \text{output} = \text{int}(\text{input} - K \times \text{output}) \]

Now look at the following model:

![Diagram of second model]

This model can be described by the dynamic equation:

\[ \text{output} = \frac{(\text{input} - \text{ddt(output)})}{K} \]

Note that we can rewrite this equation as:

\[ \text{ddt(output)} = \text{input} - K \times \text{output} \]

or

\[ \text{output} = \text{int}(\text{input} - K \times \text{output}) \]

This is the same equation as the previous model! Apparently, both models are the same! Both models can therefore be described by the dynamic equations:

\[
\begin{align*}
\text{ddt(output)} &= \text{input} - K \times \text{output} \\
\text{output} &= \text{int}(\text{input} - K \times \text{output})
\end{align*}
\]
We call the first equation the *differential form* (no integrals). The second equation is called the *integral form* (no derivatives). In 20-sim, models can be entered in integral form as well as the differential form.

**Solving Differential Equations**

During compilation, 20-sim will automatically try to rewrite equations into the integral form, since this leads to more efficient simulation. Sometimes an integral form cannot be found. Then algorithms will be applied to solve the differential directly. For example an equation like:

\[
output = ddt(sin(a*time))
\]

will be replaced by the following equation (applying the chain rule and using the known derivative for the sine function):

\[
output = a*cos(a*time)
\]

Sometimes a differential cannot be solved directly. Then only the Backward-Differentiation Methods can be used for simulation.

**Simulation Code**

After compilation simulation code is generated. The equation in integral form:

\[
output = int( input - K*output )
\]

will be written as:

\[
independent\ state = output \\
independent\ rate = input - K*output
\]

and can be handled by all integration methods. The equation in differential form:

\[
ddt(output) = input - K*output
\]

will be written as:

\[
dependent\ rate = input - K*output \\
dependent\ state = output
\]

and can only be handled by the Backward-Differentiation Methods.

**9.8.4 Order of Execution**

Equations within 20-sim may be entered in random form. During compilation, 20-sim will automatically try to rewrite equations into a correct order of execution. I.e. a form where all output variables are written as function of input variables and output variables of previous lines. Consider for example the following equations:
variables
  real u,z;
equations
  z = sin(u);
  u = cos(time);

Here the (input) variable \( z \) is given as a function of \( u \). Consequently \( u \) should be calculated first. This is exactly what 20-sim will try to do while compiling the model into simulation code. I.e. the equations will be executed as:

\[
  u = \cos(\text{time});
  z = \sin(u);
\]

**Code Blocks**

Equations in a **code block** are not reordered. A code block is a set of equations inside a statement. Suppose we have the following equations:

\[
  \text{if condition then}
  \quad \text{code block 1}
  \quad ...
  \quad ...
  \text{else}
  \quad \text{code block 2}
  \quad ...
  \quad ...
  \text{end;}
\]

To prevent incorrect executions of the if-statement, the equations of the code blocks will not be separated. Inside a code-block, equations can are not rewritten into an new order of execution. E.g. the following equations:

\[
  \text{if time > 10 then}
  \quad z = \sin(u);
  \quad a = z^2;
  \quad u = \cos(\text{time});
  \text{end;}
\]

Will be **not be reordered** and therefore not correctly executed! To get correct code, enter code blocks in a correct order, e.g.:

\[
  \text{if time > 10 then}
  \quad u = \cos(\text{time});
  \quad z = \sin(u);
  \quad a = z^2;
  \text{end;}
\]

**Prevent Order Changes**

To make all equations a code block you can use the code section. E.g.
parameters
  real y = 8;
variables
  real x1, x2, x3;
code
  x1 = time;
  x2 = sin(time);
  x3 = y\times x1;

**Integration Steps**

Some integration algorithms do more calculations before generating the next output value. These calculations are called minor steps, the output generation is called a major step. During a minor step, all model equations are executed. In most cases you will not notice this because only the results of the major step are shown in the simulator. There are however, exceptions. The next topic will discuss this in more detail.

**9.8.5 Show Equations**

During processing a complete set of equations is generated of each model. To inspect these equations or copy them for use in other programs, you have to:

1. From the **Model menu** select the **Check Complete Model** command.
2. From the **Model menu** select the **Show Equations** command.

Now a window is popped up showing all the model equations.

![The model equations after compiling.](image)
10 Toolboxes

10.1 Toolboxes

20-sim contains a number of Toolboxes. The following toolboxes can be found in the Editor:

1. Control Toolbox: A set of four tools; Controller Design Editor, MLP Network Editor, B-Spline Network Editor and the Filter Editor.
2. Mechatronics Toolbox: A set of three tools; Cam Wizard, Motion Profile Wizard, Servo Motor Editor.
3. 3D Mechanics Toolbox: With the 3D Mechanics Editor you can create 3D dynamic models of mechanical structures.
4. Frequency Domain Toolbox: This toolbox allows you to look at model properties in the frequency domain: Model Linearization, Linear System Editor.
5. Scenario Manager: With this tool you can automate tasks like testing models.

The following toolboxes can be found in the Simulator:

6. Time Domain Toolbox: The Time Domain Toolbox helps you to automatically run simulations and change parameter values.
7. Frequency Domain Toolbox: This toolbox allows you to look at model properties in the frequency domain: FFT Analysis, Model Linearization, Dynamic Error Budgetting.
8. Real Time Toolbox: The Real Time toolbox of 20-sim allows you to create C-code out of any 20-sim model for the use in real-time applications.
9. Animation Toolbox: Toolbox to show simulation results as animations.

Two toolboxes run externally from 20-sim:

10. Scripting Toolbox: 20-sim scripting allows you to run tasks in 20-sim automatically using scripts running in Python or other scripting tools. With these scripts you can open models, run simulations, change parameters, store results and much more.
11. 20-sim Unity Toolbox: This toolbox couples 20-sim with the Unity game engine. Unity allows you to make 3D animations with high quality rendering and display on screen and VR headsets. The Unity toolbox does not come standard with 20-sim, but has to be purchased separately.
10.2 3D Mechanics Toolbox

10.2.1 Introduction

Introduction

With the 3D Mechanics Editor you can create 3D dynamic models of mechanical structures. The resulting 3D mechanical model can be connected with other 20-sim components. In the example shown below (Getting Started Manual\3D Mechanics Toolbox\ScaraRobotSimulation.emx), you see a robot model that has been generated with the 3D Mechanics Editor. The model has two actuated rotation joints and one actuated translation joint. The rotation joints are directly coupled to gearboxes. The translation joint is coupled via a spindle.

In 20-sim you can use plots to show the simulation results and use the 3D Animation Toolbox to show an animation of the 3D model.

Opening The 3D Mechanics Editor

You can open the 3D Mechanics Editor by:

1. In the 20-sim Editor from the Tools menu select 3D Mechanics Toolbox and 3D Mechanics Editor.

Now a masked model is inserted in the Editor and the 3D Mechanics Editor will be opened.
If you select a 3D Mechanics model and select Go Down, the 3D Mechanics Editor will be automatically opened.

The first time you start 20-sim 3D Mechanics Editor the following screen will appear.

The 3D Mechanics Editor
Migrating from Older Versions

This topic is only important for users who are migrating from older version of 20-sim and want to use previously constructed 3D Mechanics models. Since 20-sim 4.1, the 3D Mechanics Editor operates on masked models. I.e. you can open the 3D Mechanics Editor by selecting a 3D Mechanics model and clicking the Go Down command. If you import a 20-sim 4.0 model, you will notice that this option does not work. We will explain the actions you have to perform to do make this trick work on older models.

1. Open the 20-sim model that contains a submodel that was generated by the 3D Mechanics Editor (make sure you have stored an backup copy).

The star shaped model was created using the 3D Mechanics Editor of 20-sim 4.0.

2. Select the model that was generated by the 3D Mechanics Editor and select Go Down.
3. At the top of the model enter the following code:

```
// 20-sim 3D Mechanics Editor
// C:\Program Files\20-sim 5.1\Models\Examples\3D Mechanics\hexapod.3dm
```

The first line tells 20-sim which editor should be opened. The second line shows the location of the corresponding 3D Mechanics configuration file. Enter the path and name of your own file here.
The next time you select the model and select Go Down the 3D Mechanics Editor will be opened with the proper 3D Mechanics model.

**Edit Window**

In the center of the 3D Mechanics Editor the *Edit window* is visible. At the start a reference frame and a base plane is shown. In the Edit window, you can insert components and assemble your model.

*In the Edit Window you can assemble your model.*
Model Tab

One of the two tabs at the left of the 3D Mechanics Editor is the **Model tab**. The Model tab contains a tree of all the components of in your current model. This tree can be used to select components and edit their properties.
Library Tab

One of the two tabs at the left of the 3D Mechanics Editor is the **Library tab**. The Library tab contains predefined components, which you can use to construct your model with. The components in the library tree can be dragged into the Edit window.

![Library Tree]

**Selection Properties**

Below the Bodies/Library tabs the *properties* of the selected component are shown. When no components are selected the selection properties are empty.

![Selection Properties]

When a component is selected, the edit button will be enabled. You can click the button to change the component properties.
3D Representation

Below the Selection Properties, the 3D representation of the selected component is shown. When no components, the 3D Representation is empty.

When a component is selected, the edit button will be enabled. You can click the button to change the 3D Representation of the component.

A component may be composed of several representations. Using the Add Representation and Delete Representation commands of the Actions menu you can add more representations or remove representations.

Output

In the Output part of the 3D Mechanics Editor, messages will be shown during analysis of the model.
10. Toolboxes

**Edit Modes**

At the right of the 3D Mechanics Editor you will find the **Edit Mode** buttons. You can select them to enter several edit modes.

- **Translation Mode**
  In this mode you can translate components.

- **Connection Mode**
  In this mode you can make connections between components.

- **Rotation Mode**
  In this mode you can rotate components.

- **Camera Mode**
  In this mode you can change the camera position and orientation. I.e. the way you look at your model.

**Ghost Modes**

At the right of the 3D Mechanics Editor you will find the **Ghost Mode** buttons. You can use these buttons to make components transparent. This is useful when components are hidden inside other components.

- **Ghost Mode for Bodies**
  Make every body transparent.

- **Ghost Mode for Joints**
  Make every joint transparent.

- **Ghost Mode for Sensors/Actuators**
  Make every sensor/actuator transparent.

**View Modes**

In the button bar of the 3D Mechanics Editor you will find the **View Mode** buttons. You can select them to select different views.

- **3D View**
  Default view.

- **X-Y plane**
  View perpendicular to the x-y plane. You can only move objects along the x-y plane.

- **X-Z plane**
  View perpendicular to the x-z plane. You can only move objects along the x-z plane.

- **Y-Z plane**
  View perpendicular to the y-z plane. You can only move objects along the y-z plane.

- **All**
  A combination of the all the views.
Model Settings

The model Settings command of the Tools menu will open the Model Settings dialog. In this dialog you can change some general settings such as the size of the reference frames or the amount of gravity.

The Model Setting Dialog.

**Items**

- **Gravity**: You can set the gravitational acceleration to any desired value.
  - **Hard Coded**: choose this option if you want to optimize for speed.
  - **As Parameter**: Use a gravity parameter, allowing you to change the value before the start of a simulation run.
  - **As Input Signal**: get the gravity value from an input signal, allowing you to change the value during simulation.
- **Spring Dampers for Constraint Joints**: Choose this option if you want to use spring dampers for closed kinematic chains. You can override the spring damper values for individual joints if required.
  - **Rotation Spring**: Set the desired stiffness for the rotational spring.
  - **Rotation Damper**: Set the desired rotational damping.
  - **Rotation Spring**: Set the desired stiffness for the translation spring.
  - **Translation Damper**: Set the desired translation damping.
10. Toolboxes

- Reference Frames: Choose the size and thickness of the reference frames.
- Grid: Set the grid.
- Angle Representation: 20-sim uses SI-units for the model equations (e.g. radians). You can choose to show them in non-SI-units like degrees or grads.
- Power Port Type: Choose Iconic Diagram power ports or bond Graph power ports.
- Constraint Solver: set the accuracy of the constraint solver.

**Camera Settings**

At the start of a model session, in the Edit window, a default camera is used. You can change camera settings by clicking **Camera Settings** from the **Tools** menu.

In the Camera Settings dialog you can change the range (front and back plane) and zooming of the camera, use a perspective view or orthographic, select the camera position and the point to look at.
Spring Dampers and Constraints

In the 3D Mechanics Editor you can connect bodies with joints. If no path from any body through a joint to another body and so on never returns to the starting body, we have an open chain mechanism. Open chain mechanisms are easy to simulate with all known integration methods.

Open Chain Mechanism.

If a path from any body through a joint to another body and so on returns to the starting body we have a closed chain mechanism. Closed chain mechanisms are generally more difficult to simulate.

Constraint Joint

Closed Chain Mechanism.

20-sim uses a special feature to simulate closed chain mechanisms. At an arbitrary place a joint is removed to create an open chain mechanism. Then the open chain is closed again using a spring damper joint or a constraint joint. You can choose which joint to use in the Model Settings Dialog.
Spring Damper Joint
A spring damper joint is a joint where all rigid connections are replaced by spring dampers. If weak spring dampers are used a certain amount of (unwanted) displacement will be possible. By increasing the stiffness and damping, the displacement can be decreased. You can set the spring stiffness and damping in the Model Settings Dialog. You can override these spring damper values in the Joint Constraint Settings Dialog.

Constraint Joint
The constraint joint works exactly like the original joint but uses constraint forces to do the job. Constraint forces can only be simulated with special integration methods. In 20-sim the Modified Backward Differentiation Method is able to calculate constraint forces.

The concept of constraint forces is quite easy to understand if we look at the open chain mechanism below. At the tips of the mechanism a force is applied. If we apply a force that keeps the tips at the same position at each time step, it will effectively work as a rotation joint. That is exactly what constraint forces do. At every simulation step, an iterative procedure is run to find exactly that force that keeps the position offset at zero.

This iterative procedure is not standard for most integration methods. In 20-sim only the Modified Backward Differentiation Method supports it. In the 3D Mechanics Editor you do not have to worry about closed chain mechanisms. If necessary, standard joints are replaced automatically by constraint joints. You only have to realize that simulation of a mechanism with constraint joints in 20-sim should be performed using the Modified Backward Differentiation Method.
Flexibility

Flexibility in a 3D mechanics structure can be modeled using constraint joints. All you have to do is:

1. Insert a joint into the editor.
2. Click **Edit Joint** to open the Joint Properties.
3. Click on the **More** button to show the advanced properties.
4. Select the **As Constraint Joint** option.
5. Now you will see the **Constraint Settings** button. Click this button.

The **Joint Constraint Settings** dialog will open.

4. In this dialog you can **Override the General Spring Damper Values**,
5. and select the desired stiffness and damping for the joint.
If you do not choose *Override the General Spring Damper Values*, the global settings for constraint joints are used which can be specified in the Model Settings dialog.

Only the degrees of freedom which are fixed by the joint, can be set by spring damper values. In the dialog above the spring damper values of an X-rotation joint are shown. The rotation around the x-axis can not be restricted by a spring damper. If you want to insert flexibility in all directions and rotations, use a weld joint to override the general spring damper values.

You can choose the option *Generate Global Parameters* to make the spring damper values available as global parameters.

### 10.2.2 Working Order

**3D Mechanics Editor**

From the Library tab you can drag and drop components to the Edit window. If you put the editor in translation mode you can select the components and use the mouse to put them in the correct position.
A standard model will at least consist of some bodies and joints. The bodies have to be connected with the joints to define the degrees of freedom of the model. The connecting of joints and bodies can be done in the connection mode. By clicking on a body and then on a joint a connection is defined.

If all connections are defined, you can test the possible motions of your model. Return to the translation mode and click on a body. You will see arrows that indicate the possible motion of the connected joint. By dragging the mouse you can make the body move.
When the model is ready you can check it. When no errors are found you can update it to 20-sim.

**Generating a 20-sim Model**

**Checking**
When your 3D dynamic model has been created and assembled, you can check for errors by selecting the *Check Model* command from the *Actions* menu. If everything is OK the Output will show the message "Analysis Completed Successfully".

**Generating 20-sim Model**
After the model has been checked, you can export it as a 20-sim submodel by selecting the *Generate 20-sim Model* command from the Actions menu.
10. Toolboxes

20-sim Model
As you may know from the Joint Properties dialog, all joints have an initial value. During analysis of your model, some joints may have been twisted. You can use the current (twisted) configuration to generate a 20-sim model for, or reset it to its initial values first.

Additional Outputs
For advanced users, some additional outputs may be useful. First time users are advised not to select these outputs.

Output Filename
Use the Browse button to select a folder and a filename for the generated 20-sim model.

20-sim Scenery
In 20-sim you can use the 3D Animation Toolbox to show an animation of the mechanical structure. You can export the structure to a scenery file, which can be loaded in the 3D Animation Toolbox.

- Don't Generate Joint Representations: Each joint is represented in the 3D Animation as autonomous component with variables to denote the potion and orientation. For large models you can save memory space by not exporting the joints.
- Submodel Name to be used in 20-sim: The 3D Animation will use 20-sim submodel names to identify the movements of object. You have to enter the submodel name, that you will use for the 3D dynamic model in 20-sim.
10. Toolboxes

- Scenery Filename: Use the Browse button to select a folder and a filename for the generated scenery file.

10.2.3 Library

Library

The Library Tab shows all components that can be used to create your 3D Dynamic model.
- Bodies
- Joints
- Sensors
- Actuators

Bodies

Position

When you drag and drop a body into the Edit window, its position (i.e. the position of its reference frame) will be defined with respect to the base reference frame. You can change the position with the mouse pointer. From the View menu click Mode and Translation or click the button to go to translation mode. If you put the mouse pointer on top of the body, you can change its position by pressing the left mouse button. If you pressing the Ctrl-button at the same time, the body will move up and down.

You can also set the position manually by double clicking the body. This will open the Body Properties dialog.
Using this dialog you can:
- change the name of the body
- set the inertia parameters
- change the position
- change the orientation
- make it a fixed body
- set more options

**Fixed Body**

The purpose of building a 3D model in most cases is to construct some kind of mechanism using bodies and joints. The joints make the bodies move in a particular way, which can be inspected in the 3D Editor. Every body in 3D mechanics editor is floating by default, unless specifically set to be attached to the fixed world, or connected to another body by means of a joint. Any body can be set to be a fixed body by checking the **Is Fixed World** option in the **Body Properties dialog**. Changing the position of a fixed body in a mechanism will change the base position of the mechanism. Dragging the other bodies will only make the mechanism move, but not change the base position. If you want to model a floating mechanism (e.g. a satellite in space), all bodies should remain floating.

**Orientation**

To set the orientation of a body, the same procedure can be followed as for the position of a body. If you set the Editor in Rotation mode ( ), you can change the orientation of the body with the mouse pointer. You can also use the Body Properties dialog to set the orientation precisely by clicking the orientation button.
The orientation of a body is specified by the orientation of its reference frame. You can define this orientation using various representations.

- **Direction Up Vector**: Using the Direction Up vector method you have to specify the Y-axis (Direction) and Z-axis (Up) of the body reference frame.

- **Bryant angles**: Using Bryant angles we start with the initial body reference frame. First we rotate around the X-axis of the body reference frame, then we rotate around the Y-axis of the body reference frame and finally around the Z-axis of the body reference frame. Bryant angles are also known as X-Y-Z relative Euler angles or Cardan angles.

- **X-Y-X Euler**: Using X-Y-X Euler angles we start with the initial body reference frame. First we rotate around the X-axis of the body reference frame, then we rotate around the Y-axis of the body reference frame and finally around the X-axis of the body reference frame.

- **Euler Parameters**: Using Euler parameters we start with the initial body reference frame and rotate this frame around a vector K [X,Y,Z] about an angle theta.

- **Rotation Matrix**: Using a 3x3 rotation matrix, you can enter 9 elements that will transform the initial orientation of the body reference frame to the new orientation.

**Inertia Properties**

Each body has a mass and rotational inertia. The mass indicates the resistance of the body to a change in position. Given a fixed force, a body with a large mass will accelerate more slowly. This property is the same for all directions. Therefore the mass can be indicated by a single parameter.

The rotational inertia indicates the resistance of a body to a rotation. Given a fixed torque, a body with a large rotational inertia will start to rotate more slowly. The rotational inertia is not the same for all orientations. Generally, for any body three axes can be identified that indicate a stable rotation. The rotational inertia for these three principal axes of rotation is sufficient to describe the motion of a body. The connection of these three principal axes of rotation is generally known as the center of mass.
Any body, indifferent of its shape, which has the same mass, the same principal axes of rotation and the same rotational inertia, will show the same dynamic behavior. That is why you can change the representation of a body to any size, it will not change its dynamic properties.

If you open the **Body Properties Dialog** you can click the **Edit** button to change the inertia properties. You can set mass and the rotational inertias for each of the principle inertia axis. By selecting the option **As Global Parameter** you can make the inertia parameters available as global parameters. You can enter the mass and the rotational inertias as values directly or use an Expression to calculate their values.
The center of mass does not necessarily have to coincide with the body reference frame and the orientation of the principal inertia axes do not have to coincide with the orientation of the body reference frame.

You can enter the offset position of the center of mass and the orientation of the principal inertia axes, by clicking the offset button.

**More Options**

If you click the More button in the Body Properties dialog, options are shown which form a shortcut for the normal way of building models. They are meant for experienced users.

First a list of connection points are shown and some buttons to edit these points. Connection points are used to indicate at which point a joint or other element is connected with the body. Connection Points are explained in more detail in the next section.

At the bottom two options are shown. If you choose the Generate Power Interaction Port option, a power port will be added to the body, which allows you to insert forces and torques onto the body, from other 20-sim submodels.

The Output Absolute H-matrix option, will create an 4x4 output signal that gives the position and orientation of the body, using an H-matrix. This signal can be connected to other 20-sim submodels.

**Joints**

**Properties**

In order to make two bodies move with respect to each other, we have to connect them by joints. Joints do not have any mass or rotational inertia. They only constrain the motion of bodies. The position of a joint is indicated by its reference frame. Because the joint position and orientation is completely determined by the bodies that are connected, you do not have to specify any position or orientation parameters. These are automatically derived when you make connections.

**Connections**

Making connections is not difficult when you understand how frames work. We will explain this with a simple example. Suppose we have two bodies and a rotational joint. The initial positions of the bodies and joints are indicated by their reference frames.
Now we have to define for each of the two bodies the offset to the joint. This can be done using connection points. A connection point is in fact a new frame with an offset from the body reference frame. As you can see, in the picture below, we have defined ConnectionPoint1 with an offset of \([x = 1, y = 1, z = -1]\) with respect to the Body1 and we have defined ConnectionPoint2 with an offset of \([x = 1, y = -1, z = -0.3]\) with respect to Body2.

Now the bodies and the joint can be assembled by changing the body positions in such a way that the frames of the connection points coincide with the reference frame of the joint exactly.

Suppose that Body1 is set as the reference body. Now the whole assembly will be moved until Body1 has its original position.
Creating Connections

In the 3D Mechanics Editor most of the assembly of joints and bodies is automated. You simply have to make connections between joints and bodies. To make a connection you have to drag and drop bodies and a joint to the Edit window. Then change to Connection mode ( ). First click a body and then the joint it should be connected to.

The Create Connection dialog will pop to ask you for the location of the connection point. In the connection dialog you can set the offset (both the position as well as rotation) from the body reference frame to the connection point.
In the dialog you can also change the name of the connection. After the dialog is closed the body will automatically assemble with the joint. When two bodies are assembled with a joint, you can view their constrained motions.

**Joint Properties**

When you want to change the Connection Points after the connection has been made, you have to double clicking the joint. This will open the *Joint Properties Dialog*.

You can change the name, position, orientation, and the rotation axis of the connection points. You can also change the joint type and the initial rotation or translation of the joint. The initial rotation or translation can also be entered using an expression. If you lock the joints, it will not move when you want to show the possible motions of the system.

**Advanced Properties**

At the bottom of the Joint Properties you can click the *More* button to see the advanced properties.
10. Toolboxes

- As Constraint Joint: Calculate the joint using constraints. You can use constraint joints to introduce flexibility into your 3D structure.
- Power Interaction Port: add a power port to the joint to make it an actuated joint.
- Output Position: Create an output signal that gives the joint position.
- Output Velocity: Create an output signal that gives the joint velocity.
- Output Constraint Forces: Create an output signal that gives the forces and torques that act on the joint.

**Constraint Settings**

If you click the More button to see the Advanced Joint Properties, you can click the As Constraint Joint selection box. This box allows you to manually choose to make this joint a constraint joint. A button will be visible showing the Constraint Settings. If you click this button a dialog is shown allowing your to override the constraint by a spring damper. In this way you can set each individual joint by its own spring damper constants.
Spring Damper

If you click the More button to see the Advanced Joint Properties, you can click the Spring Damper button. This will allow you to add damping to a joint or a spring and define end-stops.

- **Has Spring**: choose this option to define a spring parallel to the joint.
- **Has Damping**: select this option to define the damping (linear with the velocity).
- **Has Minimum**: set an endstop at the minimum joint rotation/extension.
- **Has Minimum**: set an endstop at the maximum joint rotation/extension.

### Joint Types

Several types of joints are available in the library:
Rotation Joints (Non-Actuated)

**joint** | **description**
---|---
XYZ-Rotation | Joints which rotate around the principal axes.
Hinge XYZ-Rotation | Same as XYZ-Rotation but with a different representation.
Balljoint connection XYZ- | Balljoints with orientations of the principal axes.

Rotation Joints (Actuated)

**joint** | **description**
---|---
XYZ-Rotation | Joints which rotate around the principal axes.
Hinge XYZ-Rotation | Same as XYZ-Rotation but with a different representation.

Translation Joints (Non-Actuated)

**joint** | **description**
---|---
XYZ-Rotation | Joints which rotate around the principal axes.
Hinge XYZ-Rotation | Same as XYZ-Rotation but with a different representation.
Balljoint connection XYZ- | Balljoints with orientations of the principal axes.

Translation Joints (Actuated)

**joint** | **description**
---|---
XYZ-Translation | Joints which rotate around the principal axes.

Other Joints

**joint** | **description**
---|---
Weld joint | A joint that welds two bodies together.
Free Moving Joint | Opposite of the weld joint. In practice this joint will only be used to give a body a fixed starting position with respect to another body.
Direction (using order of Connection Points)
If you have a rotation or translation joint, the order in which the bodies were connected to the joint will determine the direction of positive rotation or translation. You can reverse this order by swapping the connection points.

Rotation / Translation Axis
If you have a rotation or translation joint, the rotation or translation axis can be changed.

Sensors
Sensors are components that indicate the position or velocity of bodies as output signals.

Connecting Sensors
Sensors have to be connected with bodies, just like joints.

The position of the sensor is indicated by its connection point. The connection point is shown automatically when you make a connection between a body and a sensor. First change to Connection mode ( ), then click the body and then click the sensor.
The *Create Connection* dialog will pop to ask you for the location of the connection point. In the connection dialog you can set the offset (both the position as well as rotation) from the body reference frame to the connection point.
Sensor Types
Various sensor types are available in the library.

Position/Orientation

<table>
<thead>
<tr>
<th>sensor</th>
<th>output signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position-X</td>
<td>A signal with the x-position of the body.</td>
</tr>
<tr>
<td>Position-Y</td>
<td>A signal with the y-position of the body.</td>
</tr>
<tr>
<td>Position-Z</td>
<td>A signal with the z-position of the body.</td>
</tr>
<tr>
<td>Position (3x1)</td>
<td>A signal (size 3) with the x-, y- and z-position of the body.</td>
</tr>
<tr>
<td>H-matrix (4x4)</td>
<td>A 4x4 signal with the H-matrix.</td>
</tr>
<tr>
<td>Rotation (3x3)</td>
<td>A 3x3 signal with the rotation-matrix.</td>
</tr>
</tbody>
</table>

Velocity

<table>
<thead>
<tr>
<th>sensor</th>
<th>output signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity-X</td>
<td>A signal with the x-velocity of the body.</td>
</tr>
</tbody>
</table>
Velocity-Y A signal with the y-velocity of the body.
Velocity-Z A signal with the z-velocity of the body.
Velocity (3x1) A signal (size 3) with the x-, y- and z-velocity of the body.
Omega-X A signal with the rotational velocity in x-direction of the body.
Omega-Y A signal with the rotational velocity in y-direction of the body.
Omega-Z A signal with the rotational velocity in z-direction of the body.
Omega (3x1) A signal (size 3) with all three rotational velocities.

### Acceleration

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Output Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration-X</td>
<td>A signal with the x-acceleration of the body.</td>
</tr>
<tr>
<td>Acceleration-Y</td>
<td>A signal with the y-acceleration of the body.</td>
</tr>
<tr>
<td>Acceleration-Z</td>
<td>A signal with the z-acceleration of the body.</td>
</tr>
<tr>
<td>Acceleration (3x1)</td>
<td>A signal (size 3) with the x-, y- and z-acceleration of the body.</td>
</tr>
<tr>
<td>Rotational</td>
<td>A signal with the rotational acceleration in x-direction of the body.</td>
</tr>
<tr>
<td>Rotational-X</td>
<td>A signal with the rotational acceleration in y-direction of the body.</td>
</tr>
<tr>
<td>Rotational-Y</td>
<td>A signal with the rotational acceleration in z-direction of the body.</td>
</tr>
<tr>
<td>Rotational-Z</td>
<td>A signal (size 3) with all three rotational accelerations.</td>
</tr>
</tbody>
</table>

### Jacobian Matrix

This yields the Jacobian Matrix of the connected mass.

### Actuators

Actuators are components that impose a force or torque on bodies, where the force or torque is given by a power port or input signal.

### Connecting Sensors

Actuators have to be connected with bodies, just like joints.
The position of the sensor is indicated by its connection point. The connection point is shown automatically when you make a connection between a body and a sensor. First change to **Connection mode** ( ), then click the body and then click the sensor.

The **Create Connection dialog** will pop to ask you for the location of the connection point. In the connection dialog you can set the offset (both the position as well as rotation) from the body reference frame to the connection point.
Local or Global Coordinates
For each actuator, you can change its settings, by double clicking it. This will open the Actuator Properties dialog.
10.2.4 Parametric Models

Parametric Modeling

What is Parametric Modeling?
In the 3D Mechanics Editor you can enter the mass, inertia and geometry using hard coded numbers. E.g:

Mass: 8 kg

Now you can run a simulation and see the result. But suppose you are not happy with the results and want to see the effect of a 6 kg mass? Then you have to return to the 3D Mechanics Editor, enter the number 6, process the model and run a simulation. This takes a lot of time. It would be nice if the mass was just a parameter that you change during simulation. This is called parametric modeling.

Expressions
In the 3D Mechanics Editor can enter the mass as an Expression. E.g:

\[ \text{Mass} = \text{Car_weight} \]

where \text{Car_weight} is a parameter which you can give a certain value. Now before the simulation, you can simply change the the value of the parameter \text{Car_weight} and inspect the results. With expressions, you can do more. E.g.:

\[ \text{Mass} = \text{Car_length} \times \text{Car_length} \times \text{Car_width} \times \rho_{\text{steel}} / 100 \]

Now we have coupled the mass to a expression which contains other parameters. Now we can run a simulation and simply change the dimensions of the car and see the results.

How to Do Parametric Modeling?
Everwhere in the 3D Mechanics Editor, where you have to enter numbers, there is an option to enter an expression. For example if you want to enter the mass of a body, you have to open the Inertia Properties. You can enter the mass as a value directly but also choose to use an Expression to define its value.
If you click the Expression button, the Expression Editor opens, allowing you to enter the expression.
Expressions Editor

The Expressions Editor enables you to enter values in the 3D Mechanics Editor which are calculated from expression rather than a hard value.

Expressions Editor

You can type the expressions in the right upper part of the editor. Expressions are similar to the left hand side of an equation in the Equations Editor. Check the proper use of expressions by clicking the Evaluate button. The output or an error message will then be displayed in the Results section at the right lower part.

You can use parameters in the expressions typing by double-clicking in the parameters list at the top left of the editor. Click on the + sign to add new parameters. You can make a parameter global, by selecting the global selection.

Expressions

The standard arithmetic functions and operators can be used in expressions:
10.3 Animation Toolbox

10.3.1 3D Animation

3D Animation Window

The tree at the left of the Simulator, shows the various Windows that are open. If you put your mouse on top of Window1, click the right mouse button and Add Plot - 3D Animation. This will add a 3D animation plot.

![The 3D Animation window.](image)

Editing

- To start editing, put your mouse on top of the 3D Animation plot. From the right mouse menu choose Plot Properties.
- This will open 3D Properties window where you build your animation.
Running

- You can run an animation by clicking the green run button 🎬. You can also select the Run command from the Replay menu.
- At the top right of the window you see the Speed box 📊 where you can set the replay speed. The default speed is to replay an animation at real time but you can set it to play an animation faster or slower.
- If you have multiple camera’s in your animation, you can switch camera, by clicking the camera button 📸.

Ray Trace

- Ray Tracing will add shadows and mirror images to a 3D Animation. In the 3D Properties window, from the File menu, select RayTrace to apply Ray Tracing to the current window.

Creating Movies

- In the 3D Properties window, from the File menu select Create Movie to create movies from your animation.

Full Screen

- Right click your mouse when pointing on a 3D Animation. Select Full Screen to see the animation in full screen. Click the Escape button to remove the full screen view.
3D Properties

The 3D Properties window allows you to define the various objects that should be shown in a 3D Animation. The 3D Properties window can be opened, by double clicking the mouse pointer in the Animation window or using the Plot Properties menu.

Menu

The menu of the 3D Animation Properties consists of three parts.

- The File menu allows you to store and load scenes (parts of the object tree) and create movies.
- The Edit menu allows you to create and edit objects.
- The Properties menu allows you to set the General Properties.

Lights, Cameras and Objects

Two lights and five cameras are standard available when you start a new animation. You can delete or change these lights and cameras or add new additional lights and cameras. Inserting new objects can be done with the Edit menu by selecting the Insert Object command.

Object Tree

The left side of the 3D Animation Properties window shows tree-like listing of the objects that are inserted. All objects are defined with respect to a reference frame. This can be done hierarchically by inserting new reference frames.
10. Toolboxes

Object Attributes

On the right side of the 3D Animation Properties window shows the attributes of a selected object (e.g. position, orientation, scaling etc.). Objects can be selected, by clicking the mouse pointer on top of the object in the objects tree.

Show Frame

Each object has an object attached reference frame. This frame can be shown by selecting the object and clicking the *Show Frame* option. This is useful for manipulating objects. If you press the *Control* button while selecting the *Show Frame* option, all frames in the current branch are shown. Do the same for the top reference frame to quickly show or hide all reference frames.

Solo

Click the *Solo* option, to hide all other objects. This is useful for manipulating a single object. If you press the *Control* button while selecting the *Solo* option, all objects in the current branch are shown. Do the same for the top reference frame to quickly show or hide all objects.

Hidden

Click the *Hidden* option, to hide a single object. This is useful for manipulating a the other objects. If you press the *Control* button while selecting the *Hidden* option, all objects in the current branch are hidden. Do the same for the top reference frame to quickly hide or show all objects.
**Next Camera**
Click the Next Camera button to see the next camera view.

**Manipulate**
Click the Manipulate button to move an object with use of your mouse.

**Selecting Objects**
An object can be selected by pointing with the mouse in the object tree.

![Select an object in the 3D Animation Properties window.](image)

This selection is also shown in the 3D Animation window as a *pink box* around the object.
It is also possible to select an object with the mouse by clicking in the 3D Animation window. The selection will automatically jump to the object in the tree of the 3D Animation Properties window.
Moving Objects

To move an object, you have select it.

Attributes
The right side of the 3D Animation Properties window shows the attributes of a selected object (e.g. position, orientation, scaling etc.). You can change the position or orientation to move an object.

Manipulate
You can move an object directly by pushing the Manipulate button.
Manipulate an object directly.

A set of locks will be shown below the Manipulate button. You can use them to lock one or more directions and orientations. After this you must put the 3D Animation window on front (click on it with the mouse) and select one of the following keys:

<table>
<thead>
<tr>
<th>Keys</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>right arrow</td>
<td>move right (positive x-direction)</td>
</tr>
<tr>
<td>left arrow</td>
<td>move left (negative x-direction)</td>
</tr>
<tr>
<td>up arrow</td>
<td>move up (positive z-direction)</td>
</tr>
<tr>
<td>down arrow</td>
<td>move down (negative z-direction)</td>
</tr>
<tr>
<td>Ctrl + up arrow</td>
<td>move forward (positive y-direction)</td>
</tr>
<tr>
<td>Ctrl + down arrow</td>
<td>move backward (negative y-direction)</td>
</tr>
<tr>
<td>Alt + right arrow</td>
<td>yaw right (positive z-axis rotation)</td>
</tr>
<tr>
<td>Alt + left arrow</td>
<td>yaw left (negative z-axis rotation)</td>
</tr>
<tr>
<td>Alt + up arrow</td>
<td>roll forward (negative x-axis rotation)</td>
</tr>
<tr>
<td>Alt + down arrow</td>
<td>roll back (positive x-axis rotation)</td>
</tr>
<tr>
<td>Ctrl+ Alt + right arrow</td>
<td>pitch right (positive y-axis rotation)</td>
</tr>
<tr>
<td>Ctrl + Alt + left arrow</td>
<td>pitch left (negative y-axis rotation)</td>
</tr>
</tbody>
</table>
Scenes

In the 3D Animation Properties you can load and store scenes. Scenes are simply part of an object tree or a complete object tree. This option can be used to obtain scenes from other experiments or to create pre-defined environments.

Save Scene
The Save Scene command of the File menu, allows you to save a scene on file. Only the selected object and all object below will be saved.

Load Scene
The Load Scene command of the File menu, allows you to open a scene from file and insert it under the selected object of the object tree.

Movies

With a few mouse clicks you can create movies from an animation. Right click on the 3D animation window and select Create Movie.

Target List
You can create movies for various purposes:
- **YouTube**: Movies in mpg-format for placement on YouTube.
• **Avi**: Movies in avi format for use in movie editing software.
• **Windows Media Video**: Movies for the use in Microsoft programs (e.g. Powerpoint).
• **Flash**: Movies in flv format for the use on Internet sites.
• **Only Frames**: For the use in advanced movie editing programs that can handle collections of pictures

**Profiles**
You can create movies with three profiles (low, medium, high). The corresponding sizes are shown in the table below.

<table>
<thead>
<tr>
<th></th>
<th>low</th>
<th>medium</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>YouTube</strong></td>
<td>640 * 480</td>
<td>-</td>
<td>1280*720</td>
</tr>
<tr>
<td><strong>Avi</strong></td>
<td>640 * 480</td>
<td>1024*768</td>
<td>1920*1080</td>
</tr>
<tr>
<td><strong>Windows Media Video</strong></td>
<td>640 * 480</td>
<td>1024*768</td>
<td>1920*1080</td>
</tr>
<tr>
<td><strong>Flash</strong></td>
<td>640 * 360</td>
<td>1024*576</td>
<td>-</td>
</tr>
<tr>
<td><strong>Only Frames</strong></td>
<td>640 * 480</td>
<td>1024*768</td>
<td>1920*1080</td>
</tr>
</tbody>
</table>

Ray tracing will add shadows and mirror images to a 3D Animation. However ray tracing cost a lot of processing power. If you select the option Ray Tracing, the quality of your movie will be improved, but the time to create it will increase tremendously.

**More**
Choose the *More* button if the standard profiles are not up to your demands. You can set the size of a movie, the frame rate and speed up or slow down the speed.

**Create Movie**
Click the *Create Movie* button to create a movie. The movie will be stored in the output directory that you have specified using the filename that you have given.
10. Toolboxes

General Properties

Using the *General Properties* command of the 3D Properties window helps you to select several options.

- **Background Color**: Change the background color to any desired color you like.
- **Background Image**: Use a bitmap image for the background.
- **Wireframe**: You can choose to show the animation as Wireframe.
- **Fogging**: Fog in any desired color can be added to the animation. The fog is minimal at a start plane and maximal at an end plane. You can set the distance of these planes.
- **Render Type**: Choose wireframe rendering or full rendering.
- **Grid**: You can choose to show a grid.
- **Frames**: Set the frame scaling and thickness.
- **General**: Show the number of frames per second and maximize the number of frames per second.
Objects

Reference Frames

All objects in a 3D Animation are be defined with respect to the top reference frame. The top reference frame is the reference frame on top of the objects tree. If you have multiple objects that move relative to the top reference frame but have a fixed position and orientation to with respect to each other, it is useful to introduce an additional reference frame. Define all the objects with fixed position and orientation with respect to an additional reference frame and give this frame a movement with respect to the top reference frame.

Relative reference frames.

In the objects tree frame hierarchy is shown by indentation. In the example above, the Earth Reference Frame describes the earth motion with respect to the Sun Reference frame. The Moon Reference Frame describes the moon motion with respect to the Earth Reference Frame.

Each Reference Frame has a specific position, orientation and scaling. The scaling is defined with respect to the frame one level higher in the hierarchy. In the example above, the sphere and circle describing the Earth and the Launch Site can directly be copied to form the Moon and the Lunar Landing Site. Only the scaling of the Moon Reference Frame has to be set to correct values.

Properties (Specific)

- Override Group Color: You can choose to give all objects that are defined in a frame the same color.

Properties (General)

- position
- orientation
- scaling
- duplication
10. Toolboxes

**Line**

**Properties (Specific)**
You can set the start position and end position of the line, enter the line thickness and set the number of circle elements.

**Properties (General)**
- color
- mesh
- texture
- material
- duplication
Cube

Properties (Specific)
You can set the position of the origin and the rib length and choose to show the inside.

Properties (General)
- position
- orientation
- scaling
- color
- mesh
- texture
- material
- duplication
**Sphere**

You can choose to show the inside and outside. The number of segments that are used to draw the circle is fixed.

**Properties (Specific)**

**Properties (General)**

- position
- orientation
- scaling
- color
- mesh
- texture
- material
- duplication
Cylinder

Properties (Specific)
You can set the position of the origin, choose to show the inside and outside, set the number of circle elements. A cylinder can be shown with open or closed sides.

Properties (General)
- position
- orientation
- scaling
- color
- mesh
- texture
- material
- duplication
10. Toolboxes

Cone

Properties (Specific)
You can set the number of circle elements and choose to show the cone with an open or closed side.

Properties (General)
- position
- orientation
- scaling
- color
- mesh
- texture
- material
- duplication

Torus

Properties (Specific)
A Torus has some specific options:
10. Toolboxes

- The **Torus Radius** denotes the length from the origin to the center of the tube.
- The **Tube Radius** denotes the tub thickness.
- With the **Number of Segments** you can set the total number of segments for one revolution.
- The **Points Per Segment** are the number of circle elements for each segment.

**Properties (General)**

- position
- orientation
- scaling
- color
- mesh
- texture
- material
- duplication

**Spiral**

**Properties (Specific)**

- The **Height** is the length of the spiral.
- The **Spiral Radius** is the length from origin to the center of the tube.
- The **Tube Radius** denotes the tub thickness.
- The **Number of Turns** is the number of revolutions from bottom to top of the spiral. This may be a non-integer value.
- The **Number of Segments** is the total number of segments from bottom to the top of the spiral.
- The **Points Per Segment** are the number of circle elements for each segment.
• You can set the position of the origin.

**Properties (General)**

- position
- orientation
- scaling
- color
- mesh
- texture
- material
- duplication

**3D-files**

You can import object from files, using the 3D-files object. As soon as you insert a 3D-files object, 20-sim will open a file browser. Three formats are supported:

- **STL-files (*.stl)**: The STL file format or stereolithography format is another widely accepted interchange format between CAD packages.
- **DXF-files (*.dxf)**: This is AutoCAD's drawing interchange format. The DXF file format was originally designed by AutoDesk® to represent 3D models built with AutoCAD®. Now they are generally accepted as an interchange format between CAD packages.
- **Lightwave Object files (*.lwo)**: LightWave is a software package used for rendering 3D images, both animated and static.

**Properties (Specific)**

- Use the Browse button to load another file.
- Set the **Override Color** check box to give the object any desired color.
- You can set the position of the **origin**.

**Properties (General)**

- position
- orientation
- scaling
- color
- mesh
- texture
- material
- duplication
Square

Properties (Specific)
- You can set the position of the *origin*.

Properties (General)
- position
- orientation
- scaling
- color
- mesh
- texture
- material
- duplication
Circle

Properties (Specific)
- You can set the number of circle elements.

Properties (General)
- position
- orientation
- scaling
- color
- mesh
- texture
- material
- duplication

Camera
All objects in a 3D Animation are defined with respect to the Default Lights and Cameras frame. This frame coincides with the top Reference Frame. When you start up a 3D animation 5 default cameras are available showing several views of the origin of this frame.

Two cameras show the Default Lights and Cameras frame from a position of $x = 5$, $y = 5$ and $z = 10$. The cameras are pointed to the center of origin of the frame. The Camera Looking At Origin will keep looking at the origin, even if its position is changed. The Perspective Camera will not keep looking at the origin but keep its original orientation when its position is changed.
Three *Front* cameras are positioned on top of each of the axes of the *Default Lights and Cameras* frame. The front cameras do not show perspective. I.e. they can be used for 2D-Animation.

*The Camera Looking At Origin and Perspective Camera.*
Properties (Specific)

Camera Properties

- **Plane Distance**: A camera only shows objects that lie between a front plane and a back plane. You can set the distance of these planes (seen from the camera).
- **Projection**: You can show all objects in perspective (objects further away look smaller) or Orthographic (objects further away are shown equally large). You can choose to show right hand frames or left-hand frames.
- Use the slider bar to set the **Zooming**.

**LookAtProperties**

- When you enable the **Look at Position**, the camera will always look at a specific position, regardless the position of the camera itself.
- You can make the look at position **static** or connect it to **variables** of your model.
- Use the **Always Look up Vector** to let the camera have a fixed angle of view.

Properties (General)

- position
- orientation
Vector

Properties (Specific)
The Vector object is a combination of a Cylinder object and a Cone object. The length of the Vector can be constant or determined by the value of the variable, the offset and the multiplication factor. You can set the vector diameter, the cone diameter and the cone height and set the number of circle elements. The color of the Cone and the Cylinder can be specified separately by the two color property pages. The first page is for the Cylinder and the second page is for the Cone.

Properties (General)
- position
- orientation
- mesh
- texture
- material
- duplication

Ambient Light
An Ambient Light source illuminates everything with a predefined color, regardless of the orientation, position, and surface characteristics of the objects available. It is constructed by making a spot light shine everywhere.
Spot Light

A Spotlight emits a cone of light of a certain color. The cone starts at a given position and the direction is given by the orientation. Only objects within the cone are illuminated.

Color

- Ambient color: This is the main color of point light. For a spot light this option is turned off.
- Diffuse color: This is color of point light when it shines on matt surfaces.
- Specular color: This is color of point light when it is reflected in shiny surfaces.

Direction

You can select the shape of the light bundle.

- Parallel: Select this option to make the light a parallel bundle (e.g. the sun light). For a spot light this option is turned off.
- Spot Exponent [Wide-Narrow]: Select this option to make the light intensity equal in all directions (Wide) or more intensive in the center beam of the spot light (Narrow)
- Spot Angle [0..90]: Select the angle of the cone from 0 degrees (very thin bundle) to 90 degrees (light in all directions).

Attenuation

Light attenuation defines how the intensity of the light weakens as it travels away from the source. The attenuation is computed based on the following formula:

\[
\text{att} = \frac{1}{k_0 + k_1 d + k_2 d^2}
\]

where \(k_0\) is the constant attenuation, \(k_1\) is the linear attenuation, \(k_2\) is the quadratic attenuation and \(d\) is the distance from the light’s position to an object.

Directional Light

A Directional Light illuminate all objects with light of equal intensity, as if it were at an infinite distance from the objects. The directional source is commonly used to simulate distant light sources, such as the sun. It is constructed by making a spot light shine in parallel bundles.

Properties

Position

Most objects in a 20-sim Animation can be positioned with respect to the frame one level up in the object tree. This position can be fixed (using fixed values) or change (using model variables) during simulation.
Orientation
All objects in a 3D Animation have an orientation. This orientation can be made visible by showing the object attached reference frame. This orientation can be fixed (using fixed values) or changed (using model variables) during simulation.

The orientation of an object is defined as the transformation of the frame one level up the object tree \{A\} to the object attached reference frame \{B\}. Several methods can be used in 20-sim to define this transformation.

DirectX
Using the DirectX method you have to specify the Y-axis and Z-axis of the frame \{B\} in coordinates of frame \{A\}.

Bryant angles
Start with the frame \{B\} coincident with a known frame \{A\}. First rotate \{B\} about the X-axis of \{B\} by an angle of X (rad), then rotate about the Y-axis of \{B\} by an angle of Y (rad) and then rotate \{B\} about the Z-axis of \{B\} by an angle of Z (rad). **Note:** Bryant angles are also known as X-Y-Z Euler angles or Cardan angles.

X-Y-X-Euler
Start with the frame \{B\} coincident with a known frame \{A\}. First rotate \{B\} about the X-axis of \{B\} by an angle of x (rad), then rotate about the Y-axis of \{B\} by an angle of y (rad) and then rotate \{B\} about the X-axis of \{B\} by an angle of z (rad).

Euler Parameters
Start with a frame \{A\}. Rotate this frame about a vector K \[X,Y,Z\]T about an angle theta to get to the frame \{B\}.

Scaling
Most objects in a 20-sim Animation can be scaled in size. This scaling can be fixed (using fixed values) or change (using model variables) during simulation.

Color
Most objects in a 20-sim Animation can be shown with a preset color. The colors can be user defined or defined with respect to a color map.

User Defined
The additive primary colors are red (R), green (G), and blue (B). By mixing these colors in different percentages, any other color can be created. When blue and green are mixed, the resulting color is cyan. When blue and red are mixed, the resulting color is magenta. If all three primary colors are mixed together, the resulting color is white.
The color tab.

Color ranges can be set from 0 to 1 or 0 to 255. Constant values or model variables can be chosen for each primary color. Use the multiplication and addition terms for scaling and offset.

**Color Map**

The color that is chosen is defined by a color map. Color ranges can be set from 0 to 1 or 0 to 255. A constant value or a model variable can be chosen. Use the multiplication and addition term for scaling and offset.
Mesh

The rendering option defined in the General Properties can be overridden for each object. The options are: WireFrame, Unlit Flat, Flat and Gouraud.
Texture

Using the Texture attribute, you can wrap a bitmap file around an object. Using the browse button, you can easily select the desired bitmap file (bmp, jpg, gif, tif, etc.). Using the transparency option you can select a color in the bitmap that should be transparent.

Texture Origin

A texture is defined in generalized coordinates \((u,v)\). The bottom right of the texture has coordinates \((0,0)\) and the top left \((1,1)\). The offset parameters define how much offset is used to project the bitmap. This is shown in the figure below. At the left an offset of \((0,0)\) is shown and at the right an offset \((0.2,0.2)\) is shown.

Depending on the type of texture wrapping (Flat, Cylinder, Sphere or Chrome) the three wrapping vectors \((u,v)\) have a different meaning. This is explained in the next sections. To facilitate the explanation in the pictures below the origin vector equals \((0,0,0)\), the Y-vector equals \((0,1,0)\) and the Z-vector equals \((0,0,1)\).
Vectors
Using three vectors (Origin, Y-Axis and Z-Axis) and Offset parameters (X, Y) you can define how the texture should be wrapped around an object. The vectors are defined with reference to the object attached reference frame. The object attached reference frame can be made visible by selecting Show Frame. The vectors use generalized coordinates. I.e. the length, width and height of the object are defined as 1 and the vectors are scaled accordingly.

Flat
The flat wrap conforms to the faces of an object as if the texture were a piece of rubber that was stretched over the object. For a flat texture wrap, the effects of the various vectors are shown in the following illustration.

- The Origin vector defines the base from which the texture wrapping is performed.
- The Y-vector equals the v axis of the texture wrap.
- The Z-vector is always perpendicular to the texture wrap.

Cylindrical
The cylindrical wrap treats the texture as if it were a piece of paper that is wrapped around a cylinder so that the left edge is joined to the right edge. The object is then placed in the middle of the cylinder and the texture is deformed inward onto the surface of the object. For a cylindrical texture wrap, the effects of the various vectors are shown in the following illustration.
- The *Origin* vector defines the base from which the texture wrapping is performed.
- The *Y-vector* specifies the point on the outside of the cylinder where \( u \) equals 0.
- The *Z-vector* specifies the axis of the cylinder.

**Spherical**

For a spherical wrap, the \( u \)-coordinate is derived from the angle that the vector \([x \ y \ 0]\) makes with the x-axis (as in the cylindrical map) and the \( v \)-coordinate from the angle that the vector \([x \ y \ z]\) makes with the z-axis. Note that this mapping causes distortion of the texture at the z-axis.

- The *Origin* vector defines the base from which the texture wrapping is performed.
- The *Y-vector* specifies the point on the outside of the sphere where \( u \) equals 0.
- The *Z-vector* specifies the point on the outside of the sphere where \( v \) equals 0.

**Chrome**

A chrome wrap allocates texture coordinates so that the texture appears to be reflected onto the objects. The chrome wrap takes the reference frame position and uses the vertex normals in the mesh to calculate reflected vectors. The texture \( u \)- and \( v \)-coordinates are then calculated from the intersection of these reflected vectors with an imaginary sphere that surrounds the mesh. This gives the effect of the mesh reflecting whatever is wrapped on the sphere.
Material

A material defines how a surface reflects light. A material has two components: an emissive property (background color) and a specular property (reflected light), whose brightness is determined by a power setting. Using the Material tab you can set these options.

Closed Shapes

Some objects in a 20-sim Animation can be shown as a closed shape (sides closed) or open shape (sides open).

Circle Elements

All objects in a 20-sim Animation are build out of a set of planar surface elements. Curved objects have to be build up out of a lot of surface elements to give the impression of a smooth surface. For some objects you can set the amount of surface elements used to create circular surfaces.

Attenuation

The Animation Engine in 20-sim is based on the Microsoft® Direct3D. Direct3D uses the following formula to normalize the distance from a light source to the object surface into a value from 0.0 to 1.0, inclusive:

\[ D_n = \frac{R - D}{R} \]
In the preceding formula, $Dn$ is the normalized distance, $R$ is the light's range, and $D$ is the distance, in world space, from the light source to the object surface. A normalized distance is 1.0 at the light's source, and 0.0 at the light's range.

With the normalized distance in hand, Direct3D then applies the following formula to calculate light attenuation over distance for point lights and spotlights:

$$A = \text{Attenuation}_{\text{constant}} + Dn \cdot \text{Attenuation}_{\text{linear}} + Dn^2 \cdot \text{Attenuation}_{\text{quadratic}}$$

In this attenuation formula, $A$ is the calculated total attenuation and $Dn$ is the normalized distance from the light source to the object. The constant, linear and quadratic attenuation factors act as coefficients in the formula. You can produce a wide variety of attenuation curves by making simple adjustments to them. Most applications will set the linear attenuation factor to 1.0 and set the remaining factors to 0.0 to produce a light that steadily falls off over distance. Similarly, you could apply a constant attenuation factor of 1.0 by itself to make a light that doesn't attenuate (but will still be limited by range). The following illustration shows the three most common attenuation curves.
**Duplication**

All objects in a 20-sim Animation can be duplicated. This property is useful when drawing a lot of the same objects.

You can choose several options:

- **Number of Duplicates**: Select the number of duplicates of the object.
- **Position Offsets**: Select the position offset of the first duplicate from the original object. This offset is repeated for every next duplicate.
- **Orientation Offset**: Select the orientation offset of the first duplicate from the original object. This offset is repeated for every next duplicate.
- **Scaling Offset**: Select the scaling of the first duplicate compared to the original object. This scaling is repeated for every next duplicate.

The example below shows a cube that is duplicated according to the specifications given in the figure above. As shown, the first duplicate is a little larger than the original object. The second duplicate is a little larger than the first duplicate etc.
10.3.2 Graph Animation

Graph Animation

To Animate the results of a simulation in the graphical model select the *Graph Animation* command from the *Tools* menu (Simulator). During simulation, the thickness and color of bonds and signals will correspond with the values they carry.

The color of a bond or signal always corresponds with the sign, red for negative values and green for positive values. The thickness of signals corresponds with the value. For signals that is obvious but for bonds or connections carry two variables: effort and flow (also know as across and through). For bonds and connections you can choose to let the thickness correspond with the effort, flow or power (effort*flow), depending on the Animation command that was chosen.
You can start Animation in the Simulator:

1. Run a simulation until you are satisfied with the results.
2. From the **Tools** menu, select **Animation Toolbox** then **Graph Animation**.
3. A menu pops up. Choose the options you like and click **OK** to start Animation.

**Graph Animation Menu**

**Items**

- **Animation Kind**: For signals, the thickness always corresponds with their value. For bonds and connections you can choose. Select here to what the thickness of bonds and connections should represent: effort, flow or power (effort*flow).
- **Animation Ranges**: The thickness of bonds and signals can vary from 1 to 5 pixels. Select here the range that should correspond with a thickness of 5 pixels.
10.4 Control Toolbox

10.4.1 Controller Design Editor

Controller Design Editor

The 20-sim Controller Design Editor allows you to enter or edit linear time-invariant models of a plant with control loop. The control loop is separated in a compensator, prefilter and measurement. You can open the Controller Design Editor from the Tools menu of the 20-sim Editor or by clicking Go Down on a ControlledLinearSystem model that was inserted in the Editor.

Sub System

- You can choose to show a single element in the loop:
  - Plant (P), Compensator (C), Prefilter (F) or Measurement (M)
• or view the response of the system:
  • **Response (H), Loop Transfer (L), Sensitivity (S), Compl. Sensitivity (T), Plant Sensitivity (PS) or Control Sensitivty (CS).**

The corresponding transfer function is show in the editor.

### Additional Ports
Select one of the radio buttons **Input Disturbance**, **Output Disturbance**, **Measurement Dist.**, or **Feedforward**. The first three options allow you to use external disturbance in your model. The last option allows you to use an external feedforward controller (e.g. a B-Spline network). The selected inputs are shown in the picture.

### System Description
- Pressing the **Edit** button will open a dialog for editing the linear system. Each description (State Space, Transfer Function, Zeros Poles Gain or Eigen Frequency) has a special dialog and can be used to specify continuous-time and discrete-time systems.
- In the 20-sim Simulator, out of an existing (non-linear) model a symbolic linear-system can be derived by means of linearization. This means that the relevant model parameters are preserved in the Linear System and the parameters button can be used to change parameters.

### Import/Export
- Pressing the **s<->z** button will transform a continuous-time linear system into a discrete-time linear system and back.
- Pressing the **Filter** button opens the Filter Editor, where a filter can be designed. This filter can then be combined with the current linear system or replace the current linear system. If the linear system is a discrete-time system, the designed analog filter is automatically transferred into its digital equivalent.
- Pressing the **From Matlab** button and the **To Matlab** button allows for an instant exchange of the linear system with the Matlab workspace. Information is transferred numerically (no parameter relations are preserved)
- The button is only active when a Linear System has been imported through linearization. Clicking the button will import parameters from the simulation.
- The button is only active when a Linear System has been imported through linearization. Clicking the button will export the current parameters to the simulation.

### Plots
You can inspect the time- and frequency responses of the selected transfer function using:
- **Step Response**
- **Bode Plot**
- **Nyquist Plot**
- **Nichols Chart**
- **Poles and Zeros** (including root locus)
Output

- Clicking the **20-sim** button will export the linear system as a new 20-sim submodel.
- Clicking the **Matlab** button will export the 20-sim Linear System to a Matlab m-file. If the Linear System is symbolic, all parameter relations are preserved.

State Space Models

State space models use linear differential equations (continuous) or difference equations (discrete) to describe system dynamics. They are of the form:

\[
\begin{align*}
\frac{dx}{dt} &= A \cdot x + B \cdot u \\
y &= C \cdot x + D \cdot u
\end{align*}
\]

(continuous) \hspace{1cm} (discrete)

with for example:

\[
A = \begin{bmatrix} 0 & 0.5 \\ -1 & -1 \end{bmatrix} \quad B = \begin{bmatrix} -0.1 \\ 0.1 \end{bmatrix}
\]

\[
C = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad D = \begin{bmatrix} 0 \end{bmatrix}
\]

where \( x \) is the state vector and \( u \) and \( y \) are the input and output vectors. These models may arise from the equation of physics, from state space identification or as the result of linearization.
You can enter state space models by selecting the *State Space* button and clicking the *Edit* button.

![State Space Editor](image)

This opens an editor in which you can enter the A, B, C and D matrices. Depending on the selection of the Discrete Linear System check box (and Sample Time) the system is a continuous-time or discrete-time system. You can enter the matrix elements in the white space areas. Separate column elements with Spaces or Commas. Enter new rows by clicking the Enter key (new line) or using a semicolon. Brackets ( e.g. [ ... ] ) may be used to denote the a matrix or vector.

The A-matrix, shown in the figure above can for example be entered as:

```
0 1
-0.5 -1
```

or

```
0,1;-0.5,-1
```

or

```
[0,1;
-0.5,-1]
```

**Output Delay**

To inspect the effects of time delay in your model, you can add output delay. The result will be visible in the various plots that you can show of a linear system. The unit of the output delay is seconds.

**Discrete Sample Time**

If you want to transfer a linear system from continuous time to discrete time directly (i.e. replace the s by a z), select Discrete Sample time and fill in the sample time value. You can also transfer back directly by deselecting Discrete Sample time.

**Commands**

- *Help*: Open the help file.
- *Apply*: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero).
- *OK*: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero) and close the editor.
- *Cancel*: Do not apply any changes to the system and close the editor.
Transfer Functions

A continuous time or discrete time SISO transfer function:

\[
h(s) = \frac{n(s)}{d(s)} \quad h(z) = \frac{n(z)}{d(z)}
\]

(continuous) \hspace{1cm} (discrete)

is characterized by its numerator \( n \) and denominator \( d \), both polynomials of the variable \( s \) or \( z \).

You can enter transfer functions by selecting the Transfer Function button and clicking the Edit button.
This opens an editor in which you can enter the coefficients of the numerator and denominator polynomials. You can enter the elements in the white space areas. Separate the elements with Spaces. Polynomials should be entered in descending powers of \( s \) or \( z \). The Steady State Gain, Root Locus Gain and System Gain are parameters, that are automatically derived from the transfer function.

In the editor shown above the transfer function

\[
\frac{1}{s^2 + 0.5 \cdot s + 1}
\]

was given. You can enter the coefficients as:

1

and

1 0.5 1

or

0.1,0.1

and

1,1,0.5

**Output Delay**

To inspect the effects of time delay in your model, you can add output delay. The result will be visible in the various plots that you can show of a linear system. The unit of the output delay is seconds.

**Discrete Sample Time**

If you want to transfer a linear system from continuous time to discrete time directly (i.e. replace the \( s \) by a \( z \)), select Discrete Sample time and fill in the sample time value. You can also transfer back directly by deselecting Discrete Sample time.
Commands

- **Help**: Open the help file.
- **Apply**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero).
- **OK**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero) and close the editor.
- **Cancel**: Do not apply any changes to the system and close the editor.

Zeros and Poles

A continuous-time SISO transfer function can be described by the transfer function:

\[
h(s) = \frac{n(s)}{d(s)} = \frac{n_k \cdot s^k + n_{k-1} \cdot s^{k-1} + \ldots + n_0 \cdot s^0}{d_j \cdot s^j + d_{j-1} \cdot s^{j-1} + \ldots + d_0 \cdot s^0}
\]

This transfer function can be rewritten in pole zero notation with

\[
h(s) = K_{RL} \frac{(s-z_1)(s-z_{i-1})\ldots(s-z_0)}{(s-p_j)(s-p_{j-1})\ldots(s-p_0)}
\]

where \(p_i .. p_j\) are the poles and \(z_i .. z_l\) are the zeros and \(K_{RL}\) is the Root Locus Gain of the system. The same can be done for a discrete-time SISO transfer function.
You can enter zeros and poles by selecting the *Zeros & Poles* button and clicking the *Edit* button.
This opens an editor in which you can enter the real and imaginary parts of the zeros and poles as well as the Root Locus Gain. If preferred, you can also enter the System Gain. Note that zeros and poles always have conjugate when the imaginary part is non-zero. I.e. when you enter a pole with imaginary part 0.5 an extra pole is added with imaginary part -0.5.

**Output Delay**
To inspect the effects of time delay in your model, you can add output delay. The result will be visible in the various plots that you can show of a linear system. The unit of the output delay is seconds.

**Discrete Sample Time**
If you want to transfer a linear system from continuous time to discrete time directly (i.e. replace the s by a z), select Discrete Sample time and fill in the sample time value. You can also transfer back directly by deseleting Discrete Sample time.

**Commands**
- **Add/Delete**: Add or delete selected poles or zeros.
- **Help**: Open the help file.
- **Apply**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero).
- **OK**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero) and close the editor.
- **Cancel**: Do not apply any changes to the system and close the editor.
10. Toolboxes

**Eigen Frequencies**

The Eigen Frequencies view is closely related to the pole zero notation and bode plot. It shows the resonance frequencies and anti-resonance frequencies that result from the given poles and zeros as well as some characteristic parameters from the bode plot.

You can enter transfer functions by selecting the *Eigen Freqs.* button and clicking the *Edit* button.
Step Response

The Step Response command calculates the systems response $y$ on a unit step input:

\[
\begin{align*}
    u &= 0 \ (\text{time} < 0) \\
    u &= 1 \ (\text{time} \geq 0)
\end{align*}
\]

20-sim automatically generates an appropriate range for the time response, based on the system dynamics. With the Plot Properties command (right mouse menu), you can change this horizon and recalculate the step response (click the Step command again).

**Plot Options**

Using the right mouse menu, you can use several options:

- **Plot Properties**: Set the general plot properties for the step response and specify the curve properties.
- **Numerical Values**: Inspect numerical values.
- **Step Characteristics**: Display rise time, overshoot, settling time and the steady state value of the step response.
- **Copy to Clipboard**: Copy the plot to the windows clipboard.
- **Print**: Print the plot.
- **Zoom in**: Show a detail of the plot.
- **Zoom out**: Show a larger portion of the plot.
- **Zoom Normal**: Show the complete plot.
Bode Plots

Bode Plots show the amplitude and phase of a linear system as function of the frequency. Bode plots can be shown for every 20-sim model through Linearization. During Linearization you are asked to enter the input variable and output variable for which linearization should be performed. After that the linear system is calculated and shown in the Linear System Editor. From the Linear System Editor you can generate a bode plot. These actions can also be predefined using the Frequency Response command of the Properties menu.

20-sim automatically generates a range of logarithmically displayed frequencies, based on the system dynamics. With the Plot Properties command (right mouse menu), you can change this horizon and recalculate the bode response (click the Bode command again).

The magnitude part of the plot can be displayed in dB or in absolute values. The phase part can be displayed in radians or degrees. The frequency can be displayed in radians per second or in Hz.

Plot Options
Using the toolbar or the right mouse menu, you can use various options:

- Plot Properties: Set the plot properties.
- Numerical Values: Inspect numerical values.
- Magnitude (dB): Display magnitude in decibels
- Magnitude (-): Display magnitude in absolute values.
- Phase (rad): Display phase in radians.
- Phase (deg): Display phase in degrees.
- Frequency (rad/sec): Display frequency in radians per second.
- Frequency (Hz): Display frequency in Hz.
• **Phase/Gain Margins:** Display the gain and phase margins.
• **Modulus Margin:** Display the Modulus Margin.
• **Unwrap Phase:** Display the phase plot as a continuous plot by selecting this option or as a folded plot between -180 and 180 deg. by deselecting this option.
• **Peak Response:** Display the peak response.
• **Copy to Clipboard:** Copy the plot to the windows clipboard.
• **Print:** Print the plot.
• **Zoom in:** Show a detail of the plot.
• **Zoom out:** Show a larger portion of the plot.
• **Zoom Normal:** Show the complete plot.

### Pole Zero Diagram

The **Pole Zero** command plot the poles and zeros of a system and computes the root locus plot.

20-sim automatically generates a range of real and imaginary parts, based on the system dynamics. With the **Plot Properties** command (right mouse menu), you can change this horizon and recalculate the pole zero diagram (click the **Pole Zero** command again).

### Root Locus

You can show the rootlocus plot by selecting **Root Locus** from the right mouse menu. Inspect the root locus gain by selecting **Numerical Values** from the right mouse menu.

### Plot Options

Using the right mouse menu, you can use several options:
• **Plot Properties:** Set the plot properties.
• **Numerical Values:** Inspect numerical values.
• **Root Locus:** Show or hide the root locus plot.
• **Copy to Clipboard:** Copy the plot to the windows clipboard.
10. Toolboxes

- **Print**: Print the plot.
- **Zoom in**: Show a detail of the plot.
- **Zoom out**: Show a larger portion of the plot.
- **Zoom Normal**: Show the complete plot.

**Nichols Chart**

The **Nichols** command computes the Nichols chart of a system.

20-sim automatically generates a range of logarithmically displayed frequencies, based on the system dynamics. With the **Plot Properties** command (right mouse menu), you can change this horizon and recalculate the Nichols chart (click the **Nichols** command again). The magnitude part of the plot can be displayed in decibels (dB) or in absolute values. The phase part can be displayed in radians or degrees.

**Plot Options**

Using the right mouse menu, you can use several options:

- **Plot Properties**: Set the plot properties.
- **Numerical Values**: Inspect numerical values.
- **Magnitude (dB)**: Display magnitude in decibels.
- **Magnitude (-)**: Display magnitude in absolute values.
- **Phase (rad)**: Display phase in radians.
- **Phase (deg)**: Display phase in degrees.
- **Frequency (rad/sec)**: Display frequency in radians per second.
- **Frequency (Hz)**: Display frequency in Hz.
- **Phase/Gain Margins**: Display the gain and phase margins.
- **Modulus Margin**: Display the Modulus Margin.
- **Copy to Clipboard**: Copy the plot to the windows clipboard.
- **Print**: Print the plot.
- **Zoom in**: Show a detail of the plot.
10. Toolboxes

- **Zoom out:** Show a larger portion of the plot.
- **Zoom Normal:** Show the complete plot.

**Nyquist Diagram**

The **Nyquist** command computes the Nyquist plot of a system.

20-sim automatically generates a range of real and imaginary parts, based on the system dynamics. With the **Plot Properties** command (right mouse menu), you can change this horizon and recalculate the Nyquist diagram (click the **Nyquist** command again).

**Plot Options**

Using the right mouse menu, you can use several options:

- **Plot Properties:** Set the plot properties.
- **Numerical Values:** Inspect numerical values.
- **Phase/Gain Margins:** Display the gain and phase margins.
- **Modulus Margin:** Display the Modulus Margin.
- **Copy to Clipboard:** Copy the plot to the windows clipboard.
- **Print:** Print the plot.
- **Zoom in:** Show a detail of the plot.
- **Zoom out:** Show a larger portion of the plot.
- **Zoom Normal:** Show the complete plot.
10.4.2 MLP Network Editor

Neural Networks

Human brains consist of billions of neurons that continually process information. Each neuron is like a tiny computer of limited capability that processes input information from other neurons into output information to other neurons. Connected together, these neurons form the most intelligent system known.

For some years now, researchers have been developing models that mimic the activity of neurons to produce a form of artificial intelligence. These "Neural Networks" are formed from tens or hundreds of simulated neurons connected together in much the same way as the brain's neurons. Just like the neurons of the brain, artificial neurons can change their response to a given set of inputs, or "learn".

In the past many learning algorithms have been developed, mostly with limited success. The introduction of the backpropagation paradigm, however, appeared a turning point. It is an extremely effective learning tool that can be applied to a wide variety of problems.

The backpropagation paradigm require supervised training. This means neural networks must be trained by repeatedly presenting examples to the network. Each example includes both inputs (information you would use to make a decision) and desired outputs (the resulting decision, prediction, or response). Based on a calculation on the inputs, the desired outputs and the networks own response to the inputs, the backpropagation paradigms tries to adapt the response of each neuron to achieve an improved neural network behavior. This trial-and-error process continues until the network reaches a specified level of accuracy.

Once a network is trained and tested it's neurons can be "frozen". This means the neurons ability to learn" or adapt is stopped. The network can then be used to perform the task it was trained for.

BackPropagation Networks

In backpropagation type neural networks, the neurons or "nodes" are grouped in layers. We can distinct three groups of layers in a backpropagation type neural network: one input layer, one or more hidden layers and one output layer. The nodes between two adjacent layers are interconnected. Fully connected networks occur when each node of a layer is connected with each node of the adjacent layer.
As the figure shows, information (i.e. input signals) enters the network through the input layer. The sole purpose of the input layer is to distribute the information to the hidden layers. The nodes of the hidden layers do the actual processing. The processed information is captured by the nodes of the output layer, and transported as output signals to the world outside.

\[ y = f( w_1 \cdot i_1 + w_2 \cdot i_2 + w_3 \cdot i_3 + \ldots + w_n \cdot i_n ) \]

The nodes of the hidden layers process information by applying factors (weights) to each input. This is shown in the figure above. The sum of the weighted input information (S) is applied to an output function. The result is distributed to the nodes of the next layer.

When the network is in being trained, the weights of each node are adapted according to the backpropagation paradigm. When the network is in operation, the weights are constant.

Depending on the kind neural network, various topologies can be discerned. The 20-sim Neural Network Editor supports two well-known networks:

1. Adaptive B-spline networks
2. Multi-layer Perceptron networks
Introduction to MLP Networks

The basic element of the Multi Layer Perceptron (MLP) neural network, is the artificial neuron. An artificial neuron, is a unit that performs a simple mathematical operation on its inputs. In the figure below, the neuron is graphically presented.

The input, \( x \), of the neuron consists of the variables \( x_1 \ldots x_n \) and a bias term, known as the **momentum constant**, which is equal to 1. Each of the input values is multiplied by a weight, \( w_i \), after which the results are added. On the result, a simple mathematical function, \( f(x) \), is performed. This function is also known as the **activation function**. The calculations the neuron performs are thus given by:

\[
y = f \left( w_0 + x_1 w_1 + \ldots + x_n w_n \right)
\]

Numerous choices for the functions exist. Frequently used implementations are the Sigmoid functions:

\[
f(u) = \frac{1}{1 + e^{-u}}
\]

\[
f(u) = c_1 \cdot \tanh \left( c_2 u \right)
\]
MLP Network
An MLP network, as any type of back-propagation network can consist of many neurons, which are ordered in layers. The neurons in the hidden layers do the actual processing, while the neurons in the input and output layer merely distribute and collect the signals. Although many hidden layers can be used, it has been shown that an MLP with one hidden layer can approximate any continuous function. Therefore in 20-sim, the MLP networks only have one hidden layer.

Training the MLP network
The MLP network is trained by adapting the weights. During training the network output is compared with a desired output. The error between these two signals is used to adapt the weights. This rate of adaptation is controlled by the learning rate. A high learning rate will make the network adapt its weights quickly, but will make it potentially unstable. Setting the learning rate to zero, will make the network keep its weights constant.
10. Toolboxes

How to use the MLP Editor

The MLP Editor can be used to define a 20-sim Multi Layer Perceptron (MLP) network. The editor is opened when you try to edit this submodel (using the Go Down command).

General Settings

- **Network Name**: this is the local name of the submodel representing the MLP network (this option is not yet supported).
- **Number Hidden Neurons**: The MLP network specified by this editor has one layer of hidden neurons. You can specify here the number of neurons that should be used.
- **Learning Rate**: Specify the learning rate that should be used during training. If you do not want the network to learn, enter a zero value here.
- **Initial Weights Fill Scale**: To start proper learning of the network, all initial weights will be given a random value (unequal to zero!) between -scale and +scale. You can enter the scale factor here.
- **Activation Function Type**: Select one of the following activation functions
  - Unipolar Sigmoid: \( \text{act} = 1/(1 + \exp(-v)) \)
  - Bipolar Sigmoid: \( \text{act} = \text{const2} \times \tanh(\text{const1} \times v) \)
- **Bipolar Sigmoid Activation Function Scale**: If a Bipolar Sigmoid was chosen as the activation function, you can enter here the values of \( \text{const1} \) and \( \text{const2} \).
- **Momentum Constant**: Select the momentum constant here.
- **Load Weights at Start of Simulation**: Select this option, if you want to use predefined weights stored on file (saved in a previous run). Before each simulation run, you will be asked to enter the filename of this weights file.
- **Save Weights at Start of Simulation**: Select this option, if you want to store the weights on file. After each simulation run, you will be asked to enter the filename of this weights file.
- **Network is Discrete**: Select this option if the B-spline network is connected with discrete-time models. Deselect this option if the network is connected with continuous models.
10. Toolboxes

Inputs
- Add Input: Add a new input to the network. You will be prompted to give a specific input name. This name will be shown in the Inputs list.
- Delete Input: Delete the input selected in the Inputs list.

Outputs
- Add Output: Add a new output to the network. You will be prompted to give a specific output name. This name will be shown in the Outputs list.
- Delete Output: Delete the output selected in the Outputs list.

10.4.3 B-Spline Network Editor

Neural Networks

Human brains consist of billions of neurons that continually process information. Each neuron is like a tiny computer of limited capability that processes input information from other neurons into output information to other neurons. Connected together, these neurons form the most intelligent system known.

For some years now, researchers have been developing models that mimic the activity of neurons to produce a form of artificial intelligence. These "Neural Networks" are formed from tens or hundreds of simulated neurons connected together in much the same way as the brain's neurons. Just like the neurons of the brain, artificial neurons can change their response to a given set of inputs, or "learn".

In the past many learning algorithms have been developed, mostly with limited success. The introduction of the backpropagation paradigm, however, appeared a turning point. It is an extremely effective learning tool that can be applied to a wide variety of problems.

The backpropagation paradigm requires supervised training. This means neural networks must be trained by repeatedly presenting examples to the network. Each example includes both inputs (information you would use to make a decision) and desired outputs (the resulting decision, prediction, or response). Based on a calculation on the inputs, the desired outputs and the network's own response to the inputs, the backpropagation paradigms tries to adapt the response of each neuron to achieve an improved neural network behavior. This trial-and-error process continues until the network reaches a specified level of accuracy.

Once a network is trained and tested it's neurons can be "frozen". This means the neurons ability to learn" or adapt is stopped. The network can then be used to perform the task it was trained for.

Introduction to B-Spline Networks

One-dimensional B-spline network

An adaptive B-spline network can be used to relate k inputs and a single output y on a restricted domain of the input space. The following network shows a realization with one input:
The network is shown with two hidden layers. Some authors prefer to show a B-spline network with only one hidden layer. For a proper understanding of multi-dimensional B-spline networks we prefer to show the network with two hidden layers.

The first hidden layer distributes the inputs over several nodes. In the figure above input 1 is distributed over n nodes. Each node of this layer has only one input. To this input a "basis function" F is applied. As basis functions, B-splines are used of any desired order. An N-th order B-spline function consists of pieces of (N-1)th order polynomials, such that the resulting function is (N-1) times differentiable. The figure below shows examples of B-spline functions of different order. A spline function differs from zero on a finite interval.

The second hidden layer also consists of n nodes. Each node of this layer has only one input. To this input a function G is applied which is merely a multiplication by a weight:

\[ G = w \times i \]

The output node sums the results of all second hidden layer nodes. When the spline functions of the various nodes are properly spaced, every one dimensional function can be approximated. This is shown in the figure below where the various splines (F1 to Fn) combined with the various weights (w1 to wn), together form an output function.
Two-dimensional B-spline network

Two-dimensional B-spline networks have two input nodes. The first hidden layer, as with the one-dimensional network, consists of nodes, to which a basis function $F$ is applied. This is shown in the figure below. To the first input a group of $n$ nodes are applied, and to the second input a group of $m$ nodes are applied.

![Diagram of two-dimensional B-spline network]

The second hidden layer now consists of nodes which each have two inputs. For every combination of a node from one group and a node from the second group, a node exists. To each node of the second hidden layer, a function $G$ is applied which is merely a multiplication of the two inputs multiplied by a weight:

$$G = w \cdot i_1 \cdot i_2$$

Again the output node sums the results of all second hidden layer nodes. When the spline functions of the various nodes are properly spaced, every two dimensional function can be approximated. The figure below shows the spacing of various spline functions of the two inputs and one output of a node of the second hidden layer.
The output node sums the results of all second hidden layer nodes. When the spline functions of the various nodes are properly spaced, every two dimensional function can be approximated. This is shown in the figure below.

**More-dimensional B-spline networks**

In a same way more dimensional B-spline networks can be created, using more inputs. The 20-sim B-spline Editor supports networks with up to 256 inputs and one output.

**Training the B-spline network**

The B-spline network is trained by adapting the weights. During training the network output is compared with a desired output. The error between these two signals is used to adapt the weights. This rate of adaptation is controlled by the learning rate. A high learning rate will make the network adapt its weights quickly, but will make it potentially unstable. Setting the learning rate to zero, will make the network keep its weights constant. Learning of B-spline networks can either be done after each sample (learn at each sample), or after series of samples (learn after leaving spline).
Learn at each Sample
When learning at each sample, after every sample the weights are adapted according to:

\[ \Delta w_j = \gamma \cdot (y_d - y) \cdot F_j(x) \]

with

\[ \Delta w_j : \text{adaptation of the weight } w_j \]
\[ \gamma : \text{learning rate} \]
\[ F_j(x) : \text{B-spline function number } j \]
\[ x : \text{input} \]
\[ y_d : \text{desired output} \]
\[ y : \text{network output} \]

Given a certain input \( (x) \), only a limited number of splines \( F_i(x) \) are nonzero. Therefore only a few weights are adapted each sample.

Learn after Leaving Spline
When learning after leaving a spline, the network will keep track of the input \((x)\) and the corresponding nonzero splines \( F_i(x) \). For each nonzero spline, a sample will be stored consisting of the input \((x)\), the output \((y)\) and desired output \((y_d)\). Only after the input has left the region where a spline is nonzero, its weight is updated according to:

\[ \Delta w_j = \gamma \cdot \frac{\sum_{i=1}^{n} (y_{d,i} - y_i) \cdot F_j(x_i)}{\sum_{i=1}^{n} F_j(x_i)} \]

Here \( n \) is the number of samples that have been taken.
How to use the BSpline Editor

The B-Spline Editor can be used to define a 20-sim B-Spline network. The editor is opened when you try to edit this submodel (using the Go Down command).

General Settings

- **Network Name**: this is the local name of the submodel representing the B-Spline network (this option is not yet supported).
- **Order**: Enter the order of the B-Splines that must be used.
- **Learn at Each Sample**: Select this option if you want the network to adapt the weights after every simulation step
- **Learn after leaving Spline**: Select this option if you want the network to adapt the weights only leaving the spline region.
- **Learning Rate**: Specify the learning rate that should be used during training. If you do not want the network to learn, enter a zero value here.
- **Apply Regularization**: This option is not yet supported.
- **Load Weights at Start of Simulation**: Select this option, if you want to use predefined weights stored on file (saved in a previous run). Before each simulation run, you will be asked to enter the filename of this weights file.
- **Save Weights at End of Simulation**: Select this option, if you want to store the weights on file. After each simulation run, you will be asked to enter the filename of this weights file.
- **Network is Discrete**: Select this option if the B-spline network is connected with discrete-time models. Deselect this option if the network is connected with continuous models.

### Input Settings

The tabs shown in the editor is used to specify the inputs of the network. Each tab shows the specific settings of that input.

- **Add Input**: Add a new input to the network. A new tab will be added with default settings.
- **Delete Input**: Delete the input defined in the selected tab (the tab that is in front).

Each input is associated with a certain number of splines. To give the user more flexibility, each input can be divided in certain regions that each have their own density of splines.

- **Add**: Add a new region of splines.
- **Delete**: Delete the selected region of splines.
- **Split**: Split the selected region into two regions.

Each region can be edited. Just select it from the Regions list and use the following options:

- **Upper / Lower**: The upper and lower bound of a region.
- **Number of Splines**: The number of splines. The more splines you choose, the more accurate will the network output be, for this region of inputs.

### Running a 1-D B-Spline Network

Now we have trained the B-spline network and saved the weights. We can run the network with every desired input. We only have to keep in mind that the network was defined for input signals between 0 and 10.

1. In the Editor from the **File** menu select **Open**.
2. In the model library choose Examples\Control\Neural Networks
3. Select the model 1DBSplineNetwork-Run.emf. Now the predefined model will be opened.
As you can see, this is exactly the same model as used for training, but now a ramp input is used.

4. From the menu select **Model** and **Start Simulator**. Now a Simulator will be opened with the predefined experiment loaded.

5. From Simulator menu click **Simulation** and **Run**. Do **not save** the weights file at the end of the run! The results will look like:
As you can see, the B-Spline Network still has its training settings and still prompts for a weight file at the end of the simulation. Now we are going to change the settings of the B-Spline Network.

6. Open the B-Spline Editor (select the model, Go Down). To create a normal run with the network, we have to set the learning rate to zero, and load the weights file before simulation. Change the settings of the network, until it looks like:
7. Click **OK** to close the B-Spline Editor. From the Editor menu click **Model** and **Check Complete Model**. This will implement the changed settings.

8. Return to the Simulator and click **Simulation** and **Run**. Before the run, an Open dialog will asking you to enter the name of the Weights File. This is a file that contains all the weights of the trained B-Spline network. Use the file that you saved during training, or the predefined weights file 1DBSplineNetwork.wgt. The simulation results will look like:

As you can see the function is approximated by the B-Spline network by 10 first order splines.
Training a 1-D B-Spline Network

Non Linear Function
In this lesson we will use a B-spline network with one input to approximate the simple non-linear function:

\[ F = \text{input}^2 \]

The input, \( x \), of this function ranges from 0 to 10. It will be approximated by a B-Spline network with one input. As is shown in the figure below (left), 10 first order B-splines are used. The tenth B-spline is indicated with fat lines. The output of the B-spline network is a combination of all ten B-Splines. In other words, the non-linear function will be approximated by 10 intervals of constant value.
At the start the B-spline has undefined weights. They can either be chosen at random values or all set to zero. A normal session should therefore start with training the network to adjust the weights to give a best approximation of the non-linear function. With these weights we can run the network with any desired input signal.

**Defining the B-Spline Network**

We will use the model below to train the B-spline network. It has already been prepared for you.
1. In the Editor from the **File** menu select **Open**.

2. In the model library choose Examples\Control\Neural Networks

3. Select the model **1DBSplineNetwork-Train.emx**. Now the predefined model will be opened.

4. From the menu select **Model** and **Start Simulator**. Now a Simulator will be opened with the predefined experiment loaded.

5. From Simulator menu click **Simulation** and **Run**. The results will look like:

   As you can see, the B-Spline output is zero and there is no learning. Now we are going to change the settings of the B-Spline Network.

**Training the Network**

6. Return to the Editor. Select the BSplineNetwork model and click **GoDown** from the **Model** menu. Now the B-Spline Editor will pop-up. Change the settings (Network Order, Learning Rate, Input Upper Limit, Save Weights) until it looks like:
7. Click **OK** to close the B-Spline Editor. Note that the icon of the BSplineNetwork model has changed to correspond with the first order splines that are used. From the Editor menu click **Model** and **Check Complete Model**. This will implement the changes in settings.

8. Return to the Simulator and click **Simulation** and **Run**. The results will look like:

As you can see the error rapidly descends, due to the network learning. After the Simulation Run, the Save dialog opens, asking you to enter a name for the Weights File. This is a file that contains all the weights of the trained B-Spline network. We can use these weights for normal runs with the network.
9. Enter file name (do not use the predefined weights file!), e.g. test.wgt and click Save.

10. Close the Simulator.

Now all is prepared to perform a normal run with the Network.

10.4.4 Filter Editor

The Filter Editor of 20-sim allows you to create continuous-time filters and controllers. The result is a linear system presented in the Linear System Editor of 20-sim. The filter can also be applied to an existing linear system.

You can open the Controller Design Editor from the Tools menu of the 20-sim Editor or by clicking Go Down on a Filter model.

Procedure

1. Select a filter or controller of your choice from the list of available filters and controllers.

Filters

- Generic Filter
- Lead Filter
- Lag Filter
- Low Pass First Order Filter
- Low Pass Second Order Filter
10. Toolboxes

- High Pass First Order Filter
- High Pass Second Order Filter
- Notch Filter
- Universal Notch Filter

**Controllers**

- P Controller
- I Controller
- D Controller
- PI Controller
- PD Controller
- PID Controller
- PID-1 Controller
- PID-2 Controller
- PID Compensator

A short description of the selected filter will be given in the description field. Depending on the filter that was chosen three or more parameters will be shown.

2. The second step is to fill in the desired parameters.

3. Choose the desired output:

4. Select the **Linear System Editor** button to export the filter to the Linear System Editor.

5. Select the **OK** button to store the filter model on file or update the filter model in the Editor.

**Controllers**

**P-Controller**

The P Controller can be used to create an additional gain for a linear system.

- Gain $K_p$: The controller gain $K_p$ determines the amount of gain the controller adds for each frequency.

**Transfer function of the controller:**

$$H_p(s) = K_p$$
I-Controller

The I Controller can be used to create an almost ideal integrator (when the frequency goes to zero).
- **Gain $K_i$:** The filter gain $K_i$ determines the frequency gain of the controller at frequency $w = 1$ [rad/s].
- **Frequency $f_i$:** The integration behavior of the controller stops at frequency $f_i$ in Hz. A decrease of this frequency corresponds to a more pure integration behavior.

**Transfer function of the controller**

$$H_I(s) = \frac{K_i}{2\pi f_i + s}$$

D-Controller

The D Controller can be used to create an almost ideal derivative (when the frequency goes to infinity).
- **Gain $K_d$:** The controller gain $K_d$ determines the frequency gain of the controller at frequency $w = 1$ [rad/s].
- **Frequency $f_d$:** The differentiation behavior of the controller stops at frequency $f_d$ in Hz. An increase of this frequency corresponds to a more pure differentiation behavior, reducing the tameness of the controller.

**Transfer function of the controller**

$$H_D(s) = K_d \frac{2\pi f_d s}{s + 2\pi f_d}$$

PD-Controller

The PD Controller consists of a differentiator with proportional gain.
- **Gain $K_p$:** The controller gain $K_p$ determines the low frequency gain of the controller.
- **Gain $K_d$:** The controller gain $K_d$ determines the gain of the controller at frequency $w = 1$ [rad/s].
- **Frequency $f_d$:** The differentiation behavior of the controller stops at frequency $f_d$ in Hz. An increase of this frequency corresponds to a more pure differentiation behavior, reducing the tameness of the controller.

**Transfer function of the controller:**

$$H_{PD} = H_P + H_D$$

that equals
10. Toolboxes

PI-Controller

The PI Controller consists of an integrator with a proportional gain.

- **Gain $K_p$:** The controller gain $K_p$ determines the high frequency gain of the controller.
- **Gain $K_i$:** The controller gain $K_i$ determines the frequency gain of the controller at frequency $w = 1 \text{[rad/s]}$.
- **Frequency $f_i$:** The integration behavior of the controller stops after frequency $f_i$ in Hz. A decrease of this frequency corresponds to a more pure integration behavior.

**Transfer function of the controller:**

\[
H_{PI} = H_p + H_i
\]

that equals

\[
H_{PI} = \frac{(K_p + K_d 2\pi f_d) s + K_p 2\pi f_d}{s + 2\pi f_d}
\]

PID1-Controller

The PID-1 Controller consists of an integrator and differentiator with proportional gain. It resembles a PID Controller, but has different input parameters.

- **Gain $K_p$:** The controller gain $K_p$ determines the frequency gain of the controller in the pass band (where integration and differentiation are of no interest).
- **Length $L_i$:** The length $L_i$ determines the frequency at which integration starts, that is $f_i / L_i$ in Hz. A decrease of this frequency corresponds to a more pure integration behavior.
- **Length $L_d$:** The length $L_d$ determines the frequency at which differentiation stops, that is $f_d * L_d$ in Hz. An increase of this frequency corresponds to a more pure differentiation behavior, reducing the tameness of the controller.
- **Frequency $f_i$:** The integration behavior of the controller stops at frequency $f_i$ in Hz.
- **Frequency $f_d$:** The differentiation behavior of the controller starts at frequency $f_d$ in Hz.
Transfer function of the controller:

\[
H_{PID} = K_p \left( \frac{L_i - 1}{1 + \frac{L_i s}{2\pi f_i}} + \frac{(L_d - 1)s}{L_d 2\pi f_d + s} \right)
\]

that equals

\[
H_{PID} = \frac{K_p L_d L_i s^2 + K_p (-2\pi f_i + L_i L_d 2\pi f_d + (L_i + L_d) 2\pi f_i) s + K_p L_i L_d 4\pi^2 f_i f_d}{L_i s^2 + (2\pi f_i + L_i L_d 2\pi f_d) s + L_i L_d 4\pi^2 f_i f_d}
\]

**PID2-Controller**

The PID-2 Controller consists of an integrator and differentiator with proportional gain. It resembles a serial PID Controller, but has different input parameters.

- **Gain** \(K_p\): The controller gain \(K_p\) determines the frequency gain of the controller in the pass band (where integration and differentiation are of no interest).
- **Length** \(L_i\): The length \(L_i\) determines the frequency at which integration starts, that is \(f_i / L_i\) in Hz. A decrease of this frequency corresponds to a more pure integration behavior.
- **Length** \(L_d\): The length \(L_d\) determines the frequency at which differentiation stops, that is \(f_d * L_d\) in Hz. An increase of this frequency corresponds to a more pure differentiation behavior, reducing the tameness of the controller.
- **Frequency** \(f_i\): The integration behavior of the controller stops at frequency \(f_i\) in Hz.
- **Frequency** \(f_d\): The differentiation behavior of the controller starts at frequency \(f_d\) in Hz.

Transfer function of the controller:

\[
H_{PID} = K_p L_i \left( \frac{s}{2\pi f_i} + 1 \right) \left( \frac{s}{2\pi f_d} + 1 \right)
\]

that equals

\[
H_{PID} = \frac{K_p L_d L_i s^2 + K_p L_i L_d 2\pi (f_i + f_d) s + K_p L_i L_d 4\pi^2 f_i f_d}{L_i s^2 + (2\pi f_i + L_i L_d 2\pi f_d) s + L_i L_d 4\pi^2 f_i f_d}
\]
**PID-Compensator**

The PID Compensator consists of an integrator and differentiator with proportional gain (PID Controller) together with a high-frequency roll-off filter.

- **Gain** $K$: The controller gain $K$ determines the frequency gain of the controller in the pass band (where integration and differentiation are of no interest).
- **Integration $\tau_i$**: The integration time constant $\tau_i$ determines the frequency $f_i = 1 / \tau_i \, [\text{rad/s}]$ after which the integrating behavior stops.
- **Differentiation $\tau_d$**: The differentiation time constant $\tau_d$ determines the frequency $f_d = 1 / \tau_d \, [\text{rad/s}]$ after which the differentiation behavior starts.
- **HF roll-off $\tau_h$**: The filter time constant $\tau_h$ determines the frequency $f_h = 1 / \tau_h \, [\text{rad/s}]$ of the high-frequency roll-off filter. Frequencies higher than $f_h$ are filtered out.
- **Tameness $\beta$**: The tameness factor $\beta$ influences the differentiating behavior. After frequency $f_{db} = f_d / \beta$ the differentiation behavior stops. Decreasing $\beta$ increases this frequency $f_{db}$, resulting in a more pure differentiating behavior and therefore in a reduce of differentiation tameness.

**Transfer function of the controller:**

$$H_{\text{PIDH}} = H_P \cdot H_I \cdot H_D \cdot H_H$$

that equals

$$H_{\text{PID}} = K\left(\frac{\tau_i s + 1}{\tau_i s}\right)\left(\frac{\tau_d s + 1}{\tau_d \beta s + 1}\right)\left(\frac{1}{\tau_h s + 1}\right)$$

**PID-Controller**

The PID Controller consists of an integrator and differentiator with proportional gain.

- **Gain $K_p$**: The controller gain $K_p$ determines the frequency gain of the controller in the pass band (where integration and differentiation are of no interest).
- **Gain $K_i$**: The controller gain $K_i$ determines the shape of the frequency response at low frequencies.
- **Gain $K_d$**: The controller gain $K_d$ determines the shape of the frequency response at high frequencies.
- **Frequency $f_i$**: The integration behavior of the controller starts at frequency $f_i$ in Hz. A decrease of this frequency corresponds to a more pure integration behavior.
- **Frequency $f_d$**: The differentiation behavior of the controller stops at frequency $f_d$ in Hz. An increase of this frequency corresponds to a more pure differentiation behavior, reducing the tameness of the controller.

**Transfer function of the controller:**

$$H_{\text{PID}} = H_P + H_I + H_D$$

that equals
The Generic Filter can be used to design a filter of a specific order, type and characteristic shape.

Filter Characteristics

The filter can have a Bessel, Butterworth or Chebychev characteristic shape. Each characteristic has its own advantages and disadvantages; it depends on the purpose of the filter what to choose here:

A Bessel filter is maximal flat in both the pass band and the stop band. It is used when the phase response should be nearly linear throughout the pass band, i.e. the group delay is almost constant throughout the pass band. This preserves the wave shape of filtered signals in the pass band. A disadvantage is the low roll-off steepness. Often a high filter order is required to obtain the desired roll-off.

A Butterworth filter is maximally flat in the pass band and monotonic overall. As a consequence of this smoothness, the roll-off steepness is rather low. As with Bessel filters, a rather high filter order is required to obtain the desired roll-off.

A Chebychev 1 filter has a ripple in the pass band and is monotonic in the stop band. This filter rolls off faster than Bessel, Butterworth and Chebychev 2 filters at the same filter order. A disadvantage is the greater deviation and discontinuous phase response in the pass band.

A Chebychev 2 filter is monotonic in the pass band and has a ripple in the stop band. This filter rolls off faster than Bessel and Butterworth filters at the same filter order. Not as fast as a Chebychev 1 filter, but it is free of a pass band ripple. A disadvantage is the ripple and discontinuous phase response in the stop band.

Filter Type

- A low pass filter will filter out high frequencies and let low frequencies pass the filter.
- A high pass filter does the opposite; it will filter out low frequencies and let high frequencies pass the filter.
- A band pass filter will filter out low and high frequencies and let middle frequencies pass the filter.
- A band stop filter does the opposite; it will filter out the middle frequencies and let low and high frequencies pass the filter.

Filter Order

The filter order specifies how steep the filter will roll off at a specified filter frequency. The higher the order, the steeper the roll off will be. Note that the filter order also has a large influence on the phase response of the filter.
Frequency $f_1$
For a low pass filter $f_1$ is the frequency in Hz where the roll off starts. For a high pass filter it is the frequency where the roll off ends. For a band pass or band stop filter $f_1$ is the start frequency of the band.

Frequency $f_2$
For a band pass or band stop filter $f_2$ is the stop frequency in Hz of the band. It is disabled for low pass and high pass filters.

Max. Ripple $R$
Only available when a Chebychev 1 filter is selected. $R$ specifies the maximum allowed ripple in dB for the filter in the pass band.

Stop Band $R$
Only available when a Chebychev 2 filter is selected. $R$ specifies the distance of the stop band to the unity gain axis in dB. This is the amount of attenuation in dB of the filter in the stop band (the absolute value is used).

High-Pass First Order Filter
The high pass filter can be used to filter out undesired low frequencies.
- Gain $K$: The filter gain $K$ determines the high frequency gain of the filter.
- Frequency $f$: The filter roll off stops at frequency $f$ in Hz. Higher frequencies will pass the filter, lower frequencies will be filtered out.

Transfer function of the filter:

$$H(s) = K \frac{s}{s + 2\pi f}$$

High-Pass Second Order Filter
The high pass filter can be used to filter out undesired low frequencies.
- Gain $K$: The filter gain $K$ determines the high frequency gain of the filter.
- Frequency $f$: The filter roll off stops at frequency $f$ in Hz. Higher frequencies will pass the filter, lower frequencies will be filtered out.
- Quality $Q$: The filter quality indicates how steep the phase response will increase up to the frequency $f$. A quality $Q > 0.707$ results in a peak in the magnitude response at frequency $f$.

Transfer function of the filter:

$$H(s) = K \frac{s^2}{s^2 + 2\pi f \frac{s}{Q} + (2\pi f)^2}$$
Lag Filter

The Lag Filter can be used to add a lag in the phase response of a system.

- **Gain** $K$: The filter gain $K$ determines the low frequency gain of the filter.
- **Frequency** $f_1$: The lag in the phase response of the filter starts at frequency $f_1$ in Hz. This corresponds to an integrating behavior in the magnitude response from frequency $f_1$.
- **Frequency** $f_2$: The lag in the phase response of the filter stops at frequency $f_2$ in Hz. This corresponds to a constant attenuation in the magnitude response of the filter after frequency $f_2$.

**Transfer function of the filter**

\[
H_{\text{lag}}(s) = K \left( \frac{s}{2\pi f_2} + 1 \right) \frac{1}{\frac{s}{2\pi f_1} + 1}
\]

Lead Filter

The Lead Filter can be used to add a lead in the phase response of a linear system.

- **Gain** $K$: The filter gain $K$ determines the low frequency gain of the filter.
- **Frequency** $f_1$: The lead in the phase response of the filter starts at frequency $f_1$ in Hz. This corresponds to a differentiating behavior in the magnitude response from frequency $f_1$.
- **Frequency** $f_2$: The lead in the phase response of the filter stops at frequency $f_2$ in Hz. This corresponds to a constant gain in the magnitude response of the filter after frequency $f_2$.

**Transfer function of the controller**

\[
H_{\text{lead}}(s) = K \left( \frac{s}{2\pi f_1} + 1 \right) \frac{1}{\frac{s}{2\pi f_2} + 1}
\]
Low-Pass First Order Filter

The low pass filter can be used to filter out undesired high frequencies.

- Gain $K$: The filter gain $K$ determines the low frequency gain of the filter.
- Frequency $f$: The filter roll off starts at frequency $f$ in Hz. Lower frequencies will pass the filter, higher frequencies will be filtered out.

**Transfer function of the filter**

$$H(s) = \frac{K}{\frac{s}{2\pi f} + 1}$$

Low-Pass Second Order Filter

The low pass filter can be used to filter out undesired high frequencies.

- Gain $K$: The filter gain $K$ determines the low frequency gain of the filter.
- Frequency $f$: The filter roll off starts at frequency $f$ in Hz. Lower frequencies will pass the filter, higher frequencies will be filtered out.
- Quality $Q$: The filter quality indicates how steep the phase response will decrease at the frequency $f$. A quality $Q > 0.707$ results in a peak in the magnitude response at frequency $f$.

**Transfer function of the filter**

$$H(s) = \frac{K(2\pi f)^2}{s^2 + 2\pi f \cdot \frac{s}{Q} + (2\pi f)^2}$$

Notch Filter

The notch filter can be used to filter out an undesired frequency.

- Gain $K$: The filter gain $K$ determines the frequency gain of the filter.
- Frequency $f$: The filter attenuates at frequency $f$ in Hz. Lower and higher frequencies will pass the filter.
- Quality $Q$: The filter quality indicates how steep the magnitude response will be at the frequency $f$.

**Transfer function of the filter**

$$H(s) = K \frac{s^2 + (2\pi f)^2}{s^2 + 2\pi f \cdot \frac{s}{Q} + (2\pi f)^2}$$
Universal Notch Filter

The universal notch filter can be used to filter out an undesired frequencies.

- **Gain**: The filter gain $K$ determines the low frequency gain of the filter.
- **Frequency $f_z$**: The filter attenuates at the zero frequency $f_z$ in Hz. Lower and higher frequencies will pass the filter. A lead in the phase response will start at this zero frequency $f_z$.
- **Frequency $f_p$**: The filter amplifies at the pole frequency $f_p$ in Hz. The phase lead will stop at this pole frequency $f_p$.
- **Damping $d_z$**: The filter damping of the zero $d_z$ indicates how steep the magnitude response will be at the frequency $f_z$. More damping will result in a less steep behavior.
- **Damping $d_p$**: The filter damping of the pole $d_p$ indicates how steep the magnitude response will be at the frequency $f_p$. Again, more damping will result in a less steep behavior.

Transfer function of the filter:

$$H(s) = K \frac{\frac{1}{(2\pi f_z)^2} s^2}{\frac{1}{(2\pi f_p)^2} s^2 + \frac{2d_z}{2\pi f_z} s + 1}$$

10.5 Frequency Domain Toolbox

10.5.1 FFT Analysis

**FFT Analysis**

Using FFT-Analysis, the Fast Fourier Transform is used to calculate the frequency contents of simulation signal. Three representations are supported:

- **Amplitude and Phase**: This representation shows the amplitude and phase of the signal as function of the frequency, similar to a bode plot. If you want show the transfer function of a system, you have to choose the option *Pair-wise transfer function*, which is explained below in the FFT Settings.
- **Frequency Plot**: This representation shows the frequency contents of the signal. Summation of the peak values yields the average power of the original time signal.
- **Power Spectral Density**: This representation shows the frequency contents of the signal. Integration over the frequency range yields the average power of the original time signal.
FFT analysis can be performed in the Simulator by choosing the **FFT Analysis** command from the **Tools** menu. You can also choose to add an **FFT plot** in the Simulator tree. In both cases a new FFT plot is shown.

**Plot Properties**

You can define the FFT plot by opening the plot properties (from the menu choose **Properties - Plot**). Four tabs are shown: **Plot Properties**, **X-Axis**, **Y-Axis** and **FFT Settings**.

- The Plot Properties tab shows the general settings of the plot, similar to every standard plot.
- The X-axis tab shows the X-Axis variable of the FFT input. The default value is time and should not be changed.
- The Y-axis tab shows the variables that are selected to be shown as FFT curves, similar to every standard plot.
- The FFT-Settings tab shows the options that you can choose for the FFT plot.
10. Toolboxes

FFT Settings

- **Plot Properties**
  - *Pair-wise transfer function*: Shows an FFT with the frequency contents of the first plot variable subtracted from the second plot variable. Select this option if you want to show the FFT of a transfer function. The first plot variable is the input of the transfer function and the second plot variable is the output of the transfer function.
  - *Show Peaks*: Choose this option to show the peak values in the FFT plot.

- **Filter**
  - *Subtract DC-component*: If your signal contains a DC-component, the resulting Spectral Density plot will show a high peak at 0 Hz, which may obscure all other frequencies. Choose Subtract DC-component, to remove this peak from the Spectral Density plot.
  - *Integrate Data*: You can integrate the FFT data to inspect the energy contents of each frequency. This option is useful for analyzing resonance frequencies. Integrated FFT-data will usually show a sudden increase exactly at these frequencies.
  - *Anti-Leakage Window*: You can choose a Hamming, Hann or Quadratic window to prevent leakage caused by windowing.
  - *Frequency*: Show the results in Herz or radians per second.
10. Toolboxes

- **Output:** select the desired representation of the frequency data:
  - Amplitude and Phase
  - Frequency Spectrum
  - Power Spectral Density
- **Status Window:** The bottom part of the window shows the number of simulation points and the chosen frequency range.

**Quality**
The quality of an FFT plot depends on the contents of the time domain simulation:

- The number of simulation points per second, determine the frequency range of the FFT. If you want to increase the frequency range to higher frequencies, choose a smaller step size or a smaller maximum step size of the integration method.
- The quality of the FFT depends on the total time of the simulation. Increase the finish time of the simulation to get a better FFT plot.
- Make sure that you system is excited properly. If you give an input signal that does not contain higher frequencies, the FFT plot will not show them.

**FFT Window**
The Fast Fourier Transform is an approximation of the standard Fourier Transform, using a time limited set of data. The begin and end parts of this limited data set may lead to spectral leakage effects (i.e. yielding not existing frequency peaks). Especially when using small data sets leakage may lead to unwanted results.

To reduce spectral leakage, the data set can be preprocessed using special windowing functions. These windowing functions reduce the values at the begin and end of the data set and thus reduce the leakage effects. Given an input array $A[i]$ and an output array $B[i]$, with $i = 1,2,...,N$.

20-sim supports the following windows:

- **None:** no preprocessing; $B = A$
- **Hamming Window:** $B(i) = (0.54 + 0.46*cos(pi*(i-1)/(N-1)))A(i)$, $i = 1,2,...,N$.
- **Hann Window:** $B(i) = 0.5*(1 + cos(pi*(i-1)/(N-1)))A(i)$, $i = 1,2,...,N$.
- **Quadratic Window:** $B(i) = (1 - 2*((i-1)/(N-1))**2)*(1 - (i-1)/(N-1))A(i)$, $i = 1,2,...,\frac{N-1}{2}+1$; $B(i) = 2*(1 - ((i-1)/(N-1))**3)A(i)$, $i = \frac{N-1}{2}+2,...,N$. 

10.5.2  Model Linearization

Linearize

In the Simulator, select the Tools menu and then click the Linearize Model to start linearization. Linearization will generate a linear, state-space description (linear system) out of any 20-sim model:

\[
\frac{dx}{dt} = Ax + Bu \\
y = Cx + Du \\
x(0)
\]

Where:

- \(x\) = state vector
- \(x(0)\) = state vector initial value
- \(\frac{dx}{dt}\) = state vector derivative
- \(y\) = output
- \(u\) = input

And:

- \(A\) = system matrix
- \(B\) = input gain matrix
- \(C\) = output gain matrix
- \(D\) = direct link gain matrix

This linear system shows an input-output behavior that is closely related to the input-output behavior of the original model.

The result is shown in the Linear System Editor. In the Linear System Editor you can choose out of several plot options to show the response of the linear system, such as step responses and Bode plots.

Working Point

Non-linear models can show variable behaviour. Think for example of an arm. When you stretch it and push against a wall, it is very stiff. When your arm is bent and you push it against a wall, it will be more compliant. Depending on which state it is in, linearization of a non-linear system will therefore result in different linear systems.

To get the correct linear system, we have to bring the non-linear system into the correct state. This can be done by giving it the proper inputs and simulate the system for a while until the desired state is reached. This is called the working point. When the working point is reached, the simulation must be stopped to perform linearization.

When linearization is performed without simulation, the working point is the initial state of the non-linear system.

Symbolic and Numeric

In the 20-sim Simulator, out of an existing (non-linear) model, a symbolic linear-system can be derived. This means that states, rates and matrix elements are related to the parameters of the original model:
As a result you will get a linear system with the original model parameters that can be changed at will, without having to linearize again.

Symbolic linearization is not possible if the original model contains functions that cannot be differentiated. For such models linearization has to be performed numerically. The resulting linear system has to be recalculated through linearization for different model parameters.

**Procedure**

1. Run a simulation until the working point is reached.
2. Stop the simulation at operating point an select the **Linearize** command from the **Tools** menu.
3. Enter your options in the Linearization Dialog.

   ![Linearization Toolbox](image)

   *The Linearization Toolbox.*

**Items**

- **Input**: Use the button to select the input (u).
- **Output**: Use the button to select the output (y).
- **Linearization Kind**: Choose between open loop and closed loop linearization.
- **Linearize Type**: Choose between Symbolic and Numeric linearization.
- **Additional Settings**: When you are performing numeric linearization, select *At current time* when you want to linearize at the operating point where the simulation was stopped. Select *At start of simulation* when you want to linearize at the start of the simulation.
• **Tolerances:** 20-sim calculates a numerical linear state space model by small deviations of the complete model from the chosen setpoint. The deviations are based on the given absolute and relative tolerances. For most models the default values are sufficient. For stiff models you can change these values by hand.

• **OK:** click the OK button to start Linearization.

### Linearization Explained

During linearization you are asked to enter an input signal and an output signal of your (non-linear) model. During linearization, 20-sim will derive a corresponding linear system. It is important to understand that 20-sim will cut the model at the input. This will be explained with the example model below. It shows a linear system with feedback.

![Linear System Diagram](image)

**Closed Loop**

Suppose we would choose the following settings:

- `input u: WaveGenerator\output`
- `output y: Monitor\input`
- `kind: Closed Loop`

This means that 20-sim will **add an input** `u` and linearize the model between this variable and the variable `Monitor\output` (equal to `y` in the figure below). 20-sim will thus linearize the system between `u` and `y` and (in this example) yield the **closed loop system**.

**Open Loop**

Suppose we would choose the following settings:

- `input u: PlusMinus\output`
- `output y: Monitor\input`
- `kind: Open Loop`

This means that 20-sim will **cut** the model at the variable `PlusMinus\output` (equal to `u` in the figure below) and linearize the model between this variable and the variable `Monitor\input` (equal to `y` in the figure below). 20-sim will thus linearize the system between `u` and `y` and (in this example) yield the **open loop system**.
Frequency Response

Next to time domain analysis through the standard time domain plots, 20-sim can also show results in the frequency domain through FFT analysis and Bode Plots. The picture below shows the various actions and resulting plots.

Bode plots originate from linear systems theory. A bode plot shows the amplitude and phase response (as a function of the frequency) of a linear system. In 20-sim linear systems can be derived in the Simulator out of any linear or non-linear model (model linearization). The resulting linear system is shown in the Linear System Editor. In this editor you can generate Bode plots. The generation of Bode plots can be automated in the Frequency Response dialog. In this dialog you can define the linearization settings and desired linearization output (Linear System Editor or Bode plot).

Procedure

1. Select the **Frequency Response** from the command from the **Properties** menu.
2. Enter your options in the Frequency Response Dialog.
10. Toolboxes

The Frequency Response dialog.

**Items**

- **Input Probes**: Enter possible input signals for linearization here.
- **Output Probes**: Enter possible output signals for linearization here.
- **Frequency Response**: With the Add Frequency Response you can add new input/output pairs. For every input/output pair linearization will be performed with a corresponding linear system as result.
- **Symbolic/Numeric**: Select the desired linearization method.
- **Closed Loop**: By default all linearization is open loop. Select the Closed Loop option to perform closed loop linearization.
- **At start of simulation/At current time**: Select the time of the linearization.
- **Tolerances**: For numeric linearization you can enter the absolute and relative tolerances.
- **Output**: Select the desired output of the linearization.
- **Frequency Range**: Select the desired frequency range.
- **OK**: click the OK button to close the dialog.
10. Toolboxes

Linearization Tolerances

When using numerical linearization, absolute and relative tolerances can be set. In this section is explained how 20-sim uses these tolerances to derive a linear system for the model equations.

Algorithm

Suppose you have chosen the following tolerance values.

\[ \alpha = \text{absolute tolerance (e.g. } 1e^{-6} \) \\
\[ \beta = \text{relative tolerance (e.g. } 1e^{-3} \)

Suppose we have the following model:

\[ \text{ddt (x)} = 4 \times x + 2 \times u; \quad \text{// with } u = 1 \]
\[ y = 1 \times x + 3 \times u; \quad \text{// with } x = 2 \]

During the linearization procedure (suppose linearization from \( u \) to \( y \)) 20-sim will vary the input variable and state variables. First we will show the variation for the input \( u \):

\[ u' = (1 + \beta)u + \alpha \]
\[ u'' = (1 - \beta)u - \alpha \]
\[ \text{delta}_u = \beta u + \alpha \]

this will yield

\[ x_{dot'} = 10.002002 \quad \text{and} \quad y' = 5.003003 \]
\[ x_{dot''} = 9.997998 \quad \text{en} \quad y'' = 4.996997 \]

Out of this 20-sim will calculate the \( B \) and \( D \) vectors of the state-space \( ABCD \) representation:
The variation of state variables is done accordingly:

\[ x' = (1 + \beta)x + \alpha \]
\[ x'' = (1 - \beta)x - \alpha \]
\[ \delta_x = \beta x + \alpha \]

this will yield

\[ x_{dot}' = 10.008004 \text{ en } y' = 5.002001 \]
\[ x_{dot}'' = 9.991996 \text{ en } y'' = 4.997999 \]

Out of this 20-sim will calculate the A matrix and C vector of the state-space ABCD representation:

\[ A = (x_{dot}' - x_{dot}'') / 2*\delta_x = 4 \]
\[ C = (y' - y'') / 2*\delta_x = 1 \]

The example system is linear, so the corresponding ABCD representation will give an equal system. The shown algorithm works equivalent for non-linear models. Suppose we have the following non-linear model:

\[ ddt(x) = 4 \times \sin(x) + 2 \times u; \text{ // with } u = 1 \]
\[ y = 1 \times x + 3 \times u; \text{ // with } x = 2 \]

This will yield:

\[ B = 2, D = 3, A = -1.668445, C = 1; \]

**Tolerance Values**

The absolute tolerance is necessary only if the input or state is zero. In that case the contribution of the relative tolerance is zero and will not give a contribution to the algorithm. There is however a problem with the absolute tolerance. Suppose the input = 1e-12 and the state = 1e+6 (ill-scaled model). For the input an absolute tolerance of 1e-6 will yield a far too large deviation, while the same absolute tolerance is negligible compared to the state. Only if both the state and input are nonzero the absolute tolerance can be made non-zero to yield good results.
10.5.3 Linear System Editor

Linear System Editor

The Linear System Editor of 20-sim allows you to enter or edit linear time-invariant models. It supports continuous and discrete-time single input/single output (SISO) systems with and without time delay. You can open the Linear System Editor from the Tools menu of the 20-sim Editor or by clicking Go Down on the Linear System model. A linear system can also be the result of a linearization operation in the 20-sim Simulator.

Menu

Some menu items are of particular importance.

- **File**: You can use the file menu to open, import and export linear systems.
- **Edit - Tolerance**: You can specify the tolerance for transforming between state-space and transfer functions.
- **Edit - Reduce System**: You can reduce the system order by pole-zero cancelation. The distance between poles and zeros to match for cancelation is given by the Reduction Tolerance.
- **View**: The view menu can be used for holding, clearing and refreshing plots.
**System Description**

- Pressing the **Edit** button will open a dialog for editing the linear system. Each description (State Space, Transfer Function, Zeros Poles Gain or Eigen Frequency) has a special dialog and can be used to specify continuous-time and discrete-time systems.

- In the 20-sim Simulator, out of an existing (non-linear) model a symbolic linear-system can be derived by means of linearization. This means that the relevant model parameters are preserved in the Linear System and the parameters button can be used to change parameters.

**Import/Export**

- Pressing the **s<->z** button will transform a continuous-time linear system into a discrete-time linear system and back.

- Pressing the **Filter** button opens the Filter Editor, where a filter can be designed. This filter can then be combined with the current linear system or replace the current linear system. If the linear system is a discrete-time system, the designed analog filter is automatically transferred into its digital equivalent.

- Pressing the **From Matlab** button and the **To Matlab** button allows for an instant exchange of the linear system with the Matlab workspace. Information is transferred numerically (no parameter relations are preserved)

- The button is only active when a Linear System has been imported through linearization. Clicking the button will import parameters from the simulation.

- The button is only active when a Linear System has been imported through linearization. Clicking the button will export the current parameters to the simulation.

**Plots**

You can inspect the time- and frequency responses of the linear system using:

- Step Response
- Bode Plot
- Nyquist Plot
- Nichols Chart
- Poles and Zeros (including root locus)

**Output**

- Clicking the **20-sim** button will export the linear system as a new 20-sim submodel.

- Clicking the **Matlab** button will export the 20-sim Linear System to a Matlab m-file. If the Linear System is symbolic, all parameter relations are preserved.
Symbolic Linear Systems

In the 20-sim Simulator, out of an existing (non-linear) model a symbolic linear-system can be derived by means of linearization. This means that the relevant model parameters are preserved in the Linear System.

The relation between the original model parameters and the linear system elements is always shown in the white square of Linear System editor, just below the system description. An example is shown in the first figure below:

As you can see, the some elements of the A, B, C and D matrix are related to the spring constant and masses of the original model.

**Editing**

A symbolic linear system can be edited by changing the original model parameters. Click the Edit Parameters button and a Parameters Editor pops-up. Change the desired parameters, close the Parameters Editor and the linear system will updated.


### Updating Parameters

When the parameters have been changed in the Linear System Editor you can update the parameters in the Simulator by clicking the **Update to Simulator** button. Click the **Update from Simulator** button to do it the other way.

### Exporting

You can export a symbolic Linear System to Matlab, with preservation of the parameter relations, by clicking the Matlab button or selecting Export to Matlab command from the File menu. This will generate an m-file that you can use in Matlab.

### Continuous and Discrete Linear Systems

The Linear System Editor works on continuous time as well as discrete time system. Pressing the $s \leftrightarrow z$ button will transform a continuous-time linear system into a discrete-time linear system and back. You can choose between a Bilinear transformation (Tustin), a Forward Euler transformation and a Backward Difference transformation. When a continuous-time system is transferred, the user is asked to specify the sample time of the discrete-time system.

If you want to transfer a linear system directly (i.e. replace the $z$ by and $s$ or vice versa), click the Edit button and select or deselect the Discrete Sample time.

### Output Delay

In the Linear System Editor you can add an output delay. Open the editor and click the Edit button to edit the system. Now a editor will open where you can set the output delay. The effects of this output delay is shown in the various plots that you can show of a linear system. The unit of the output delay is seconds.

The output delay is shown as an exponential added to the transfer function.

### Editor

### State Space Models

State space models use linear differential equations (continuous) or difference equations (discrete) to describe system dynamics. They are of the form:

\[
\frac{dx}{dt} = A \cdot x + B \cdot u \\
y = C \cdot x + D \cdot u
\]

\[
x_{n+1} = A \cdot x_n + B \cdot u_n \\
y_n = C \cdot x_n + D \cdot u_n
\]
with for example:

\[
A = \begin{bmatrix} 0 & 0.5 \\ -1 & -1 \end{bmatrix} \quad B = \begin{bmatrix} -0.1 \\ 0.1 \end{bmatrix} \\
C = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad D = [0]
\]

where x is the state vector and u and y are the input and output vectors. These models may arise from the equation of physics, from state space identification or as the result of linearization.

You can enter state space models by selecting the *State Space* button and clicking the *Edit* button.

This opens an editor in which you can enter the A, B, C and D matrices. Depending on the selection of the Discrete Linear System check box (and Sample Time) the system is a continuous-time or discrete-time system. You can enter the matrix elements in the white space areas. Separate column elements with Spaces or Commas. Enter new rows by clicking the Enter key (new line) or using a semicolon. Brackets ( e.g. [ ... ] ) may be used to denote the a matrix or vector.
The A-matrix, shown in the figure above can for example be entered as:

\[
\begin{bmatrix}
0 & 1 \\
-0.5 & -1
\end{bmatrix}
\]

or

\[0,1;-0.5,-1\]

or

\[
\begin{bmatrix}
0,1; \\
-0.5,-1
\end{bmatrix}
\]

**Output Delay**

To inspect the effects of time delay in your model, you can add output delay. The result will be visible in the various plots that you can show of a linear system. The unit of the output delay is seconds.

**Discrete Sample Time**

If you want to transfer a linear system from continuous time to discrete time directly (i.e. replace the \(s\) by a \(z\)), select Discrete Sample time and fill in the sample time value. You can also transfer back directly by deselecting Discrete Sample time.

**Commands**

- **Help**: Open the help file.
- **Apply**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero).
- **OK**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero) and close the editor.
- **Cancel**: Do not apply any changes to the system and close the editor.

**Transfer Functions**

A continuous time or discrete time SISO transfer function:

\[
h(s) = \frac{n(s)}{d(s)} \quad h(z) = \frac{n(z)}{d(z)}
\]

(continuous) \hspace{1cm} (discrete)

is characterized by its numerator \(n\) and denominator \(d\), both polynomials of the variable \(s\) or \(z\).
You can enter transfer functions by selecting the *Transfer Function* button and clicking the *Edit* button.

This opens an editor in which you can enter the coefficients of the numerator and denominator polynomials. You can enter the elements in the white space areas. Separate the elements with Spaces. Polynomials should be entered in descending powers of \( s \) or \( z \). The Steady State Gain, Root Locus Gain and System Gain are parameters, that are automatically derived from the transfer function.

In the editor shown above the transfer function
was given. You can enter the coefficients as:

1

and

1 0.5 1

or

0.1,0.1

and

1,1,0.5

**Output Delay**

To inspect the effects of time delay in your model, you can add output delay. The result will be visible in the various plots that you can show of a linear system. The unit of the output delay is seconds.

**Discrete Sample Time**

If you want to transfer a linear system from continuous time to discrete time directly (i.e. replace the $s$ by a $z$), select Discrete Sample time and fill in the sample time value. You can also transfer back directly by deselecting Discrete Sample time.

**Commands**

- **Help**: Open the help file.
- **Apply**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero).
- **OK**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero) and close the editor.
- **Cancel**: Do not apply any changes to the system and close the editor.

**Gains**

**Steady State Gain**

Given the transfer function:

$$ h(s) = \frac{n(s)}{d(s)} = \frac{n_i \cdot s^i + n_{i-1} \cdot s^{i-1} + \ldots + n_0 \cdot s^0}{d_j \cdot s^j + d_{j-1} \cdot s^{j-1} + \ldots + d_0 \cdot s^0} $$

the **Steady State Gain** is defined as:
Note that the steady state gain can be zero or infinite depending on the element values of the numerator and denominator!

**Root Locus Gain**

Given a system described by the transfer function:

\[
K_{RL} = \lim_{s \to 0} h(s) = \frac{n_i \cdot s^i + n_{i-1} \cdot s^{i-1} + \ldots + n_0 \cdot s^0}{d_j \cdot s^j + d_{j-1} \cdot s^{j-1} + \ldots + d_0 \cdot s^0}
\]

This transfer function can be rewritten in pole zero notation with

\[
h(s) = K_{RL} \frac{(s - z_1)(s - z_{i-1}) \ldots (s - z_0)}{(s - p_j)(s - p_{j-1}) \ldots (s - p_0)}
\]

where \(p_i \ldots p_j\) are the poles and \(z_i \ldots z_1\) are the zeros of the system. The gain \(K_{RL}\) is known as the **Root Locus Gain**. Note that it can easily be derived from the transfer function as:

\[
K_{RL} = \frac{\text{first element of } n(s)}{\text{first element of } d(s)} = \frac{n_i}{d_j}
\]

**System Gain**

Given the transfer function:

\[
h(s) = \frac{n(s)}{d(s)} = \frac{n_i \cdot s^i + n_{i-1} \cdot s^{i-1} + \ldots + n_0 \cdot s^0}{d_j \cdot s^j + d_{j-1} \cdot s^{j-1} + \ldots + d_0 \cdot s^0}
\]

If \(n0\) and \(d0\) are unequal to zero, this transfer function can be rewritten in pole zero notation with:

\[
h(s) = K_S \frac{(z'_i s + 1)(z'_{i-1}s + 1) \ldots (z'_0 s + 1)}{(p'_i s + 1)(p'_{i-1}s + 1) \ldots (p'_0 s + 1)}
\]

The gain \(K_S\) is known as the **System Gain**. If \(n0\) is zero and \(n1\) is nonzero an equivalent notation can be found with an extra \(s\) multiplied:

\[
h(s) = K_S \frac{(z'_i s + 1)(z'_{i-1}s + 1) \ldots (z'_0 s + 1) \cdot s}{(p'_i s + 1)(p'_{i-1}s + 1) \ldots (p'_0 s + 1)}
\]

If more numerator element are zero, extra multiplications with \(s\) are added. The same goes for denominator elements equal to zero. In general the System Gain can be derived from the transfer function as:
\[ K_S = \frac{\text{last nonzero element of } n(s)}{\text{last nonzero element of } d(s)} \]

**Relating the Gains**

The elements of the System Gain are related to the poles and zeros of the Root Locus Gain as:

\[ z'_i = -\frac{1}{z_i}, \quad p'_j = -\frac{1}{p_j} \quad \text{etc.} \]

If \( z_0 \) and \( p_0 \) are unequal to zero, the following equation holds:

\[ K_{RL} = K_S \frac{z_1 \cdot z_{i-1} \cdots z_0}{p_j \cdot p_{j-1} \cdots p_0} \]

The Root Locus Gain and the Steady State Gain are related as:

\[ K_{SS} = K_{RL} \frac{-z_1 \cdot -z_{i-1} \cdots -z_0}{-p_j \cdot -p_{j-1} \cdots -p_0} \]

**Zeros and Poles**

A continuous-time SISO transfer function can be described by the transfer function:

\[ h(s) = \frac{n(s)}{d(s)} = \frac{n_i \cdot s^i + n_{i-1} \cdot s^{i-1} + \ldots + n_0 \cdot s^0}{d_j \cdot s^j + d_{j-1} \cdot s^{j-1} + \ldots + d_0 \cdot s^0} \]

This transfer function can be rewritten in pole zero notation with

\[ h(s) = K_{RL} \frac{(s - z_1)(s - z_{i-1}) \ldots (s - z_0)}{(s - p_j)(s - p_{j-1}) \ldots (s - p_0)} \]

where \( p_1 \ldots p_l \) are the poles and \( z_1 \ldots z_l \) are the zeros and \( K_{RL} \) is the Root Locus Gain of the system. The same can be done for a discrete-time SISO transfer function.
You can enter zeros and poles by selecting the Zeros & Poles button and clicking the Edit button.
This opens an editor in which you can enter the real and imaginary parts of the zeros and poles as well as the Root Locus Gain. If preferred, you can also enter the System Gain. Note that zeros and poles always have conjugate when the imaginary part is non-zero. I.e. when you enter a pole with imaginary part 0.5 an extra pole is added with imaginary part -0.5.

**Output Delay**

To inspect the effects of time delay in your model, you can add output delay. The result will be visible in the various plots that you can show of a linear system. The unit of the output delay is seconds.

**Discrete Sample Time**

If you want to transfer a linear system from continuous time to discrete time directly (i.e. replace the s by a z), select Discrete Sample time and fill in the sample time value. You can also transfer back directly by deselecting Discrete Sample time.

**Commands**

- **Add/Delete**: Add or delete selected poles or zeros.
- **Help**: Open the help file.
- **Apply**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero).
- **OK**: Apply the current changes of the system, recalculate each plot that is active (step, Bode, Nyquist, Nichols, pole zero) and close the editor.
- **Cancel**: Do not apply any changes to the system and close the editor.
**Eigen Frequencies**

The Eigen Frequencies view is closely related to the pole zero notation and bode plot. It shows the resonance frequencies and anti-resonance frequencies that result from the given poles and zeros as well as some characteristic parameters from the bode plot.

You can enter transfer functions by selecting the *Eigen Freqs.* button and clicking the *Edit* button.
**Step Response**

The *Step Response* command calculates the systems response $y$ on a unit step input:

$$u = 0 \ (time < 0)$$
$$u = 1 \ (time >= 0)$$

20-sim automatically generates an appropriate range for the time response, based on the system dynamics. With the Plot Properties command (right mouse menu), you can change this horizon and recalculate the step response (click the Step command again).

**Plot Options**

Using the right mouse menu, you can use several options:

- *Plot Properties*: Set the general plot properties for the step response and specify the curve properties.
- *Numerical Values*: Inspect numerical values.
- *Step Characteristics*: Display rise time, overshoot, settling time and the steady state value of the step response.
- *Copy to Clipboard*: Copy the plot to the windows clipboard.
- *Print*: Print the plot.
- *Zoom in*: Show a detail of the plot.
- *Zoom out*: Show a larger portion of the plot.
- *Zoom Normal*: Show the complete plot.
Bode Plots

Bode Plots show the amplitude and phase of a linear system as function of the frequency. Bode plots can be shown for every 20-sim model through Linearization. During Linearization you are asked to enter the input variable and output variable for which linearization should be performed. After that the linear system is calculated and shown in the Linear System Editor. From the Linear System Editor you can generate a bode plot. These actions can also be predefined using the Frequency Response command of the Properties menu.

20-sim automatically generates a range of logarithmically displayed frequencies, based on the system dynamics. With the Plot Properties command (right mouse menu), you can change this horizon and recalculate the bode response (click the Bode command again).

The magnitude part of the plot can be displayed in dB or in absolute values. The phase part can be displayed in radians or degrees. The frequency can be displayed in radians per second or in Hz.

Plot Options

Using the toolbar or the right mouse menu, you can use various options:

- **Plot Properties**: Set the plot properties.
- **Numerical Values**: Inspect numerical values.
- **Magnitude (dB)**: Display magnitude in decibels
- **Magnitude (−)**: Display magnitude in absolute values.
- **Phase (rad)**: Display phase in radians.
- **Phase (deg)**: Display phase in degrees.
- **Frequency (rad/sec)**: Display frequency in radians per second.
- **Frequency (Hz)**: Display frequency in Hz.
- **Phase/Gain Margins**: Display the gain and phase margins.
- **Modulus Margin**: Display the Modulus Margin.
- **Unwrap Phase**: Display the phase plot as a continuous plot by selecting this option or as a folded plot between -180 and 180 deg. by deselecting this option.
- **Peak Response**: Display the peak response.
- **Copy to Clipboard**: Copy the plot to the windows clipboard.
- **Print**: Print the plot.
- **Zoom in**: Show a detail of the plot.
- **Zoom out**: Show a larger portion of the plot.
- **Zoom Normal**: Show the complete plot.

### Nyquist Diagram

The **Nyquist** command computes the Nyquist plot of a system.

20-sim automatically generates a range of real and imaginary parts, based on the system dynamics. With the **Plot Properties** command (right mouse menu), you can change this horizon and recalculate the Nyquist diagram (click the **Nyquist** command again).

### Plot Options

Using the right mouse menu, you can use several options:
- **Plot Properties**: Set the plot properties.
- **Numerical Values**: Inspect numerical values.
- **Phase/Gain Margins**: Display the gain and phase margins.
- **Modulus Margin**: Display the Modulus Margin.
- **Copy to Clipboard**: Copy the plot to the windows clipboard.
10. Toolboxes

- **Print**: Print the plot.
- **Zoom in**: Show a detail of the plot.
- **Zoom out**: Show a larger portion of the plot.
- **Zoom Normal**: Show the complete plot.

**Nichols Chart**

The *Nichols* command computes the Nichols chart of a system.

20-sim automatically generates a range of logarithmically displayed frequencies, based on the system dynamics. With the **Plot Properties** command (right mouse menu), you can change this horizon and recalculate the Nichols chart (click the *Nichols* command again). The magnitude part of the plot can be displayed in decibels (dB) or in absolute values. The phase part can be displayed in radians or degrees.

**Plot Options**

Using the right mouse menu, you can use several options:

- **Plot Properties**: Set the plot properties.
- **Numerical Values**: Inspect numerical values.
- **Magnitude (dB)**: Display magnitude in decibels.
- **Magnitude (-)**: Display magnitude in absolute values.
- **Phase (rad)**: Display phase in radians.
- **Phase (deg)**: Display phase in degrees.
- **Frequency (rad/sec)**: Display frequency in radians per second.
- **Frequency (Hz)**: Display frequency in Hz.
- **Phase/Gain Margins**: Display the gain and phase margins.
- **Modulus Margin**: Display the Modulus Margin.
- **Copy to Clipboard**: Copy the plot to the windows clipboard.
- **Print**: Print the plot.
- **Zoom in**: Show a detail of the plot.
10. Toolboxes

- **Zoom out**: Show a larger portion of the plot.
- **Zoom Normal**: Show the complete plot.

**Pole Zero Diagram**

The **Pole Zero** command plot the poles and zeros of a system and computes the root locus plot.

20-sim automatically generates a range of real and imaginary parts, based on the system dynamics. With the **Plot Properties** command (right mouse menu), you can change this horizon and recalculate the pole zero diagram (click the **Pole Zero** command again).

**Root Locus**

You can show the rootlocus plot by selecting **Root Locus** from the right mouse menu. Inspect the root locus gain by selecting **Numerical Values** from the right mouse menu.

**Plot Options**

Using the right mouse menu, you can use several options:

- **Plot Properties**: Set the plot properties.
- **Numerical Values**: Inspect numerical values.
- **Root Locus**: Show or hide the root locus plot.
- **Copy to Clipboard**: Copy the plot to the windows clipboard.
- **Print**: Print the plot.
- **Zoom in**: Show a detail of the plot.
- **Zoom out**: Show a larger portion of the plot.
- **Zoom Normal**: Show the complete plot.
Import Data

You can import data from measurements or other software tools to compare it with the response of your model. 20-sim accepts data in two formats:

- **Gain-Phase**: The data should be stored in a text-file with three columns. The first column should contain the frequency and the second and third column, the corresponding gain and phase data.

- **Real-Imag**: The data should be stored in a text-file with three columns. The first column should contain the frequency and the second and third column, the corresponding real and imaginary data.

Import Data

1. Open the Linear System Editor with your linear system.
2. Open the plot (e.g. Bode, Nyquist) in which you want to show the data.
3. Set the Magnitude (- or dB), Phase (rad or deg) and Frequency (rad/s or Hz) according to the data you want to import.
4. In the Linear System Editor from the **File** menu select **Import**.
5. Select Import **Gain-Phase** or **Import Real-Imag**.

Now a file dialog opens helping you to select the file to import. When you have selected a file and closed the dialog, the data should be visible in your plot. An example is shown in the figure above.
10.5.4 Dynamic Error Budgeting

Dynamic Error Budgeting

The performance of precision machines is mostly limited by the disturbances that are injected in these machines. These disturbances are often stochastic in nature. Dynamic Error Budgeting is a method whereby the effect of these disturbances on the final performance can be calculated. The advantage of this method is that it enables the designer to enter the contributions of the individual disturbances and view and optimize the overall machine performance.

The Dynamic Error Budgeting toolbox shows the total error as a result of injected disturbances.

Running the Toolbox

1. Open the example model Dynamic Error Budgetting from the Getting Started/Frequency Domain Toolbox.

You can open the Dynamic Error Budgeting tool in the Simulator:

2. From the Tools menu select Frequency Domain Toolbox and Dynamic Error Budgeting.
The Dynamic Error Budgeting tool.

The tool allows you to enter disturbances (as power spectral density) in the Input Noises section.

3. For each disturbance you have to select a corresponding variable by clicking the Add input noise button.

Each disturbance is effectively a summation to the chosen variable, just like closed loop linearization. You can inspect each disturbance in the graph on the top right.

Next you have to select an output variable, where the result of the disturbances is calculated.

4. Select the output by clicking the Add Output button.

In the graph on the bottom right you can see the resulting error at the selected output as a result of the disturbances. The error is given in the form of a power spectral density (PSD) and cumulative power spectral density (CPS). The square root of the final value of the CPS is equal to the standard deviation of the output error. The standard deviations are shown in the Output Sigma tab.
10.6 Scenario Manager

10.6.1 Introduction

Introduction
Scripting is very useful to run tasks automatically but they are not very user friendly and intuitive for users with little knowledge of scripting languages. The Scenario Manager fills this gap. You can use it to add actions (basic scripting functions) into a scenario (a set of actions) and run that automatically, without any knowledge of scripting languages.

The Scenario Manager can be used to run all kinds of tasks automatically:

- Change all kinds of model settings and run simulations (experiments)
- Check simulation outputs against pre-defined results (test automation)
- Run simulations and store the results on file (data storage)
- Generate C-code of submodels (code generation)

How does the Scenario Manager Work?
When you have a model ready for testing, you can open the Scenario Manager.

1. From the Tools menu select Scenario Manager.
2. Click on Scenario1.

Now you will see an empty Scenario Manager with Scenario1 selected:
The Pre-simulation bar, Simulation bar and Post-simulation bar allow you to add Actions. Actions in the Pre-Simulation bar will be carried out before the model is simulated. Actions in the Simulation bar will be carried out during a simulation. Actions in the Post-Simulation bar will be carried out after the model is simulated.

3. Click on the **Pre-simulation bar**, the **Simulation bar** or the **Post-simulation bar** to add Actions.
Under the bar a list of Actions is presented. If you click on an Action, it will be added to the bar.

4. Click on the **Action** to see its **Properties** at the right
You can set the Properties for the selected Action at the left. If you click on the Recycle Bin button at the top left, the Action will be removed from the bar.

**Scenario**

A set of Actions is called a Scenario. You may change the name of the Scenario in the tree at the left. If you select a Scenario in the tree, you can run it by clicking the **Play** button (white circle with black triangle) at the top middle.
Category

A Category may contain a set of Scenarios. You may change the name of the Category in the tree at the left. If you select a Category in the tree, and click the Play button (white circle with black triangle) at the top middle, all Scenarios in the Category will be run.
As you can see, the Pre-simulation bar, Simulation bar and Post-simulation bar have different color when a Category is selected. If you add an Action, this action will be present for all Scenarios under the Category. This is very useful if you have Actions that have to repeat for every Scenario.

Learn More

To learn more about the Scenario Manager:

1. Run the example model to see how it all works.
2. See which Actions can be used.
3. Inspect the results of an Action, using the logs.
4. Reset the changes made during a Scenario.
5. See where the Scenarios are stored on file.

Tips

You can use the Scenario Manager for a number of tasks. Here are some examples:

1. Run a simulation a number of seconds: You can run a simulation for a certain time by executing the Modules: Start Simulation - Wait for seconds - Stop Simulation.

2. Compare a simulation output with a previously recorded output: You can log a variable during a simulation with the module Log Variables, store it in a .csv-file with the Module Generate CSV and then use the Module Compare CSV to compare this value with a previously recorded value.
10. Toolboxes

3. Unit Testing: Insert a model from a library with the **Update Submodel** Module and then run a test.

4. Parameter Sweep: Set a parameter value and compare the simulation output with a previous run.

5. Test Automation: Defined the desired output of a simulation run and compare this with the real simulation output using an Assert model.

6. Change all kinds of model settings and run simulations (experiments)

7. Check simulation outputs against pre-defined results (test automation)

8. Run simulations and store the results on file (data storage)

9. Generate C-code of submodels (code generation)

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### 10.6.2 Example

Introduction

You can see the toolbox in action with the example model *Lifting System - Test Automation*. We will run this model to show you how the Scenario Manager can be used.

Editor

1. In the 20-sim **Editor** go to the **Library** tab

2. In the Library tab select **Examples - Signal Processing - Lifting System - Test Automation**.

3. **Drag and drop** the model to the right to open the model.

Now the Editor will look like:
As you can see, in the model two AssertSignal blocks have been added.

- **AssertSignal1 (Continuous):** compares the actual position with the set-point position. If both deviate more than 5 cm, the output testResult goes from true to false.

- **AssertSignal2 (Boolean):** The minimum value of the pressures in both chambers is compared with a constant signal of 5 bar. If any one of the pressures is lower, the output of the AssertSignal2 block testResult goes from true to false.

We will use the two AssertSignal blocks to verify the outcomes of several Scenarios in the Scenario Manager.

**Scenario Manager**

Now we will open the Scenario Manager and run some scenarios:

1. From the **Tools menu** select **Scenario Manager**.

2. Select **Proportional Gains**.

The Scenario Manager will look like:
Category
At the left in the Scenario Manager you will see a tree with Categories and Scenarios. Categories are listed directly under Home. In the picture above you see the category Proportional Gains, the Category Valve Settings and the Category Failing Tests. Under the Categories, the Scenarios are listed (kp = 4 etc, kp = 5, kp = 6, Gleak = 1e-14 etc.).

In the middle of the Scenario Manager, you can see the various Actions that have been selected. Each Action will perform a certain task. Actions are carried out sequentially, from the left to the right, and from the top to the bottom. In the picture above, the category Proportional Gains is selected. The Actions that apply for this Category are indicated in purple:

- Pre-simulation: The Actions that are shown here, are carried out before the simulation. In the picture above no Actions have been selected.
- Simulation: The Actions that are shown here, are carried out during the simulation. In the picture above the Actions Run Simulation and OK to Continue are shown.
- Post-simulation: The Actions that are shown here, are carried after a simulation. In the picture above the two Actions AssertTest are shown.

Scenario

Now the Scenario Manager will look like:
As you can see, the Pre-simulation bar shows one Action extra, *Set Parameter*. The color of the Actions is blue.

- Actions from a Category are shown in purple.
- Actions from a Scenario are shown in blue.
- When running a scenario, all Actions will be executed.

In the Scenario of the picture above a parameter value will be set, the simulation will be run followed by asking the user to press OK and then check the output of the *AssertSignal* modules.

**Running a Category**

4. Open the 20-sim Simulator: In the 20-sim Editor click **Model - Start Simulator**.

5. Move the **Simulator** window on aside from the **Scenario** Manager window, so you can see both.

6. In the Scenario Manager choose the Category **Proportional Gains**

7. Click on the **Play** button 🏃

Now the first scenario of this Category will be run. In the Simulator window you can see the simulation run:
8. Press **OK** after each run.

After the three runs have been performed, the Scenario Manager will look like:

![Scenario Manager](image)

Left of the Scenarios, you will see V-signs indicating that the Scenarios were run successfully: the AssertSignal blocks have given a **true** output at the end of each run.

9. In the Scenario Manager choose the Category **Valve Settings**.
10. Toolboxes

10. Click on the **Run category** button.

Now three Scenarios will be run without asking you to click OK. Left of the Scenarios, you will see V-signs indicating that the tests were successful.

11. In the Scenario Manager choose the Category **Failing Tests**

12. Click on the **Run category** button.

Left of the Scenarios, you will see red crosses, indicating that the tests were not successful: the AssertSignal blocks have given a **false** output at the end of each run.

**Running a Scenario**

You can also run a Scenario individually.

13. In the Scenario Manager choose the Scenario **Amax = 1e-8**

14. Click on the **Play** button.

Now the Scenario will run. After the Scenario has been run, one of the Actions has a red edge. If you click on the Action, you will see the corresponding log. It will show that at a time = 0.16 s the simulation output was deviating too much from the desired value.

**Inspecting a Module**

You can inspect a module by clicking on it.

15. In the Scenario Manager **click** on the Module **Set Parameter**.
Now the Scenario Manager will look like:

At the right of the Scenario manager, you can see the settings of this Action. It will set the parameter of the 20-sim model to a certain value. By clicking on the pencil buttons, you can change the settings.
10.6.3 Actions

The following Actions are available in the Scenario Manager.

**Pre-simulation**

- **Add Plot Window**: Create a new plot in 20-sim and show variables.
- **Generate Code**: Create C-code from a 20-sim model.
- **Implementation**: Change the implementation of a submodel.
- **Log Variables**: Log a variable in memory during a simulation run.
- **OK to Continue**: Ask the user to click OK to continue.
- **Set Parameter**: Change the value of a parameter.
- **Simulator Setting**: Change the settings of the Simulator: Fast mode, Endless mode, Start time, Finish Time, Event Delta, Output after each, Integration method.
- **Update Submodel**: Exchange a submodel in your model with a submodel from file.

**Simulation**

- **Generate Code**: Create C-code from a 20-sim model.
- **Generate CSV**: Store the variables that have been logged on a .csv-file.
- **Log Variables**: Log a variable in memory during a simulation run.
- **OK to Continue**: Ask the user to click OK to continue.
- **Run Simulation**: Run a simulation from start time to finish time. If the finish time is passed, the simulation will stop, even if endless simulation has been chosen. After passing the finish time the next Module will be executed.
- **Set Parameter**: Change the value of a parameter.
- **Simulator Setting**: Change the settings of the Simulator: Fast mode, Endless mode, Start time, Finish Time, Event Delta, Output after each, Integration method.
- **Start Simulation**: Start a simulation run and execute the next module. The simulation will stop when all Modules have been executed or the Stop Simulation Module is executed.
- **Stop Simulation**: Stop a running Simulation.
- **Update Submodel**: Exchange a submodel in your model with a submodel from file.
- **Wait for Seconds**: Wait a number of second before executing the next Module.

**Post-simulation**

- **Assert Test**: This Module will ask you to select a submodel. It will look inside this submodel for a boolean output signal testResult. If this signal is true at the end of the simulation run, the test was successful and a V-sign is placed next to the scenario, otherwise a red cross will be placed.
- **Compare CSV**: Compare the values in two .csv-files.
- **Generate Code**: Create C-code from a 20-sim model.
- **Generate CSV**: Store the variables that have been logged on a .csv-file.
- **Implementation**: Change the implementation of a submodel.
- **OK to Continue**: Ask the user to click OK to continue.
- **Set Parameter**: Change the value of a parameter.
### 10.6.4 Action Logs

With the Logging Active button displayed:

Logging will be active during the running of the Scenario. After a run is complete, you can inspect the log, by clicking on an Action. Now the log of that Action will be displayed below the Action.

Inspecting the log is useful to see if an action was carried out properly. If an Action fails (e.g. file cannot be found, no writing permission,..), the cause will be displayed in the log.

### 10.6.5 Reset Model

With the Reset Model button displayed:
all changes made to a model, during a scenario, will be reset after the scenario has been run. This very useful if you do not want to mess up you model, but sometimes unwanted. Uncheck this button, if you want to keep the changes made to the model.

10.6.6 File Storage

File Locations
All settings for the Scenario Manager are stored in a folder named *Scenario Manager* with the same folder as the 20-sim model. Suppose you have stored a 20-sim model as:

C:\temp\models\my 20sim model.emx

Then the Scenario Manager files are stored in the folder:

C:\temp\models\ScenarioManager\my20simmodel\n
Inside this folder you will find a log file

C:\temp\models\ScenarioManager\my20simmodel\build_server_log.txt

Inside the log file you can see the outcomes of the Scenarios that have been run.

Copies
If you want to copy the Scenario Manager with a 20-sim model, make sure that you copy the folder

ScenarioManager\my20simmodel\n
with the 20-sim model.
10.7 Mechatronics Toolbox

10.7.1 Cam Wizard

How to use the Cam Wizard

Introduction
Cams and mechanisms are all based on the same principle. The motion of an input axis is transformed to an output axis or translation. The transformation is a function of the input angle. This function is called the **cam motion profile**.

The 20-sim cam wizard helps you to generate cam and mechanism models. You can use various types of motion profiles which are continuous in velocity, acceleration or even in jerk! An example of a mechanism that can be generated by the Cam wizard is the crank-rod mechanism, where a rotary input motion is transformed to a translating output motion.

The models that are generated by the 20-sim Cam wizard are fully dynamic! This means:

- The models describe the output velocity as function of the input velocity but also the input torque as function of the output load.
- The speed of the input axis does not have to be constant nor does the output load.
- No inertia, stiffness or other dynamic behavior is included, but this can be easily incorporated by coupling elements from the 20-sim library (inertias, springs etc.) to the input or output of the model.

Example
To generate a cam or mechanism model in 20-sim, follow the next steps.
1. Open the 20-sim model library and go to the section Iconic Diagram\Mechanical \Rotation\Gears and drag the model Cam-Wizard.emx to the editor. You can also select in the Editor: Tools - Mechatronics Toolbox - Cam Wizard.

2. Select the Cam-Wizard model and click Go Down. Now the wizard will be opened.

3. Choose the desired motion profile, the profile parameters and type of output (translation/rotation):

5. Select the type of cam motion profile:
6. Enter the parameters values (Stroke, Start Angle Stop Angle). If you have chosen a continuous pulse as output, you must also enter the values for the Return Angle and End Angle:

7. In the last page, the resulting values are shown:
8. Click Finish and the cam model will be defined. All you have to do is to connect the input axis \((p_{\text{in}}, \text{rotation})\) and the output axis \((p_{\text{out}}, \text{rotation or translation})\) of the cam model.

**Note**

1. If you have changed the settings of this wizard, you have to process the model first (from the **Model** menu, choose **Check Complete Model**) before the changes become effective.

2. You can change parameter values during simulation (from the **Properties** menu select **Parameters**).

3. This is a masked model that uses the dll-file MotionProfile.dll to open the wizard. This dll-function must be stored in the bin directory of 20-sim. To see the SIDOPS code of a masked model press the **shift-key**, while clicking the **Go Down** command.
Cam Motion Profiles

Motion Types
Two types of motion profiles can be generated by the Cam wizard: intermittent steps and continuous pulses. The intermittent step motion does not return to its starting position, but gradually moves further away. It is characterized by the parameters stroke, start_angle and stop_angle.

The continuous pulse motion output returns at the end of each cycle returns to the starting position. It is characterized by the parameters stroke, start_angle, stop_angle, return_angle and end_angle.

Motion Profiles
In mechanical engineering an important part of design is the reduction of vibrations. Every time a construction is in motion, vibrations are induced. When cams or mechanisms are used, the amount of vibrations, depend on the kind of motion that is induced. E.g. a sudden step change will induce violent vibrations in comparison with with a fluent motion. An important parameter to characterize motions, is the order:

1. Zero Order: Motions that are discontinuous in the position (e.g. a step).
2. First Order: Motions that are continuous in the position but discontinuous in the velocity (e.g. a ramp).
3. Second Order: Motions that are continuous in the position and velocity but discontinuous in the acceleration.
4. Third Order: Motions that are continuous in the position, velocity and acceleration.
5. **Fourth Order**: Motions that are continuous in the position, velocity, acceleration and jerk.

The specific shape of a motion profile can have a significant influence on the dynamic behavior. Some profiles minimize the maximum velocity, some profile minimize acceleration, while other profiles tend to make a tradeoff between the maximum velocity and acceleration. If we take a standard motion with stroke 1 and motion time 1 sec., the following table can be generated:

<table>
<thead>
<tr>
<th>profile</th>
<th>order</th>
<th>(v_{\text{max}})</th>
<th>(a_{\text{max}})</th>
<th>(y(0))</th>
<th>(y(1/2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp</td>
<td>1</td>
<td>1</td>
<td>infinite</td>
<td>infinite</td>
<td>0</td>
</tr>
<tr>
<td>Crank-Rod(^2)</td>
<td>2</td>
<td>&gt; 1.57</td>
<td>&gt; 4.93</td>
<td>infinite</td>
<td>&lt; -15.5</td>
</tr>
<tr>
<td>Trapezoidal</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>infinite</td>
<td>-infinite</td>
</tr>
<tr>
<td>Partial Trapezoidal(^1)</td>
<td>2</td>
<td>1.67</td>
<td>4.17</td>
<td>infinite</td>
<td>0</td>
</tr>
<tr>
<td>Geneva Mechanism</td>
<td>2</td>
<td>2.41</td>
<td>8.49</td>
<td>infinite</td>
<td>-118.5</td>
</tr>
<tr>
<td>Sine</td>
<td>2</td>
<td>1.57</td>
<td>4.93</td>
<td>infinite</td>
<td>-15.5</td>
</tr>
<tr>
<td>Cubic</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>32</td>
<td>-32</td>
</tr>
<tr>
<td>Partial Cubic(^3)</td>
<td>3</td>
<td>1.67</td>
<td>5.55</td>
<td>55.6</td>
<td>0</td>
</tr>
<tr>
<td>Cycloidal</td>
<td>3</td>
<td>2</td>
<td>6.28</td>
<td>39.5</td>
<td>-39.5</td>
</tr>
<tr>
<td>Modified Sine</td>
<td>3</td>
<td>1.76</td>
<td>5.53</td>
<td>69.4</td>
<td>-23.2</td>
</tr>
<tr>
<td>Modified Trapezoidal</td>
<td>3</td>
<td>2</td>
<td>4.88</td>
<td>61.4</td>
<td>-61.4</td>
</tr>
<tr>
<td>MSC50</td>
<td>3</td>
<td>1.26</td>
<td>9.20</td>
<td>173.6</td>
<td>0</td>
</tr>
<tr>
<td>MSC%(^4)</td>
<td>3</td>
<td>1.37</td>
<td>7.20</td>
<td>113.1</td>
<td>0</td>
</tr>
<tr>
<td>3-4-5 Polynomial</td>
<td>3</td>
<td>1.88</td>
<td>5.77</td>
<td>60</td>
<td>-30</td>
</tr>
<tr>
<td>1-3-5-7-9 Polynomial(^5)</td>
<td>3/4</td>
<td>2.05</td>
<td>10.25</td>
<td>BB</td>
<td>BM</td>
</tr>
</tbody>
</table>

1: Parameter CV = 20%
2: For \(lw >> lc\) the Crank Rod profile equals the sine profile, for \(lw > lc\) performance deteriorates.
3: Parameter CV = 20%, CA = 20%
4: Parameter \(n = 30\%\), alpha = 10%
5: Parameter BB = 30%, BM = 10%
Here \( y(0) \) is the initial jerk (derivative of acceleration) and \( y(1/2) \) the crossover (halftime) jerk.

**Ramp**
The ramp profile is a first order profile. It has a constant velocity and acceleration peaks at the start and end of the motion.

**Crank Rod Mechanism**
A Crank Rod mechanism converts a rotary motion into a repeating translation and

If the rod is much longer than the crank, the resulting motion profile will approach the sine profile. Below the motion profile is shown for half a rotation of the crank (angle from 0 to 180 degrees in 1 sec.).
If the rod gets smaller, the maximum velocity and acceleration increase.

**Note:** A real crank-rod mechanism will not suddenly stop at half a rotation and therefore not show a discontinuous acceleration.

**Trapezoidal**

The trapezoidal profile is a second order profile. It has a constant acceleration at the start of the motion and a constant deceleration at the end of the motion.
This profile is most widely used in early servo systems. Because of the discontinuity in the acceleration this motion profile can still induce a lot of vibrations. Therefore in modern servo systems third order profiles are preferred.

**Partial Trapezoidal**

The partial trapezoidal profile is a second order profile. It has an equal to the trapezoidal motion, but has a constant velocity part, during a fraction $CV$ (%) of the motion.

**Geneva Mechanism**

A Geneva mechanism is an old motion profile generation mechanism. A continuously rotating crankshaft (a) generates an intermittent motion of a second shaft (b). The result is a second order profile.

The motion profile generator yields the motion of the second shaft (b). It is shown below:
The sine profile is a second order profile of which the displacement can be described as:

\[ x = 0.5 - \cos (p \times t) / 2. \]

The cubic profile is a third order profile of which the acceleration is constantly increasing and decreasing.

The partial cubic profile (3rd order) is a modified cubic profile with a constant velocity during a fraction $CV$ (%) of the motion and a constant acceleration during a fraction $CA$ (%) of the motion.
Cycloidal
The cycloidal profile is a third order profile, of which the velocity can be described as:

\[ v = \text{stroke} \times (1 - \cos(t \times a)) \]

Modified Sine
The modified sine profile is also a third order profile. It is a modification of the cycloidal profile to get a lower maximum velocity and a lower maximum acceleration.

Modified Trapezoidal
The modified trapezoidal profile is a modification of the trapezoidal profile (to make it a third order profile). This profile yields a very low maximum acceleration.
**Modified Sine with Constant Velocity (MSC50)**

The modified sine with constant velocity profile (3rd order) is a modification of the modified sine profile. It has a constant velocity during 50% of the motion.

**General Modified Sine with Constant Velocity (MSC%)**

The modified sine with constant velocity profile (3rd order) is a modification of the modified sine profile. It has a constant velocity during a user definable part of the motion. The non-zero acceleration part is defined by two parameters which are both defined as a fraction of the motion. The first parameters $\alpha$ (%) defines the start of the acceleration and the second parameters $n$ (%) defines the end of the acceleration.

**3-4-5 Polynomial**

The is a third profile described by a 5th order polynomial.
\textbf{1-3-5-7-9 Polynomial}

The is a third/fourth order profile described by a 9th order polynomial. The profile is characterized by two parameters that denote the initial jerk, $BB$, and the crossover jerk, $BM$. If $BB$ is chosen zero, this is a fourth order profile. If $BB$ is chosen non-zero, this is a third order profile.

\textbf{10.7.2 Motion Profile Wizard}

\textbf{Motion Profile Wizard}

The 20-sim Motion Profile Wizard helps you to define motion profiles. To generate such a profile, follow the next steps.

1. Open the 20-sim model library an go to the section Signal\Sources and drag and drop the model MotionProfileWizard.emx to the editor. You can also select in the Editor: \textit{Tools - Mechatronics Toolbox - Motion Profile Wizard}.

2. Select the model and click \textbf{Go Down}.

This is a masked model. Clicking Go Down will open the \textit{Motion Profile Wizard}.

4. Select the inputs and outputs:
A number of inputs and outputs are available:

- **External Input**: Normally the time will be used for the x-axis of the profile. You can however use an external input as x-axis variable.
- **On/Off**: Use this input signal to start (onoff = TRUE) and stop (onoff = FALSE) the profile.
- **Reset**: When the reset signal gets high (reset = TRUE) the profile will be started.
- **Reference**: The motion profile reference signal, e.g. position.
- **First Derivative**: The first derivative of the motion profile reference signal, e.g. velocity.
- **Second Derivative**: The second derivative of the motion profile reference signal, e.g. velocity.
- **Profile Counter**: Gives the number of profiles that have been generated.
- **Ready Signal**: Gets high (ready = TRUE) when the profile is completely generated.

5. Click **Next** to enter the desired profile.

6. You can enter as many profiles as needed to design the complete motion. You can choose out of a number of predefined profiles.
7. Choose the number of times the motion should be repeated.

8. Click **Next** to go to the last page.

In the last page, you can choose to generate Time Events and what to show the next time (the wizard or the generated code). Use the default settings if you are not sure what to use.
9. Click **Next** to go to close the Wizard.

10. In the Editor from the **Model** menu Check Complete Model to make the changes effective.

**Motion Profile Wizard (Old Style)**

If you select the model `MotionProfile.emx` and click **Go Down**, the old style Motion Profile Wizard will open. This wizard is kept in 20-sim to allow you to run old models. The wizard has been replaced by a new wizard which is far more powerful.

**Description**

The 20-sim Motion Profile Wizard helps you to define motion profiles. To generate such a profile, follow the next steps.

1. Open the 20-sim model library an go to the section **Signal\Sources**.
2. Drag and drop the model `MotionProfile.emx` to the editor.
3. Select the model and click **Go Down**. Now the wizard will be opened.
4. Select the type of motion.
5. Choose the desired profile and output signals.
6. Enter the profile parameters.
7. Close the wizard.

During simulation the parameter values are used that you have selected in the wizard. These parameters are available in the Parameters Editor where you can change them as you would do with any other model. If you have changed the settings of this wizard, you have to process the model first (from the Model menu, choose Check Complete Model) before the changes become effective.

**Motion Profiles**

You can choose out of a number of predefined motion profiles in the Motion Profile Wizard.

- Flat
- Ramp
- Trapezoidal
- Partial Trapezoidal
- Geneva Mechanism
- Sine
- Cubic
- Partial Cubic
- Cycloidal
- Standard Modified Sine
- Modified Trapezoidal
- Modified Sine with Constant Velocity (MSC50)
- General Modified Sine with Constant Velocity (MSC%)
- 3-4-5 Polynomial
- 1-3-5-7-9 Polynomial

**Flat**

The flat profile is a zero order profile. It has a constant position, zero velocity and acceleration.

**Ramp**

The ramp profile is a first order profile. It has a constant velocity and acceleration peaks at the start and end of the motion.
The ramp profile.

Trapezoidal
The trapezoidal profile is a second order profile. It has a constant acceleration at the start of the motion and a constant deceleration at the end of the motion.

Partial Trapezoidal
The partial trapezoidal profile is a second order profile. It has is equal to the trapezoidal motion, but has a constant velocity part, during a fraction CV (%) of the motion.

This profile is most widely used in early servo systems. Because of the discontinuity in the acceleration this motion profile can still induce a lot of vibrations. Therefore in modern servo systems third order profiles are preferred.
Geneva Mechanism
A Geneva mechanism is an old motion profile generation mechanism. A continuously rotating crankshaft (a) generates an intermittent motion of a second shaft (b). The result is a second order profile.

The motion profile generator yields the motion of the second shaft (b). It is shown below:

Sine
The sine profile is a second order profile of which the displacement can be described as:
\[ x = 0.5 - \cos(p \times t)/2. \]

**Cubic**

The cubic profile is a third order profile of which the acceleration is constantly increasing and decreasing.

**Partial Cubic**

The partial cubic profile (3rd order) is a modified cubic profile with a constant velocity during a fraction CV (%) of the motion and a constant acceleration during a fraction CA (%) of the motion.
The cycloidal profile is a third order profile, of which the velocity can be described as:

\[ v = \text{stroke} \cdot (1 - \cos(t \cdot a)) \]

**Modified Sine**

The modified sine profile is also a third order profile. It is a modification of the cycloidal profile to get a lower maximum velocity and a lower maximum acceleration.
Modified Trapezoidal
The modified trapezoidal profile is a modification of the trapezoidal profile (to make it a third order profile). This profile yields a very low maximum acceleration.

Modified Sine with Constant Velocity (MSC50)
The modified sine with constant velocity profile (3rd order) is a modification of the modified sine profile. It has a constant velocity during 50% of the motion.
**General Modified Sine with Constant Velocity (MSC%)**

The modified sine with constant velocity profile (3rd order) is a modification of the modified sine profile. It has a constant velocity during a user definable part of the motion. The non-zero acceleration part is defined by two parameters which are both defined as a fraction of the motion. The first parameters \( \alpha \) (%) defines the start of the acceleration and the second parameters \( n \) (%) defines the end of the acceleration.

![General Modified Sine Constant Velocity](image)

The general modified sine with constant velocity profile.

**3-4-5 Polynomial**

This is a third profile described by a 5th order polynomial.

![3-4-5 Polynomial](image)

The 1-3-5 polynomial profile.

**1-3-5-7-9 Polynomial**

This is a third/fourth order profile described by a 9th order polynomial. The profile is characterized by two parameters that denote the initial jerk, \( BB \), and the crossover jerk, \( BM \). If \( BB \) is chosen zero, this is a fourth order profile. If \( BB \) is chosen non-zero, this is a third order profile.
To keep the polynomial consistent, i.e. the polynomial does not change when the amplitude is changed, the initial jerk ($BB$) and the crossover jerk ($BM$) are defined for a standard motion with:

- $stroke = 1$
- $start\_time = 0$
- $stop\_time = 1$

**Comparison of Profiles**

The specific shape of a motion profile can have a significant influence on the dynamic behavior. Some profiles minimize the maximum velocity, some profile minimize acceleration, while other profiles tend to make a tradeoff between the maximum velocity and acceleration. If we take a standard motion with stroke 1 and motion time 1 sec., the following table can be generated:

<table>
<thead>
<tr>
<th>profile</th>
<th>order</th>
<th>vmax</th>
<th>amax</th>
<th>j(0)</th>
<th>j(1/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ramp</td>
<td>1</td>
<td>1</td>
<td>infinite</td>
<td>infinite</td>
<td>0</td>
</tr>
<tr>
<td>Trapezoidal</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>infinite</td>
<td>-infinite</td>
</tr>
<tr>
<td>Partial Trapezoidal1</td>
<td>2</td>
<td>1.67</td>
<td>4.17</td>
<td>infinite</td>
<td>0</td>
</tr>
<tr>
<td>Geneva Mechanism</td>
<td>2</td>
<td>2.41</td>
<td>8.49</td>
<td>infinite</td>
<td>-118.5</td>
</tr>
<tr>
<td>Sine</td>
<td>2</td>
<td>1.57</td>
<td>4.93</td>
<td>infinite</td>
<td>-15.5</td>
</tr>
<tr>
<td>Cubic</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>32</td>
<td>-32</td>
</tr>
<tr>
<td>Partial Cubic3</td>
<td>3</td>
<td>1.67</td>
<td>5.55</td>
<td>55.6</td>
<td>0</td>
</tr>
<tr>
<td>Cycloidal</td>
<td>3</td>
<td>2</td>
<td>6.28</td>
<td>39.5</td>
<td>-39.5</td>
</tr>
<tr>
<td>Modified Sine</td>
<td>3</td>
<td>1.76</td>
<td>5.53</td>
<td>69.4</td>
<td>-23.2</td>
</tr>
<tr>
<td>Modified Trapezoidal</td>
<td>3</td>
<td>2</td>
<td>4.88</td>
<td>61.4</td>
<td>-61.4</td>
</tr>
<tr>
<td>MSC50</td>
<td>3</td>
<td>1.26</td>
<td>9.20</td>
<td>173.6</td>
<td>0</td>
</tr>
<tr>
<td>MSC%4</td>
<td>3</td>
<td>1.37</td>
<td>7.20</td>
<td>113.1</td>
<td>0</td>
</tr>
<tr>
<td>3-4-5 Polynomial</td>
<td>3</td>
<td>1.88</td>
<td>5.77</td>
<td>60</td>
<td>-30</td>
</tr>
</tbody>
</table>
1: Parameter CV = 20%
2: For lw >> lc the Crank Rod profile equals the sine profile, for lw > lc performance deteriorates.
3: Parameter CV = 20%, CA = 20%
4: Parameter n = 30%, alpha = 10%
5: Parameter BB = 30%, BM = 10%

Here j(0) is the initial jerk yerk (derivative of acceleration) and j(1/2) the crossover (halftime) jerk.

10.7.3 Servo Motor Editor

Servo Motor Editor

Introduction

The 20-sim Servo Motor Editor is a tool to generate dynamic models of servo motors for the use in 20-sim. These models describe the complete dynamic behaviour of servo motors, including the electrical, mechanical and thermal behaviour. The following classes of motors are supported in the editor:

1. Brush DC
2. Brushless DC (trapezoidal EMC and square wave currents)
3. AC synchronous (sinusoidal EMC and sinusoidal currents)
4. AC synchronous linear (sinusoidal EMC and sinusoidal currents)

The dynamic models are generated automatically from data files containing commercially available motors, but you can also enter your own motor parameters. The following motors are available on data files:

2. The complete Tecnotion 2006 program.
3. The Faulhaber 2006 program.

In the first part of these help files, the use of the 20-sim Servo Motor Editor is explained. The Editor uses a data table with motor parameters of commercial servo motors. You can select any motor from the table, inspect the corresponding torque speed curve and let the Servo Motor Editor generate a 20-sim dynamic model from the parameters.
The second part of these help files, explains the operating principles of the motors. A good indication of the performance of permanent magnet motors can be given by the torque speed plot. Various curves of the torque speed plot and how this can be used to choose the proper motor for a given task. An important part of the torque speed plot is the maximum continuous torque. It is the maximum torque that a motor can deliver without overheating. This curve is based on a thermal model of the motor, which is also explained.

How to use the Servo Motor Editor

The 20-sim Servo Motor Editor is part of the Mechatronics Toolbox of 20-sim. You can open the editor by selecting the Servo Motor Editor command (Tools - Mechatronics Toolbox). If you have a valid license, a servo motor model will be inserted:

Normally the editor will be opened automatically. If this does not happen, force the editor to open by clicking the Go Down button. This Editor looks like:
The top of the editor shows a list of motors. You can select one of the motors from the list by selecting it with your mouse pointer. The selected motor is shown with the blue line. The parameters of the selected motor are shown below the list.

To see the torque speed plot of the selected motor, click the Plot tab at the bottom of the editor. To find a motor based on specific searching conditions, click the Search tab. By clicking the OK button, a dynamic model will be created automatically, based on the selected motor in the list.

Using the Edit menu, new motors can be added to the list or deleted. By double clicking the mouse pointer on a parameter value, it can be changed.

Data Files

If you open the Servo motor Editor, default data from file ServoMotor.csv is shown. You can open other data files by using the file menu.

Currently the following data files are available:

1. ServoMotor.csv: A selection of various motors to show the capabilities of the Servo Motor Editor.
Parameters

Unfortunately not all motor suppliers use the same parameters in the data sheets. Therefore the Servo Motor Editor uses the most common parameters as described in this section. All parameters are defined using a motor temperature and ambient temperature of 25° C.

General Data

This general section contains the unique identifier of the motor (Keyname) and some additional data, which can be filled in freely.

<table>
<thead>
<tr>
<th>Name</th>
<th>The name of the motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Info</td>
<td>Additional Info</td>
</tr>
<tr>
<td>Keyname</td>
<td>A unique name (no duplicates allowed in the motor list) to identify the motor.</td>
</tr>
<tr>
<td>Type</td>
<td>The motor type:</td>
</tr>
<tr>
<td></td>
<td>1. AC Synchronous</td>
</tr>
<tr>
<td></td>
<td>2. Brush DC Iron</td>
</tr>
<tr>
<td></td>
<td>3. Brush DC moving coil</td>
</tr>
<tr>
<td></td>
<td>4. Brush DC Disc Rotor</td>
</tr>
<tr>
<td></td>
<td>5. AC Synchronous Linear</td>
</tr>
<tr>
<td></td>
<td>6. Brushless DC</td>
</tr>
</tbody>
</table>

In the Editor, you can select from a drop down list. In the data file (see next section, the corresponding numbers are used).

<table>
<thead>
<tr>
<th>Date</th>
<th>Date at which the motor info was entered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price</td>
<td>The price of the motor</td>
</tr>
<tr>
<td>Delivery Time</td>
<td>Delivery Time</td>
</tr>
<tr>
<td>Library</td>
<td>The name of the data file that is used</td>
</tr>
</tbody>
</table>

Nominal Data

Many data sheets describe the nominal operating point of a motor. The nominal operation point is characterized by a fixed current that is supplied to a motor with an initial temperature of 25° C that will result in a heating up of the coils to the exactly the maximum temperature. Because a current alone is not enough to describe the state of a motor, the operating point is always given at a certain speed. Although the other parameters (torque and power) can be derived from the current and speed they are usually printed in most data sheets.

- Torque [N.m]or Force[N] Torque or force at nominal operation.
- Speed [rpm]or [m/s] Speed at nominal operation.
- Voltage [V] or [Vrms] Voltage at nominal operation.
Power [W] The output power at nominal operation.
Life [hour] Expected Lifetime of the motor under normal operation.

As described, the definition of current and voltage depends on the selected motor:

<table>
<thead>
<tr>
<th>Motor</th>
<th>Current</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. AC Synchronous</td>
<td>rms phase current (A)</td>
<td>rms phase to phase voltage (V)</td>
</tr>
<tr>
<td>2. Brush DC Iron</td>
<td>current (A)</td>
<td>voltage (V)</td>
</tr>
<tr>
<td>3. Brush DC moving coil</td>
<td>current (A)</td>
<td>voltage (V)</td>
</tr>
<tr>
<td>4. Brush DC Disc Rotor</td>
<td>current (A)</td>
<td>voltage (V)</td>
</tr>
<tr>
<td>5. AC Synchronous Linear</td>
<td>rms phase current (A)</td>
<td>rms phase to phase voltage (V)</td>
</tr>
<tr>
<td>6. Brushless DC</td>
<td>peak current (A)</td>
<td>peak phase to phase voltage (V)</td>
</tr>
</tbody>
</table>

Max/Peak Values
The maximum parameters indicate the maximum performance of the motor and are used to show the limits in the torque speed plot as explained in chapter 3. The parameters do not indicate an operating point on the torque speed curve. The maximum parameters are preferably measured at a temperature of 25° C.

Torque [N.m] or Force[N] The maximum short-time or torque or force (also known as stall torque).
Speed [rpm] or [m/s] The maximum speed.
Power [W] The maximum short time power.

The currents and voltages are defined the same as for the nominal parameters.

Electrical Data

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R [ohm]</td>
<td>The resistance at 25° C.</td>
</tr>
<tr>
<td>L [H]</td>
<td>The terminal inductance.</td>
</tr>
<tr>
<td>alpha_c [1/degC]</td>
<td>The temperature dependency of the coil resistance.</td>
</tr>
<tr>
<td>ktc [1/degC]</td>
<td>The temperature dependency of the magnets.</td>
</tr>
<tr>
<td>poles [-] or pitch[m]</td>
<td>The number of poles (always an even number) or pole pitch (distance N-N poles).</td>
</tr>
</tbody>
</table>

As described, the definition of resistance and inductance depends on the selected motor:
10. Toolboxes

<table>
<thead>
<tr>
<th>Motor Type</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Synchronous</td>
<td>Resistance (Ω) to phase phase resistance (Ω)</td>
</tr>
<tr>
<td>Brush DC Iron</td>
<td>Resistance (Ω) to phase phase inductance (H)</td>
</tr>
<tr>
<td>Brush DC moving coil</td>
<td>Resistance (Ω) to phase phase inductance (H)</td>
</tr>
<tr>
<td>Brush DC Disc Rotor</td>
<td>Resistance (Ω) to phase phase inductance (H)</td>
</tr>
<tr>
<td>AC Synchronous Linear</td>
<td>Resistance (Ω) to phase phase inductance (H)</td>
</tr>
<tr>
<td>Brushless DC</td>
<td>Resistance (Ω) to phase phase inductance (H)</td>
</tr>
</tbody>
</table>

**Mechanical Data**

The mechanical data describes the motor inertia and losses.

- J_rotor [kg.m2] or m_motor [kg]: The rotor inertia or the moving mass of the motor.
- d [N.m.s/rad] or [N.s/m]: Mechanical damping and eddy current losses.
- T_fric [N.m] or [N]: Mechanical friction and hysteresis losses.
- T_cog [N.m] or [N]: The amplitude of the cogging torque.

**Thermal Data**

The thermal data is used for the thermal model as explained in chapter 4. Zero values for the thermal resistances are replaced by a small value (1e-2) to prevent division by zero.

- Temp_amb [°C]: The ambient temperature.
- Temp_initial [°C]: The initial temperature of the coils and housing.
- Temp_max [°C]: The maximum coil temperature.
- RT1 [°C/W]: The thermal resistance between rotor and stator.
- RT2 [°C/W]: The thermal resistance between stator and environment.
- CT1 [J/°C]: Thermal capacity of the rotor.
- CT2 [J/°C]: Thermal capacity of the stator.

**Physical Data**

This section describes the motor dimensions and maximal load.
10. Toolboxes

F_axial [N] The maximum axial force applied to the motor shaft.
F_radial [N] The maximum radial force applied to the motor shaft.
m [kg] The motor weight.
D_motor [m] The motor diameter.
L_motor [m] The motor length.
D_shaft [m] The shaft diameter.
L_shaft [m] The shaft length.

**Derived Data**
These are values that can be found in many data sheets. They are useful for selection criteria when searching for motors.

K_nom [N.m/A], [N.m/Arms] or [N/Arms] The torque constant or force constant at 25° C and nominal currents.
K_max [N.m/A], [N.m/Arms] or [N/Arms] The torque constant or force constant at 25° C and at peak currents.
S [N.m.s/rad] or [N.s/m] The steepness.
tau_m [s] The mechanical time constant (JRotor/S or mMotor/S).
P_dis [W] The maximal continuous dissipation.
tau_T1 [s] The thermal time constant of the rotor (RT1*CT1).
tau_T2 [s] The thermal time constant of the stator (RT2*CT2).

**Additional Data**

20-sim model [] Not implemented yet.

**How to use the Parameters**
When you enter a new motor, not all parameters have to be filled in. In this section the critical and non critical parameters are listed.

**Critical**
Only a few parameters are critical. I.e. they are necessary to generate a 20-sim dynamic model.

**Keyname** A unique name to identify the motor.
**Type** The motor type.
Maximum Torque or Force: The maximum short-time or torque or force.

Maximum Current: The maximum short-time current.

R: The resistance at 25° C.
L: The terminal inductance.

J_rotor or m_motor: The rotor inertia or the moving mass of the motor.

**Desired**

Some parameters are desired. I.e., they add more detail to the model:

Nominal Torque or Force: Torque or force at nominal operation.
Nominal Current: Current at nominal operation.
Nominal Speed: Speed at nominal operation.

alpha_c: The temperature dependency of the coil resistance.
ktc: The temperature dependency of the magnets.
poles or pitch: The number of poles (always an even number) or pole pitch (distance N-N poles).

d: Mechanical damping and eddy current losses.
T_fric: Mechanical friction and hysteresis losses.
T_cog: The amplitude of the cogging torque.

Temp_amb: The ambient temperature.
Temp_initial: The initial temperature of the coils and housing.
Temp_max: The maximum coil temperature.
RT1: The thermal resistance between rotor and stator.
RT2: The thermal resistance between stator and environment.
CT1: Thermal capacity of the rotor.
CT2

Thermal capacity of the stator.

If you do not know the values of these parameters, fill in zero. 20-sim will automatically change some into small numbers to prevent division by zero. Because the nominal torque and current are used to derive the torque constant at nominal operation, they will be replaced by the maximum current and torque if you fill in a zero value.

**Torque Speed Plot**

Some parameters will add more detail to the torque speed plot:

- **Speed**
  - The maximum speed.
- **Voltage**
  - Maximum short-time voltage.
- **Power**
  - The maximum short time power.

**Additional**

The remaining parameters are not used in the torque speed plot or the 20-sim model. They are useful for selection criteria when searching motors. If you do not know the values of these parameters, fill in zero.

**Dynamic Model**

If you have selected a motor, clicking the OK button will close the editor and generate a dynamic model. The model will be filled with the parameters from the selected motor and is ready for the use in a simulation. The model contains a number of variables that may be useful to show in a simulation plot.

**General Part**

- **R**
  - resistance at simulated (fluctuating) temperature
- **K**
  - torque constant at simulated (fluctuating) temperature
- **u_rms_ff**
  - effective terminal (phase-phase) voltage
- **u_tt_ff**
  - maximum terminal (phase-phase)
- **i_tt**
  - maximum phase current
- **phi**
  - shaft angle

**Thermal part**

- **Temp_coil**
  - coil temperature
- **Temp_housing**
  - housing temperature
Torque speed plot

- omega_range: speed ranging from zero to over 5% of maximum speed
- T_range: torque ranging from zero to over 5% of maximum torque
- Torquemax: maximum torque
- Speedmax: maximum speed
- T_max_power: torque at maximum power
- T_max_current: torque at maximum current
- T_max_outputpower: line of maximum output torque
- T_max_voltage: torque at maximum voltage
- T_max_efficiency: line of torque at maximum efficiency
- T_100: maximum allowable continuous torque, (i.e. a 100% duty cycle)
- T_50: maximum allowable torque for a 50% duty cycle
- T_25: maximum allowable torque for a 25% duty cycle
- T_10: maximum allowable torque for a 10% duty cycle
- T_abs: absolute output (load) torque
- omega_abs: absolute velocity

Creating your own data files

The motor parameters are visible in the Grid tab. These parameters are stored in a comma separated data file (extension .csv) or in an encrypted comma separated data file (extension .cse).

By default, the file ServoMotor.csv is shown. Using the File menu you can store and open csv files. The csv files can be edited with the Servo Motor Editor or an external spreadsheet program like OpenOffice. In OpenOffice Calc the file looks like:
The top 5 rows contain the description of the motor parameters and the corresponding units. The first and second row are used for rotation motors and the third and fourth row are used for linear (translation) motors. The fifth row contains the parameter names.

The other rows contain the motor parameters. The meaning of these parameters is described in the previous sections. Please use the following guidelines when editing data files:

1. Never change the first five lines
2. Do no use duplicate names in the first column (keyname)
3. Do use commas
4. Do no use strange formatting (in Excel use the General format)
5. Do no enter extra columns
6. Do not enter other information in additional rows or columns. The Servo Motor Editor will try to read all cells and halt if the content is not according to the specifications.
7. Do no add comment.
8. The last column entry (20-sim) should contain one white space character.

**Data Files**

**Maxon 2005 / 2006**

**File**
20-sim 3.6\Tools\Servo Motor Dynamics\Maxon 2006.cse

**Date**
November 2005
More information
www.maxonmotors.com

Description
The data file Maxon 2006.cse contains the complete set of Maxon motors, program 2005 / 2006. Most of the data has been extracted from the Maxon data sheets. The tables below shows the 20-sim names and the corresponding data sheet names. Some parameters were not available in the data sheets and have been given by the Maxon motor company. These parameters are indicated as Given by Maxon. Some parameters were calculated. These are indicated as Calculated.

DC motors

<table>
<thead>
<tr>
<th>Servo Motor Editor</th>
<th>Maxon Data Sheets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Data</strong></td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Motor Series</td>
</tr>
<tr>
<td>Keyname</td>
<td>Maxon Order Number</td>
</tr>
<tr>
<td>Info</td>
<td>Additional Information</td>
</tr>
<tr>
<td>Type</td>
<td>DC</td>
</tr>
<tr>
<td>Date</td>
<td>21 October 2005</td>
</tr>
<tr>
<td>Price</td>
<td>-</td>
</tr>
<tr>
<td>Delivery Time</td>
<td>stock / standard / special</td>
</tr>
<tr>
<td>Library</td>
<td>Maxon 2006.cse</td>
</tr>
<tr>
<td><strong>Nominal Data</strong></td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>Max. continuous torque</td>
</tr>
<tr>
<td>Current</td>
<td>Max. continuous current</td>
</tr>
<tr>
<td>Speed</td>
<td>No load speed divided by 2</td>
</tr>
<tr>
<td>Voltage</td>
<td>Calculated</td>
</tr>
<tr>
<td>Power</td>
<td>Calculated</td>
</tr>
<tr>
<td><strong>Max/Peak Data</strong></td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>Stall torque</td>
</tr>
<tr>
<td>Current</td>
<td>Starting current</td>
</tr>
<tr>
<td>Power</td>
<td>Assigned Power Rating</td>
</tr>
<tr>
<td>Voltage</td>
<td>Calculated*</td>
</tr>
<tr>
<td>Speed</td>
<td>Max. permissible speed</td>
</tr>
<tr>
<td><strong>Thermal Data</strong></td>
<td></td>
</tr>
<tr>
<td>Temp_amb</td>
<td>Set to 25</td>
</tr>
<tr>
<td>Temp_initial</td>
<td>Set to 25</td>
</tr>
<tr>
<td>Temp_max</td>
<td>Maximum rotor temperature</td>
</tr>
<tr>
<td>RT1</td>
<td>Thermal resistance rotor-housing</td>
</tr>
<tr>
<td>RT2</td>
<td>Thermal resistance housing-ambient</td>
</tr>
<tr>
<td>CT1</td>
<td>Calculated</td>
</tr>
<tr>
<td>CT2</td>
<td>Given by Maxon</td>
</tr>
<tr>
<td><strong>Physical Data</strong></td>
<td></td>
</tr>
<tr>
<td>F_axial</td>
<td>Maximum Axial load</td>
</tr>
<tr>
<td>F_Radial</td>
<td>Maximum radial load</td>
</tr>
<tr>
<td>m</td>
<td>Weight of motor</td>
</tr>
<tr>
<td>D_motor</td>
<td>Diameter of motor</td>
</tr>
<tr>
<td>L_motor</td>
<td>Length of motor</td>
</tr>
<tr>
<td>D_shaft</td>
<td>Diameter shaft</td>
</tr>
<tr>
<td>L_shaft</td>
<td>Length Shaft</td>
</tr>
</tbody>
</table>
10. Toolboxes

**Electrical Data**
- R: Terminal resistance
- L: Terminal inductance
- alpha_c: Given by Maxon
- Ktc: Given by Maxon
- Poles: Number of poles

**Mechanical Data**
- J_rotor: Rotor inertia
- d: Given by Maxon
- T_fric: Given by Maxon
- T_cog: 0

**Derived Data**
- K_nom: Calculated
- K_max: Calculated
- S_nom: Calculated
- P_dis: Calculated

* In the data sheets Maxon only gives a nominal voltage. According to Maxon higher operating voltages are permissible provided that other limits are not exceeded. Therefore the maximum voltage is chosen equal to the voltage that is needed to run a motor with zero load at maximum speed.

**EC motors with block commutation**
Maxon EC motors can be driven by block commutation and sine commutation. The Maxon data sheets give the parameters for block commutation. To distinguish between block commutation and sine commutation the character b or s is added to the keyname.

**Servo Motor Editor**

**Maxon Data Sheets**

**General Data**
- Name: Motor Series
- Keyname: Maxon Order Number + b
- Info: Additional Information
- Type: Brushless DC
- Date: 21 October 2005
- Price: -
- Delivery Time: stock / standard / special
- Library: Maxon 2006.csv

**Nominal Data**
- Torque: Calculated
- Current: Max. continuous current
- Speed: Nominal speed
- Voltage: Calculated
- Power: Calculated

**Max/Peak Data**
- Torque: Stall torque
- Current: Calculated
- Power: Assigned Power Rating
- Voltage: Calculated*
- Speed: Max. permissible speed
Thermal Data
Temp_amb Set to 25
Temp_initial Set to 25
Temp_max Maximum rotor temperature
RT1 Thermal resistance rotor-housing
RT2 Thermal resistance housing-ambient
CT1 Calculated
CT2 Calculated

Physical Data
F_axial Maximum Axial load
F_Radial Maximum radial load
m Weight of motor
D_motor Diameter of motor
L_motor Length of motor
D_shaft Diameter shaft
L_shaft Length Shaft

Electrical Data
R Terminal resistance phase to phase
L Terminal inductance phase to phase
alpha_c Given by Maxon
Ktc Given by Maxon
Poles Number of poles

Mechanical Data
J_rotor Rotor inertia
d Given by Maxon
T_fric Given by Maxon
T_cog 0

Derived Data
K_nom Calculated
K_max Calculated
S_nom Calculated
P_dis Calculated

* In the data sheets Maxon only gives a nominal voltage. According to Maxon higher operating voltages are permissible provided that other limits are not exceeded. Therefore the maximum voltage is chosen equal to the voltage that is needed to run a motor with zero load at maximum speed.

EC motors with sine commutation
Maxon EC motors can be driven by block commutation and sine commutation. The Maxon data sheets give the parameters for block commutation. The parameters for sine commutation can be calculated from the block commutation parameters. To distinguish between block commutation and sine commutation the character b or s is added to the keyname.

Servo Motor Editor
Maxon Data Sheets

General Data
Name
Keyname Maxon Order Number + s
Info Additional Information
Type AC Synchronous

20-sim 5.1 Reference Manual 489
<table>
<thead>
<tr>
<th>Date</th>
<th>21 October 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price</td>
<td>-</td>
</tr>
<tr>
<td>Delivery Time</td>
<td>stock / standard / special</td>
</tr>
<tr>
<td>Library</td>
<td>Maxon 2006.csv</td>
</tr>
</tbody>
</table>

**Nominal Data**

- Torque: Calculated
- Current: Calculated
- Speed: Nominal speed
- Voltage: Calculated
- Power: Calculated

**Max/Peak Data**

- Torque: Calculated
- Current: Calculated
- Power: Assigned Power Rating
- Voltage: Calculated
- Speed: Calculated

**Thermal Data**

- Temp_amb: Set to 25
- Temp_initial: Set to 25
- Temp_max: Maximum rotor temperature
- RT1: Thermal resistance rotor-housing
- RT2: Thermal resistance housing-ambient
- CT1: Calculated
- CT2: Calculated

**Physical Data**

- F_axial: Maximum Axial load
- F_Radial: Maximum radial load
- m: Weight of motor
- D_motor: Diameter of motor
- L_motor: Length of motor
- D_shaft: Diameter shaft
- L_shaft: Length Shaft

**Electrical Data**

- R: Terminal resistance phase to phase
- L: Terminal inductance phase to phase
- alpha_c: Given by Maxon
- Ktc: Given by Maxon
- Poles: Number of poles

**Mechanical Data**

- JRotor: Rotor inertia
- d: Given by Maxon
- T_fric: Given by Maxon
- T_cog: 0

**Derived Data**

- K_nom: Calculated
- K_max: Calculated
- S_nom: Calculated
- P_dis: Calculated
* In the data sheets Maxon only gives a nominal voltage. According to Maxon higher operating voltages are permissible provided that other limits are not exceeded. Therefore the maximum voltage is chosen equal to the voltage that is needed to run a motor with zero load at maximum speed.

**Tecnotion 2006**

**File**

20-sim 3.6\Tools\Servo Motor Dynamics\Tecnotion 2006.cse

**Date**

November 2006

**More information**

www.tecnotion.com

**Description**

The data file Tecnotion 2006.cse contains the complete set of Tecnotion motors, program 2006. Most of the data has been extracted from the Tecnotion data sheets. The tables below shows the 20-sim names and the corresponding data sheet names. Some parameters were not available in the data sheets and have been given by the Tecnotion motor company. These parameters are indicated as *Given by Tecnotion*. Some parameters were calculated. These are indicated as *Calculated*.

**Important**: The nominal data and the default value of the thermal resistance RT2 are calculated for *air cooling*. The value for RT2 can be changed using a slider. *If water cooling is used, change the value of RT2 to its minimum value.*

<table>
<thead>
<tr>
<th>Servo Motor Editor</th>
<th>Tecnotion Data Sheets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Data</strong></td>
<td><strong>Motor Series</strong></td>
</tr>
<tr>
<td>Name</td>
<td>Order Number</td>
</tr>
<tr>
<td>Keyname</td>
<td>Additional Information</td>
</tr>
<tr>
<td>Info</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>AC Synchronous Linear</td>
</tr>
<tr>
<td>Date</td>
<td>21 October 2005</td>
</tr>
<tr>
<td>Price</td>
<td></td>
</tr>
<tr>
<td>Delivery Time</td>
<td></td>
</tr>
<tr>
<td>Library</td>
<td>Tecnotion 2006.cse</td>
</tr>
</tbody>
</table>

**Nominal Data**

| Force               | Continuous Force (air cooled*) |
| Current             | Continuous Current (air cooled*) |
| Speed               | 0 m/s                          |
| Voltage             | Calculated                     |
| Power               |                               |

**Max/Peak Data**

| Force               | Ultimate Force / Peak Force   |
| Current             | Ultimate Current / Peak Current|
| Power               | Calculated                     |
| Voltage             | Max. voltage ph-ph             |
| Speed               | Maximum speed                  |

**Thermal Data**
Temp_amb
Temp_initial
Temp_max
RT1
RT2
CT1
CT2

**Physical Data**
- F_axial
- F_Radial
- m
- D_motor
- L_motor
- D_shaft
- L_shaft

**Electrical Data**
- R
- L
- alpha_c
- Ktc
- Pitch

**Mechanical Data**
- m_motor
- d
- F_fric
- F_cog

**Derived Data**
- K_nom
- K_max
- S_nom
- P_dis

* Note: The nominal data and the default value of the thermal resistance RT2 are calculated for air cooling. The value for RT2 can be changed using a slider. If water cooling is used, change the value of RT2 to its minimum value.

**Faulhaber 2006**

**File**
20-sim 3.6\Tools\Servo Motor Dynamics\Faulhaber 2006.cse

**Date**
February 2006

**More information**
www.faulhaber-group.com or www.minimotor.ch
Description
The data file Faulhaber 2006.cse contains the most of the Faulhaber servo motors, program 2006. Most of the data has been extracted from the Faulhaber data sheets. The tables below show the 20-sim names and the corresponding data sheet names. Some parameters were not available in the data sheets and have been given by Faulhaber. These parameters are indicated as Given by Faulhaber. Some parameters were calculated. These are indicated as Calculated.

DC motors

<table>
<thead>
<tr>
<th>Servo Motor Editor</th>
<th>Faulhaber Data Sheets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Data</strong></td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Motor Name</td>
</tr>
<tr>
<td>Keyname</td>
<td>Faulhaber Order Number</td>
</tr>
<tr>
<td>Info</td>
<td>Additional Information</td>
</tr>
<tr>
<td>Type</td>
<td>DC</td>
</tr>
<tr>
<td>Date</td>
<td>23 February 2006</td>
</tr>
<tr>
<td>Price</td>
<td>-</td>
</tr>
<tr>
<td>Delivery Time</td>
<td>-</td>
</tr>
<tr>
<td>Library</td>
<td>Faulhaber 2006.cse</td>
</tr>
<tr>
<td><strong>Nominal Data</strong></td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>Calculated</td>
</tr>
<tr>
<td>Current</td>
<td>Current up to</td>
</tr>
<tr>
<td>Speed</td>
<td>No load speed divided by 2</td>
</tr>
<tr>
<td>Voltage</td>
<td>Calculated</td>
</tr>
<tr>
<td>Power</td>
<td>Calculated</td>
</tr>
<tr>
<td><strong>Max/Peak Data</strong></td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>Stall torque</td>
</tr>
<tr>
<td>Current</td>
<td>Calculated</td>
</tr>
<tr>
<td>Power</td>
<td>Output Power</td>
</tr>
<tr>
<td>Voltage</td>
<td>Nominal Voltage</td>
</tr>
<tr>
<td>Speed</td>
<td>No-load speed</td>
</tr>
<tr>
<td><strong>Thermal Data</strong></td>
<td></td>
</tr>
<tr>
<td>Temp_amb</td>
<td>Set to 25</td>
</tr>
<tr>
<td>Temp_initial</td>
<td>Set to 25</td>
</tr>
<tr>
<td>Temp_max</td>
<td>Maximum coil temperature</td>
</tr>
<tr>
<td>RT1</td>
<td>Thermal resistance rotor – housing Rth1</td>
</tr>
<tr>
<td>RT2</td>
<td>Thermal resistance housing-ambient Rth1</td>
</tr>
<tr>
<td>CT1</td>
<td>Calculated</td>
</tr>
<tr>
<td>CT2</td>
<td>Calculated</td>
</tr>
<tr>
<td><strong>Physical Data</strong></td>
<td></td>
</tr>
<tr>
<td>F_axial</td>
<td>Maximum Axial load</td>
</tr>
<tr>
<td>F_Radial</td>
<td>Maximum radial load</td>
</tr>
<tr>
<td>m</td>
<td>Weight of motor</td>
</tr>
<tr>
<td>D_motor</td>
<td>Diameter of motor</td>
</tr>
<tr>
<td>L_motor</td>
<td>Length of motor</td>
</tr>
<tr>
<td>D_shaft</td>
<td>Diameter shaft</td>
</tr>
<tr>
<td>L_shaft</td>
<td>Length Shaft</td>
</tr>
<tr>
<td><strong>Electrical Data</strong></td>
<td></td>
</tr>
</tbody>
</table>
R  Terminal resistance
L  Rotor Inductance
alpha_c  Temperature coefficient of resistance of copper
Ktc  Given by Faulhaber
Poles  Given by Faulhaber

**Mechanical Data**

\( J_{\text{rotor}} \)  Rotor inertia
\( d \)  Friction torque, dynamic
\( T_{\text{fric}} \)  Friction torque, static
\( T_{\text{cog}} \)  0

**Derived Data**

\( K_{\text{nom}} \)  Calculated
\( K_{\text{max}} \)  Calculated
\( S_{\text{nom}} \)  Calculated
\( P_{\text{dis}} \)  Calculated

**DC Brushless motors with block commutation**

**Servo Motor Editor**  **Faulhaber Data Sheets**

**General Data**

Name  Motor Name
Keyname  Faulhaber Order Number
Info  Additional Information
Type  DC Brushless
Date  23 February 2006
Price  -
Delivery Time  -
Library  Faulhaber 2006.cse

**Nominal Data**

Torque  Torque up to
Current  Current up to
Speed  At speed
Voltage  Calculated
Power  Calculated

**Max/Peak Data**

Torque  Stall torque
Current  Calculated
Power  Output Power
Voltage  Nominal Voltage
Speed  No-load speed

**Thermal Data**

Temp_amb  Set to 25
Temp_initial  Set to 25
Temp_max  Maximum coil temperature
RT1  Thermal resistance rotor – housing Rth1
RT2  Thermal resistance housing-ambient Rth1
CT1  Calculated
CT2  Calculated
### Physical Data
- **F_axial**: Maximum Axial load
- **F_Radial**: Maximum radial load
- **m**: Weight of motor
- **D_motor**: Diameter of motor
- **L_motor**: Length of motor
- **D_shaft**: Diameter shaft
- **L_shaft**: Length Shaft

### Electrical Data
- **R**: Terminal resistance
- **L**: Rotor Inductance
- **alpha_c**: Temperature coefficient of resistance of copper (Given by Faulhaber)
- **Ktc**: Given by Faulhaber

### Mechanical Data
- **J_rotor**: Rotor inertia
- **d**: Friction torque, dynamic
- **T_fric**: Friction torque, static
- **T_cog**: 0

### Derived Data
- **K_nom**: Calculated
- **K_max**: Calculated
- **S_nom**: Calculated
- **P_dis**: Calculated
Theory

Basic Principles

Permanent Magnet Motors

When permanent magnets are used in a motor, a magnetic field will be present with a magnetic flux density $B$. Suppose an electric coil is placed in this magnetic field. When an electric current $i$ is forced to flow through this coil, a force acting on the coil will occur.

The resulting torque can be found as:

$$T = K_{tc}(\theta) \cdot i$$

where $K_{tc}(\theta)$ denotes the transfer of current to torque. It is a function of the angle, shape of the coil, magnetic field density, current distribution etc. When the current is kept equal to zero and we start to rotate the coil, a voltage will be induced. This voltage is called the electromotive force (EMF) and can be found as:

$$EMF = K_{ec}(\theta) \cdot \omega$$

where $K_{ec}(\theta)$ denotes the transfer of speed to voltage. It is also function of the angle, shape of the coil, magnetic field density, current distribution etc. For an ideal coil the input power should be equal to the output power

$$P_{in} = EMF \cdot i = K_{ec}(\theta) \cdot \omega \cdot \frac{T}{K_{tc}(\theta)} = \omega \cdot T = P_{out}$$

and thus
In most literature the $Kc(q)$ is calculated out of the magnetic field and coil distribution. Here it is simply assumed to be given and is called the **torque function**.

In normal operation a coil will have a resistance and inductance. A basic coil model is thus equal to:

By a proper design of the motor, i.e. geometry of the coil windings, magnets etc., the torque function $Kc(q)$ can be given a particular shape. Then by proper manipulation of the current a positive torque can be created during the whole rotation of the coil. All permanent magnet motors are based on this principle.

### Brush DC Motors

In DC motors, the torque function $Kc(q)$ is sinusoidal:

$$K_c(\theta) = \hat{K}_c \cdot \sin(\theta)$$

In DC motors a constant current is supplied. Through a process called commutation, the coil is connected the other way around (i.e the current changes sign) when the coil function crosses zero. The resulting torque will then always be positive but will vary between zero and maximum:

$$T = i(\theta) \cdot \hat{K}_c \cdot \sin(\theta) = \hat{i} \cdot \hat{K}_c \cdot \text{abs}(\sin(\theta))$$

By combining coils, the resulting torque variation or **ripple** will decrease. The graph below shows the resulting torque when three coils are used.
The more coils are used the more the torque ripple decreases.

<table>
<thead>
<tr>
<th>number of coils</th>
<th>torque ripple (top-top)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>14%</td>
</tr>
<tr>
<td>5</td>
<td>5%</td>
</tr>
<tr>
<td>7</td>
<td>2.5%</td>
</tr>
<tr>
<td>9</td>
<td>1.5%</td>
</tr>
<tr>
<td>11</td>
<td>1%</td>
</tr>
</tbody>
</table>

If we neglect the torque ripple, we get the common DC motor equations:

\[ T = K \cdot i \]

\[ EMF = K \cdot \omega \]

**Commutation**

In practical motors, the rotor is equipped with a commutator. A commutator consists of insulated collector bars that are connected with the coils. Each coil is connected with one end to a collector and the next end to the neighboring collector. A pair of brushes is used to connect an outside current source to the collectors.
Every rotation the current changes sign twice, resulting in a continuous positive torque addition of every coil.

**Limits**

Commutation is the largest limiting factor in DC motor performance. Sparks between the brushes and the collectors are the main causes for brush wear. There are several causes for sparking, which limit the maximum speed, current, voltage and power of a brush DC motor.

When the brush leaves a collector, the current has to be reversed. The time that is needed to reverse the current depends directly on the current amplitude and thus on the generated torque. Because the time that is available depends on the motor speed, the result is a limit on the power that can be generated.

Another limitation of the motor speed is due to imperfect dimensions of the collectors. Differences in height of a few microns may cause the brushes to jump at high speeds.

Just a small part of the contact area of a brush and collector is actually used for the current transfer. As a result highly localized, short time "hot spots" develop. When the currents get greater than permitted, local temperatures occur that lead to material evaporation.

Above a voltage of 15 to 18V experience shows that the air will experience ionization phenomena, which leads to arcing. This arc extends from one collector bar to another. When enough voltage is applied, the arc will extend several collector bars and reach the other brush, leading to serious damage. The maximum motor voltage is therefore the result of multiplying the number of collector bars between the brushes and the maximum collector bar voltage.

Permanent magnets can lose their strength when operating above temperatures of 60 °C and suppressed by a high external magnetic field. Such a field can occur when large current changes occur. Therefore the maximum current of a motor should be limited.
10. Toolboxes

**Brushless DC Motors**

Given motor with three coils, where the coils are mounted in the stator with a spatial displacement of 120°. The coils are connected in a star-formation as shown in the figure below.

In Brushless DC motors, the coils and magnets are designed so that a trapezoidal torque function $K_c(q)$ is found as shown below:

To get a constant torque each coil current is a block wave as shown in the figure below. Although the current is thus alternating, the term DC is used to distinguish this type of motor from motors that used a sinusoidal current. The block wave current is provided through "electronic commutation". The current is generated by a three phase amplifier that gets the exact switching points from a motor controller.
As can easily be seen from the graphs, the resulting torque is constant and twice the current times the amplitude of the coil function:

\[ T = 2 \cdot \hat{i}_c \cdot \hat{K}_c \]

To get an equivalent of the coil model we can write this equation as:

\[ T = K \cdot i_{\text{phase, max}} \]

We have to realize that here \( i \) is not a constant current anymore but the maximum coil current! Because the coil current is the current of one of the three phases, in literature \( i \) is mostly written as the maximum phase current. It is the maximum current that can be measured at each of the three terminals of the motor.

In a derivation that goes beyond the scope of this introduction (see Compter, 2004), it can be shown that the electromotive force can be found as:

\[ E\text{M}F_{\text{phase-phase, max}} = K \cdot \omega \]

Here the electromotive force is defined as the maximum induced voltage between two phases. The resulting motor model is shown below:
The voltage of the motor model is commonly known as the **maximum phase to phase voltage**. It is the maximum voltage that can be measured between any pair of two terminals. The **phase to phase resistance** and **phase to phase inductance** are defined equivalent as the resistance and inductance that can be measured between any pair of two terminals.

**Limits**

Brushless DC motors have no mechanical commutation, and therefore do not suffer from the limits caused by mechanical commutation. Consequently Brushless DC motors can run at much higher speeds and are not limited by a maximum voltage. The speed of Brushless DC motors is only limited by the bearings.

Just like brush DC motors the magnets impose an upper limit for the current and torque in a Brushless DC motor.

**AC synchronous motor**

AC synchronous motors use the same principle as Brushless DC-motors. The coils are also mounted in the stator with a spatial displacement of 120°.

The coils and magnets are designed so that a sinusoidal torque function $Kc(q)$ is found as shown below:
To get a constant torque each coil current is a sinusoidal wave as shown in the figure below.

As can be seen from the graph, the resulting torque is constant and one and a half times the current times the amplitude of the coil function:

\[ T_a = \frac{3}{2} \cdot \hat{K}_c \cdot \hat{i}_c \]

To get an equivalent of the coil model we can write this equation as:

\[ T = K \cdot i_{\text{rms, phase}} \]

We have to realize that here \( i \) is not a constant current anymore but the root mean square coil current! Because the coil current is the current of one phase in literature \( i \) is mostly denoted as the \textbf{rms phase current}. It is the rms current that can be measured at each of the three terminals of the motor.
In a derivation that goes beyond the scope of this introduction (see Compter, 2004), it can be shown that the electromotive force can be found as:

$$EMF_{\text{rms, phase-phase}} = \frac{K}{\sqrt{3}} \cdot \omega$$

Here the electromotive force is defined as the induced rms voltage between two phases. The resulting motor model is shown below:

The voltage of the motor model is mostly denoted as the **rms phase to phase voltage**. It is the rms voltage that can be measured between any pair of two terminals. The **phase to phase resistance** and **phase to phase inductance** are defined equivalent as the resistance and inductance that could be measured between any pair of two terminals.

**Limits**

AC synchronous motors have no mechanical commutation, and therefore do not suffer from the limits caused by mechanical commutation. Consequently AC synchronous motors can run at much higher speeds and are not limited by a maximum voltage. The speed of AC synchronous motors is only limited by the bearings.

Just like brush DC motors the magnets impose an upper limit for the current and torque in a AC synchronous motor.

**Linear Motors**

The working principle of linear motors is exactly the same as for rotary motors. Magnets are place on a flat surface, as shown in the figure below. A carriage holding the coils can run over the magnets.

When the carriage runs over the magnets an electromotive voltage will be induced:
with $K_c(x)$ the **force function** of the coil. It is a function of the carriage position, shape of the coil, magnetic field density, current distribution etc. The force function in a linear motor is equivalent to the torque function of a rotary motor. When a current runs through the coil a force results:

$$F = K_c(x) \cdot i$$

The principle for linear motor is the same as the principle of rotary motors. By a proper design of the motor, i.e. geometry of the coil windings, magnets etc., the force function $K_c(x)$ can be given a particular shape. By proper manipulation of the current a positive force can be created during the movement of the carriage. Because mechanical commutation is not very useful for linear movements, linear motors use electronic commutation. Like their rotary counterparts, linear motors can be driven by block shape currents (Brushless DC Linear) and sinusoidal currents (AC Synchronous Linear).

**Limits**

The limits for linear motors are equal to the Brushless DC and AC synchronous motors when torque is replaced by force and angular speed by linear speed.

### Star and Delta Networks

Brushless DC motors and AC synchronous motors use three phase currents to connect to three groups of coils. The connection can be made use a star network or a delta network. Compared to star networks, in a delta network less voltage and more current is needed to produce the same amount of torque. For amplifiers the maximum current is directly related to the costs. That is why delta networks are only used in special cases where higher speeds than normal are required.

In 20-sim the electrical resistance and inductance are measured between the terminals (e.g. between 1 and 2 or 2 and 3 or 3 an 1). This is known as the **terminal resistance** and **inductance** or as the **phase to phase resistance** and **inductance**. There are two reasons for using terminal values. Most motor suppliers give the terminal values in their data sheet and by using terminal values the same dynamic model can be used for star networks and delta networks.
If the motor supplier gives coil values instead of terminal values, you have to calculate them by hand. The relation between the terminal values and the coil values is:

\[
R_y = 2 \cdot R_{coil} \quad R_A = \frac{2}{3} \cdot R_{coil} \\
L_y = 2 \cdot L_{coil} \quad L_A = \frac{2}{3} \cdot L_{coil}
\]

**Torque Speed Plot**

**General Model**

The DC motor model can serve as a prototype model for all permanent magnet motors.

![DC Motor Model Diagram]

Although the models for DC Brushless and AC synchronous motors are slightly different, the DC motor model is still very useful to explain their operation. In this chapter the DC motor model will be used to derive the torque speed plot of a motor and show the use of the torque speed plot for motor selection.

The working principle for all permanent magnet motors is the same: get a constant torque by manipulation of the coil function and the current. The relation between the torque and current is:

\[ T = K_T \cdot i \]

The constant \( K_T \) is generally known as the **torque constant**. The relation between the induced current and the rotational speed is:

\[ EMF = K_e \cdot \omega \]

The constant \( K_e \) is generally known as the **voltage constant**. For DC motors the torque constant and voltage constant have the same value. Therefore the subscripts \( T \) and \( e \) are usually omitted. The total voltage can be described as:

\[ u = i \cdot R + L \cdot \frac{di}{dt} + K \cdot \omega \]

If we assume the current is changing only very slowly, the current derivative can be neglected:
With the torque equation:

\[ T = K \cdot i \]

this leads to

\[ T = \frac{K \cdot (u - K \cdot \omega)}{R} \]

The torque at zero speed (stall torque) is found as

\[ T_{\text{stall}} = \frac{K \cdot u}{R} \]

which enables us to write the torque as:

\[ T = T_{\text{stall}} - \frac{K^2}{R} \cdot \omega = T_{\text{stall}} - S \cdot \omega \]

where S is commonly known as the steepness. The steepness has many definitions:

\[ S = \frac{T^2}{i^2 \cdot R} = \frac{K^2}{R} = \frac{\Delta T}{\Delta \omega} \]

The speed where the current is zero (no load speed) is equal to

\[ \omega_0 = \frac{u}{K} \]

The relation between stall torque and no load speed is obvious:

\[ T_{\text{stall}} = S \cdot \omega_0 \]

which leads to the general torque equation:

\[ T = S \cdot (\omega_0 - \omega) \]

This equation can be displayed graphically and is commonly known as the torque speed plot. The graph shows the generated torque as a function of the speed. For constant voltages a straight line from the stall torque to the no load speed is found. The slope of the line is equal to the steepness S.
The torque speed plot is a useful representation of a motor because we can draw the desired load torque in this plot and to see if the motor is able to produce this torque. In the figure below the load curve is shown in red. It is a constant torque applied to a load, which makes it accelerate until a certain velocity is reached and the torque gets zero.

The red dot indicates the point of maximum load power. This point is important because it indicates the maximum power that the motor has to deliver.

**Limits**

To find out if a motor is sufficient, we have to plot the motor limits in the torque speed plot. In the previous chapter we have described the following limits:

<table>
<thead>
<tr>
<th>Limit</th>
<th>Brush DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>torque / current</td>
<td>V</td>
</tr>
<tr>
<td>speed</td>
<td>V</td>
</tr>
<tr>
<td>power</td>
<td>V</td>
</tr>
</tbody>
</table>
Maximum Voltage
For higher voltages, a higher stall torque and no load speed is found but the steepness does not change.

Maximum Torque / Maximum Current
In many data sheets a maximum torque is given. This is directly connected with a maximum current limit through the equation:

\[ i = \frac{T}{K} \]

So both the maximum current and the maximum torque appear as horizontal lines in the torque speed plot.

Maximum Velocity
The maximum velocity can be directly indicated in the torque speed plot as a vertical line.
Maximum Power
The line of maximum power can be indicated as a parabola in the torque speed plot.
Safe Operating Area

If the limits are plotted in the torque speed plot, an Area of Safe Operation is found. For a proper motor, the torque speed curve of the load should be inside the **Safe Operating Area (SOA)**. The figures below show the safe operating areas for the various motor types. Brush DC-motors (left figure) have a safe operating area that is more limited than Brushless DC motors and AC synchronous motor (right figure).

In practice motor suppliers of Brushless DC motors and AC synchronous motors may impose limits on the maximum voltage and power. This is mostly done to prevent heating up the motor too quickly during continuous operation, or material limits. This makes the Safe Operating Area of these motors look like that of a DC motor. Compared to DC motors, Brushless DC motors and AC synchronous motors will always allow higher torques and speeds because of the absence of mechanical commutation.

Losses

Every motor will experience losses, which results in a temperature rise. The maximum allowed temperature is limited by the magnets, the oil in the bearings and the mechanical behaviour of the brushes. Analysis of the cause of losses is therefore important for the correct choice of a motor.

**Electric Dissipation**

All motor coils have resistance and will therefore generate heat. The heat flow generated is equal to:

\[
dQ = \frac{1}{\Delta T} \int_0^{\Delta T} i^2 \cdot R \, dt = \frac{R}{\Delta T} \int_0^{\Delta T} i^2 \, dt
\]

which can also be written as:

\[
dQ = i_{rms}^2 \cdot R
\]

with *irms* the **root mean square** current:
For constant DC currents the root mean square value is equal to the current itself. For sinusoidal currents, the root mean square value is equal to the amplitude of the current times the square root of 2.

**Hysteresis losses**

In all motors except from hollow rotor motors, the magnets move with respect to the iron core of the motor. This results in a reversing magnetic field in the iron which leads to hysteresis.

Each rotation produces an energy loss proportional to the area of the hysteresis curve (B/H). The power loss due to hysteresis is proportional to the motor speed and can therefore be represented as a friction torque. Due to this friction torque the motor can produce less output torque. This friction torque can therefore be represented in the torque speed plot as a drop down of all curves.

**Eddy Current losses**

A reversing magnetic field in iron also leads to an induce voltage. The resistance of the iron determines the resulting currents in the iron. These currents are named eddy currents.
Eddy currents heat up the iron because of its resistance. If a massive iron return is used large eddy currents will be induced with high power losses. Therefore in most motors laminated is applied, which reduce eddy currents by decreasing the path length and thus lead to smaller small power losses. The power loss due to eddy currents is proportional to the square of the motor speed and can therefore be modeled as mechanical damping. Damping will decrease the performance of the motor. It can be represented in the torque speed plot as a falling down of curves that increases with the speed.

![Diagram of eddy currents](image)

Cogging
In a permanent magnet motors cogging torque manifests itself by the tendency of the rotor to align in a number of stable positions when unexcited. The cogging torque can be described as:

\[ T_{\text{cog}} = \hat{T}_{\text{cog}} \cdot \sin \left( \frac{p \cdot \theta}{2} \right) \]

where \( q \) is the motor angle and \( p \) the number of poles. Although cogging does not consume power and is not visible in the torque speed plot, under dynamic conditions it may cause undesirable speed pulsation and also may induce vibrations and acoustic noise.

Mechanical Losses
Mechanical losses in motors are caused by bearings, brushes and air friction. Only when an air fan is mounted air friction becomes significant. The effects of brushes and bearings can be represented by coulomb friction and damping.
Temperature
As a result of the heat flow, the motor will warm up leading to two major effects. First of all the coil resistance will increase. Because all coils are made of copper, the temperature dependency of the coil resistance can be written as:

\[ R_T = R_{25} \cdot \left(1 + 0.004 \cdot (T_{\text{coil}} - 25)\right) \]

where \( R_{25} \) is the coil resistance at room temperature (25 degrees centigrade) and \( T_{\text{coil}} \) the actual coil temperature in degrees centigrade. As a result of the increase of motor temperature, the performance of the magnets will decrease. The result is a decrease of the torque constant:

\[ K_T = K_{25} \cdot \left(1 + k_{tc} \cdot (T_{\text{magnet}} - 25)\right) \]

where \( K_{25} \) is the torque constant at room temperature (25 degrees centigrade), \( T_{\text{magnet}} \) the actual magnet temperature in degrees centigrade and \( k_{tc} \) the temperature dependency of the used magnet.

<table>
<thead>
<tr>
<th>Magnets</th>
<th>( k_{tc} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrites</td>
<td>-0.002</td>
</tr>
<tr>
<td>( \text{Nd}<em>2\text{Fe}</em>{14}\text{B} )</td>
<td>-0.0013</td>
</tr>
<tr>
<td>SmCo</td>
<td>-0.0005</td>
</tr>
<tr>
<td>AlNiCo</td>
<td>-0.0002</td>
</tr>
</tbody>
</table>

Because the steepness is directly dependent of the torque constant and motor resistance

\[ s = \frac{K^2}{R} \]

an increase of temperature will lead to a decrease of the steepness. The results of a temperature increase can therefore be shown in the torque speed plot indirectly through the decrease of the maximum torque and steepness.
Thermal Duty Cycle

Motor losses result in an increase of the temperature. During short-term operation the temperature increase will be limited. During long-term operation, the generated heat and the amount of heat that can be removed via the air and motor mounting determine the temperature increase.

In most motors, the largest portion of the generated heat is caused by electric dissipation. The generated heat is therefore directly proportional to the current and thus the torque. Imagine a motor in long-term operation generating a constant torque. A small torque will lead to only a moderate increase of the motor temperature, but there will be a certain torque where the generated heat leads to an increase of the maximum motor temperature. This is called the maximum continuous torque or the 100% Thermal Duty Cycle (TDC). The line of the maximum continuous torque can be shown in the torque speed plot and is often denoted as T100. For lower speeds the T100 curve will be straight because the heat generation mainly depends on electric dissipation. For higher speeds the T100 curve will decrease because eddy current losses start to become significant.

If the motor is in continuous operation, but a constant torque is just delivered 50% of the time, a higher torque is permissible. This torque is denoted as T50 and sometimes called the 50% thermal duty cycle. In a similar way T25 and T10 are defined.
**Nominal Operating Point**

Many motor manufacturers give in their data sheets a nominal or continuous current at a certain speed. This indicates an operating point on the T100 curve. The nominal or continuous current is the current that continuously be supplied to the motor at the given speed, which will result in a heating up of the coils to the maximum temperature.

The nominal operating point is always based on a certain ambient temperature. In the 20-sim Servo Motor Editor an ambient temperature of 25 °C is used.

The choice of the speed for the nominal operation point is arbitrary. Some motor suppliers use the speed that results in a maximum power output at the motor shaft. Some motor suppliers use a speed that is half of the maximum allowed speed.

**Maximum Power and Maximum Efficiency**

The purpose of a motor is to deliver power to a load. Given a certain voltage $u$, the delivered power is equal to the torque times the speed:

$$P = S \cdot \left( \frac{u}{K} - \omega \right) \cdot \omega$$

The maximum delivered power $P_{out,max}$ for a given voltage can be found by differentiating this function and setting it to zero. The result will be a specific torque and speed. If this process is repeated for other voltages, a line of points where maximum power is delivered will result.

The efficiency $h$ of a motor is defined as the net output power divided by the input power. For a given voltage, the maximum efficiency can be found just like the maximum power and will lead to a certain torque and speed. By repeating this procedure for other voltages, a line of points where maximum efficiency is obtained will result.
The resulting lines of maximum power and maximum efficiency can be shown in the torque speed plot. Choosing a good motor is always a compromise between efficiency and output power. A good choice is to choose a motor that has the major part of the load curve inside the lines of maximum power and maximum efficiency. This area is called the Desired Operating Area.

Choosing a Motor

If we combine the results of the previous sections, a torque speed plot results as shown below. The arrows indicate the load curve with the circle as point of maximum load power. The Safe Operating Area shows the limits of operation due to motor specific parameters such as the maximum torque and speed.

The lines of maximum output power and maximum efficiency are the edges of the Desired Operating Area. The procedure for choosing a proper motor is:

1. Determine the load curve and the point of maximum load power.
2. Determine the duty cycle \(d\) (the percentage of the time that torque is required) and estimate the corresponding \(Td\) line with help of the shown \(T100, T50, T25\) and \(T10\) lines.
3. Select a motor such that the following demands are satisfied:
The load curve is completely beneath the Td line (no overheating).
- The complete load curve is in the Save Operating Area.
- The point of maximum load power is in the Desired Operating Area.
- The point of maximum load power is as close to maximum voltage line as possible (we want to choose the smallest motor that can do the job).
- The load curve is as much in the Desired Operating Area as possible.

**Thermal Behaviour**

**DC Motors**

Every motor generates heat, even when at zero speed, and this will lead to an increase in the motor temperature. Especially when running in continuous operation, there is a good chance that a motor, which is perfectly capable of generating the needed output power, will heat up beyond its thermal limit and break down.

As explained in the previous section the thermal limit is indicated in the torque speed curve by the maximum continuous torque line. To generate such a line, a thermal model is used. This thermal model is also part of the dynamic model that is used in 20-sim. This section describes the thermal model of permanent magnets motors.

In standard brush DC motors the coils are part of the rotor. To create a thermal model, various components will be identified first.

**Heat Generation**

Heat is generated in the motor at every place where energy is lost: coils, bearings, iron etc. Because the main source of energy loss is in the coils due to the coil resistance, we start at the coils. The coils act as a heat source and generate a heat flow equal to:

\[ dQ = i^2 \cdot R \]

**Thermal Capacity**

The rotor package, consisting of the coils and possibly iron and other material, will heat up due to the generated heat. The temperature increase depends on the generated heat \(dQ\), the heat capacity of the rotor \(C_{coil}\) and the transfer of heat to the stationary housing of the motor \(dQ_{coil-housing}\):

\[ T_{coil} = \frac{1}{C_{coil}} \cdot \int dQ - dQ_{coil-housing} \, dt \]

**Thermal Resistance**

The heat flow from the coils to the housing \(dQ_{coil-housing}\) depends on the temperature difference between the rotor and the housing and the thermal resistance \(R_{coil-housing}\):
10. Toolboxes

\[dQ_{\text{coil-housing}} = \frac{(T_{\text{coil}} - T_{\text{housing}})}{R_{\text{coil-housing}}}\]

**Thermal Capacity**

Like the rotor, the housing will also heat up. The temperature increase depends on the heat coming from the rotor \(dQ_{\text{rotor-stator}}\), the heat capacity of the housing \(C_{\text{housing}}\) and the transfer of heat to the environment \(dQ_{\text{housing-amb}}\):

\[T_{\text{stator}} = \frac{1}{C_{\text{housing}}} \int dQ_{\text{coil-housing}} - dQ_{\text{housing-amb}} \, dt\]

**Thermal Resistance**

The heat flow from the stator to the environment stator \(dQ_{\text{housing-amb}}\) depends on the temperature difference between the housing and the environment and the thermal resistance \(R_{\text{housing-amb}}\):

\[dQ_{\text{housing-amb}} = \frac{(T_{\text{housing}} - T_{\text{amb}})}{R_{\text{housing-amb}}}\]

The thermal resistance \(R_{\text{housing-amb}}\) depends on the motor mounting and external cooling. In most data sheets, a value for the thermal resistance can be found based on standard motor mounting.

**Environment**

The environment is supposed to have a fixed temperature \(T_{\text{amb}}\).

**Other Motors**

The same components as found for the DC brush motor can be found for other motor types. We only have to realize that for Brushless DC motors and AC Synchronous motors the coils are mounted on the housing. This means the thermal resistance \(R_{\text{coil-housing}}\) is relatively small and excess heat can be transferred relatively easy. Therefore these motors are very robust for overheating.

In AC synchronous linear motors, the coils are mounted are part of a platform, on which the load can be attached. To get the same thermal model we consider the platform to be the housing. Depending on the type of motor the housing can have a medium thermal capacity (iron core motors) or a very small thermal capacity (ironless motors). Because the all excess heat has to be removed through the air, linear motors will heat up easily. That is why sometimes forced cooling (water) is applied.
**Thermal Model**

If we combine all components we get the complete thermal model. It can be represented as shown in the figure below.

The values for thermal capacities and resistances can be found in most data sheets. These values are, however, based on general conditions. The value of the thermal resistance $R_{\text{housing-amb}}$ can vary considerably, based on the specific mounting of the motor and use of passive or active cooling. Most motor suppliers will indicate the how the thermal parameters were derived and how the motor should be mounted to meet the general conditions.

### 10.8 Real-Time Toolbox

#### 10.8.1 Introduction

**Real Time Toolbox**

The Real Time toolbox of 20-sim allows you to create C-code out of any 20-sim model for the use in real-time applications:

1. Create ANSI-C code for use in a real-time environment.

The generation of Matlab / Simulink code is can be performed using the Export command of the Editor File menu. You can also use the C-code generation command of the Simulator **Tools** menu.

The generation of C-code can be done with the C-code generation command of the Simulator **Tools** menu.
10.8.2 C-Code Generation

C-Code Generation

20-sim has a C-Code Generator which automatically converts a complete 20-sim model or submodel into C-Code. The application can be used to generate Matlab™/Simulink™ S-Functions, to generate Stand-Alone executables or to generate input/output functions for use in other C and C++ programs. The ANSI C-Code Generator can be opened from the Simulator (Tools menu, C-Code Generation command).

- Depending on the target selected, 20-sim will generate specific C-code.
- You can add more targets by adding paths in the General Properties.

By default, the following targets are supported:

1. **20-sim Dynamic DLL**: Generate C-code of a 20-sim submodel and compile the code into a DLL-call for use inside 20-sim.
2. **20-sim submodel for Arduino/AVR**: Generate C-code for the use on a Arduino/AVR. Note: not all functions (e.g. matrix) are supported!
3. **C-Code for 20-sim submodel**: Generate C-code of a 20-sim submodel.
4. **C++ class for 20-sim submodel**: Generate object oriented C-code of a 20-sim submodel.
5. **Simulink S-function**: Generate C-code of a 20-sim submodel in the Simulink format and compile it into an S-function. Note: this option requires the Matlab mex-compiler.
6. **Stand-alone C-code**: Generate C-code of a 20-sim main model including integration method.
7. **FMU 1.0 export for 20-sim submodel**: Export a 20-sim submodel using the FMI 1.0 standard.

8. **FMU 2.0 export for 20-sim submodel**: Export a 20-sim submodel using the FMI 2.0 standard.

---

### Generating ANSI C-Code

#### Overview

The modeling and simulation package 20-sim is capable of generating ANSI C-Code for several targets. Possible targets are Stand-Alone C, a C-Function, or a Simulink S-Function. Since 20-sim generates well-documented ANSI C-Code, it is easy for a user to make modifications or extensions to the generated code by hand. However it is also possible to fully define your own code target using C-Code templates, and to make modifications in these templates, so the resulting source code is tailor made for your application.

#### General Structure

The code generation process of 20-sim typically has the following structure:

![Diagram showing the code generation process of 20-sim.](image)

1. **Step 1**
   
   1. The process starts with a model and simulation in 20-sim.
   2. In the 20-sim Simulator, the user selects the **C-Code Generation** command from the **Tools** menu.
   3. 20-sim collects information about the current model.
   4. A target configuration file is read that specifies the different code generation targets that exist.
   5. The **C-code generation dialog** is opened, allowing the user to specify the target to use.

2. **Step 2**
   
   1. The selected target refers to specific template files (source files) in a target specific subdirectory.
   2. 20-sim adapts these template files with the model information and generated code for the model.
Step 3

1. The resulting files are placed in a destination directory.
2. These files are now specific for the target and the model.
3. If desired, 20-sim can call additional commands for further processing (f.i. make, run etc).

Code Generation Dialog

After 20-sim reads the target configuration file, the code generation dialog is shown with the information of this file:

The target list shows the names of the available targets. When a selection is made, the description of the selected target is given at the right. A submodel can be selected when the target requires this. The output directory can be overruled.

Targets

The user can create own targets. All targets are defined in the target definition file Targets.ini. This file has a typical INI-file structure and starts with a section that simply enumerates which targets exist. Each target then has its own section that holds the remaining information, like a short description of the target, the name of the template directory, the names of the template source files, additional commands to perform, etc. The following keywords may appear in a target section:
Templates
Each target can point to a set of template files that are used to create C-Code with. Own template files can be created by the user, with the help of the most powerful feature of 20-sim C-Code generation: the use of tokens! A token is a placeholder for model-dependent information. For instance in the C-Code Generation Dialog, the target destination directory contains the name of the selected submodel (e.g. c:\ temp\%SUBMODEL_NAME%) by default. Since this information is not yet known when the targets.ini file is created, a specific token that refers to this name is used instead. A complete description of predefined tokens is described in the section about Available 20-sim Tokens.

Generation Result
After the tokens in the target template files are replaced, the resulting target and model specific files will be placed in the destination directory. If commands are specified in the Targets.ini file, these commands are performed. This allows the user to call scripts automatically. E.g. for automatic compilation, linking and running of the code in a certain target environment.

Target.Ini File
The user can create own targets. All targets are defined in the target definition file Targets.ini. This file has a typical INI-file structure and starts with a section that simply enumerates which targets exist. Each target then has its own section that holds the remaining information, like a short description of the target, the name of the template directory, the names of the template source files, additional commands to perform, etc. The following keywords may appear in a target section:

targetName = "string"
The name that will appear in the 20-sim C-Code Generation Dialog.

iconFile = "string"
The name of an icon file (.ico) that contains an icon to appear in the 20-sim C-Code Generation Dialog.

description = "string"
The string that will appear in the description field in the 20-sim C-Code Generation Dialog.

templateDirectory = "string"
Here the path name where the template files for the c-code can be found can be specified. The default name is the target name in the CCode directory of 20-sim. If no full path is specified, the Ccode directory in 20-sim is taken as a starting point.
**templateFiles**

=filename1; filename2; filename3...

A list of files, semicolon-separated, that specify the files that are generated in the targetDirectory.

**targetDirectory**

="string"

This holds the default target directory where the files will be generated. This directory name will appear in the 20-sim dialog box when C-Code is generated and can be overruled by the user.

**submodelSelection**

=TRUE (default)

=FALSE

Determines whether C-Code is generated for the complete 20-sim model, or that a submodel selection is required.

**preCommand**

="string"

A command which will be executed in the target directory before that the C-Code will be generated.

**postCommand**

="string"

A command which will be executed in the target directory after that the C-Code has been generated. For example a "make" command can be given to automatically compile the generated code for the specific target.

**newLineCharacter**

    =0    CRLF (0x0d0a = DOS Standard)
    =1    CR (0x0d = Macintosh Standard)
    =2    LF (0x0a = Unix Standard)

Enter a number for the kind of newline character that should be used.

**%KEYWORD%**

=value

This (re)defines the keyword "KEYWORD" and gives it the contents "value". Own keywords can be defined in this manner as well.

**example:**

   %XX_TIME%=someTime

will redefine the time variable with the value "someTime"
Example

A valid Targets.ini file (defining three targets) may look like below. The file may also contain specific 20-sim tokens (%MODEL_NAME%) that are described later on.

```
; Possible targets for 20-sim C-Code Generation
;
[targets]
StandAloneC
CFunction
20simDLL
Simulink

; Generate Stand-Alone C-Code for the complete 20-sim model
;
[StandAloneC]
targetName="Stand-Alone C-Code"
iconFile="20sim.ico"
description="Use this target when testing the complete 20-sim model as a single process."
SubmodelSelection=FALSE
templateDirectory="StandAloneC"
templateFiles=xxfuncs.c;xxfuncs.h;xxinteg.c;xxinteg.h;xxinverse.c
templateFiles=xxmain.c;xxmatrix.c;xxmatrix.h;xxmodel.c;xxmodel.h
templateFiles=xxtypes.h;%MODEL_NAME%.dsp;%MODEL_NAME%.dsw
targetDirectory="c:\temp\%MODEL_NAME%"

; Generate C-Code for a selected Submodel
;
[CFunction]
targetName="C-Code for 20-sim submodel"
iconFile="20sim.ico"
description="This is the C-Code as it was generated for a submodel in 20-sim version 3.1"
templateDirectory="CFunction"
templateFiles=xxfuncs.c;xxfuncs.h;xxinteg.c;xxinteg.h;xxinverse.c
templateFiles=xxmain.c;xxmatrix.c;xxmatrix.h;xxmodel.c;xxmodel.h
templateFiles=xsubmod.c;xsubmod.h;xxtypes.h;%SUBMODEL_NAME%.dsp;%SUBMODEL_NAME%.dsw
SUBMODEL_NAME
E%.dsw
targetDirectory="c:\temp\%SUBMODEL_NAME%"

; Generate C-Code for a dynamic DLL-call to be used in 20-sim
;
[20simDLL]
targetName="20sim Dynamic Dll"
iconFile="20sim.ico"
description="Generate C-Code for a dynamic DLL-call to be used in 20-sim"
templateDirectory="20simDLL"
templateFiles=xxfuncs.c;xxfuncs.h;xxinverse.c
templateFiles=xxmatrix.c;xxmatrix.h;xxmodel.c;xxmodel.h
templateFiles=xxtypes.h;%SUBMODEL_NAME%.c
```
templateFiles=%SUBMODEL_NAME%.dsw;%SUBMODEL_NAME%.dsp;%SUBMODEL_NAME%.emx
targetDirectory="C:\temp\%SUBMODEL_NAME%"

; Generate C-Code for a Simulink S-Function
;
[Simulink]
targetName="Simulink S-Function"
iconFile="mdl.ico"
description="This generates C-Code for a submodel to be used in Matlab/Simulink"
templateDirectory="Simulink"
templateFiles=%SUBMODEL_NAME%.c;xxinverse.c;xxmatrix.c;xxmatrix.h
templateFiles=xxmexfcs.c;xxmextps.h;xxtypes.h;%SUBMODEL_NAME%_.mdl
targetDirectory=c:\temp\%SUBMODEL_NAME%
potCommand=mex %SUBMODEL_NAME%.c

Available 20-sim Tokens

Both the target configuration file and the code generation dialog revealed the most important part of the 20-sim code generation process, the use of tokens!

A token is a placeholder for model-dependent information. For instance in the code generation dialog, the target destination directory contains the name of the selected submodel by default. Since this information is not yet known when the targets.ini file is created, a specific token that refers to this name is used instead.

The idea is to create targets from template source files that contain tokens instead of actual model-dependent information (like equations, names, parameters, inputs etc). The files that are specified in a target section will be scanned for these tokens and tokens will be replaced by the corresponding model-dependent information.

Predefined variable names

The following variables should be declared in the C-Code template, because 20-sim uses these names in the generation of the equations:

c: constant array
P: parameters array
V: variables array
s: states array
R: rates array
M: matrix array
U: unnamed variables array
F: favorite variables array
f: favorite parameters array

Note that these parameters are case-sensitive!

Model Data

The following tokens will be replaced by numbers indicating the number of model parameters etc., typically used in memory allocation parts and loops.
% The number of constants in the model
NUMBER_CONSTANTS The number of parameters in the model
% The number of variables in the model
% The number of states in the model
NUMBER_PARAMETERS The number of inputs of the model
% The number of outputs of the model
%NUMBER_VARIABLES The number of matrices used in the model
% The number of unnamed variables in the model
%NUMBER_STATES% The number of favorite parameters in the model
%NUMBER_INPUTS% The number of favorite variables in the model
%NUMBER_OUTPUTS% The size of the largest workarray necessary in calculating
%NUMBER_MATRICES some matrix functions
%
%NUMBERUnnamed
%
%
NUMBER_FAVORITE_PARAMETERS%
%
NUMBER_FAVORITE_VARIABLES%
%WORK_ARRAY_SIZE
%

The following tokens are already reserved for future use:

%NUMBER_DEPENDENT_STATES The number of dependent states in the model
% The number of algebraic loop variable pairs in the model
%NUMBER_ALGLOOPs The number of constraint variable pairs in the model
% The number of import variables in the model
% The number of export variables in the model
NUMBER_CONSTRAINTS%
%NUMBER_IMPORTS%
%NUMBER_EXPORTS%

Example

Variable name arrays
If you want to use parameters etc. that are specific to a model you can use arrays of names using the following tokens:
%CONSTANT_NAMES% All the constants used in the model.
%PARAMETER_NAMES% All the parameters used in the model.
%VARIABLE_NAMES% All the variables used in the model.
%STATE_NAMES% All the states used in the model.
%RATE_NAMES% All the rates used in the model.
%DEPSTATE_NAMES% All the dependent states used in the model.
%DEPRATE_NAMES% All the dependent rates used in the model.
%ALGLOOP_NAMES% All the algebraic loop variables used in the model.
%CONSTRAINT_NAMES% All the constraint variables used in the model.
%INPUT_NAMES% All the inputs used in the model.
%OUTPUT_NAMES% All the outputs used in the model.
%MATRIX_NAMES% All the matrices used in the model.
%FAVORITE_PARAMETER_NAMES% All the favorite parameters used in the model.
%FAVORITE_VARIABLE_NAMES% All the favorite variables used in the model.

Example

Initialization code
An important part of a model are the parameters, initial values states etc. To match these with the generated model code and use the correct values the following tokens can be used:

%INITIALIZE_CONSTANTS%
%INITIALIZE_PARAMETERS%
%INITIALIZE_MATRICES%
%INITIALIZE_STATES%
%INITIALIZE_DEPSTATES%
%INITIALIZE_ALGLOOPS%
%INITIALIZE_CONSTRAINTS%
%INITIALIZE_INPUTS%
%INITIALIZE_OUTPUTS%
%INITIALIZE_FAVORITE_PARS%
%INITIALIZE_FAVORITE_VARS%

Example

Equations
The following tokens can be used to place 20-sim simulation model equations into the C-Code:
%INITIAL_EQUATIONS Equations that should be calculated once for initialization of the model
%STATIC_EQUATIONS Equations that should be calculated once
%INPUT_EQUATIONS Equations that should be calculated once at the beginning of every simulation step
% DYNAMIC_EQUATIONS Equations that calculates the dynamic part of the model, calculates the rates
%OUTPUT_EQUATIONS Equations that should be calculated once at the end of every simulation step
%OUTPUT2_EQUATIONS Reduced set of equations that should be calculated at the end of every simulation step
%FINAL_EQUATIONS Equations that should be calculated once for termination of the model

Inputs/Outputs
To match model inputs and model outputs to for example sensor signals and actuator signals you can use:

%INPUT_TO_VARIABLE_EQUATIONS%
%VARIABLE_TO_OUTPUT_EQUATIONS%
%ALIAS_EQUATIONS%
%FAVORITE_PARS_EQUATIONS%
%FAVORITE_VARS_EQUATIONS%

Example

Additional tokens

%INTEGRATION_METHOD D_NAME% A string representing the name of the selected integration method, for now only Euler, RungeKutta4 and Discrete are available.
%XX_TIME% The name of the simulation time variable (combined with %VARPREFIX%)
%XX_INITIALIZE% The name of the variable that indicates the initialization phase(combined with %VARPREFIX%).
%START_TIME% Start time of the simulation (floating point notation).
%FINISH_TIME% Finish time of the simulation (floating point notation).
%TIME_STEP_SIZE% Step size of the simulation (floating point notation).
Either TRUE or FALSE, depending if the model is discrete in time or continuous in time.
10. Toolboxes

% MODEL_IS_DISCRETE %

Experiment Tokens
Tokens which hold information about the model, experiment, user and system:

%FILE_NAME% The file name of the generated C-Code.
%MODEL_FILE% The complete path and file name of the original 20-sim model.
%MODEL_NAME% The name of the 20-sim model out of which C-Code was generated.
%SUBMODEL_NAME% The name of the 20-sim submodel out of which C-Code was generated.
%EXPERIMENT_NAME% The experiment name accompanying the 20-sim (sub)model.
%GENERATION_TIME% The time of C-Code generation.
%GENERATION_DATE% The date of C-Code generation.
%GENERATION_BUILD% The 20-sim version and build number.
%GENERATION_DIR% The directory where the generated C-Code files are stored.
%USER_NAME% The user name given in the 20-sim license.
%COMPANY_NAME% The company name given in the 20-sim license.
%20SIM_DIR% The directory where 20-sim is installed.

10.9 Time Domain Toolbox

10.9.1 Time Domain Toolbox
The Time Domain Toolbox contains powerful tools to inspect the behaviour of your model using time domain simulation.

- **Parameter sweep**: Perform a number of simulation runs, while changing model parameters.
- **Optimization**: Optimize a given result by changing parameters.
- **Curve Fitting**: Fit your model to a given result by changing parameters.
- **Tolerance Analysis**
  - **Sensitivity**: Change parameters by a given percentage and monitor results.
  - **Monte Carlo**: Change parameters statistically and monitor results.
Variation Analysis: Find the statistical range of parameters to yield a given result.

External DLL: Let the multiple run be controlled by a user-defined function in a DLL.

Procedure

1. From the Toolbox menu select the Time Domain Toolbox and then the tool that you want to use.

2. This will open the Multiple Run Wizard. Follow the instructions and after all settings have been entered, close the wizard.

3. Select the Multiple Run command from the Simulation menu to perform the specified analysis.

4. After simulation is completed a special window will open to showing the results. If it is not available, you can always open this window, by selecting the Multiple Run Results command of the View Menu.

Multiple Run Wizard

All tools of the Time Domain Toolbox are started use the Multiple Run Wizard. You can open this Wizard directly by selecting the Multiple Run command from the Properties menu.

10.9.2 Parameter Sweep

Introduction

Using the Parameter Sweep option of the Time Domain Toolbox, you can perform a predefined number of simulation runs with variation of parameters / initial values.

Example

1. From the Getting Started Manual\Time Domain Toolbox library open the model ParameterSweep.

2. Open the Simulator.

3. In the Simulator, from the Tools menu select the Time Domain Toolbox and then Parameter Sweep.

A window will open, asking you which parameters values should be changed during the multiple simulations. Here the parameters Lever\L\r and Bellows\K\k are already entered.
4. Click the **Next** button.

**Result**
A window opens asking you which result (optional) should be shown after the simulations:
Here the integral of the pipe air flow (e.g. the total air volume) is chosen. For a parameter sweep, you do not have to fill in a value, but it is nice to see which set of parameters will give a maximum air flow.

5. Click the **Next** button.

**Run options**

A window will open, asking some simulation run options:
You can select the following items:

- **Steps**: Number of simulations runs.
- **Copy from States**: Use the result of the previous simulation runs as the starting value of the numerical output of the parameter sweep.
- **Join Parameter Variation**: Change all parameters simultaneously.
- **Clear After Every Run**: Clear the simulation plot when a new simulation run starts.
- **Redraw After Every Run**: Update the scaling after every run.

Here the two parameters will be varied 5 times independently, requiring 25 simulation runs.

6. Click the **Next** button.

A window will open with a summary of the chosen options. If you are not satisfied you can use the **Back** button to go to a previous window and change settings.

7. Click the **Finish** button to close the Multiple Run Wizard.

8. From the **Simulation** menu click the **Multiple Run** command to perform the Parameter Sweep.

Now the Simulator will perform the 25 runs and show the results in the plots. If you click View - Numerical values, you can inspect the runs and see that run number 10 will give the largest air flow.
Parameter Sweep Results

After simulation has been done, a Multiple Run Results window will open, showing the minimum and maximum value of the result and chosen parameters.

Here the maximum and minimum air flow volume is shown. You can select the following items:
10. Toolboxes

- **Values**: Choose this button to open the list that shows the numerical output of the parameter sweep.
- **Matlab**: Export the results to Matlab.
- **OK**: Close the Multiple Run Results Window.

You can always re-open the Multiple Run Results window, by selecting the **Multiple Run Results** command of the **View** Menu.

9. By choosing the **Values** button, a new window is opened, showing the numerical results of the parameter sweep.

In the **Results** list of this window the subsequent runs are shown and (if available) the value of the chosen result:

![Multiple Run Results Window](image)

Here the 25 runs are shown with the parameter values and resulting air flow volume. As you can see, run number 10 gives the maximum air flow. You can select the following items:

- **Step**: Click on **Step** or the other column headers to sort the runs.
- **Set Values**: Choose the values of the selected run, as new parameter values of your model.
• *Create Datafile*: Use this button to store the values of the selected variables on file. Use the control-key and shift-key to make multiple selections.

### 10.9.3 Optimization

Using the Optimization option of the *Time Domain Toolbox*, you can optimize a given result using variation of parameters / initial values.

**Optimization Method**

1. From the *Getting Started Manual\Time Domain* Toolbox library open the model *Optimization*.

2. Open the *Simulator*.

3. In the *Simulator*, from the *Tools* menu select the *Time Domain Toolbox* and then *Optimization*.

A window opens asking you which optimization method should used:

![Optimization/Curvefitting Window](image)

Here the optimization method is already chosen.

4. Click the *Next* button.

**Parameters / Initial Values**

A window will open, asking you which parameters values should be use for the optimization. Here the parameters *Lever\L\r* and *Bellows\K\k* are already entered.
5. Click the **Next** button.

**Result**

A window opens asking you which result should optimized:
Here the integral of the pipe air flow (e.g. the total air volume) is chosen.

6. Click the **Next** button.

**Run options**

A window opens asking some simulation run options:
7. Click the **Next** button.  

A window opens with a summary of the chosen options. If your are not satisfied you can use the **Back** button to go to a previous window and change settings.

9. Click the **Finish** button to close the **Multiple Run** Wizard.

10. From the **Simulation** menu click the **Multiple Run** command to perform the Optimization.

You will see the Simulator perform many simulation runs. After a maximum has been found on the starting run and the runs with the maximum air flow is shown.
Optimization Results

After simulation has been done, an Optimization Results window will open, showing the optimum value of the result and corresponding parameters:

Here the maximum air flow volume is shown. You can select the following items:

- **Values**: Choose this button to open the list that shows the numerical output of the optimization runs.
- **Matlab**: Export the results to Matlab.
- **OK**: Close the Optimization Results Window.
You can always re-open the Multiple Run Results window, by selecting the **Multiple Run Results** command of the **View** Menu.

11. By choosing the **Values** button, a new window is opened, showing the numerical results of the parameter sweep.

In the **Results list** of this window the subsequent runs are shown and (if available) the value of the chosen result:

As you can see here the 81 runs are performed and shown with the parameter values and resulting air flow volume. As you can see, run number 81 gives the maximum air flow. You can select the following items:

- **Set Values**: Choose the values of the selected run, as new parameter values of your model.
- **Create Datafile**: Use this button to store the values of the selected variables on file. Use the control-key and shift-key to make multiple selections.
### 10.9.4 Optimization Methods

In the Multiple Run Wizard you have to specify a result which will be optimized. The result is a function of model variables and the simulation run:

$$\text{result} = f(i,v1,v2,\ldots)$$

with $i$ the number of the simulation run. You also have to specify the parameters that should be varied to find the optimum result. We can group these parameters in a parameter vector:

$$\text{parameter vector} = p(i)$$

with again $i$ the number of the simulation run. All methods in 20-sim for finding an optimum of the result use the same iterative process:

1. The initial parameter vector is determined, e.g. $p(1)$ and the corresponding function value $f(1)$.
2. A search direction $r(1)$ and a stepsize $s(1)$ are determined.
3. Perform a new simulation run to find the parameter vector $p(2) = p(1) + s(1)*r(1)$.
4. Calculate $f(2)$.
5. When the $f(2)$ is smaller than $f(1)$ and the difference between the two is smaller than a given tolerance, stop the process. The optimum has been found.
6. When the $f(2)$ is smaller than $f(1)$ and the difference between the two is larger than a given tolerance, proceed the process at step 2.
7. Otherwise a new stepsize and/or a new search direction are determined and the process is proceeded at step 3.

The choice of the stepsize is of importance for the speed and accuracy of the search process. A small stepsize will make the optimization process last very long. A large stepsize will make it less accurate. Most methods will therefore use a variable stepsize.

Of equal importance is the proper choice of the search direction. Methods for finding the search direction, can be divided in two groups: direct search methods and gradient search methods. The gradient of a function, is its slope at a certain point. Gradient search methods use this slope to find the optimal direction of search.

**Methods**

The optimization methods that are supported in 20-sim will now be explained. The pictures at the right visualize the methods with two varying parameters $x$ (horizontal) and $y$ (horizontal) and the corresponding result (vertical).
1. **Perpendicular Search** (direct search)
The perpendicular search method uses a search direction that is always perpendicular to the parameter axis. This means that only one parameter at a time is varied. All other parameters keep the same value. After one step, a next parameter is taken and the process continues.

2. **Line Climber** (direct search)
The line climber method uses a search direction that is always perpendicular to the parameter axis. This means that only one parameter at a time is varied. All other parameters keep the same value. After a minimum has been found the next parameter is varied and the process continues.
3. Steepest Descent (gradient search)
The steepest descent method starts its search in the direction of the steepest slope. This direction is kept for each new step until a minimum has been found. Then a new search direction is determined and the process continues.

4. Continuous Descent (gradient search)
The continuous descent method starts its search in the direction of the steepest slope. After each new step a new search direction is determined and the process continues.
5. Newton Raphson (gradient search)

The Newton Raphson method not only uses the gradient of a function, but also the second order gradient to determine the search direction. This direction is kept for each new step until a minimum has been found. Then a new search direction is determined and the process continues. Note: The method only converges for a positive second order gradient, i.e. near the minimum. This is shown in the figure to the right. For $x = -0.7$ and $y = -0.9$ the method does not converge. For $x = -0.5$ and $y = -0.3$ the method does converge.

6. Polack Ribiere (gradient search)

The Polack Ribiere method not only uses the gradient of a function, but also the second order gradient to determine the search direction. The second order gradient is estimated based on previous search directions. The search direction is kept for each new step until a minimum has been found. Then a new search direction is determined and the process continues.
7. Davidson Fletcher Powel (gradient search)
The Davidson Fletcher Powel method not only uses the gradient of a function, but also the second order gradient to determine the search direction. The second order gradient is estimated based on previous search directions. The search direction is kept for each new step until a minimum has been found. Then a new search direction is determined and the process continues.

8. Broydon Fletcher Goldfarb Shanno (gradient search)
The Broydon Fletcher Goldfarb Shanno method not only uses the gradient of a function, but also the second order gradient to determine the search direction. The second order gradient is estimated based on previous search directions. The search direction is kept for each new step until a minimum has been found. Then a new search direction is determined and the process continues.

What method should be used?
There is no general answer to this question. Some remarks can however be made:

1. Gradient search methods (3 to 8), need more steps (note that each step means a simulation run) to determine the gradient. The Newton Raphson methods needs the most steps, because this method also needs additional steps for the determination of the second order gradient.
2. When the direction of the slope is not exactly the same as the search direction, direct search methods (1 and 2) may start to bounce, i.e. continuously change direction while making little progress. This is shown in the figure below:

Users are therefore advised to use methods 1 and 2 only for optimizations with one parameter, and use the methods 7 and 8 for optimizations with more parameters. Use the other methods for checking the results or educational purposes.

More information on these methods can be found in:


### 10.9.5 Curve Fitting

Using the Parameter Sweep option of the *Time Domain Toolbox*, you can fit your model to a given result using variation of parameters / initial values.

**Optimization Method**

1. From the *Getting Started Manual\Time Domain Toolbox* library open the model *CurveFitting*.
2. Open the *Simulator*.
3. From the *Tools* menu select the *Time Domain Toolbox* and then *Curve Fitting*.

A window opens asking you which optimization method should used for curve fitting:
Here the optimization method is already chosen.

4. Click the **Next** button.

**Parameters / Initial Values**

A window will open, asking you which parameters values should be use for the curve fitting. Here the parameters $\text{Model}\omega$ and $\text{Model}\zeta$ are already entered.
5. Click the **Next** button.

**Result**

A window opens asking you which result should minimized to fit your model (variable 1) to a given result (variable 2):
6. Click the **Next** button.

**Run options**

A window opens asking some simulation run options:
7. Select the desired run options and click the **Next** button.

A window opens with a summary of the chosen options. If you are not satisfied you can use the Back button to go to a previous window and change settings.

8. Click the **Finish** button to close the **Multiple Run Wizard**.

9. From the **Simulation** menu click the **Multiple Run** command to perform the Curve Fitting.

You will see the Simulator perform many simulation runs. After a good fit has been found on the starting run and the runs with the best fit is shown.
Optimization Results

After the curve fit has been done, the Optimization Results window will open, showing the minimum value of the result and corresponding parameters:

You can select the following items:

- **Values**: Choose this button to open the list that shows the numerical output of the curve fitting runs.
- **Matlab**: Export the results to Matlab.
- **OK**: Close the Optimization Results Window.
You can always re-open the **Multiple Run Results** window, by selecting the **Multiple Run Results** command of the **View** Menu.

11. By choosing the **Values** button, a new window is opened, showing the numerical results of the parameter sweep.

In the **Results list** of this window the subsequent runs are shown and the value of the chosen result:

![Multiple Run Results window](image)

You can select the following items:

- **Set Values**: Choose the values of the selected run, as new parameter values of your model.
- **Create Datafile**: Use this button to store the values of the selected variables on file. Use the control-key and shift-key to make multiple selections.
10.9.6 Sensitivity Analysis

Using the Sensitivity Analysis option of the Time Domain Toolbox, you can detect which variations in parameter values will give the largest deviation of a given metric. If, for example, the metric is the accuracy of a machine, with sensitivity analysis you can detect how sensitive the machine is for parameter changes, with respect to that accuracy.

Sensitivity analysis starts with a simulation run with nominal parameter values. After the run a given result is monitored \( r \). Then, one by one, each parameter \( p_i \) is changed with a given percentage \( (p_i + dpi) \) and a simulation run is performed. After the simulation run the changed result is monitored \( r + dri \). After all the runs, the results are displayed as sensitivities, where sensitivity is defined as the change in result divided by the change in parameter:

\[
Si = \frac{dri}{dpi}
\]

A large sensitivity means that the result is highly dependent of the parameter value. This can be used for optimization (change the parameter value) or design (change the design to make it less dependant of the parameter).

Parameters / Initial Values

1. From the Getting Started Manual\Time Domain Toolbox library open the model SensitivityAnalysis.
2. Open the Simulator.
3. From the Tools menu select the Time Domain Toolbox and then Sensitivity Analysis.

A window opens asking you which parameters / initial values should be changed for the sensitivity analysis:
As you can see the parameters have already been entered.

4. Click the **Next** button.

**Result**
A window opens asking you which result should be monitored for the sensitivity:
The integral absolute value of the position error is chosen here.

5. Click the **Next** button.

**Run options**

A window opens asking some simulation run options:
6. Click the **Next** button.

A window opens with a summary of the chosen options. If your are not satisfied you can use the **Back** button to go to a previous window and change settings.

7. Click the **Finish** button to close the Multiple Run Wizard.

8. From the **Simulation** menu click the **Multiple Run** command to perform the Sensitivity Analysis.

Now the Simulator will perform a number of simulation runs and show the results.

**Sensitivity Analysis Results**

After simulation has been done, a Sensitivity Analysis Results window will open, showing the sensitivities:
As you can see, a change in pulley2 radius will by far give the largest change in error. I.e. the system is very sensitive to changes in the pulley2 radius. You can select the following items:

- **Multiple Run Values**: Choose this button to open the list that shows the output of the various runs performed during the sensitivity analysis.
- **Close**: Close the Sensitivity Analysis Results Window.

You can always re-open the *Multiple Run Results* window, by selecting the *Multiple Run Results* command of the View Menu.

### 10.9.7 Monte Carlo Analysis

Using the Monte Carlo analysis option of the *Time Domain Toolbox*, you can perform a predefined number of simulation runs with variation of parameter values according to a predefined distribution function.

#### Parameters / Initial Values

1. From the *Getting Started Manual*\Time Domain Toolbox library open the model *Parameter Sweep*.
2. Open the *Simulator*.
3. From the *Tools* menu select the *Time Domain Toolbox* and then *Monte Carlo Analysis*.

A window opens asking you which parameters / initial values should be varied for the Monte Carlo analysis:
Two parameters have already been entered.

4. Click the **Next** button.

**Result**

A window opens asking you which result should be monitored during the Monte Carlo Analysis:
Here the integrated absolute error of the machine is chosen.

5. Click the **Next** button.

**Run options**

A window opens asking some simulation run options:
Because this is a statistical method, we have to do many simulations runs. We therefore choose not to display the results in a plot to speed up simulation and prevent using too much computer memory.

6. Click the **Next** button.

A window opens with a summary of the chosen options. If you are not satisfied you can use the **Back** button to go to a previous window and change settings.

7. Click the **Finish** button to close the Multiple Run Wizard.

8. From the **Simulation menu** click the **Multiple Run** command to perform the Monte Carlo Analysis.

**Monte Carlo Analysis Results**

After the simulations have been done, a Monte Carlo Analysis Results window will open, showing the results:
You can select the following items:

- **Values**: Choose this button to open the list that shows the output of the various runs performed during the Monte Carlo analysis.
- **Histogram**: Choose this button to open a histogram of the selected item.
- **Matlab**: Export the results to Matlab.
- **OK**: Close the Multiple Run Results Window.

You can always re-open the **Multiple Run Results** window, by selecting the **Multiple Run Results** command of the **View** Menu.

9. By choosing the **Values** button, a new window is opened, showing output of the various runs performed during the Monte Carlo analysis.
You can select the following items:

- **Set Values**: Choose the values of the selected run, as new parameter values of your model.

- **Create Datafile**: Use this button to store the values of the selected variables on file. Use the control-key and shift-key to make multiple selections.

By choosing the **Histogram** button, a new window is opened, showing distribution of the integrated absolute error:
10.9.8 Variation Analysis

Using the Monte Carlo analysis option of the *Time Domain Toolbox*, you can perform a predefined number of simulation runs with variation of parameter values according to a predefined distribution function. We will then restrict the parameter variation until the error is within certain bounds. This is called Variation analysis.

**Parameters / Initial Values**

1. From the Getting Started Manual\Time Domain Toolbox library open the model ParameterSweep.
2. Open the Simulator.
3. From the **Tools** menu select the **Time Domain Toolbox** and then **Variation Analysis**.

A window opens asking you which parameters / initial values should be varied for the Variation analysis:
Here the integrated absolute error of the machine is chosen.

5. Click the **Next** button.

**Result**

A window opens asking you which result should be monitored during the Variation Analysis:
Two parameters have already been entered.

6. Click the **Next** button.

**Run options**

A window opens asking some simulation run options:
Because this is a statistical method, we have to do many simulations runs. We therefore choose not to display the results in a plot to speed up simulation and prevent using too much computer memory.

6. click the **Next** button.

A window opens with a summary of the chosen options. If you are not satisfied you can use the **Back** button to go to a previous window and change settings.

7. Click the **Finish** button to close the **Multiple Run Wizard**.

8. From the **Simulation menu** click the **Multiple Run command** to perform the **Variation Analysis**.

**Variation Analysis Results**

After simulation has been done, a Variation Analysis Results window will open, showing the results. A histogram shows the distribution of the result. Using the slider bar you can see how restraining the distribution of the parameters effects the distribution of the result.
The histogram shows the value of the integrated absolute error on the x-axis and the number of runs on the y-axis.

You can select the following items:

- **Slider Bar**: Select a parameter and restrict its distribution with the slider bar. You will see the results distribution change.
- **Multiple Run Values**: Choose this button to open the list that shows the output of the various runs performed during the Variation Analysis.
- **OK**: Close the Multiple Run Results Window.

You can always re-open the Multiple Run Results window, by selecting the **Multiple Run Results** command of the **View** Menu.

9. Change the slider bar for the two parameters and inspect the results.

You can see the following:

- An increase of the end effector mass will not reduce the maximum error.
- A decrease of the stiffness will not reduce the maximum error.

We can slide the maximum mass to the middle and minimum stiffness to the middle to decrease the error:
10.9.9 Multiple Run Wizard - External DLL

You can analyze the effects of variation of parameters / initial values using your own method with the use of an external DLL-function. Ask Controllab Products for details.

Deprecation warning
20-sim provides a Scripting toolbox since 20-sim 4.4 that allows you to write your own automation scripts around a 20-sim model. It is strongly advised to implement new customized multiple run experiments is by means of a script in either Octave/Matlab or Python. The multiple run external DLL feature will be removed in a future version of 20-sim.
10.9.10 Cost Function

In the Multiple Run Wizard, the Result window allows you to define a result (the Cost Function) that will be used during simulations (Optimization, Curve Fitting) and displayed after the simulations runs (Parameter sweep, Optimization, Curve Fitting, Sensitivity, Monte Carlo, Variation Analysis, External DLL).

The result can be a function of one or two variables. Instead of the second variable an (offset) value can be entered.

**Items**
- **Choose Variable**: Select this button to select a model variable
- **Clear**: Use this button the remove a chosen model variable.
- **Function**:
  - **End value**: The value at the end of the simulation run.
  - **Sum Absolute Value**: The sum of all absolute values during a simulation run.
  - **Sum Square Value**: The sum of all values squared during a simulation run.
  - **Integral Absolute Value**: The integral of all absolute values during a simulation run (uses Euler integration).
  - **Integral Square Value**: The integral of all values squared during a simulation run (uses Euler integration).

**User Defined Cost Function**
You can easily use your own Cost Function for the result variable:

1. Create your own cost function in the model.
2. Use the Choose button to select as var1 the output of your function.
3. Set var2 to a zero value.
4. Choose **End Value** to prevent further operations on your function.

## 10.10 Scripting Toolbox

### 10.10.1 Introduction

20-sim scripting allows you to run tasks in 20-sim automatically using scripts running in Python or other scripting tools. With these scripts you can open models, run simulations, change parameters, store results and much more.

20-sim provides a set of script functions for numerical computation environments like Octave and Matlab and for the Python programming language. The 20-sim scripting functions are based on XML-RPC calls, so any other programming language with support for XML-RPC can be used to automate various 20-sim steps. In this chapter you will learn how to run basic scripts and make scripts on your own.

The next sections explain:

- **Installation for scripting**:
  - *20-sim*: enabling the XML-RPC scripting interface in 20-sim
  - *Octave*: installing Octave as scripting environment
  - *Matlab*: installing Matlab as scripting environment
  - *Python*: installing Python as scripting environment
- **Prepare Scripting Folder**: extract the 20-sim scripting functions and documentation to your work directory.
- **Basic Script**: run your first script and see how a basic script is made in Octave/Matlab or Python.
- **Advanced Scripts**: see how you can expand the basic script to perform more advanced tasks in Octave/Matlab.
- **Writing your own Scripts**: How to write your own scripts in Octave/Matlab or Python.

**Note**: Scripting is not supported in the 20-sim Viewer/Demonstration Version. If you would like to try the scripting functionality, you will need licensed 20-sim version or a trial license.
10.10.2 Scripting API

All scripting functions can be found in the scripting API. In the 20-sim Editor click:

1. Help - Python Scripting API
2. Editor - Octave Scripting API

10.10.3 Installation for Scripting: 20-sim

20-sim uses XML-RPC as a protocol to communicate scripting functions with external packages. By default the XML-RPC interface is turned on only for your local computer.

To enable/disable and configure the 20-sim scripting support:

1. Open 20-sim.
2. Go to Tools/Options and select the Scripting Interface tab.

3. To enable the 20-sim scripting support, make sure that the HTTP and TCP checkboxes under XMLRPC Interface are enabled.

By default, 20-sim will only accept scripting connections from your local computer (Localhost only option is enabled).

Your firewall may generate a warning message and ask you to allow network communication for 20-sim.
4. Set the **firewall** to **allow communication**.

### 10.10.4 Scripting Menu

If you store the scripts in a folder "Scripting" next to your 20-sim model, a Scripting menu will appear in the 20-sim Editor.

The Examples\Scripting folder contains models with scripting. If you open one of these models, the Scripting menu will be visible showing several scripts. You can run these scripts directly from the menu.

### 10.10.5 Scripting in Octave/Matlab

**Installation for Scripting: Octave**

What is Octave?

GNU Octave is a high-level language, primarily intended for numerical computations. The package is open source and can be freely distributed. GNU Octave offers functionality similar to Matlab users. If you have experience with Matlab, using Octave will be familiar. Users with no experience with Octave nor Matlab are advised to read a proper introduction to GNU Octave first. You will find lot of pages and videos on the Internet.

**Installation**

The Windows versions of Octave 8.2.0, 8.1.0, 7.x, 6.x, 5.x, 4.x, 3.8.x, 3.6.x have been tested with 20-sim scripting at the time of this release.

Note that for older versions of Octave only the 32-bit Octave is supported. 64-bit versions of Octave are supported since Octave 4.2.1.

First choose the Octave version you wish to install and go to the corresponding section below:

**Octave 8.x / 7.x / 6.x / 5.x / 4.x**

1. Go to: https://www.gnu.org/software/octave/
2. Go to the download page and download the Windows installer (direct link: https://ftp.gnu.org/gnu/octave/windows/octave-8.2.0-w64-installer.exe)
3. **Run** the installer and follow the wizard. The steps below assume default installation settings.
4. **Octave 4.0.x only:** Unfortunately Octave 4.0.x has a Windows specific bug in its internal run() function. This bug is resolved in Octave 4.2 and above. For Octave 4.0.x you will need to manually replace the default run() implementation with a corrected version. **Copy** the file:
10. Toolboxes

C:\Program Files (x86)\20-sim 5.1\Scripting\Octave-patch\4.0.0\run.m

or on 32-bit versions of Windows:

C:\Program Files\20-sim 5.1\Scripting\Octave-patch\4.0.0\run.m
to:

C:\Octave\Octave-4.0.0\share\octave\4.0.0\m\miscellaneous\run.m

5. **Launch Octave** from the Start menu or using the script: C:\Octave\Octave-x.y.z\octave.bat

6. **Execute** the following commands to make sure that the io, control and signal are installed.

   pkg install -forge io
   pkg install -forge control
   pkg install -forge signal

---

The Octave GUI.

Your Octave installation is now ready to use.

**Octave 3.8.x**

2. **Run** the installer and follow the wizard.

3. **Launch Octave** using the script: `C:\Octave\Octave-3.8.2\octave.bat`

4. **Execute** the following commands to install packages io, control and signal:
   
   ```
   pkg install -forge io
   pkg install -forge control
   pkg install -forge signal
   ```

   Your Octave installation is now ready to use.

---

**Octave 3.6.x**

1. Go to the Octave download site (http://sourceforge.net/projects/octave/).

2. Click on the **Files** tab and click on **Octave Windows Binaries**.

3. Select the **Octave 3.6.4 for Windows MinGW installer**.

4. Now you can **download** the files `Octave3.6.4_gcc4.6.2_yyyxxxxxx.7z` (Octave Installation) and `Octave3.6.4_gcc4.6.2_pkgs_yyyxxxxxx.7z` (Octaveforge Packages).

5. Create an installation directory which doesn't have space chars (i.e. C:\Octave).

6. **Unzip** the file `Octave3.6.4_gcc4.6.2_yyyxxxxxx.7z` and **copy** it to the installation directory.

7. Copy the **shortcut link** `C:\Octave\Octave3.6.4_gcc4.6.2.lnk` to your **desktop**.
   
   This is a shortcut to start Octave.exe.

   **Note:** Unzipping can be done with programs like 7-zip (http://www.7-zip.org/)

   **Note:** There is a bug with Windows 8 and running Octave. In order to use Octave start Octave with `octave.exe -i --line-editing`. See the Octave wiki webpage for more information.

8. **Unzip** the file `Octave3.6.4_gcc4.6.2_pkgs_yyyxxxxxx.7z` and **copy** it to the installation directory.

9. **Launch Octave** (e.g. the link to Octave.exe).

10. **Execute** the following five rebuild commands from the Octave console (e.g. re-type every line followed by ENTER):

    ```
    pkg rebuild -auto
    pkg rebuild -noauto ad
    pkg rebuild -noauto nan % shadows many statistics functions
    pkg rebuild -noauto gsl % shadows some core functions
    pkg rebuild -auto java
    ```
10. Toolboxes

11. Close and **restart Octave**.

**Setting the Octave Location**

1. In the 20-sim Editor choose **Tools - Options - Scripting Client - Octave Folder** to enter the location where Octave is installed on your computer.

**Installation for Scripting: Matlab**

**What is Matlab?**
Matlab is a high-level language, primarily intended for numerical computations. The package is commercially distributed by the Mathworks. If you don't have the resources to purchase Matlab, you can run use Octave, which offers similar functionality.

**Versions**
Matlab R2011, R2012, R2013, R2014, R2015, R2016 and R2017 have been tested with 20-sim scripting but older and newer versions may also work fine.

**Installation**
See the Matlab documentation from the Mathworks for information on installing Matlab. No special (additional) installation is needed to use 20-sim scripting from Matlab.

**Note**: Scripting in Matlab is similar to Octave. You can type exactly the same commands as given for Octave in the next sections.

**Prepare Scripting Folder**
20-sim comes with a **Scripting Folder** that contains documentation of all scripting functions, the function library and example scripts. You have to install this folder to use scripting.
10. Toolboxes

Installation

1. Open the **Install Scripting** program from the Windows Start menu (located under *20-sim 5.1*)
   - or -
   Go to the folder where 20-sim is installed (e.g. `C:\Program Files\20-sim 5.1\Scripting` or `C:\Program Files (x86)\20-sim 5.1\Scripting`) and open `20simScripting.exe`

2. This will open a dialog where you can choose where to extract the 20-sim scripting files. **Change** the path to a local working folder of your choice (for example: `C:\Users\yourusername\Documents\20simscripting`)

![20-sim Scripts extraction](image)

Note: To write/modify scripts, the scripting folder should be accessible and writable by the user. Do not install the scripting folder on `C:\Program Files (x86)` or `C:\Program Files`.

For the remainder of this chapter, we use the name **scripting working folder** when we refer to the folder where you just extracted the 20-sim scripting files.

Contents

Your newly created **scripting working folder** contains a number of subfolders:

1. **Models**: This folder contains the 20-sim models and data files that are used for the example and tutorial scripts.

2. **Octave**: This folder contains all Octave/Matlab scripting functionality and documentation
   a. **documentation**: This folder contains the scripting API documentation: a list of supported functions and their syntax. It is a copy of the help file that you can open in the 20-sim Editor by selecting **Help - Octave Scripting API**.

   Note: the API documentation is also accessible from the Windows Start menu under *20-sim 5.1\Scripting API documentation*
   b. **library**: This folder contains the core scripting functions.
   c. **tutorials**: This folder contains basis scripts with a step by step explanation. You can use these scripts as a base for your own scripts.
   d. **examples**: This folder contains some more advanced scripts.

3. **Octave-patch**: This folder contains modified Octave scripts for certain Octave versions to fix bugs in the core Octave scripts that are not yet fixed in the latest release (currently 4.0.3)
4. **Python**: This folder contains all Python scripting functionality and documentation (see the Scripting in Python section for more information).

### Basic Script

When the scripting files are properly installed in your *scripting working folder*, we can run some tutorial scripts. Tutorial scripts are a step by step demonstrations of usage of the scripting functionality in 20-sim. These scripts are found in the *tutorials* subfolder of the *scripting working folder*. We will start with a basic script that opens and runs a 20-sim model.

1. Open **20-sim**.
2. Open **Octave** (or **Matlab**).
3. In Octave/Matlab, change the local working directory to the tutorial folder inside your *scripting working folder*. E.g. type:
   ```
   cd 'C:\Users\yourusername\Documents\20simscripting\Octave\tutorials'
   ```
   **Note**: 20-sim should be open before running the script!
4. In Octave/Matlab, execute the following command (e.g. type the following **case sensitive** command followed by ENTER):
   ```
   runSimulation
   ```
   **Note**: Octave may give a cryptic "*undefined near line x column 1*" message, if you type the command as *runsimulation* instead of *runSimulation*!
5. Now Octave / Matlab will give a message and ask you to press **ENTER** to continue. The model *ControlledSystem.emx* is loaded into 20-sim and simulated.
6. Again Octave/Matlab will give a message and ask you to press **ENTER** to continue.

Now the simulation and model will be unloaded.
Inspecting the script
To see how the script is made, you can inspect it with a text editor.

1. Open a file browser and go to the tutorials folder (e.g. C:\Users\yourusername\Documents\20simscripting\Octave\tutorials)
2. Open the file runSimulation.m with a text editor like Notepad.

Core Functions
The core functions of the runSimulation script are:

- **addpath**: The script starts with the command addpath('..\library\xxsim'); This will enable Octave / Matlab to use the 20-sim scripting functions that are stored in the library subfolder of your scripting working folder.
- **xxsimConnect**: This command opens a connection to 20-sim.
- **xxSimOpenModel**: This command opens a model in 20-sim by giving the filename including the full path.
- **xxsimProcessModel**: This command will process the model.
- **xxsimRun**: This command will run a simulation.
- **xxsimCloseModel**: This command will remove the simulation model from 20-sim.

These functions are the basis of scripting in 20-sim and will be present in this order in most scripts. Therefore you can use the script runSimulation.m as a template for any new script that you create.

Advanced Scripts
Now that we have seen the core functions of a script we will run and check some more advanced scripts.

1. Open 20-sim.
2. Open Octave (or Matlab).
3. In Octave/Matlab, change the local working directory to the tutorial folder inside your scripting working folder. E.g. type:
   
   `cd 'C:\Users\yourusername\Documents\20simscripting\Octave\tutorials'`

Set Parameter Values

4. In Octave/Matlab, execute the following script (e.g. type the command followed by ENTER):

   ```
   SetParameterAndRun
   ```

   This script will open the model ControlledSystem.emx and run a simulation. Then a model parameter is changed and a second simulation run is performed. As explained in the previous topic, you can inspect the script in a text editor.
Compared to the basic script you will find a new function:

- **xxsimSetParameters**: This function is used to set the parameter in the model with the new value.

### Multiple Runs

5. In Octave/Matlab, execute the following script (e.g. type the command followed by ENTER):

   ```octave
   multipleRun
   ``

   This script will open the model `ControlledSystem.emx` and run a simulation multiple times while changing a parameter. Then a model parameter is changed and a second simulation run is performed.

### Read Parameter Values

6. In Octave/Matlab, execute the following script (e.g. type the command followed by ENTER):

   ```octave
   readAndSetParameters
   ``

   This script will open the model `ControlledSystem.emx` and run a simulation. Then a model parameter is read from file and changed accordingly in the model, followed by a second simulation run.

You will find these new functions:

- **addpath**: An additional path is given (`../library/xxlib`) to allow additional (user defined) functions.
- **xxlibReadCsv**: This function is used to read a parameter name and value from a spreadsheet file.

### Store Simulation Results

7. In Octave/Matlab, execute the following script (e.g. type the command followed by ENTER):

   ```octave
   modelVerification
   ``

   This script will open the model `ControlledSystem.emx` and run a simulation. After the run the simulation results are stored and plotted in Octave/Matlab. You will find these new functions:

   - **xxsimSetLogVariables**: Define which variables are going to be logged during the simulation run.
   - **xxsimGetLogVariables**: Export the logged variables after the simulation run to Octave/Matlab.

### Examples

8. In Octave/Matlab, change the local working directory to the tutorial folder. E.g. type:

   ```octave
   cd 'C:\Users\yourusername\Documents\20simscripting\examples'
   ```
Writing your own Scripts

Example
We will show you how to write your own scripts using a simple example. We assume that you have installed a scripting folder and its location is:

'C:\Users\yourusername\Documents\20simscripting'

of course you can use own location. We will copy a 20-sim model to the scripting folder and write a script that will open this model in 20-sim and run a simulation.

1. **Copy** the example model **FastManipulator.emx** to the Octave\tutorials folder. E.g copy:

'C:\Program Files (x86)\20-sim 5.1\Models\Examples\Drivetrains \FastManipulator.emx'

to

'C:\Users\yourusername\Documents\20simscripting\Octave\tutorials \FastManipulator.emx'

2. **Open a text editor (e.g. notepad) and enter the following lines:**

```matlab
run('../library/xxsim/xxsimAddToPath.m');
xxsimConnect();
xxsimOpenModel('FastManipulator.emx');
xxsimProcessModel();
xxsimRun();
xxsimDisconnect();
```

3. **Save** the text file as:

'C:\Users\yourusername\Documents\20simscripting\Octave\tutorials \MyScript.m'

4. **Open 20-sim.**
5. **Open Octave (or Matlab).**
6. **In Octave/Matlab, change the local working directory. Type in the command line:**

```
cd 'C:\Users\yourusername\Documents\20simscripting\Octave\tutorials'
```
7. In Octave/Matlab, run your own script. Type in the command line:

MyScript

Now you will see the model being loaded in 20-sim and a simulation being run.

**Writing your own scripts**

In the tutorial folder there are more scripts. Use these as a template for writing your own scripts and follow the guidelines below:

**Location**

Create your own subfolder inside your scripting working folder. This allows you to update the 20-sim scripting files when new versions of 20-sim are released.

**Functions**

You can find help on scripting functions in the 20-sim Editor by selecting **Help - Octave Scripting API**.

### 10.10.6 Scripting in Python

**Installation for Scripting: Python**

**What is Python**

Python is a general-purpose high-level programming language with an emphasis on code readability and writing algorithms in fewer lines of code than other programming languages. Python is open-source and managed by the Python Software Foundation. It has an extensive standard library and can be extended with many external libraries including a rapidly growing set of scientific and mathematical libraries such as SciPy, NumPy and Sympy and an extensive plotting library Matplotlib. 20-sim scripting has been tested with the following versions of Python: Python 2.7.x, Python 3.4.x-3.7.x (32-bit and 64-bit).

**Installation**

During installation of 20-sim, you are asked to install the (optional) **Python 3.7 package**. We advise to keep the default setting (Yes) which will install the Python 3.7 installation that includes 20-sim scripting support and the following packages: NumPy, Matplotlib, Sympy, Pandas and IPython. This installation provides just enough support to get started with 20-sim scripting. However, it does not provide a development IDE or an extensive set of scientific and mathematical libraries.
Prepare Scripting Folder

20-sim comes with a Scripting Folder that contains documentation of all scripting functions, the function library and example scripts. You have to install this folder to use scripting.

Installation

1. Open the Install Scripting program from the Windows Start menu (located under 20-sim 5.1)
   - or -
   Go to the folder where 20-sim is installed (e.g. C:\Program Files (x86)\20-sim 5.1\Scripting or C:\Program Files (x86)\20-sim 5.1\Scripting) and open 20simScripting.exe

2. This will open a dialog where you can choose where to extract the 20-sim scripting files. Change the path to a local working folder of your choice (for example: C:\Users\yourusername\Documents\20simscripting)

Note: To write/modify scripts, the scripting folder should be accessible and writable by the user. Do not install the scripting folder on C:\Program Files (x86) or C:\Program Files.

For the remainder of this chapter, we use the name scripting working folder when we refer to the folder where you just extracted the 20-sim scripting files.

Contents

Your newly created scripting working folder contains a number of subfolders:

1. Models: This folder contains the 20-sim models and data files that are used for the example and tutorial scripts.

2. Octave and Octave-patch: These folders contain Octave/Matlab scripting functionality and documentation (see the Scripting in Octave/Matlab section for more information)

3. Python: This folder contains all Python scripting functionality and documentation:
   a. controllab: Folder containing the Python classes that allow communication with 20-sim.
   b. documentation: This folder contains the scripting API documentation: a list of supported functions and their syntax. It is a copy of the help file that you can open in the 20-sim Editor by selecting Help - Python Scripting API.
   c. examples: This folder contains some more advanced scripts.
10. Toolboxes

d. tutorials: This folder contains basis scripts with a step by step explanation. You can use these scripts as a base for your own scripts.

Basic Script

When the scripting files are properly installed in your scripting working folder, we can run some tutorial scripts. Tutorial scripts are step by step demonstrations of usage of the scripting functionality in 20-sim. These scripts can be found in the tutorials subfolder of the scripting working folder. We will start with a basic script that opens and runs a 20-sim model.

1. Open 20-sim.
2. Open IPython (Interactive Python shell) from the Start menu (under 20-sim 5.1).
3. In IPython, change the local working directory to the tutorial folder inside your scripting working folder. E.g. type:

   ```
   cd 'C:\Users\yourusername\Documents\20simscripting\Python'
   ```

4. In IPython, execute the following command (e.g. type the following case sensitive command followed by ENTER):

   ```
   run main_menu
   ```

Note that the run command is specific for IPython. For a standard Python session, you can start this script on the command line using: python.exe menu.py. This command will show a menu with several options including T for Tutorials.

![IPython session for the tutorials](image-url)
5. **Select option T - Tutorials (press t, ENTER) to show the tutorial menu:**

   - Tutorial menu -
   - Select a tutorial:
     1 - Run a simulation.
     2 - Set a parameter in 20-sim, then run a simulation.
     3 - Execute multiple runs with a changing parameter.
     4 - Basic simulation result analysis.
     5 - Read a parameter from a CSV file and set it in 20-sim.
     6 - Retrieve 20-sim model variables and their properties.

   Or choose a menu option:
   - Q - Quit
   - I - Show the introduction text again.

   Your choice > 1

6. **Press ENTER again to show the available tutorials and choose option 1 Run a simulation followed by ENTER.**

   In this tutorial the scripting interface will:
   - Open a 20-sim model (starting 20-sim if necessary)
   - Process and run the model
   - Close the 20-sim model

7. **Press ENTER**

   The Python scripting interface will now connect to 20-sim.
   If 20-sim is not running it will be started automatically.

8. **Press ENTER**

   Connecting, please wait...

   The scripting interface has successfully connected to 20-sim.
   The tutorial model will be opened.
   If you still have an open model. SAVE YOUR MODEL, unsaved changes will be overwritten.

9. **Press ENTER**

   The model ControlledSystem.emx has been opened in 20-sim.
   The model will be processed and simulated.
   The 20-sim plot window will open.

10. **Press ENTER to load the model ControlledSystem.emx in 20-sim and to simulate it.**

    The tutorial will now close the 20-sim model and exit.

11. **Press ENTER to close the simulation and this 20-sim model**
Inspecting the script

Tutorial completed!
Do you want to see the source code? [y/N]

To see how the script is made, you can inspect it by choosing y. This will print the relevant script lines on the Python console. You can also open the real script in a text editor like Notepad by opening the file: C:\Users\yourusername\Documents\20sim scripting\Python\tutorials\run_simulation.py.

Important Functions

The important functions / lines of the runSimulation script are:

- **import controllab:** Tell Python to load the Controllab package with the 20-sim scripting functions in the XXSim() class.
- **my20sim = controllab.XXSim():** create a 20-sim scripting object
- **my20sim.connect():** This command opens a connection to 20-sim.
- **my20sim.set_scriptmode():** Tell 20-sim that we are in scripting mode (does not show confirmation dialogs)
- **my20sim.open_model():** This command opens a model in 20-sim by giving the file name including the full path.
- **my20sim.process_model():** This command will process the model.
- **my20sim.run():** This command will run a simulation.
- **my20sim.close_model():** This command will remove the simulation model from 20-sim.

These functions are the basis of scripting in 20-sim and will be present in this order in most scripts.

Python Scripting Help

When you need help on Python Scripting for 20-sim:

1. In the **Editor** from the **Help** menu select **Python Scripting Api**.

This will open a Webhelp with documentation on Python Scripting and all functions that are supported.
Writing your own Scripts

Example
We will show you how to write your own scripts using a simple example. We assume that you have installed a scripting folder and its location is:

'C:\Users\yourusername\Documents\20simscripting'

Of course you can use own location. We will copy a 20-sim model to the scripting folder and write a script that will open this model in 20-sim and run a simulation.

1. Copy the example model **FastManipulator.emx** to the Octave\tutorials folder. E.g copy:

'C:\Program Files (x86)\20-sim 5.1\Models\Examples\Drivetrains \FastManipulator.emx'

   to

   'C:\Users\yourusername\Documents\20simscripting\Python\tutorials \FastManipulator.emx'

2. Open a text editor (e.g. notepad) and enter the following lines:

   ```python
   import controllab
   xxsim = controllab.XXSim()
   xxsim.connect()
   xxsim.open_model('FastManipulator.emx')
   xxsim.process_model()
   xxsim.run()
   xxsim.disconnect()
   ```

3. Save the text file as:

   'C:\Users\yourusername\Documents\20simscripting\Python\tutorials \myscript.py'

4. Open **20-sim**.
5. Open **IPython**.
6. In IPython, change the local working directory. Type in the command line:
   ```
   cd 'C:\Users\yourusername\Documents\20simscripting\Python\tutorials'
   ```

7. In IPython, run your own script. Type in the command line:
   ```
   run myscript
   ```

Now you will see the model being loaded in 20-sim and a simulation being run.

**Writing your own scripts**

In the tutorial folder there are more scripts. Use these as a template for writing your own scripts and follow the guidelines below:

**Location**

Create your own subfolder inside your scripting working folder. This allows you to update the 20-sim scripting files when new versions of 20-sim are released.

**Functions**

You can find help on scripting functions in the 20-sim Editor by selecting **Help - Python Scripting API**.

---

**Advanced Functionality**

**Python Distributions**

When you need more functionality or prefer to use an IDE with syntax highlighting and debugging support, it is strongly advised to install one of the following external Python distributions or IDEs:

- Spyder: the Scientific PYthon Development EnviRonment with a powerful IDE for the Python language with advanced editing, interactive testing, debugging and introspection features and a numerical computing environment based on SciPy, NumPy, Matplotlib and IPython.

**Running 20-sim scripts in Python distributions**

To add the 20-sim scripting support to your Python distribution, you can use the Python pip command (installed by default since Python 2.7.10 and 3.4.x) to install the Controllab package.

1. Open a Windows command prompt (**cmd.exe**) and type:
   ```
   cd YOUR_PYTHON_INSTALLATION_DIR\python -m pip install --no-cache-dir --upgrade "C:\Program Files (x86)\20-sim 5.1\Scripting\Python\whl\controllab-1.3.3-py2.py3-none-any.whl"
   ```

   *Note: use C:\Program Files\20-sim 5.1\ on 32-bit Windows systems.*
10.11 Unity Toolbox

10.11.1 Unity Toolbox

Unity is a game engine developed by Unity Technologies that allows you to create high visual fidelity, 3D real-time interactive user experiences. The Unity Toolbox allows you to couple animations created in Unity with a 20-sim simulation model. When you run the 20-sim simulation, the Unity application is shown and moves/changes with the simulation.

Features

The Unity Toolbox will allow you to couple variables from a 20-sim model to objects in Unity. You can for example couple the position of an object with the simulated position. Every time you start a 20-sim simulation, a Unity window will be shown and changes/moves while the 20-sim simulation advances.

The Unity Toolbox does exactly the same as the 20-sim 3D Animation, but is far more advanced. In Unity far more objects are available, the quality of rendering (shadow, light, etc.) is far better and there are more display options (single screen, multiple screen, VR/AR headsets etc.).

License

The Unity Toolbox does not come standard with 20-sim. It has to be purchased separately. If you have purchased the Unity Toolbox you will receive a license key that will enable the toolbox in 20-sim.

Supported Unity Versions

The Unity Toolbox is verified to work with Unity 2018.4, 2019.2, 2020.3.x (LTS), 2021.2.9f1. It is possible that it will work in intermediate or newer versions of Unity.

Example

To see a Unity Animation in action (if you have a valid license) open the example model Examples\2D Mechanics\ScaraRobot_UnityAnimation.emx.

Getting Started

To get started and learn to work with the Unity Toolbox, follow these steps:

1. Install the Unity Toolbox
2. Read the next sections of this help file.
License Required
The Unity Toolbox is not part of the set of standard toolboxes of 20-sim. It has to be purchased separately. When you have purchased the Unity Toolbox, you will receive a license code for 20-sim that will enable the plug-in to establish a run-time communication between 20-sim and Unity.

10.11.2 License

Purchase
The Unity Toolbox does not come standard with 20-sim. It has to be purchased separately. If you have purchased the Unity Toolbox you will receive a license key that will enable the toolbox in 20-sim.

No License
Without a valid license, the Unity Toolbox plug-in will stop the simulation and present an error message in the 20-sim Editor:

Message: Could not find Unity toolbox license.

Error Message when you do not have a license for the Unity Toolbox.
10.11.3 How does the Unity Toolbox work?

Plug-in
The Unity Toolbox comes with a plug-in that has to be installed in Unity. The plug-in connects objects created in Unity with variables from a 20-sim model:

1. You can connect objects manually with 20-sim variables.
2. You can import a 20-sim 3D Scenery into Unity.

Coupling with 20-sim
When the Unity 3D Animation is completed and all objects have been connected with the proper variables from the 20-sim model, you can generate an .fmu (Functional Mockup Interface) file. You can drag and drop the .fmu file into the 20-sim model.

Simulation
The .fmu file will connect the 20-sim variables with the Unity application. When you start the simulation, the Unity application will start up. The Unity application will show moves/changes during simulation. Set the 20-sim simulation to run in real-time to show the Unity application at the right speed.

Export
If you want to use the model with Unity Application on another location, make sure that you copy both the 20-sim model (.emx file) and the Unity application (.fmu file).

10.11.4 Installing
To get the Unity Toolbox running, you need a working version of Unity and install a plug-in for the Unity project that you are working on.

Unity
Unity is a commercial package by Unity Technologies. You can purchase the commercial Pro version or the free Personal version. There are various videos available on Youtube that show you how to install Unity. Note that the Unity Toolbox has been verified to work with Unity 2018.4, 2019.2 and 2020.3.x (LTS). It is possible that it will work in newer versions of Unity.

Plug-In
The Unity Toolbox comes with a plug-in that has to be installed in Unity. The plug-in is located in the 20-sim installation folder, usually at:

C:\Program Files (x86)\20-sim 5.1\addons\unity\20-sim-unity-toolbox-x.y.z.unitypackage

Here x,y,z are the version number of the plug-in. For every new project in Unity, you have to install the plug-in in your version of Unity:
1. **Open** Unity and open/start a new (3D) project

2. From the **Assets** menu select **Import Package** and **Custom Package**.

3. **Select** the plug-in that is located in the 20-sim installaton folder:
   
   C:\Program Files (x86)\20-sim 5.1\addons\unity\20-sim-unity-toolbox-x.y.z.unitypackage.

4. Click **Import**.

5. From the **GameObject** menu select **20-sim** and **20-sim Unity Toolbox**.

Now the plug-in is installed and ready for use.
In the Hierarchy you will see the 20-sim Unity Toolbox listed. You can start to build your Unity application now.

10.11.5 Example: Cube

GameObjects

When you have installed the 20-sim Unity Toolbox correctly, it should be visible in Unity in the Hierarchy at the left. You can insert all kinds of Game Objects and connect them with variables coming from the 20-sim model. Let's start with a Cube.

1. From the GameObject menu select 3D Object - Cube.

Now Cube object is visible in the Hierarchy.
2. In the Hierachy select the Cube object.

3. In the Inspector at the bottom right click **Add Component - 20-sim Unity Toolbox - 20-sim coordinates**.

Now you will see a **20-sim Variable** component in the Inspector. Here you can connect the properties of the Cube with variables in your 20-sim model. If our 20-sim model contains a Submodel named *Cube* with three variables \( x \), \( y \) and \( z \), we can connect these with the position of the cube.

4. In the **20-sim Variable** component keep the Input/Output button on **Input**.

5. Add the variable names to the \( x \)-, \( y \)- and \( z \)-axis as shown in the next figure.
In a similar manner you can create many more Game Objects and connect them with 20-sim variables.

**Building a Unity Animation**

When all objects have been defined we can generate a Unity Animation. Unity Animations are stored in an `.fmu` file.

6. In the Hierarchy at the left select **20-sim Unity Toolbox**.
7. In the Inspector at the right go to 20-sim Unity Toolbox and **Build Unity Animation**.
8. Enter the **Export Location** (a folder where you have read and write access) and **Animation Name** (e.g. Cube) and click **Build Unity Animation**.
Now the file *Cube.fmu* will be created in the export location that you have chosen.

**Importing the Unity Animation in 20-sim**

We will drag and drop the *Cube.fmu* file into 20-sim and connect the x, y and z input with signal generators.

9. Open 20-sim

10. From the export location, drag and drop the file *Cube.fmu* to the Editor.

11. From the **Signal/Sources** library **drag and drop** the following submodels in the Editor:

   - **WaveGenerator-Sine**
   - **WaveGenerator-Cosine**
   - **WaveGenerator-Saw**

12. Connect the **sine** model with the Cube model (x), the **cosine** model with Cube (y) and the **saw** model with Cube (z).
Connecting the FMU.

Running the Unity Animation
When you simulate the 20-sim model, a Unity Animation will pop up and run with the simulation. Generally the simulation will be much too fast to follow. Therefore we must force the simulation to run in real-time.

13. In the Editor, from the **Model** menu select **Start Simulator**.

14. In the **Simulator** from the **Properties** Menu select **Run**.

Forcing a real-time simulation.

15. In the Run Properties dialog click the **More** button and select **Attempting Realtime Simulation On**.
16. Click **Ok** to close the Run Properties dialog.

17. From the **Simulation** menu select **Run**.

Now you will see a Unity Animation window appear showing the cube moving.

![Image](image_url)

*The unity Animation with the cube.*

18. In case Unity Animation Window is displayed in windowed mode, Click **Alt-Enter** to change the full screen mode.

### 10.11.6 Example: Scara Robot

**Scenery**

The easiest way to start building a Unity Animation is by importing a 3D Animation from 20-sim. First you build the 3D Animation in 20-sim with simple objects and make sure it is running correctly. Then you import the 3D Animation to Unity and use the power of Unity to create the Animation. Here we will show how this is done with the Scara Robot example model.

1. **Open 20-sim.**

2. From the **Examples\2D Mechanics** library drag and drop the **ScaraRobot** model.

3. Open the **Simulator** and **run** a simulation.

4. Put you mouse pointer on top of the **3D Animation** and from the right mouse menu select **Plot Properties**.
Opening the 3D Properties.

5. In the **3D Properties** from the **File** menu select **Save Scene**.

6. Click **Yes** to save the whole scenery.

7. Save the scenery in a location where you have read and write access using the name **ScaraRobot.scn**.

Now the 3D Animation is stored in a scenery file.
Import in Unity

The next job is to import the scenery file into Unity and create a Unity Animation.

8. Open Unity.
9. From the GameObject menu select 20-sim and 20-sim Unity Toolbox.
10. In the Hierarchy at the left select 20-sim Unity Toolbox.
11. In the Inspector at the right go to 20-sim Unity Toolbox and Import 20-sim Scenery File.
12. Click the Browse button to find the scenery file ScaraRobot.scn.
13. Click the Import 20-sim Scenery button to import the scenery file.

The Scara Robot should now be visible in the scene at the center.

Building the Unity Animation

Now we could work on the scene and enrich it by adding all kind of GameObjects. We will leave this up to your own imagination. The final part of the job is to create a Unity Animation, generate an .fmu file and import this into 20-sim.

14. In the Hierarchy at the left select 20-sim Unity Toolbox.
15. In the Inspector at the right go to 20-sim Unity Toolbox and Build Unity Animation.
16. Enter the **Export Location** (a folder where you have read and write access) and **Animation Name** (e.g. ScaraRobot) and click **Build Unity Animation**.

### Importing the Unity Animation into 20-sim

17. Open 20-sim with the Scara Robot model.

18. Drag and drop the file `ScaraRobot.fmu` to the Editor.

![Connecting the FMU.](image)

The Unity Animation does not have any inputs. It uses global variables to connect the simulation to the animation. Therefore we do not have to make connections.

### Running the Unity Animation

When you simulate the 20-sim model, a Unity Animation will pop up and run with the simulation. Generally the simulation will be much too fast to follow. Therefore we must force the simulation to run in real-time.

19. In the Editor, from the **Model** menu select **Start Simulator**.

20. In the **Simulator** from the **Properties** Menu select **Run**.

21. In the Run Properties dialog click the **More** button and select **Attempting Realtime Simulation On**.

22. Click **Ok** to close the Run Properties dialog.

23. From the **Simulation** menu select **Run**.

Now you will see a Unity Animation window appear showing the Scara Robot moving.
24. Click **Alt-Enter** to change the Unity Animation from full screen to a window.

### 10.11.7 20-sim Inspector Properties

If the 20-sim Unity Toolbox is installed, any GameObject can be connected to the variables coming from a 20-sim simulation. The following object properties can specified.

**Input / Output**

- In most cases the variables that are calculated in 20-sim and exported to Unity. You can keep the Input/Output button to its default setting: **Input**.
- In some cases, however, a variable coming from Unity and exported to 20-sim. Then you have to set the Input/Output button to **Output**.

**20-sim Coordinates / Unity Coordinates**

When you add the 20-sim Toolbox to a GameObject, you can use 20-sim coordinates or Unity Coordinates:

- 20-sim uses a right-handed coordinate system for the position and rotation of objects.
- Unity uses a left-handed coordinate system frame.

**Position / Rotation / Scale**

You can couple 20-sim variables with the position, orientation and scale of objects, which works just like the position, orientation and scale of a 20-sim 3D Animation.

**Scripting**

In Unity you can create script in C# to tailor make GameObjects. If you choose the Scripting option in the 20-sim Variable section, you can connect 20-sim variables with the public member variables of your C# script.

### 10.11.8 Importing 3D Scenery

3D animations created in 20-sim can be exported to Unity. You first have to create a 20-sim model, simulate it and create a 3D Animation. From the 3D Animation, you can create a scenery file that can be imported in Unity:

1. In 20-sim go to the **Simulator** and put you **mouse pointer** on top of the 3D animation.
2. From the **right mouse menu**, select **Plot Properties**.
3. In the Plot Properties window, select **File - Save Scene**.

Now you can open a Unity 3D project and install the 20-sim Unity Toolbox plug-in. When this is done properly, the Inspector at the left will show a **20-sim Unity Toolbox**.
You can now import the 20-sim 3D animation into your Unity project:

4. In the Inspector at the right go to the 20-sim Unity Toolbox and **Import 20-sim Scenery File**.
8. Click the **Browse** button to find the scenery file **ScaraRobot.scn**.
9. Click the **Import 20-sim Scenery** button to import the scenery file.
10.11.9 Generating the Unity Animation

In Unity when you select the 20-sim Unity Toolbox from the Hierarchy at the left, a menu named **20sim unity Toolbox** (scripting) is visible in the Inspector at the right. You can use this menu to create a Unity Animation.

1. In the Export Location, choose the folder where you want to store the .fmu file with the Unity application.
2. In the **Animation Name** section enter the **file name** for the .fmu file.
3. Click on the **Build Unity Animation button**.

Now an .fmu file will be generated. You can drag and drop this file into your 20-sim model to run the animation.
10.11.1 Drag and Drop to 20-sim

Once you have created the .fmu file with the Unity application, you can drag and drop it to your 20-sim model.

1. Open your 20-sim model.
2. Drag and drop the .fmu file from a File Explorer into the 20-sim Editor.

Scenery File
If the .fmu file was generated from an 20-sim 3D Animation using a scenery file, it will only run properly when dropped into the original 20-sim model.

Inputs
If the .fmu was created from scratch assigning variables to GameObjects, these variables will be inputs in the .fmu in 20-sim. You have to connect these inputs with the proper generators to get the animation working.
10.11.1 Running the Unity Animation

When you have inserted the .fmu file with the Unity application into 20-sim, you can start a simulation and the Unity Animation will appear. Generally the simulation will be much too fast. You have to force the simulation to run in real-time, to see a good result.

1. In the **20-sim Editor**, from the **Model** menu select **Start Simulator**.
2. In the **20-sim Simulator**, from the **Properties** menu select **Run**.
3. In the **Run Properties** window click the **More button**.
4. Set the **Attempting Realtime Simulation** button to **On** and click **OK**.

Make sure the simulation is set to realtime.

5. In the **20-sim Simulator**, from the **Simulation** menu select **Run**.

Now Unity application will open and the simulation will start.
6. Click \texttt{Alt-Enter} to change the Unity Animation from full screen to a window.


11. Library

11.1 Bond Graph

11.1.1 Bond Graph Models

Bond graphs are a network-like description of physical systems in terms of ideal physical processes. With the bond graph method we split up the system characteristics into an (imaginary) set of separate elements. Each element describes an idealized physical process. To facilitate drawing of bond graphs, the common elements are denoted by special symbols. This library contains all kind of bond graph elements. If you want to know more about modeling with bond graphs, please have a look at the modeling tutorial.


11.1.2 C

Library
Bond Graph

Use

Description
This model represents a power continuous storage element. The element has a preferred effort out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred flow out causality. The constitutive equations then contain a derivation.

effort out causality (preferred):

\[
\begin{align*}
\text{state} &= \text{int}(p.f) + \text{state}(0); \\
p.e &= \text{state}/c; \\
\text{output} &= \text{state};
\end{align*}
\]

flow out causality:

\[
\begin{align*}
\text{state} &= c*p.e; \\
p.f &= d \text{ state} / dt; \\
\text{output} &= \text{state};
\end{align*}
\]

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Input port of the storage element.</td>
</tr>
</tbody>
</table>
Causality
preferred effort out
A flow out causality results in a derivative constitutive equation.

Outputs
output
The output signal is equal to the state.

Parameters
c
The storage element constant.

Initial Values
state(0)
The initial value of the storage element.

11.1.3 CC

Library
Bond Graph

Use

Description
This model represents a two port C-element. Normally the equation of a two port C-element is written in vector notation as:

\[ p.e = \frac{1}{C} \int p.f \]

When the C matrix is singular simulation will not be possible. Therefore the element is described in a safer notation as:

\[ p.e = A \cdot \int p.f \], with \( A = \frac{1}{C} \);

Both ports have a preferred effort out causality:

\[
\begin{align*}
\text{state1} &= \int (p1.f); \\
\text{state2} &= \int (p2.f); \\
p1.e &= a11\cdot\text{state1} + a12\cdot\text{state2}; \\
p2.e &= a21\cdot\text{state1} + a22\cdot\text{state2};
\end{align*}
\]

Interface

Ports
p1, p2
Input ports of the storage element.

Causality
preferred effort out p1
preferred effort out p2

A flow out causality results in a derivative constitutive equation.

**Outputs**
state1
state2

**Parameters**
a11, a12, a21, a22

The storage element constants.

**Initial Values**
state1_initial
state2_initial

The initial values of the storage element.

### 11.1.4 De

**Library**
Bond Graph

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Bond Graphs.

**Description**
This model represents an ideal effort detector. The flow is always 0.

\[
\begin{align*}
\text{effort} &= p.e; \\
\text{p.f} &= 0;
\end{align*}
\]

**Ports**
p

**Description**
Input port of the effort source.

**Causality**
fixed flow out

**Outputs**
effort

**Description**
The detected effort
11. Library

11.1.5  Df

Library
Bond Graph

Use

Description
This model represents an ideal flow detector. The effort is always 0.

\[
\begin{align*}
p.e & = 0; \\
\text{flow} & = p.f;
\end{align*}
\]

Ports
Description

p
Input port of the flow source.

Causality
fixed effort out

Outputs
flow
The detected flow

11.1.6  EffortSensor

Library
System, Bond Graph

Use
Domains: Continuous. Size: [n,m]. Kind: Bond Graphs.

Description
This model can be inserted in any bond to yield the effort of that bond as an output signal.

To ensure success, use drag and drop to place the sensor exactly on top in the middle of the bond. As a result the model will be automatically connected.

Interface

Ports

p1, p2
Input and output port of the effort sensor.
Outputs

effort Effort of the bond.

11.1.7 EnergySensor

Library
System, Bond Graph

Use
Domains: Continuous. Size: [n,m]. Kind: Bond Graphs.

Description
This model can be inserted in any bond to yield the energy that is carried through that bond as an output signal.

To ensure success, use drag and drop to place the sensor exactly on top in the middle of the bond. As a result the model will be automatically connected.

Interface

Ports
p1, p2 Input and output port of the energy sensor.

Outputs
E Energy carried through the bond.

11.1.8 FlowSensor

Library
System, Bond Graph

Use
Domains: Continuous. Size: [n,m]. Kind: Bond Graphs.

Description
This model can be inserted in any bond to yield the flow of that bond as an output signal.
To ensure success, use drag and drop to place the sensor exactly on top in the middle of the bond. As a result the model will be automatically connected.

**Interface**

**Ports**

p1, p2

Input and output port of the flow sensor.

**Outputs**

flow

Flow of the bond.

**11.1.9 GY**

**Library**

Bond Graph

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Bond Graphs.

**Description**

This model represents an ideal gyrator, a power continuous relation between the effort of one port and the flow of the other port and vice-versa. The model can have both ports with an effort out causality or both ports with a flow out causality:

**effort out causality:**

\[
\begin{align*}
p1.e &= r \times p2.f; \\
p2.e &= r \times p1.f;
\end{align*}
\]

**flow out causality:**

\[
\begin{align*}
p1.f &= \frac{1}{r} \times p2.e; \\
p2.f &= \frac{1}{r} \times p1.e;
\end{align*}
\]

**Interface**

**Ports**

p1, p2

Input and output port of the gyrator.

**Causality**

p1 equal p2

The causality of both ports must be equal.

**Parameters**
11.1.10 I

Library
Bond Graph

Use

Description
This model represents a power continuous storage element. The element has a preferred flow out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred effort out causality. The constitutive equations then contain a derivation.

flow out causality (preferred):

\[
state = \text{int}(p.e) + state(0);
\]
\[
p.f = state/i;
\]
\[
output = state;
\]

effort out causality:

\[
state = i*p.f;
\]
\[
p.e = \frac{d state}{dt};
\]
\[
output = state;
\]

Interface

Ports
p

Description
Input port of the storage element.

Causality
preferred flow out

Description
An effort out causality results in a derivative constitutive equation.

Outputs
output

Description
The output signal is equal to the state.

Parameters
i

Description
The storage element constant.

Initial Values
state(0)

Description
The initial value of the storage element.
11.11.11 II

Library
Bond Graph

Use
**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams, Bond Graphs.

Description
This model represents a two port I-element. Normally the equation of a two port I-element is written in vector notation as:

\[ p.f = (1/I) * \int (p.e) \]

When the I matrix is singular simulation will not be possible. Therefore the element is described in a safer notation as:

\[ p.f = A * \int (p.e), \text{ with } A = (1/I); \]

Both ports have a preferred effort out causality:

\[
\begin{align*}
state1 &= \int (p1.e); \\
state2 &= \int (p2.e); \\
p1.f &= a11*state1 + a12*state2; \\
p2.f &= a21*state1 + a22*state2;
\end{align*}
\]

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1, p2</td>
<td>Input ports of the storage element.</td>
</tr>
</tbody>
</table>

**Causality**

<table>
<thead>
<tr>
<th>preferred effort out p1</th>
<th>A flow out causality results in a derivative constitutive equation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferred effort out p2</td>
<td></td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>state1</th>
<th>state2</th>
</tr>
</thead>
</table>

**Parameters**

| a11, a12, a21, a22 | The storage element constants. |

**Initial Values**

| state1_initial | state2_initial | The initial values of the storage element. |
11.1.12 IC

**Library**
Bond Graph

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Block Diagrams, Bond Graphs.

**Description**
This model is a combination of an I storage element and a C storage element. Consequently the constitutive equation must be written as a matrix-vector multiplication. The constitutive equation of this element is given below:

\[
\begin{align*}
\text{state1} &= \text{int}(p1.f); \\
\text{state2} &= \text{int}(p2.e); \\
p1.e &= \text{state1}a11 + \text{state2}a21; \\
p2.f &= \text{state1}a21 + \text{state2}a22; \\
\text{output2} &= \text{state1}; \\
\text{output2} &= \text{state2};
\end{align*}
\]

The Maxwell reciprocity demands \(a12 = a21\). Therefore only 3 matrix parameters are necessary.

**Interface**

**Ports**
p1,p2

**Description**
Input ports of the storage element.

**Causality**
fixed effort out p1
fixed flow out p2

**Outputs**
output1, output2

**Description**
The output signals are equal to the states.

**Parameters**
a11,a21,a22

**Description**
The storage element constants.

**Initial Values**
state1(0), state2(0)

**Description**
The initial values of the storage element.
11.1.13  MGY

Library
Bond Graph

Use

Description
This model represents an ideal modulated gyrator, a power continuous relation between the effort of one port and the flow of the other port and vice-versa. The gyration ratio can be set to a certain (fluctuating) value, given by an input signal. The model can have both ports with an effort causality or both ports with a flow causality:

effort out causality:

\[
\begin{align*}
p1.e &= \text{input} \times p2.f; \\
p2.e &= \text{input} \times p1.f; 
\end{align*}
\]

flow out causality:

\[
\begin{align*}
p1.f &= \frac{1}{\text{input}} \times p2.e; \\
p2.f &= \frac{1}{\text{input}} \times p1.e; 
\end{align*}
\]

Interface

Ports
p1, p2

Description
Input and output port of gyrator.

Causality
p1 equal p2

The causality of both ports must be equal.

Inputs
input

Modulated gyration ratio.

11.1.14  MR

Library
Bond Graph

Use

Description
This model represents a linear friction/resistor equation. It can have an effort as well as a flow causality. In that case the constitutive equation, as shown below, is simply inverted. The friction/resistor parameter can be set to a (fluctuating) value, given by an input signal.

effort out causality:
\[ p.e = input \times p.f \]

flow out causality:
\[ p.f = p.e / input \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Input port of the R-element.</td>
</tr>
</tbody>
</table>

**Causality**

indifferent

**Inputs**

| input  | The (modulated) friction/resistor parameter. |

### 11.1.15 MSe

**Library**
Bond Graph

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Bond Graphs.

**Description**
This model represents an ideal modulated effort source. The effort can be set to a (fluctuating) value given by an input signal. The flow is indifferent.

\[ p.e = input; \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Output port of the effort source.</td>
</tr>
</tbody>
</table>

**Causality**

fixed effort out

**Inputs**

| input  | Modulation signal. |
11.1.16 MSf

Library
Bond Graph

Use

Description
This model represents an ideal modulated flow source. The flow can be set to a (fluctuating) value given by an input signal. The effort is indifferent.

\[ p.f = \text{input}; \]

Interface

Ports

<table>
<thead>
<tr>
<th>Port</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Output port of the flow source.</td>
</tr>
</tbody>
</table>

Causality
fixed flow out

Inputs

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>Modulation signal.</td>
</tr>
</tbody>
</table>

11.1.17 MTF

Library
Bond Graph

Use

Description
This model represents an ideal modulated transformer. The model represents a power continuous relation between the efforts and flows of both its ports. The transform ratio can be set to a certain (fluctuating) value, given by an input signal. The causality is always mixed: one port has an effort out causality while the other has a flow out causality:

\[ p1.e = \text{input} \times p2.e; \]
\[ p2.f = \text{input} \times p1.f; \]

or:
\[ p2.e = \frac{1}{\text{input}} \times p1.e; \]
\[ p1.f = \frac{1}{\text{input}} \times p2.f; \]

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>p1, p2</th>
</tr>
</thead>
</table>

**Description**

Input and output port of the transformer.

**Causality**

p1 notequal p2

**Inputs**

<table>
<thead>
<tr>
<th>input</th>
</tr>
</thead>
</table>

Modulated transform ratio.

### 11.1.18 OneJunction

**Library**

Bond Graph

**Use**

- **Domains**: Continuous. **Size**: [n,m]. **Kind**: Bond Graphs.

**Description**

This junction represents a power continuous (no energy storage, dissipation or generation) connection of elements. The sum of the efforts on all ports is zero and the flows on all ports are equal. The constitutive equations are for example:

\[ p1.e + p2.e - p3.e - p4.e = 0; \]
\[ p1.f = p2.f = p3.f = p4.f; \]
\[ \text{flow} = p4.f; \]

A one junction has only one initial port p defined. Because any number of bonds may be connected, successive connected bonds are named p1, p2, p3 etc.

The plus or minus signs of the effort equation depend on the direction of the bonds. A bond pointing towards the one junction results in a plus sign and vice-versa. Only one port of a one junction may determine the flow. In the example port p4 determines the flow.

**Multi Bonds**

Bonds with a size larger than one (multi bonds) can also be connected to a one junction. All connected bonds, however, must have the same size.
\[ p1.e + p2.e - p3.e + p4.e = 0; \]
\[ p1.f = p2.f = p3.f = p4.f; \]
\[ \text{flow} = p4.f; \]

Naming conventions are equal to those of the single bond (size 1) junctions. Successive connected bonds are named p1, p2, p3 etc. To denote single elements of a multibond, matrix notation is used. E.g. the effort of bond number 3 of a multibond p2 can be denoted as p2.e[3] (columnvector notation) or p2.e[3,1] (matrix notation).

**Interface**

<table>
<thead>
<tr>
<th><strong>Ports</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of ports may be connected.</td>
</tr>
</tbody>
</table>

**Causality**

1_effort p

Only one port may have an effort out causality (as seen from the element).

**Outputs**

flow

The output signal is equal to the flow of the ports.

**Limitations**

All connected bonds must have the same size.

### 11.1.19 OneJunction-Activity

**Library**
Bond Graph

**Use**

**Description**
This junction is equal to a normal one junction but monitors the powerflows through the connected bonds. If you use this junction and connect some bonds, it could look like the figure below. The bond numbers are important for identification. You can see them by clicking **Port Names** from the **View** menu.
The constitutive equations for this example are:

\[
p1.e - p2.e - p3.e - p4.e = 0; \]
\[
p1.f = p2.f = p3.f = p4.f; \]
\[
\text{flow} = p4.f; \]

The powerflows through the junction are monitored:

\[
\text{power} = p.e .* p.f; \]

Note that power is a vector with a size equal to the number of bonds that are attached to the junction. The first element of the vector is the power of the first bond (p1 in the example figure), the second element is the power of the second bond (p2 in the example figure) and so on. To see which bonds are active and which bonds are not, the activity is calculated:

\[
\text{activity} = \text{int} (\text{abs} (\text{power})); \]

To get an easy comparison, the relative activity is calculated:

\[
\text{maximum_activity} = \text{max} (\text{activity}); \]
\[
\text{relative_activity} = \text{activity} ./ \text{maximum_activity} \]

**Interface**

**Ports**

- p[any]
  - Any number of ports may be connected.

**Causality**

- 1_effort p
  - Only one port may have a effort out causality (as seen from the element).

**Outputs**

- flow
  - The output signal is equal to the effort of the ports.

**Variables**

- power
  - Vector of which the elements are the powers of the connected bonds.
activity Vector of which the elements are the integrated absolute powers of the connected bonds.

relative_activity Vector of which the elements are the relative activities of the connected bonds.

Limitations
All connected bonds must have size 1.

11.1.20 PowerSensor

Library
System, Bond Graph

Use
Domains: Continuous. Size: [n,m]. Kind: Bond Graphs.

Description
This model can be inserted in any bond to yield the power that is carried through that bond as an output signal.

To ensure success, use drag and drop to place the sensor exactly on top in the middle of the bond. As a result the model will be automatically connected.

Interface

Ports
p1, p2 Input and output port of the power sensor.

Outputs
E Power carried through the bond.
11.1.21 Power Splitter

Library
System, Bond Graph

Use

Description
This model can be used to split a multi-bond into single bonds or vice versa. Default 2 bonds can be connected. Use the right mouse menu and choose Edit Implementation to change the number of bonds.

Interface

Inputs/Outputs
P(any) Multi-bond (dimension \([n,m]\)).
p single bonds (a total of n*m)

Note
The multi-bond and corresponding single bonds must have opposite orientations. I.e. when the multi-bond is pointing towards the the power-splitter, all single bonds must point from the power splitter and when the multi-bond is pointing from the the power-splitter, all single bonds must point towards the signal splitter.

11.1.22 PSensor

Library
System, Bond Graph

Use
Domains: Continuous. Size: \([n,m]\). Kind: Bond Graphs.

Description
This model can be inserted in any bond to yield the integral of the effort of that bond as an output signal.

To ensure success, use drag and drop to place the sensor exactly on top in the middle of the bond. As a result the model will be automatically connected.

Interface

Ports
p1, p2 Input and output port of the flow sensor.
11.1.23 Qsensor

Library
System, Bond Graph

Use
Domains: Continuous. Size: [n,m]. Kind: Bond Graphs.

Description
This model can be inserted in any bond to yield the integral of the flow of that bond as an output signal.

To ensure success, use drag and drop to place the sensor exactly on top in the middle of the bond. As a result the model will be automatically connected.

Interface

Ports
p1, p2 Input and output port of the flow sensor.

Outputs
q Integral of the flow of the bond.
Description
This model represents a linear friction/resistor equation. It can have an effort out as well as a flow out causality. In the last case the constitutive equation, as shown below, is simply inverted.

effort out causality:
\[ p.e = r \times p.f; \]
flow out causality:
\[ p.f = p.e / r; \]

Interface

Ports

\( p \) 
Input port of the R-element.

Causality

indifferent

Parameters

\( r \) 
The friction/resistor parameter.

11.1.25 Se

Library
Bond Graph

Use


Description
This model represents an ideal effort source. The effort can be set to a certain constant value, the flow is indifferent.

\[ p.e = s; \]

Ports

\( p \) 
Output port of the effort source.

Causality

fixed effort out

Parameters

\( s \) 
The constant value of the generated effort
11.1.26 Sf

Library
Bond Graph

Use

Description
This model represents an ideal flow source. The flow can be set to a certain constant value, the effort is indifferent.

\[ p.f = s; \]

Interface

Ports
Description
p
Output port of the flow source.

Causality
fixed flow out

Parameters
s
The constant value of the generated flow.

11.1.27 SGY

Library
Bond Graph

Use

Description
This model represents an ideal gyrator with gyration ratio 1. The model represents a one to one power continuous relation between the effort of one port and the flow of the other port and vice-versa. The model can be used to transform a C element into a I element etc. The model can have both ports with an effort causality or both ports with a flow causality:

effort out causality:

\[ p1.e = p2.f; \]
\[ p2.e = p1.f; \]

flow out causality:
\[ p1.f = p2.e; \]
\[ p2.f = p1.e; \]

**Interface**

**Ports**
p1, p2  

**Description**
Input and output port of the gyrator.

**Causality**
p1 equal p2

---

**11.1.28 STF**

**Library**
Bond Graph

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Bond Graphs.

**Description**
This model represents an ideal transformer with transform ratio 1. The model has no real effect but allows for domain changes (one port having another domain as the other). The model represents a power continuous relation between the efforts and flows of both its ports. The causality is always mixed: one port has an effort causality while the other has a flow causality:

\[ p1.e = p2.e \]
\[ p2.f = p1.f \]

or:

\[ p2.e = p1.e \]
\[ p1.f = p2.f \]

**Interface**

**Ports**
p1, p2  

**Description**
Input and output port of the simple transformer.

**Causality**
p1 notequal p2  

The causality of both ports must be different.
11.1.29 SwitchingOneJunction

Library
Bond Graph

Use
Domains: Continuous. Size: [n,m]. Kind: Bond Graphs.

Description
This junction represents a switching 1 junction. Depending on the condition value it can connect / disconnect additional elements to / from the bond graph.

The p12 junction port is connected when condition <> 0. The sum of the efforts on all three ports is zero and the flows on all ports are equal. When disconnected (condition == 0), the effort and flow of port p12 are both zero. Ports p1 and p2 are still connected (flow = zero, efforts are equal).

Interface

Ports
p1, p2 Input and output port of the 1 junction.
p12 Conditional port (only connected when condition evaluates to a non-zero value)

Inputs
condition Switching condition (non-zero value = connected)

Limitations
All connected bonds must have the same size.

11.1.30 SwitchingZeroJunction

Library
Bond Graph

Use
Domains: Continuous. Size: [n,m]. Kind: Bond Graphs.

Description
This junction represents a switching 0 junction. Depending on the condition value it can connect / disconnect additional elements to / from the bond graph.

The p12 junction port is connected when condition <> 0. The sum of the flows on all three ports is zero and the efforts on all ports are equal. When disconnected (condition == 0), the effort and flow of port p12 are both zero. Ports p1 and p2 are still connected (effort = zero, flows are equal).
Interface

Ports
p1, p2 Input and output port of the 1 junction.
p12 Conditional port (only connected when condition evaluates to a non-zero value)

Inputs
condition Switching condition (non-zero value = connected)

Limitations
All connected bonds must have the same size.

11.1.31 TF

Library
Bond Graph

Use

Description
This model represents an ideal transformer. The model represents a power continuous relation between the efforts and flows of both its ports. The causality is always mixed: one port has an effort causality while the other has a flow causality:

\[ p1.e = r \times p2.e \]
\[ p2.f = r \times p1.f \]
or:

\[ p2.e = \frac{1}{r} \times p1.e \]
\[ p1.f = \frac{1}{r} \times p2.f \]

Interface

Ports p1, p2 Input and output port of the transformer.

Causality p1 notequal p2 The causality of both ports must be different.

Parameters r Transform ratio
11.1.32 ZeroJunction

Library
Bond Graph

Use
Domains: Continuous. Size: [n,m]. Kind: Bond Graphs.

Description
This junction represents a power continuous (no energy storage, dissipation or generation) connection of elements. The sum of the flows on all ports is zero and the efforts on all ports are equal. The constitutive equations are for example:

\[ p1.f + p2.f - p3.f - p4.f = 0; \]
\[ p1.e = p2.e = p3.e = p4.e; \]
\[ \text{effort} = p1.e; \]

A zero junction has only one initial port p defined. Because any number of bonds may be connected, successive connected bonds are named p1, p2, p3 etc. The plus or minus signs of the flow equation depend on the direction of the bonds. A bond pointing towards the zero junction results in a plus sign and vice-versa. Only one port of a zero junction may determine the effort. In the example port p1 determines the effort.

Multi Bonds
Bonds with a size larger than one (multi bonds) can also be connected to a zero junction. All connected bonds, however, must have the same size.
\[
p_1.f + p_2.f - p_3.f + p_4.f = 0; \\
p_1.e = p_2.e = p_3.e = p_4.e; \\
effort = p_1.e; \\
\]

Naming conventions are equal to those of the single bond (size 1) junctions. Successive connected bonds are named \(p_1, p_2, p_3\) etc. To denote single elements of a multibond, matrix notation is used. E.g the effort of bond number 3 of a multibond \(p_2\) can be denoted as \(p_2.e[3]\) (columnvector notation) or \(p_2.e[3,1]\) (matrix notation).

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p[\text{any}])</td>
<td>Any number of ports may be connected.</td>
</tr>
</tbody>
</table>

**Causality**

| 1_flow p | Only one port may have a flow out causality (as seen from the element). |

**Outputs**

| effort | The output signal is equal to the effort of the ports. |

**Limitations**

All connected bonds must have the same size.

### 11.1.33 ZeroJunction-Activity

**Library**

Bond Graph

**Use**

Domains: Continuous. **Size**: 1-D. **Kind**: Bond Graphs.

**Description**

This junction is equal to a normal zero junction but monitors the powerflows through the connected bonds. If you use this junction and connect some bonds, it could look like the figure below. The bond numbers are important for identification. You can see them by clicking **Port Names** from the **View** menu.
The constitutive equations for this example are:

\[
p_{1.f} - p_{2.f} - p_{3.f} - p_{4.f} = 0;
p_{1.e} = p_{2.e} = p_{3.e} = p_{4.e};
output = p_{2.e};
\]

The powerflows through the junction are monitored:

\[
power = p.e \times p.f;
\]

Note that power is a vector with a size equal to the number of bonds that are attached to the junction. The first element of the vector is the power of the first bond (p1 in the example figure), the second element is the power of the second bond (p2 in the example figure) and so on. To see which bonds are active and which bonds are not, the activity is calculated:

\[
activity = \text{int} (\text{abs} (power));
\]

To get an easy comparison, the relative activity is calculated:

\[
\text{maximum\_activity} = \text{max} (activity);
\text{relative\_activity} = \text{activity} ./ \text{maximum\_activity}
\]

**Interface**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any number of ports may be connected.</td>
<td>p[any]</td>
</tr>
</tbody>
</table>

**Causality**

<table>
<thead>
<tr>
<th>Description</th>
<th>1_flow p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only one port may have a flow out causality (as seen from the element).</td>
<td></td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>The output signal is equal to the effort of the ports.</td>
<td></td>
</tr>
</tbody>
</table>

**Variables**

<table>
<thead>
<tr>
<th>Description</th>
<th>power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector of which the elements are the powers of the connected bonds.</td>
<td></td>
</tr>
</tbody>
</table>
activity Vector of which the elements are the integrated absolute powers of the connected bonds.

relative_activity Vector of which the elements are the relative activities of the connected bonds.

Limitations
All connected bonds must have size 1.

11.1.34 3d

C-3

Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Block Diagrams, Bond Graphs.

Description
This model is the multiport equivalent of the single C storage element. Consequently the constitutive equation must be written as a matrix-vector multiplication. The element has a preferred effort out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred flow out causality. The constitutive equations then contain a derivation, which can only be simulated when the Backward Differentiation Formula integration algorithm is available:

effort out causality (preferred):

\[
\text{state} = \text{int}(p.f) + \text{state}(0);
\]
\[
p.e = \text{inverse}(C) \times \text{state};
\]
\[
\text{outp} = \text{state};
\]

flow out causality:

\[
\text{state} = C \times p.e;
\]
\[
p.f = \frac{d \text{state}}{dt};
\]
\[
\text{output} = \text{state};
\]

Interface

Ports
\[\text{p}[3]\]

Description
Input port of the storage element (columnvector with size 3).
**Causality**
preferred effort out
A flow out causality results in a derivative constitutive equation.

**Outputs**
output[3]
The output signal is equal to the state (columnvector with size 3).

**Parameters**
C[3,3]
The storage element constants (matrix of size [3,3]).

**Initial Values**
state(0)[3]
The initial values of the storage element (columnvector with size 3).

**Limitations**
The preferred equation contains an inverted C matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.

---

**GY-3**

**Library**
Bond Graph

**Use**
Domains: Continuous. **Size**: 3-D. **Kind**: Bond Graphs.

**Description**
This model is the multiport equivalent of the single gyrator. Consequently the constitutive equation must be written as a matrix-vector multiplication. The model can have both ports with an effort out causality or both ports with a flow out causality:

effort out causality:

\[
p1.e = \text{transpose}(R) \ast p2.f; \\
p2.e = R \ast p1.f;
\]

flow out causality:

\[
p1.f = \text{inverse(transpose}(R)) \ast p2.e; \\
p2.f = \text{inverse}(R) \ast p1.e;
\]
## Interface

### Ports

| p1[3], p2[3] | Input and output port of the gyrator (columnvectors with size 3). |

### Causality

| p1 equal p2 | The causality of both ports must be equal. |

### Parameters

| R[3] | Gyration ratio (matrix of size [3,3]). |

### Limitations

The flow out equations contain an inverted $R$ matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.

---

## I-3

### Library

Bond Graph

### Use

**Domains:** Continuous. **Size:** 3-D. **Kind:** Block Diagrams, Bond Graphs.

### Description

This model is the multiport equivalent of the single I storage element. Consequently the constitutive equation must be written as a matrix-vector multiplication. The element has a preferred flow out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred effort out causality. The constitutive equations then contain a derivation, which can only be simulated when the Backward Differentiation Formula integration algorithm is available:

flow out causality (preferred):

```plaintext
state = int(p.e) + state(0);
p.f = inverse(I)*state;
output = state;
```
effort out causality:

\[
\begin{align*}
\text{state} &= I \times p.f; \\
p.e &= \frac{d \text{state}}{dt}; \\
\text{output} &= \text{state};
\end{align*}
\]

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[3]</td>
</tr>
</tbody>
</table>

Input port of the storage element (columnvector with size 3).

**Causality**

preferred effort out

A flow out causality results in a derivative constitutive equation.

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output[3]</td>
</tr>
</tbody>
</table>

The output signal is equal to the state (columnvector with size 3).

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I[3,3]</td>
</tr>
</tbody>
</table>

The storage element constants (matrix of size [3,3]).

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>state(0)[3]</td>
</tr>
</tbody>
</table>

The initial values of the storage element (columnvector with size 3).

**Limitations**

The preferred equation contains an inverted I matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.

**MGY-3**

**Library**

Bond Graph

**Use**

Domains: Continuous. Size: 3-D. Kind: Bond Graphs.
**Description**

This model is the multiport equivalent of the single modulated gyrator. Consequently the constitutive equation must be written as a matrix-vector multiplication. The gyration ratio can be set to a certain (fluctuating) value, given by an input signal. The model can have both ports with an effort out causality or both ports with a flow out causality:

**effort out causality:**

\[
\begin{align*}
p1.e &= \text{transpose}(r) * p2.f; \\
p2.e &= r * p2.f;
\end{align*}
\]

**flow out causality:**

\[
\begin{align*}
p1.f &= \text{inverse(transpose}(r)) * p2.e; \\
p2.f &= \text{inverse}(r) * p1.e;
\end{align*}
\]

**Interface**

**Ports**

- **p1[3], p2[3]**
  - **Description**: Input and output port of the gyrator (columnvectors with size 3).

**Causality**

- **p1 equal p2**
  - **Description**: The causality of both ports must be equal.

**Inputs**

- **r[3,3]**
  - **Description**: Modulated gyration ratio (size [3,3]).

**Limitations**

The flow out equations contain a matrix inversion of the modulation signal. The elements of this input signal should always have non-singular values.
MR-3

Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Bond Graphs.

Description
This model is the multiport equivalent of the single dissipative element. Consequently the constitutive equation must be written as a matrix-vector multiplication. This model can have an effort out as well as a flow out causality. In the last case the constitutive equation, as shown below, is simply inverted. The friction/resistor parameter can be set to a (fluctuating) value, given by an input signal.

effort out causality:
\[ p.e = r*p.f; \]

flow out causality:
\[ p.f = \text{inverse}(r)*p.e; \]

Interface

Ports

Causality
indifferent

Input
r[3,3] The (modulated) friction/resistor parameter (size [3,3]).

Parameters
R The friction parameters (matrix of size [3,3]).

Limitations
The flow out equation contains an inverted R matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.
MSe-3

Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Bond Graphs.

Description
This model is the multiport equivalent of the single modulated effort source. The effort can be set to a (fluctuating) value given by an input signal. The flow is indifferent.

\[ p.e = \text{input}; \]

Ports

Description

Causality
fixed effort out

Inputs


MSf-3

Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Bond Graphs.

Description
This model is the multiport equivalent of the single modulated flow source. The flow can be set to a (fluctuating) value given by an input signal. The flow is indifferent.

\[ p.f = \text{input}; \]

Ports

Description

Causality
fixed flow out
**Inputs**


---

**MTF-3**

**Library**
Bond Graph

**Use**
Domains: Continuous. **Size**: 3-D. **Kind**: Bond Graphs.

**Description**
This model is the multiport equivalent of the single modulated transformer. Consequently the constitutive equation must be written as a matrix-vector multiplication. The transform ratio can be set to a certain (fluctuating) value, given by an input signal. The causality is always mixed: one port has an effort out causality while the other has a flow out causality:

\[
p1.e = \text{transpose}(r) \times p2.e; \\
p2.f = r \times p1.f;
\]

or:

\[
p2.e = \text{inverse}(\text{transpose}(r)) \times p1.e; \\
p1.f = \text{inverse}(r) \times p2.f;
\]

**Interface**

**Ports**  
p1[3], p2[3]  Input and output port of the gyrator (columnvectors with size 3).

**Causality**
p1 notequal p2

**Inputs**
r[3,3]  Modulated transform ratio (size [3,3]).

**Limitations**
The second set of equations contain a matrix inversion of the modulation signal. The elements of this input signal should always have non-singular values.
Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Bond Graphs.

Description
This model is the multiport equivalent of the single dissipative element. Consequently
the constitutive equation must be written as a matrix-vector multiplication. This model
can have an effort out as well as a flow out causality. In the last case the constitutive
equation, as shown below, is simply inverted.

effort out causality:

\[ p.e = R*p.f; \]

flow out causality:

\[ p.f = \text{inverse}(R)*p.e; \]

Interface

Ports
p[3]
Description
Input port of the R-element (columnvector with size 3).

Causality
indifferent

Parameters
R
Description
The friction parameters (matrix of size [3,3]).

Limitations
The flow out equation contains an inverted R matrix. The elements of this matrix should
be chosen with care to prevent this matrix from becoming singular.
Se-3

Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Block Diagrams, Bond Graphs.

Description
This model is the multiport equivalent of the single effort source. The effort can be set to a certain constant value, the flow is indifferent.

\[ p.e = S; \]

Ports
\[ p[3] \]

Description
Output port of the effort source (columnvector with size 3).

Causality
fixed effort out

Parameters
\[ S[3] \]

The constant value of the generated effort (columnvector with size 3).

Sf-3

Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Block Diagrams, Bond Graphs.

Description
This model is the multiport equivalent of the single flow source. The effort can be set to a certain constant value, the flow is indifferent.

\[ p.f = S; \]

Ports
\[ p[3] \]

Description
Output port of the flow source (columnvector with size 3).

Causality
fixed flow out
Parameters

s[3]  The constant value of the generated flow (columnvector with size 3).

SGY-3

Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Bond Graphs.

Description
This model is the multiport equivalent of the single symplectic gyrator. Consequently the constitutive equation must be written as a matrix-vector multiplication. This model represents an ideal gyrator with gyration ratio equal to the identity matrix. The model represents a one to one power continuous relation between the effort of one port and the flow of the other port and vice-versa. The model can be used to transform a C-3 element into a I-3 element etc. The model can have both ports with an effort causality or both ports with a flow causality:

effort out causality:

\[
\begin{align*}
p1.e &= p2.f; \\
p2.e &= p1.f;
\end{align*}
\]

flow out causality:

\[
\begin{align*}
p1.f &= p2.e; \\
p2.f &= p1.e;
\end{align*}
\]

Interface

Ports

p1[3], p2[3]  Input and output port of the gyrator (columnvectors with size 3).

Causality

p1 equal p2  The causality of both ports must be equal.
STF-3

Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Bond Graphs.

Description
This model is the multiport equivalent of the single symplectic transformer. This model represents an ideal transformer with a transform ratio equal to the identity matrix. The model represents a one to one power continuous relation between the effort of one port and the flow of the other port and vice-versa. The causality is always mixed: one port has an effort causality while the other has a flow causality:

\[ p1.e = p2.e; \]
\[ p2.f = p1.f; \]

or:

\[ p2.e = p1.e \]
\[ p1.f = p2.f \]

Interface

Ports
p1[3], p2[3]

Description
Input and output port of the transformer (columnvectors with size 3).

Causality
p1 notequal p2

The causality of both ports must be different.

TF-3

Library
Bond Graph

Use
Domains: Continuous. Size: 3-D. Kind: Bond Graphs.

Description
This model is the multiport equivalent of the single transformer. Consequently the constitutive equation must be written as a matrix-vector multiplication. The causality is always mixed: one port has an effort causality while the other has a flow causality:
\[ p1.e = \text{transpose}(R) \ast p2.e; \]
\[ p2.f = R \ast p1.f; \]

or:

\[ p2.e = \text{inverse}({\text{transpose}(R)}) \ast p1.e \]
\[ p1.f = \text{inverse}(R) \ast p2.f \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1[3], p2[3]</td>
<td>Input and output port of the transformer (columnvectors with size 3).</td>
</tr>
</tbody>
</table>

**Causality**

p1 notequal p2

The causality of both ports must be different.

**Parameters**

R[3,3]

Transform ratio (matrix of size [3,3]).

**Limitations**

The lower set of equations contain an inverted R matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.

### 11.1.35 2d

**C-2**

**Library**
Bond Graph

**Use**
Domains: Continuous. **Size**: 2-D. **Kind**: Block Diagrams, Bond Graphs.

**Description**

This model is the multiport equivalent of the single C storage element. Consequently the constitutive equation must be written as a matrix-vector multiplication. The element has a preferred effort out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred flow out causality. The constitutive equations then contain a derivation, which can only be simulated when the Backward Differentiation Formula integration algorithm is available:

Effort out causality (preferred):

\[ p1.e = \text{transpose}(R) \ast p2.e; \]
\[ p2.f = R \ast p1.f; \]
```plaintext
state = int(p.f) + state(0);
p.e = inverse(C)*state;
outp = state;

flow out causality:

state = C*p.e;
p.f = d state / dt;
output = state;
```

### Interface

#### Ports

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[2]</td>
<td>Input port of the storage element (columnvector with size 2).</td>
</tr>
</tbody>
</table>

#### Causality

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferred effort out</td>
<td>A flow out causality results in a derivative constitutive equation.</td>
</tr>
</tbody>
</table>

#### Outputs

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output[2]</td>
<td>The output signal is equal to the state (columnvector with size 2).</td>
</tr>
</tbody>
</table>

#### Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C[2,2]</td>
<td>The storage element constants (matrix of size [2,2]).</td>
</tr>
</tbody>
</table>

#### Initial Values

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>state(0)[2]</td>
<td>The initial values of the storage element (columnvector with size 2).</td>
</tr>
</tbody>
</table>

#### Limitations

The preferred equation contains an inverted C matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.
**GY-2**

**Library**
Bond Graph

**Use**

**Domains**: Continuous. **Size**: 2-D. **Kind**: Bond Graphs.

**Description**
This model is the multiport equivalent of the single gyrator. Consequently the constitutive equation must be written as a matrix-vector multiplication. The model can have both ports with an effort out causality or both ports with a flow out causality:

**Effort out causality**:

\[
p1.e = \text{transpose}(R) * p2.f; \\
p2.e = R * p1.f; 
\]

**Flow out causality**:

\[
p1.f = \text{inverse(\text{transpose}(R))} * p2.e; \\
p2.f = \text{inverse}(R) * p1.e; 
\]

**Interface**

**Ports**
p1[2], p2[2]  
**Description**  
Input and output port of the gyrator (columnvectors with size 2).

**Causality**
p1 equal p2  
**Description**  
The causality of both ports must be equal.

**Parameters**
R[2]  
**Description**  
Gyration ratio (matrix of size [2,2]).

**Limitations**
The flow out equations contain an inverted R matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.
Library
Bond Graph

Use

Description
This model is the multiport equivalent of the single I storage element. Consequently the
constitutive equation must be written as a matrix-vector multiplication. The element has
a preferred flow out causality. The corresponding constitutive equations then contain an
integration. The element can also have the non-preferred effort out causality. The
constitutive equations then contain a derivation, which can only be simulated when the
Backward Differentiation Formula integration algorithm is available:

flow out causality (preferred):

\[
\begin{align*}
\text{state} &= \text{int}(p.e) + \text{state}(0); \\
p.f &= \text{inverse}(I) \ast \text{state}; \\
\text{output} &= \text{state};
\end{align*}
\]

effort out causality:

\[
\begin{align*}
\text{state} &= I \ast p.f; \\
p.e &= \frac{d}{dt} \text{state}; \\
\text{output} &= \text{state};
\end{align*}
\]

Interface

Ports
p[2]

Description
Input port of the storage element (columnvector with size 2).

Causality
preferred effort out

A flow out causality results in a derivative constitutive equation.

Outputs
output[2]

The output signal is equal to the state (columnvector with size 2).

Parameters
I[2,2]

The storage element constants (matrix of size [2,2]).

Initial Values
state(0)[2] The initial values of the storage element (columnvector with size 2).

Limitations
The preferred equation contains an inverted I matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.

MGY-2

Library
Bond Graph

Use

Description
This model is the multiport equivalent of the single modulated gyrator. Consequently the constitutive equation must be written as a matrix-vector multiplication. The gyration ratio can be set to a certain (fluctuating) value, given by an input signal. The model can have both ports with an effort out causality or both ports with a flow out causality:

effort out causality:

\[ p1.e = \text{transpose}(r) \times p2.f; \]
\[ p2.e = r \times p2.f; \]

flow out causality:

\[ p1.f = \text{inverse(\text{transpose}(r))} \times p2.e; \]
\[ p2.f = \text{inverse}(r) \times p1.e; \]

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1[2], p2[2]</td>
<td>Input and output port of the gyrator (columnvectors with size 2).</td>
</tr>
</tbody>
</table>

Causality
p1 equal p2
The causality of both ports must be equal.

Inputs
r[2,2]
Modulated gyration ratio (size [2,2]).
Limitations
The flow out equations contain a matrix inversion of the modulation signal. The elements of this input signal should always have non-singular values.

MR-2

Library
Bond Graph

Use

Description
This model is the multiport equivalent of the single dissipative element. Consequently the constitutive equation must be written as a matrix-vector multiplication. This model can have an effort out as well as a flow out causality. In the last case the constitutive equation, as shown below, is simply inverted. The friction/resistor parameter can be set to a (fluctuating) value, given by an input signal.

effort out causality:

\[ p.e = r*p.f; \]

flow out causality:

\[ p.f = \text{inverse}(r)*p.e; \]

Interface

Ports
p[2]

Description
Input port of the R-element (columnvector with size 2).

Causality
indifferent

Input
The (modulated) friction/resistor parameter (size [2,2]).

**Parameters**

**R**

The friction parameters (matrix of size [2,2]).

**Limitations**

The flow out equation contains an inverted R matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.

---

**MSe-2**

**Library**
Bond Graph

**Use**
Domains: Continuous. **Size**: 2-D. **Kind**: Bond Graphs.

**Description**
This model is the multiport equivalent of the single modulated effort source. The effort can be set to a (fluctuating) value given by an input signal. The flow is indifferent.

\[ p.e = \text{input}; \]

**Ports**

**p[2]**

Output port of the effort source (columnvector with size 2).

**Causality**

fixed effort out

**Inputs**

**input[2]**

Modulation signal (columnvector with size 2).
**MSf-2**

**Library**
Bond Graph

**Use**

**Domains**: Continuous. **Size**: 2-D. **Kind**: Bond Graphs.

**Description**
This model is the multiport equivalent of the single modulated flow source. The flow can be set to a (fluctuating) value given by an input signal. The flow is indifferent.

\[ p.f = \text{input}; \]

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

**Causality**

fixed flow out

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input[2]</td>
</tr>
</tbody>
</table>

**MTF-2**

**Library**
Bond Graph

**Use**

**Domains**: Continuous. **Size**: 2-D. **Kind**: Bond Graphs.

**Description**
This model is the multiport equivalent of the single modulated transformer. Consequently the constitutive equation must be written as a matrix-vector multiplication. The transform ratio can be set to a certain (fluctuating) value, given by an input signal. The causality is always mixed: one port has an effort out causality while the other has a flow out causality:

\[ p1.e = \text{transpose}(r) \ast p2.e; \]
\[ p2.f = r \ast p1.f; \]

or:

\[ p2.e = \text{inverse(\text{transpose}(r))} \ast p1.e; \]
\[ p1.f = \text{inverse}(r) \times p2.f; \]

**Interface**

**Ports**

| p1[2], p2[2] | Input and output port of the gyrator (columnvectors with size 2). |

**Causality**

p1 notequal p2

**Inputs**

| r[2,2] | Modulated transform ratio (size [2,2]). |

**Limitations**

The second set of equations contain a matrix inversion of the modulation signal. The elements of this input signal should always have non-singular values.

---

**R-2**

**Library**

Bond Graph

**Use**

Domains: Continuous. **Size**: 2-D. **Kind**: Bond Graphs.

**Description**

This model is the multiport equivalent of the single dissipative element. Consequently the constitutive equation must be written as a matrix-vector multiplication. This model can have an effort out as well as a flow out causality. In the last case the constitutive equation, as shown below, is simply inverted.

effort out causality:

\[ p.e = R \times p.f; \]

flow out causality:

\[ p.f = \text{inverse}(R) \times p.e; \]
### Interface

**Ports**

- p[2]  
  Input port of the R-element (columnvector with size 2).

**Causality**

- indifferent

**Parameters**

- R  
  The friction parameters (matrix of size [2,2]).

**Limitations**

The flow out equation contains an inverted R matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.

---

### Se-2

**Library**

Bond Graph

**Use**

- **Domains**: Continuous.  
  - **Size**: 2-D.  
  - **Kind**: Block Diagrams, Bond Graphs.

**Description**

This model is the multiport equivalent of the single effort source. The effort can be set to a certain constant value, the flow is indifferent.

\[ p.e = S; \]

**Ports**

- p[2]  
  Output port of the effort source (columnvector with size 2).

**Causality**

- fixed effort out

**Parameters**

- S[2]  
  The constant value of the generated effort (columnvector with size 2).
**Sf-2**

**Library**
Bond Graph

**Use**
**Domains:** Continuous. **Size:** 2-D. **Kind:** Block Diagrams, Bond Graphs.

**Description**
This model is the multiport equivalent of the single flow source. The effort can be set to a certain constant value, the flow is indifferent.

\[ p.f = S; \]

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>p[2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output port of the flow source (columnvector with size 2).</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

fixed flow out

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>s[2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>The constant value of the generated flow (columnvector with size 2).</td>
<td></td>
</tr>
</tbody>
</table>

**SGY-2**

**Library**
Bond Graph

**Use**
**Domains:** Continuous. **Size:** 2-D. **Kind:** Bond Graphs.

**Description**
This model is the multiport equivalent of the single symplectic gyrator. Consequently the constitutive equation must be written as a matrix-vector multiplication. This model represents an ideal gyrator with gyration ratio equal to the identity matrix. The model represents a one to one power continuous relation between the effort of one port and the flow of the other port and vice-versa. The model can be used to transform a C-2 element into a I-2 element etc. The model can have both ports with an effort causality or both ports with a flow causality: effort out causality:

\[
\begin{align*}
p1.e &= p2.f; \\
p2.e &= p1.f;
\end{align*}
\]
flow out causality:

\[ p1.f = p2.e; \]
\[ p2.f = p1.e; \]

**Interface**

**Ports**

- \[ p1[2], p2[2] \]

**Description**

Input and output port of the gyrator (columnvectors with size 2).

**Causality**

- \[ p1 \text{ equal } p2 \]

The causality of both ports must be equal.

---

**STF-2**

**Library**

Bond Graph

**Use**

**Domains**: Continuous. **Size**: 2-D. **Kind**: Bond Graphs.

**Description**

This model is the multiport equivalent of the single simple transformer. This model represents an ideal transformer with a transform ratio equal to the identity matrix. The model has no real effect but allows for domain changes (one port having another domain as the other). The model represents a power continuous relation between the efforts and flows of both its ports. The causality is always mixed: one port has an effort causality while the other has a flow causality:

\[ p1.e = p2.e; \]
\[ p2.f = p1.f; \]

or:

\[ p2.e = p1.e \]
\[ p1.f = p2.f \]

**Interface**

**Ports**

- **Description**
p1[2], p2[2]  
Input and output port of the transformer (columnvectors with size 2).

**Causality**

p1 notequal p2  
The causality of both ports must be different.

---

**TF-2**

**Library**
Bond Graph

**Use**

**Domains:** Continuous. **Size:** 2-D. **Kind:** Bond Graphs.

**Description**

This model is the multiport equivalent of the single transformer. Consequently the constitutive equation must be written as a matrix-vector multiplication. The causality is always mixed: one port has an effort causality while the other has a flow causality:

\[ p1.e = \text{transpose}(R) \times p2.e; \]
\[ p2.f = R \times p1.f; \]

or:

\[ p2.e = \text{inverse}(\text{transpose}(R)) \times p1.e \]
\[ p1.f = \text{inverse}(R) \times p2.f \]

**Interface**

**Ports**
p1[2], p2[2]  
Input and output port of the transformer (columnvectors with size 2).

**Causality**
p1 notequal p2  
The causality of both ports must be different.

**Parameters**
R[2,2]  
Transform ratio (matrix of size [2,2]).

**Limitations**
The lower set of equations contain an inverted R matrix. The elements of this matrix should be chosen with care to prevent this matrix from becoming singular.
11.2 Iconic Diagrams

11.2.1 Iconic Diagrams
The Iconic Diagram library contains components which are very useful for modeling physical systems. The following libraries are available.

- Electric
- Hydraulics
- Mechanical
- Thermal

11.2.2 Electric

Electric
The Electric library contains components which are very useful for modeling electrical systems. The library contains the following sections:

- Actuators
- Components
- Sources

Actuators

CMABender

Library
Iconic Diagrams\Electric\Actuators
Iconic Diagrams\Mechanical\Translation\Actuators

Use

Description
This model represents a piezo actuator. The actuator translates a voltage difference at port $p1$ to a mechanical position difference between the base at port $p2$ and the end effector at port $p3$.

Although the underlying equations of this model are equal to the equations of the CMAStrecher.emx model, the default parameter values are typical for bending.

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>
fixed force out

**Input**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Capacitance [F]</td>
</tr>
<tr>
<td>KF</td>
<td>Voltage to force conversion factor [N/V]</td>
</tr>
<tr>
<td>m</td>
<td>Equivalent mass [kg]</td>
</tr>
<tr>
<td>k</td>
<td>Stiffness [N/m]</td>
</tr>
<tr>
<td>B</td>
<td>Relative damping ratio []</td>
</tr>
<tr>
<td>KB</td>
<td>Force to voltage conversion factor [V/N]</td>
</tr>
</tbody>
</table>

**CMAStretcher**

**Library**

Iconic Diagrams\Electric\Actuators  
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**


**Description**

This model represents a piezo actuator. The actuator translates a voltage difference at port `p1` to a mechanical position difference between the base at port `p2` and the end effector at port `p3`.

Although the underlying equations of this model are equal to the equations of the CMABender.emx model, the default parameter values are typical for stretching.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Port</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out

**Input**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Capacitance [F]</td>
</tr>
<tr>
<td>KF</td>
<td>Voltage to force conversion factor [N/V]</td>
</tr>
<tr>
<td>m</td>
<td>Equivalent mass [kg]</td>
</tr>
<tr>
<td>k</td>
<td>Stiffness [N/m]</td>
</tr>
<tr>
<td>B</td>
<td>Relative damping ratio []</td>
</tr>
<tr>
<td>KB</td>
<td>Force to voltage conversion factor [V/N]</td>
</tr>
</tbody>
</table>
**DCMotor**

**Library**
Iconic Diagrams\Electric\Actuators
Iconic Diagrams\Mechanical\Electric

**Implementations**
Default
IR

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Electric, Electric).

**Description - Default**
This models represents an ideal DC-motor with no energy loss. The electric port has separate high and low terminals. The equations are

\[
\begin{align*}
p1.i &= p1\_high.i = p1\_low.i; \\
p1.u &= p1\_high.u - p1\_low.u;
\end{align*}
\]

The model can have mixed forms of causality

\[
\begin{align*}
p1.u &= k \times p2.omega; \\
p2.T &= k \times p1.i;
\end{align*}
\]

or:

\[
\begin{align*}
p2.omega &= p1.u / k; \\
p1.i &= p2.T / k;
\end{align*}
\]

**Interface - Default**

**Ports**
- p1\_high, p1\_low
- p2

**Description**
Both terminals of the Electric port p1.
Rotation port.

**Causality**
mixed
See equations above.

**Parameters**
k
motor constant [Nm/A]

**Description - IR**
This models represents an ideal DC-motor with inductance and resistance.
The electric port has separate high and low terminals. The equations are:

\[
\begin{align*}
    p1.i &= p1\_high.i = p1\_low.i; \\
    p1.u &= p1\_high.u - p1\_low.u;
\end{align*}
\]

**Interface - IR**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1_high, p1_low</td>
<td>Both terminals of the Electric port p1.</td>
</tr>
<tr>
<td>p2</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**

mixed  
See equations above.

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>motor constant [Nm/A]</td>
</tr>
<tr>
<td>L</td>
<td>motor inductance [H]</td>
</tr>
<tr>
<td>R</td>
<td>motor resistance [Ohm]</td>
</tr>
</tbody>
</table>

**Components**

**Capacitor**

**Library**
Iconic Diagrams\Electric\Components

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Electric).

**Description**
This model represents an ideal capacitor. The element has a preferred voltage out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred current out causality. The constitutive equations then contain a derivation. The port p of the inductor model has separate high and low terminals. The equations are:

\[
\begin{align*}
    p.i &= p\_high.i = p\_low.i; \\
    p.u &= p\_high.u - p\_low.u;
\end{align*}
\]
voltage out causality (preferred):

\[ p.u = (1/C) \times \text{int}(p.i); \]

current out causality:

\[ p.i = C \times ddt(p.u); \]

### Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Electric port p.</td>
</tr>
</tbody>
</table>

### Causality

- preferred voltage out

A current out causality results in a derivative constitutive equation.

### Parameters

| C       | capacitance [F] |

### Initial Values

| p.u_initial | The initial charge of the capacitor [V]. |

---

### CurrentSensor

**Library**

Iconic Diagrams\Electric\Components

**Use**

- **Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Electric), Block Diagrams.

**Description**

This model translates a current to an output signal. It has a voltage out causality. The port p of the model has separate high and low terminals. The equations are:

\[
\begin{align*}
p.i &= p\text{\_high}.i = p\text{\_low}.i; \\
p.u &= p\text{\_high}.u - p\text{\_low}.u; \\
p.u &= 0; \\
i &= p.i;
\end{align*}
\]

### Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Electric port p.</td>
</tr>
</tbody>
</table>
Output
i Current [A].

Diode

Library
Iconic Diagrams\Electric\Components

Implementations
Default
Exponential

Use

Description - Default
This is an ideal electrical diode. The model is a switch which is open when the voltage drop \( v < 0 \) and closed when the voltage drop \( v > 0 \). The heart of the model consist of a resistance that is changed by the input voltage from almost zero (on) to a very large value (off). By proper selection of the on and off resistances, they can be effectively zero and infinity in comparison to other circuit elements. The port \( p \) of the diode model has separate high and low terminals. The equations are:

\[
\begin{align*}
p.i & = p_{\text{high}}.i = p_{\text{low}}.i; \\
p.u & = p_{\text{high}}.u - p_{\text{low}}.u;
\end{align*}
\]

voltage out causality:

\[
R = \begin{cases} 
Ron & \text{if } p.i > 0 \\
Roff & \text{else}
\end{cases}
\]

\[
p.u = R * p.i;
\]

current out causality:

\[
R = \begin{cases} 
Ron & \text{if } p.u > 0 \\
Roff & \text{else}
\end{cases}
\]

\[
p.i = p.u / R;
\]

Interface - Default

Ports
p_high, p_low Both terminals of the Electric port \( p \).

Causality
indifferent \( p \)

Parameters
Ron Resistance when diode is turned on [Ohm]
Roff Resistance when diode is turned off [Ohm]
**Description - Exponential**

This is an electrical diode described by an exponential expression. The port \( p \) of the diode model has separate high and low terminals. The equations are:

\[
\begin{align*}
    p.i &= p_{\text{high}}.i = p_{\text{low}}.i \\
    p.u &= p_{\text{high}}.u - p_{\text{low}}.u \\
    uT &= (k \times T) / e; \\
    p.i &= I_s \times (\exp(p.u / uT) - 1);
\end{align*}
\]

with \( k \) the Boltzmann constant \( (k = 1.380658\times10^{-23} \text{J/K}) \)

**Interface - Exponential**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{\text{high}}, p_{\text{low}} )</td>
<td>Both terminals of the Electric port ( p ).</td>
</tr>
</tbody>
</table>

**Causality**

indifferent \( p \)

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T )</td>
<td>operating temperature [K]</td>
</tr>
<tr>
<td>( I_s )</td>
<td>reverse saturation current [A]</td>
</tr>
</tbody>
</table>

**DoubleSwitch**

**Library**

Iconic Diagrams\Electric\Components

**Implementations**

Level
Amplitude

**Use**


**Description - Level**

This model represents an almost ideal switch. The switch connects port \( p1 \) with \( p2 \) when the input signal is larger than the threshold value \( v_t \) and connects port \( p1 \) with \( p3 \) when the input signal is smaller or equal to the threshold value \( v_t \).

The heart of the model consist of two resistances that can be changed by an input signal from almost zero (on) to a very large value (off). By proper selection of the on and off resistances, they can be effectively zero and infinity in comparison to other circuit elements.
The equations of the resistances are:

\[ R = \text{if} \ input > \ vt \ then \ Ron \ else \ Roff \ end; \]
\[ p.u = R \ast p.i; \]

**Interface - Level**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1, p2, p3</td>
<td>The electric ports (Electric).</td>
</tr>
<tr>
<td>input</td>
<td>The switching signal.</td>
</tr>
</tbody>
</table>

**Causality**

indifferent p1, p2, p3

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1\R</td>
<td>Ground resistance at port 1 [Ohm]</td>
</tr>
<tr>
<td>R2\R</td>
<td>Ground resistance at port 2 [Ohm]</td>
</tr>
<tr>
<td>R3\R</td>
<td>Ground resistance at port 3 [Ohm]</td>
</tr>
<tr>
<td>Resistance12\Ron</td>
<td>Resistance between p1 and p2 when switch is turned on [Ohm]</td>
</tr>
<tr>
<td>Resistance12\Roff</td>
<td>Resistance between p1 and p2 when switch is turned off [Ohm]</td>
</tr>
<tr>
<td>Resistance12\vt</td>
<td>Threshold value between p1 and p2, switch is turned on when input &gt;</td>
</tr>
<tr>
<td>Resistance13\Ron</td>
<td>Resistance between p1 and p3 when switch is turned on [Ohm]</td>
</tr>
<tr>
<td>Resistance13\Roff</td>
<td>Resistance between p1 and p3 when switch is turned off [Ohm]</td>
</tr>
<tr>
<td>Resistance13\vt</td>
<td>Threshold value between p1 and p3, switch is turned on when input &gt;</td>
</tr>
</tbody>
</table>
**Description - Amplitude**

This model represents an almost ideal switch. The switch connects port $p_1$ with $p_2$ when the **absolute value** of the input signal is larger than the threshold value $Resistance_{12}\ \backslash vt$ and connects port $p_1$ with $p_3$ when the **absolute value** of the input signal is smaller or equal to the threshold value $Resistance_{13}\ \backslash vt$.

The heart of the model consist of two resistances that can be changed by an input signal from almost zero (on) to a very large value (off). By proper selection of the on and off resistances, they can be effectively zero and infinity in comparison to other circuit elements.

![Layout of the switch model.](image)

The equations of the resistances are:

\[
R = \text{if abs(input) > vt then Ron else Roff end;}
\]
\[
p.u = R \times p.i;
\]

**Interface - Amplitude**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>The electric ports (Electric).</td>
<td>p1, p2, p3</td>
</tr>
<tr>
<td>The switching signal.</td>
<td>input</td>
</tr>
</tbody>
</table>

**Causality**

indifferent p1, p2, p3

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground resistance at port 1 [Ohm]</td>
<td>$R_1$</td>
</tr>
<tr>
<td>Ground resistance at port 2 [Ohm]</td>
<td>$R_2$</td>
</tr>
<tr>
<td>Ground resistance at port 3 [Ohm]</td>
<td>$R_3$</td>
</tr>
<tr>
<td>Resistance between p1 and p2 when switch is turned on [Ohm]</td>
<td>$Resistance_{12}\ Ron$</td>
</tr>
<tr>
<td>Resistance between p1 and p2 when switch is turned off [Ohm]</td>
<td>$Resistance_{12}\ Roff$</td>
</tr>
<tr>
<td>Resistance \vt</td>
<td>$Resistance_{12}\ vt$</td>
</tr>
</tbody>
</table>
Threshold value between p1 and p2, switch is turned on when
abs(input) > Resistance12\vt
Resistance13\Ron Resistance between p1 and p3 when switch is turned on [Ohm]
Resistance13\Roff Resistance between p1 and p3 when switch is turned off [Ohm]
Resistance13\vt Threshold value between p1 and p3, switch is turned on when
abs(input) > Resistance13\vt

Note
To get a simple switching behavior, pay attention to chose the parameters Resistance12 \vt and Resistance13\vt equal. When these parameters are not chosen equal a more complex switching behavior can be obtained.

Ground

Library

Iconic Diagrams\Electric\Components
Use
Description
This model represents the ground (voltage = 0). The model has only one initial port p
defined. Because any number of connections can be made, successive ports are named
p1, p2, p3 etc. which gives the constitutive equations:

\[ p1.u = p2.u = \ldots = pn.u = 0; \]
\[ p1.i = \text{free}; p2.i = \text{free}; \ldots; pn.i = \text{free}; \]

Interface

Ports  Description
p [any]  Any number of connections can be made (Electric).
Causality  Fixed voltage out  All ports have a fixed voltage out causality.
**Inductor**

**Library**
Iconic Diagrams\Electric\Components

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Electric).

**Description**
This model represents an ideal electrical inductance. The element has a preferred current out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred voltage out causality. The constitutive equations then contain a derivation. The port p of the inductor model has separate high and low terminals. The equations are:

\[
\begin{align*}
\text{current out causality (preferred):} \\
p.i &= p\_high.i = p\_low.i; \\
p.u &= p\_high.u - p\_low.u;
\end{align*}
\]

\[
\begin{align*}
\text{voltage out causality:} \\
p.u &= L \cdot \text{ddt}(p.i);
\end{align*}
\]

**Interface**

**Ports**
p\_high, p\_low

**Description**
Both terminals of the Electric port p.

**Causality**
preferred current out

**Description**
An voltage out causality results in a derivative constitutive equation.

**Parameters**
L

**Description**
Inductance [H]

**Initial Values**
p\_i\_initial

**Description**
The initial flux in the inductor.
**Node**

**Library**
Iconic Diagrams\Electric\Components

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Electric).

**Description**
This node model represents a structural connection between two or more branches of an electrical circuit. The model has only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>p [any]</td>
<td></td>
</tr>
</tbody>
</table>

**OpAmp**

**Library**
Iconic Diagrams\Electric\Components

**Implementations**

Default
Universal

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Electric).

**Description - Default**
This model represents an ideal operational amplifier. The input resistance is infinite and the output resistance is zero. The port $p_{in}$ of the OpAmp model has separate high and low terminals:

$p_{in}.u = p_{in\_high}.u - p_{in\_low}.u$
$p_{in\_high}.i = p_{in\_low}.i = p_{in}.i = 0$
$p_{out}.u = A*p_{in}.u$

**Interface - Default**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both terminals of the input port $p_{in}$ (Electric).</td>
<td>$p_{in_high}$, $p_{in_low}$</td>
</tr>
<tr>
<td>Output port (Electric).</td>
<td>$p_{out}$</td>
</tr>
</tbody>
</table>
fixed current out
p_in
fixed voltage out
p_out

**Parameters**

A Amplification []

**Description - Universal**

This model represents an operational amplifier with a first order decreasing voltage amplification.

The amplification is parameterized by a DC-gain (A) and a cut-off frequency (f). This yields a unity gain frequency of:

unity gain frequency = A*f;

The gain is limited to yield an output that is between the positive (VDD) and negative (VEE) supply voltage.
The input resistance is infinite and the output resistance is equal to the parameter R. The port p_in of the OpAmp model has separate high and low terminals:

\[
\begin{align*}
    p_{in}.u &= p_{in\text{-}high}.u - p_{in\text{-}low}.u \\
    p_{in\text{-}high}.i &= p_{in\text{-}low}.i = p_{in}.i = 0; \\
    p_{out}.u &= \text{Adiff}*p_{in}.u - R*p_{out}.u;
\end{align*}
\]

where Adiff is a dynamic gain according to the bode and gain plot.

**Interface - Universal**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in_high</td>
<td>Both terminals of the input port p_in (Electric).</td>
</tr>
<tr>
<td>p_in_low</td>
<td>Output port (Electric).</td>
</tr>
<tr>
<td>p_out</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

fixed current out

| p_in            | preferred voltage out p_out                                      |

**Parameters**

| A    | DC gain or DC Amplification                                   |
| f    | Cut-off frequency [Hz]                                        |
| VDD  | Positive supply voltage [V], choose VDD > VEE!                |
| VEE  | Negative supply voltage [V], choose VDD > VEE!                |
| R    | Output impedance [Ohm]                                       |
Potentiometer

Library
Iconic Diagrams\Electric\Components

Use

Description
This model represents an ideal potentiometer.

It can have various forms of causality. The equations are:

\[
\begin{align*}
R1 &= (1 - \alpha) \times R; \\
R2 &= \alpha \times R; \\
p_{\text{high}}.u - p_{\text{var}}.u &= p_{\text{high}}.i \times R1; \\
p_{\text{var}}.u - p_{\text{low}}.u &= p_{\text{low}}.i \times R2; \\
p_{\text{high}}.i + p_{\text{var}}.i &= p_{\text{low}}.i;
\end{align*}
\]

where \( \alpha \) denotes the position of the indicator and can vary from zero to one.

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the resistor.</td>
</tr>
<tr>
<td>p_var</td>
<td>Indicator terminal.</td>
</tr>
</tbody>
</table>

Causality
indifferent

Parameters

<table>
<thead>
<tr>
<th>R</th>
<th>Resistance [Ohm].</th>
</tr>
</thead>
<tbody>
<tr>
<td>alpha</td>
<td>Indicator position (0 &lt;= alpha &lt;= 1).</td>
</tr>
</tbody>
</table>
Rectifier

Library
Iconic Diagrams\Electric\Components

Use

Description
This model represents an diode bridge rectifier consisting of a set four diodes. Given an alternating input current, the bridge produces an output current which is always positively oriented and has the same amplitude as the input current. The bridge behavior is ideal. No diode characteristics are implemented and no power is dissipated.

A circuit with a diode bridge rectifier.

Interface

Ports
p1_high, p1_low
p2_high, p2_low

Description
Both terminals of the Electric input port p1.
Both terminals of the Electric output port p2.

Causality
p1 not equal p2

Resistor

Library
Iconic Diagrams\Electric\Components

Use

Description
This model represents an ideal electrical resistor. It can have an voltage out as well as a current out causality. In the last case the constitutive equation, as shown below, is simply inverted. The port p of the damper model has separate high and low terminals. The equations are:
\[ p_i = p_{\text{high}.i} = p_{\text{low}.i}; \]
\[ p_u = p_{\text{high}.u} - p_{\text{low}.u}; \]

Voltage out causality:
\[ p_u = R \times p_i; \]

Current out causality:
\[ p_i = p_u / R; \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Electric port p.</td>
</tr>
</tbody>
</table>

**Causality**

indifferent

**Parameters**

| R       | Resistance [Ohm]. |

**Switch**

**Library**

Iconic Diagrams\Electric\Components

**Implementations**

Level
Amplitude

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Electric).

**Description - Level**

This model represents an almost ideal switch. The switch is turned on when the input signal is larger than the threshold value \( vt \) and it is turned off when the input signal is smaller or equal to the threshold value \( vt \).

The heart of the model consist of a resistance that can be changed by an input signal from almost zero (on) to a very large value (off). By proper selection of the on and off resistances, they can be effectively zero and infinity in comparison to other circuit elements.
The equations of the resistance are:

\[ R = \text{if input} > vt \text{ then Ron else Roff end}; \]
\[ p.u = R \times p.i; \]

**Interface - Level**

**Ports**
- **p1, p2**: Both electric ports (Electric).
- **input**: The switching signal.

**Causality**
- indifferent p1, p2

**Parameters**
- **R1\R**: Ground resistance at port 1 [Ohm]
- **R2\R**: Ground resistance at port 2 [Ohm]
- **Resistance12\Ron**: Resistance when switch is turned on [Ohm]
- **Resistance12\Roff**: Resistance when switch is turned off [Ohm]
- **Resistance12\vt**: Threshold value, switch is turned on when input > vt

**Description - Amplitude**

This model represents an almost ideal switch. The switch is turned on when the amplitude of the input signal is larger than the threshold value \( vt \) and it is turned off when the amplitude of the input signal is smaller or equal to the threshold value \( vt \).

The heart of the model consist of a resistance that can be changed by an input signal from almost zero (on) to a very large value (off). By proper selection of the on and off resistances, they can be effectively zero and infinity in comparison to other circuit elements.
The equations of the resistance are:

\[
R = \text{if } \text{abs}(\text{input}) > \text{vt} \text{ then } \text{Ron} \text{ else } \text{Roff} \text{ end};
\]

\[
p.u = R \times p.i;
\]

Interface - Amplitude

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1, p2</td>
<td>Both electric ports (Electric).</td>
</tr>
<tr>
<td>input</td>
<td>The switching signal.</td>
</tr>
</tbody>
</table>

Causality

indifferent p1,p2

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1\R</td>
<td>Ground resistance at port 1 [Ohm]</td>
</tr>
<tr>
<td>R2\R</td>
<td>Ground resistance at port 2 [Ohm]</td>
</tr>
<tr>
<td>Resistance12\Ron</td>
<td>Resistance when switch is turned on [Ohm]</td>
</tr>
<tr>
<td>Resistance12\Roff</td>
<td>Resistance when switch is turned off [Ohm]</td>
</tr>
<tr>
<td>Resistance12\vt</td>
<td>Threshold value, switch is turned on when abs(input) &gt; vt</td>
</tr>
</tbody>
</table>

Transformer

Library

Iconic Diagrams\Electric\Components

Implementations

Default

Induction
Use


Description - Default

This model represents an ideal transformer. The transformer does not have internal resistors, capacitance or inductance. The causality of this model is always mixed: one port has a voltage causality while the other has a current out causality:

\[ p_1.u = n \cdot p_2.u; \]
\[ p_2.i = n \cdot p_1.i; \]

or:

\[ p_2.u = \frac{1}{n} \cdot p_1.u; \]
\[ p_1.i = \frac{1}{n} \cdot p_2.i; \]

Interface - Default

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_1,p_2</td>
<td>Electrical ports</td>
</tr>
</tbody>
</table>

Causality

p_small notequal
p_large

Parameters

n turns ratio [ ]

Description - Induction

This model represents a transformer with inductance and mutual inductance. The equations are:

\[ p_1.u = L1 \cdot \frac{d}{dt}(p_1.i) + M \cdot \frac{d}{dt}(p_2.i); \]
\[ p_2.u = M \cdot \frac{d}{dt}(p_1.i) + L2 \cdot \frac{d}{dt}(p_2.i); \]

Interface - Induction

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_1,p_2</td>
<td>Electrical ports</td>
</tr>
</tbody>
</table>

Causality

indifferent

Parameters

L1 Primary inductance [H]
L2 Secondary Inductance [H]
M Coupling Inductance [H]
VoltageSensor

Library
Iconic Diagrams\Electric\Components

Use

Description
This model translates a voltage difference to an output signal. It has a current out causality. The port p of the model has separate high and low terminals. The equations are:

\[
\begin{align*}
p.i &= p\_high.i = p\_low.i; \\
p.u &= p\_high.u - p\_low.u; \\
p.i &= 0; \\
u &= p.u;
\end{align*}
\]

Interface

Ports Description
p\_high, p\_low Both terminals of the Electric port p.

Causality
fixed current out

Output
u Voltage [V].

Sources

ControlledCurrentSource

Library
Iconic Diagrams\Electric\Sources

Implementations
Voltage Current

Use

Description - Voltage
This model represents an ideal voltage controlled current source. Both ports of the model have separate high and low terminals:
\[ p_{\text{in}.u} = p_{\text{in}\_high.u} - p_{\text{in}\_low.u}; \]
\[ p_{\text{in}\_high.i} = p_{\text{in}\_low.i} = p_{\text{in}.i}; \]
\[ p_{\text{out}.u} = p_{\text{out}\_high.u} - p_{\text{out}\_low.u} = 0 \]
\[ p_{\text{out}\_high.i} = p_{\text{out}\_low.i} = p_{\text{in}.i}; \]

The equations of this model are:

\[ p_{\text{in}.i} = 0; \]
\[ p_{\text{out}.i} = p_{\text{in}.u}; \]
\[ p_{\text{out}.u} = \text{indifferent}; \]

**Interface - Voltage**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{p_in_high}, \text{P_in_low}</td>
<td>Both terminals of the input port \text{p_in} (Electric).</td>
</tr>
<tr>
<td>\text{p_out_high}, \text{P_out_low}</td>
<td>Both terminals of the output port \text{p_out} (Electric).</td>
</tr>
</tbody>
</table>

**Causality**

- fixed current out \text{p\_in}
- fixed current out \text{p\_out}

**Description - Current**

This model represents an ideal current controlled current source. Both ports of the model have separate high and low terminals:

\[ p_{\text{in}.u} = p_{\text{in}\_high.u} - p_{\text{in}\_low.u}; \]
\[ p_{\text{in}\_high.i} = p_{\text{in}\_low.i} = p_{\text{in}.i}; \]
\[ p_{\text{out}.u} = p_{\text{out}\_high.u} - p_{\text{out}\_low.u} = 0 \]
\[ p_{\text{out}\_high.i} = p_{\text{out}\_low.i} = p_{\text{in}.i}; \]

The equations of this model are:

\[ p_{\text{in}.u} = 0; \]
\[ p_{\text{out}.i} = p_{\text{in}.i}; \]
\[ p_{\text{out}.u} = \text{indifferent}; \]

**Interface - Current**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{p_in_high}, \text{P_in_low}</td>
<td>Both terminals of the input port \text{p_in} (Electric).</td>
</tr>
<tr>
<td>\text{p_out_high}, \text{P_out_low}</td>
<td>Both terminals of the output port \text{p_out} (Electric).</td>
</tr>
</tbody>
</table>
**Causality**

fixed voltage out  
\( p_{\text{in}} \)

fixed current out  
\( p_{\text{out}} \)

**ControlledVoltageSource**

**Library**

Iconic Diagrams\Electric\Sources

**Implementations**

Voltage  
Current  
PI  
KP

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Electric).

**Description - Voltage**

This model represents an ideal voltage controlled voltage source. Both ports of the model have separate high and low terminals:

\[
\begin{align*}
  p_{\text{in}.u} &= p_{\text{in\_high}.u} - p_{\text{in\_low}.u} \\
  p_{\text{in\_high}.i} &= p_{\text{in\_low}.i} = p_{\text{in}.i} \\
  p_{\text{out}.u} &= p_{\text{out\_high}.u} - p_{\text{out\_low}.u} = 0 \\
  p_{\text{out\_high}.i} &= p_{\text{out\_low}.i} = p_{\text{in}.i}
\end{align*}
\]

The equations of this model are:

\[
\begin{align*}
  p_{\text{in}.i} &= 0 \\
  p_{\text{out}.u} &= p_{\text{in}.u} \\
  p_{\text{out}.i} &= \text{indifferent}
\end{align*}
\]

**Interface - Voltage**

**Ports**  
\( p_{\text{in\_high}} \), \( p_{\text{in\_low}} \), \( p_{\text{out\_high}} \), \( p_{\text{out\_low}} \)

**Description**  
Both terminals of the input port \( p_{\text{in}} \) (Electric).  
Both terminals of the output port \( p_{\text{out}} \) (Electric).
fixed voltage out  
p_out

**Description - Current**

This model represents an ideal current controlled voltage source. Both ports of the model have separate high and low terminals:

\[
p_{in}.u = p_{in\_high}.u - p_{in\_low}.u;  
p_{in\_high}.i = p_{in\_low}.i = p_{in}.i;  
p_{out}.u = p_{out\_high}.u - p_{out\_low}.u = 0  
p_{out\_high}.i = p_{out\_low}.i = p_{in}.i;  
\]

The equations of this model are:

\[
p_{in}.u = 0;  
p_{out}.u = p_{in}.i;  
p_{out}.i = indifferent;  
\]

**Interface - Current**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in_high, P_in_low</td>
<td>Both terminals of the input port p_in (Electric).</td>
</tr>
<tr>
<td>p_out_high, P_out_low</td>
<td>Both terminals of the output port p_out (Electric).</td>
</tr>
</tbody>
</table>

**Causality**

fixed voltage out  
p_in  
fixed voltage out  
p_out

**Description - PI**

This model represents a voltage controlled voltage source. The output voltage is connected to the input voltage through a PI-controller and limited to a maximum and minimum value of ±V_{max}. The output voltage is subjected to an output resistance R.

Both ports of the model have separate high and low terminals:
Interface - PI

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in_high,</td>
<td>Both terminals of the input port p_in (Electric).</td>
</tr>
<tr>
<td>p_in</td>
<td></td>
</tr>
<tr>
<td>p_out_high,</td>
<td>Both terminals of the output port p_out (Electric).</td>
</tr>
<tr>
<td>p_out_low</td>
<td></td>
</tr>
</tbody>
</table>

Causality
fixed current out
p_in
fixed voltage out
p_out

Parameters
Kp                     Proportional gain [ ]
f                      Integration frequency [Hz]
Vmax                    Maximum output voltage [V]
R                       Output resistance [Ohm]

Description - KP
This model represents a voltage controlled voltage source. The output voltage is proportional to the input voltage and is limited to a maximum and minimum value of ±Vmax. The output voltage is subjected to an output resistance R.

Both ports of the model have separate high and low terminals:

\[
p_{in}.u = p_{in\_high}.u - p_{in\_low}.u; \\
p_{in\_high}.i = p_{in\_low}.i = p_{in}.i; \\
p_{out}.u = p_{out\_high}.u - p_{out\_low}.u = 0 \\
p_{out\_high}.i = p_{out\_low}.i = p_{in}.i; \\
\]
### Interface - KP

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in_high,</td>
<td>Both terminals of the input port p_in (Electric).</td>
</tr>
<tr>
<td>p_in_low</td>
<td></td>
</tr>
<tr>
<td>p_out_high,</td>
<td>Both terminals of the output port p_out (Electric).</td>
</tr>
<tr>
<td>p_out_low</td>
<td></td>
</tr>
</tbody>
</table>

#### Causality
- fixed current out
- p_in
- fixed voltage out
- p_out

#### Parameters
- Kp: Proportional gain []
- Vmax: Maximum output voltage [V]
- R: Output resistance [Ohm]

### CurrentSource

**Library**
Iconic Diagrams\Electric\Sources

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Electric).

**Description**
This model represents an ideal current source with a constant current. The current can be set to a certain constant value, the voltage is indifferent. The port $p$ of the model has separate high and low terminals. The equations are:

\[
p.i = p\text{\_high}.i = p\text{\_low}.i; \\
p.u = p\text{\_high}.u - p\text{\_low}.u; \\
p.u = \text{indifferent}; \\
p.i = i;
\]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_low, p_high</td>
<td>Both terminals of the Electric port p.</td>
</tr>
</tbody>
</table>

#### Causality
- fixed current out

#### Parameters
- i: Current [A].
ModulatedCurrentSource

Library
Iconic Diagrams\Electric\Sources
Use
Description
This model represents an ideal current source with a variable current. The current can be set to a (fluctuating) value given by the input signal $i$, the voltage is indifferent.

    p.i = i;

Interface

Ports  Description
p      Electric port.

Causality
fixed current out

Input
i      Current [A].

ModulatedVoltageSource

Library
Iconic Diagrams\Electric\Sources
Use
Description
This model represents an ideal voltage source with a variable voltage. The voltage can be set to a (fluctuating) value given by the input signal $u$, the current is indifferent.

    p.u = u;

Interface

Ports  Description
p      Electric port.

Causality
**VoltageSource**

**Library**
Iconic Diagrams\Electric\Sources

**Implementations**
DC
AC

**Use**

**Description - DC**
This model represents an ideal voltage source with a constant voltage. The voltage can be set to a certain constant value, the current is indifferent. The port $p$ of the model has separate high and low terminals. The equations are:

$$p.i = p\_high.i = p\_low.i;$$
$$p.u = p\_high.u - p\_low.u;$$

$$p.i = \text{indifferent};$$
$$p.u = u;$$

**Interface - DC**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Both terminals of the Electric port $p$.</td>
</tr>
</tbody>
</table>

**Causality**
fixed voltage out

**Parameters**

| u     | Voltage [V]. |

**Description - AC**
This model represents an ideal voltage source with a sinusoidal voltage. The voltage can be set to a certain constant value, the current is indifferent. The port $p$ of the model has separate high and low terminals. The equations are:
\[ p.i = p\_high.i = p\_low.i; \]
\[ p.u = p\_high.u - p\_low.u; \]
\[ p.i = \text{indifferent}; \]
\[ p.u = U*\sin(2*pi*f*time); \]

**Interface - AC**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Both terminals of the Electric port ( p ).</td>
</tr>
</tbody>
</table>

**Causality**

fixed voltage out

**Parameters**

<table>
<thead>
<tr>
<th>U</th>
<th>Voltage amplitude [V].</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>Voltage frequency [Hz]</td>
</tr>
</tbody>
</table>

### 11.2.3 Hydraulics

**Hydraulics**

The 20-sim Hydraulics library contains components to model the dynamic behavior of hydraulic circuits. The library has been completely revised in 20-sim 4.9. Compared to older versions of 20-sim the following changes are made:

1. Most valves and components now use the nominal flow at a given pressure drop to determine the laminar and turbulent flow characteristics.
2. Fluid Properties are now defined with a separate component.

To get a good impression of the use the components of this library, have a look at the example circuits.

**Library**

The Hydraulics library is divided in a number of sections:

- Components: Connectors and lines
- Cylinders: translational actuators
- Fluids: fluid properties
- Motors: motors
- Pumps: flow and pressure sources, pumps
- Restrictions: orifices and restrictions
- Sensors: flow and pressure sensor
- Valves: check valves, pressure reducing valves, 4-3 way valves and more
• Volumes: volumes, tanks and accumulators

Some of these sections contain subsection with basic components. These elementary components (without parasitic volumes) should only be used by experienced modelers who want to create their own library components.

**Fluid Properties**

In previous versions of 20-sim, the hydraulic fluid properties (e.g., bulk modulus, viscosity) were stored in every component. In this library, the fluid properties are stored in the Fluid Properties component. This means that you only have to define the properties once and use them in every component automatically.

**Ports**

Every library component has one or more hydraulic connectors, which are called ports in 20-sim. Ports always have two variables: pressure [Pa] and volume flow [m\(^3\)/s]. The following ports a and b are usually provided:

\[
\begin{align*}
a & \quad \text{a.p} \quad \text{Pressure in [Pa] with respect to atmospheric pressure (p stands for pressure).} \\
\quad \text{a.phi} & \quad \text{Volume flow [m}\(^3\)/s], positive if oil is entering the component at port a (phi stands for flow).} \\
\end{align*}
\]

\[
\begin{align*}
b & \quad \text{b.p} \quad \text{Pressure in [Pa] with respect to atmospheric pressure (p stands for pressure).} \\
\quad \text{b.phi} & \quad \text{Volume flow [m}\(^3\)/s], negative if oil is entering the component at port b (phi stands for flow).} \\
\end{align*}
\]

Hydraulic components can easily be coupled to other library models. The pumps and motors have a rotation port that can be coupled to models of the Rotation library. The cylinder models have a translation port that can be coupled to models of the Translation library. Some models have a variable input that can be coupled to models of the Signal library.

**Units**

20-sim uses SI-units for the hydraulic components. If you want to use other units select them in the Parameters Editor or the Variables Chooser. The 20-sim hydraulics library uses the common definition of pressure in Pa:

\[1 \text{ Pa} = 1 \text{ N/m}^2 = 1e-5 \text{ bar}\]

The air pressure at sea level is taken as the zero value:

\[0 \text{ Pa} = \text{air pressure}\]
Consequently the pressure for liquid oil that starts to vaporize is negative. In 20-sim the default value of the vapour pressure is:

\[ p_{\text{vapour}} = -0.999e5 \text{ Pa} \]

The vapour pressure is the minimum pressure. Some models have a safeguard on the pressure to prevent it to become smaller. You can change the value of the vapour pressure but take care that always a value is chosen that is smaller than zero. Otherwise some of the models will not work correctly.

**Parasitic Volumes**

Most components have parasitic volumes to ensure a seamless connection with other components. Therefore almost all components can be connected arbitrarily.

**Disclaimer**

All models have been tested with standard configurations. This will however not ensure that valid results will be found at all times. For example temperature effects are not included and certain parameter values will lead to unstable simulations. Therefore any application of the library without validation of the user is at his own risk!

**Literature**

The 20-sim hydraulic library has been based on the following literature:


The models have been designed as close as possible to the Modelica hydraulic library (www.modelica.org). To compare both libraries the example model Closed Circuit Drive Train.emx has been added.

**Building Hydraulic Models**

**Example Models**

The quickest way to learn how to create hydraulic circuit models is to open some models from the Examples library.

**Model Creation**

To create hydraulic circuit models you have to:

1. Drag and drop components from the Hydraulics library to the Editor.
2. Connect the components.
3. Add the Fluid Properties component.
Simulation

If the model is properly constructed you can start a simulation. Hydraulic circuits can be simulated with all the available integration methods. In practice the default integration method (BDF) will give the most accurate and quickest response. Take care with hydraulic circuits that will give high pressure peaks and small flow rates. These circuits are sometimes hard to simulate. In practice high pressure peaks should be reduced with pressure relief valves to avoid damage. Fortunately adding pressure relief valves will in most cases improve the simulation response.

Common Errors

Simulation will not Run

The most common error with hydraulics models is to forget to insert the Fluid Properties component. Without this component, the fluid properties are zero and the simulation will not run.

Flow

Laminar flow

Many hydraulic models have a laminar (leakage) flow:

\[ \text{flow} = G \times \text{dp} \]

with \( G \) the flow conductance and \( \text{dp} \) the pressure difference. The table below shows the flow rates for various conductance values and pressure differences of 10 [bar] and 400 [bar].
If the flow rate is very small (leakage flow), choose $G$ below $1.0\times10^{-14} \text{[m}^3/\text{s.Pa]}$. If the flow rate is very large (open connection to a tank), choose $G > 1.0\times10^{-9}$ or higher if desired.

**Leakage Flow**

For the valve models in the library, the leakage flow is described with the laminar flow equation. For leakage flow the conductance is not often given in datasheets. Therefore the conductance is calculated out of the leakage flow at a nominal pressure drop:

$$Q_{\text{leak}} = G \times p_{\text{nom}}$$

which gives:

$$G = Q_{\text{leak}}/p_{\text{nom}}$$

**Turbulent flow**

The turbulent flow in an orifice or valve can be described by:

$$\text{flow} = Cd \times A \times \sqrt{\left(\frac{2}{\rho}\right) \times dp}$$

with $Cd$ the discharge coefficient, $A$ the orifice area, $\rho$ the fluid density and $dp$ the pressure difference. The discharge coefficient depends on the shape of the orifice and is generally not listed in data sheets. Therefore we will write the turbulent flow with nominal parameters. Given a nominal pressure drop $p_{\text{nom}}$ we find a nominal flow:

$$Q_{\text{nom}} = Cd \times A \times \sqrt{\left(\frac{2}{\rho}\right) \times p_{\text{nom}}}$$

we can use this to rewrite the flow equation as:

$$\text{flow} = Q_{\text{nom}} \times \sqrt{dp/p_{\text{nom}}}$$

This is the flow equation, that is found in most datasheets. Therefore all the models in the hydraulics library where the turbulent flow equation is used (orifices, valves) use this equation.
Older 20-sim Models
If you have an old 20-sim model that uses the flow equation with a discharge coefficient and area, and you want to replace it with a new model using the nominal flows here is what you have to do:

1. Write down the values of the discharge coefficient $Cd$, valve area $A$ and fluid density $\rho$ of your component.
2. Choose a nominal pressure drop $p_{\text{nom}}$, e.g. 10e5 Pa (10 bar).
3. Calculate the nominal flow: $Q_{\text{nom}} = Cd \times A \times \sqrt{\frac{2}{\rho} \times p_{\text{nom}}}$
4. Insert the new library component and fill in the values for $p_{\text{nom}}$ and $Q_{\text{nom}}$.

Components

HydraulicInertia

Library
Iconic Diagrams\Hydraulics\Components

Use

Description
When a fluid flow changes speed, a force is needed to accelerate the fluid. This force is equal to the acceleration multiplied by the mass of the fluid.

$$F = m \times \frac{dv}{dt}$$

The fluid mass is equal to the pipe area multiplied by the pipe length and the fluid density:

$$m = A \times l \times \rho$$

The force will result in a pressure differential:

$$F = A \times dp = A \times (pa.p - pb.p)$$

We can rewrite the formulas as

$$dp = \rho \times l \times \frac{dv}{dt}$$

and by introducing the fluid flow $\phi$:
we get the formula for an hydraulic inertia:

$$dp = (\rho * l / A) * d\phi/dt$$

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa, pb</td>
<td>Both terminals of the hydraulic inertia.</td>
</tr>
</tbody>
</table>

**Causality**

fixed pressure out

<table>
<thead>
<tr>
<th>pa</th>
<th>fixed pressure out</th>
</tr>
</thead>
<tbody>
<tr>
<td>pb</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>d</th>
<th>pipe diameter [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>l</td>
<td>pipe length [m]</td>
</tr>
</tbody>
</table>

**Line**

**Library**

Iconic Diagrams\Hydraulics\Components

**Use**

Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**

The line model represents a hydraulic pipe or hose with elasticity, inertia and pressure drop. It is assumed that the pipe or hose is round and has a certain length. The line model has two implementations: **Default** and **MultipleCells**.

**Default**

The default model of a line consists of two volumes for the compressibility of the fluid, a hydraulic inertia for the mass of the fluid and a friction element to model to friction of the fluid with the walls.
The default line model contains the smallest number of elements to correctly represent the behaviour of a hydraulic line. A more detailed model is obtained by repeating these elements in cells. The more cells are used, the more detailed the fluid flow inside the line can be simulated.

**MultipleCells**

![Line model with multiple cells.](image)

In general, the default line model will do fine for modelling hydraulic circuits. Only if long lines are used and the resonances, inside the line are important, the multiple cells line model should be applied.

1. Select the Line model in the 20-sim Editor
2. Make sure it has the MultipleCells implementation: select Right mouse menu – Edit Implementation – MultipleCells.
3. Click Go Down to inspect the equations.
4. Change the value of the constant $n$ from 4 to the number of cells that you require ($n>1$).

![20-sim Editor on Line Volume Test MultipleCells.mlx](image)

**Volume**

The pipe with length $L$ [m], diameter $D$ [m] and thickness $th$ [m] will expand under if a pressure is applied by the fluid flowing in the pipe.
The expansion is modelled in the radial direction (pipe wall expanding) and in the length of of the pipe (pipe extending). This expansion can be modelled by a reduction of the Bulk modulus:

\[ p = B \cdot \text{int}(Q/V) \text{ with } B = \frac{4 \cdot \text{th} \cdot E \cdot B}{4 \cdot \text{th} \cdot E + 5 \cdot D \cdot B} \]

where \( E \) is Young’s modulus [Pa].

**Inertia**

The fluid in the pipe will oppose any change in velocity by a pressure drop. This is modelled by a hydraulic inertia. The equation for the inertia is:

\[ Q = A/(\rho \cdot L) \]

where \( A \) is the pipe cross sectional area [m\(^2\)] and \( \rho \) is the fluid density [kg/m\(^3\)].

**Friction**

Any fluid flowing through a pipe will experience friction resulting in a pressure drop. The pressure drop depends on the fluid velocity and flow conditions. The flow condition can be determined by the Reynolds number:

\[ Re = \frac{Q \cdot D}{A \cdot kv} \]

where \( Q \) is the fluid flow [m\(^3\)/s], \( D \) the pipe diameter [m], \( A \) the pipe cross sectional area [m\(^2\)] and \( kv \) the kinematic viscosity [m\(^2\)/s].

For low Reynolds numbers the flow is laminar and for high Reynolds numbers the flow is turbulent. According to Beater (1999), for a smooth pipe, the friction factor \( \lambda \) can be described as:

\[ \lambda = 2 \cdot dp \cdot D / (v^2 \cdot \rho \cdot L) \]

with \( dp \) the pressure drop [Pa] over the line, \( \rho \) the density of the fluid [kg/m\(^3\)] and \( v \) the average flow velocity of the fluid.

The friction factor \( \lambda \) depends on the Reynolds number:

<table>
<thead>
<tr>
<th>( Re )</th>
<th>( \lambda )</th>
<th>flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1404</td>
<td>64/Re</td>
<td>laminar (Hagen=Poiseuille)</td>
</tr>
<tr>
<td>1404-2320</td>
<td>0.0456</td>
<td>transition from laminar to turbulent</td>
</tr>
<tr>
<td>&gt; 2320</td>
<td>0.3164 / Re(^{0.25})</td>
<td>turbulent (Blasius)</td>
</tr>
</tbody>
</table>
### Interface

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>pa, pb</th>
<th>Both terminals of the hydraulic inertia.</th>
</tr>
</thead>
</table>

**Causality**

<table>
<thead>
<tr>
<th>Description</th>
<th>pa</th>
<th>fixed pressure out pa</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>pb</th>
<th>fixed pressure out pb</th>
</tr>
</thead>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>D</th>
<th>Line inner diameter [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
<td>Line length [m]</td>
</tr>
<tr>
<td></td>
<td>th</td>
<td>Wall thickness [m]</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>Modulus of elasticity [N/m²]</td>
</tr>
</tbody>
</table>

### Node

**Library**

Iconic Diagrams\Hydraulics\Components

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Electric).

**Description**

This node model represents a connection between two or more lines of an hydraulic circuit. The model has only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>p [any]</th>
<th>Any number of connections can be made.</th>
</tr>
</thead>
</table>
Cylinders

Basic Cylinders

Cylinder

Library
Iconic Diagrams\Hydraulics\Cylinders\Basic Cylinders

Use

Description

This is an ideal model of cylinder with no mass and no friction. The volume of the chambers is given by:

\[
V_a = V_{\text{dead}} + A_a \cdot (x + x_{\text{initial}})
\]

\[
V_b = V_{\text{dead}} + A_b \cdot (\text{stroke} - x - x_{\text{initial}})
\]

with \(A_a\) the piston area and \(A_b\) the effective area at the rod side. \(x\) is the piston position and \(V_{\text{dead}}\) the initial volume when piston position is zero. The piston areas \(A_a\) and \(A_b\) are related to the piston diameter \(dp\) and rod diameter \(dr\) by:

\[
A_a = \pi \cdot \frac{dp^2}{4}
\]

\[
A_b = \pi \cdot \frac{dp^2}{4} - \pi \cdot \frac{dr^2}{4}
\]

There is no restriction on the travel of the piston. Only a warning is given when the maximum stroke is exceeded or the piston position gets negative.

Interface

Ports | Description
--- | ---

stroke

Vdead

pa

pb

pm

dp

dr
11. Library

**Causality**
preferred pressure out pa
preferred force out pm

**Parameters**
- Vdead
  rest volume of oil in cylinder chamber when closed [N.s/m]
- stroke
  stroke length [m]
- x_initial
  starting position of piston [m]
- dp
  piston diameter [m]
- dr
  rod diameter [m]

**CylinderChamberA**

**Library**
Iconic Diagrams\Hydraulics\Cylinders\Basic Cylinders

**Use**

**Description**

This is an ideal model of a single acting cylinder with no mass and no friction. The volume of the chamber is given by:

\[ V = V_{dead} + A_a(x + x_{\text{initial}}) \]

with \( A_a \) the piston area, \( x \) the piston position and \( V_{dead} \) the initial volume when piston position is zero. The piston area \( A_a \) is related to the piston diameter \( dp \) by:
There is no restriction on the travel of the piston. Only a warning is given when the maximum stroke is exceeded or the piston position gets negative.

**Interface**

**Ports**
- **pa**: hydraulic port
- **pm**: translation port

**Causality**
- preferred pressure out **pa**
- preferred force out **pm**

**Parameters**
- **Vdead**: rest volume of oil in cylinder chamber when closed [N.s/m]
- **stroke**: stroke length [m]
- **x_initial**: starting position of piston [m]
- **dp**: piston diameter [m]

**CylinderChamberB**

**Library**
Iconic Diagrams\Hydraulics\Cylinders\Basic Cylinders

**Use**
- **Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics/Translational).
Description

This is an ideal model of a single acting cylinder with no mass and no friction. The volume of the chamber is given by:

\[ V = V_{\text{dead}} + A_a(x + x_{\text{initial}}) \]

with \( A_a \) the piston area, \( x \) the piston position and \( V_{\text{dead}} \) the initial volume when piston position is zero. The piston area \( A_a \) is related to the piston diameter \( dp \) by:

\[ A_a = \pi \cdot dp^2 / 4 \]

There is no restriction on the travel of the piston. Only a warning is given when the maximum stroke is exceeded or the piston position gets negative.

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pa )</td>
<td>hydraulic port</td>
</tr>
<tr>
<td>( pm )</td>
<td>translation port</td>
</tr>
</tbody>
</table>

Causality

preferred pressure out \( pa \)
preferred force out \( pm \)

Parameters

- \( V_{\text{dead}} \): rest volume of oil in cylinder chamber when closed [N.s/m]
- \( \text{stroke} \): stroke length [m]
- \( x_{\text{initial}} \): starting position of piston [m]
- \( dp \): piston diameter [m]
CylinderSpringReturn

Library
Iconic Diagrams\Hydraulics\Cylinders\Basic Cylinders

Use

Description

This is an ideal model of a single acting cylinder with no mass and no friction and a return spring to drive the cylinder back when there is no pressure in the chamber. The volume of the chamber is given by:

\[ V = V_{\text{dead}} + A_a(x + x_{\text{initial}}) \]

with \( A_a \) the piston area, \( x \) the piston position and \( V_{\text{dead}} \) the initial volume when piston position is zero. The piston area \( A_a \) is related to the piston diameter \( dp \) by:

\[ A_a = \pi * dp^2 / 4 \]

The driving force of the return spring is determined by two parameters: the force for piston position zero (\( F_{\text{spr\_min}} \)) and the force when the piston is at the other side (\( F_{\text{spr\_max}} \)). The spring constant (\( k_{\text{spr}} \)) and initial spring position (\( x_0 \)) are calculated out of these parameters by:

\[ k_{\text{spr}} = (F_{\text{spr\_max}} - F_{\text{spr\_min}})/\text{stroke} \]
\[ x_0 = -F_{\text{spr\_min}}/k_{\text{spr}} \]

There is no restriction on the travel of the piston. Only a warning is given when the maximum stroke is exceeded or the piston position gets negative.
**Interface**

**Ports**
- pa: hydraulic port
- pm: translation port

**Causality**
- preferred pressure out pa
- preferred force out pm

**Parameters**
- Vdead: rest volume of oil in cylinder chamber when closed [N.s/m]
- stroke: stroke length [m]
- x_initial: starting position of piston [m]
- dp: piston diameter [m]
- Fspr_min: minimum return spring force (at x = 0) [N]
- Fspr_max: maximum return spring force (at x = stroke) [N]

**CylinderDouble**

**Library**
Iconic Diagrams\Hydraulics\Cylinders

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics/Translational).

**Description-Default**
This model is the extended model of a double acting cylinder with mass, friction and end stops.
The volume of the chambers is given by:

\[ V_a = V_{\text{dead}} + A_a(x + x_{\text{initial}}) \]
\[ V_b = V_{\text{dead}} + A_b(\text{stroke} - x - x_{\text{initial}}) \]

with \( A_a \) the piston area and \( A_b \) the effective area at the rod side. \( x \) is the piston position and \( V_{\text{dead}} \) the initial volume when piston position is zero. The piston areas \( A_a \) and \( A_b \) are related to the piston diameter \( dp \) and rod diameter \( dr \) by:

\[ A_a = \pi \frac{dp^2}{4} \]
\[ A_b = \pi \frac{dp^2}{4} - \pi \frac{dr^2}{4} \]

The travel of the piston is restricted. At the cylinder heads two collision models prevent the piston from traveling any further. The friction between the piston and the cylinder walls is modeled by static and viscous friction.

**Description - Special_Use**

When two cylinders are used in parallel, the chambers are connected and the resulting model will have algebraic loops. To prevent this, the special_use implementation can be used. In this implementation, the volumes of the cylinder are described with a Parasitic Volume.
CylinderSingleSpringReturn

**Library**
Iconic Diagrams\Hydraulics\Cylinders

**Use**

**Description**

This is the extended model of a single acting cylinder with mass, friction, end stops and a return spring to drive the cylinder back when there is no pressure in the chamber.
The volume of the chamber is given by:

\[ V = V_{dead} + A_a(x + x_{\text{initial}}) \]

with \( A_a \) the piston area, \( x \) the piston position and \( V_{dead} \) the initial volume when piston position is zero. The piston area \( A_a \) is related to the piston diameter \( dp \) by:

\[ A_a = \pi \frac{dp^2}{4} \]

The driving force of the return spring is determined by two parameters: the force for piston position zero \( (Fspr_{\text{min}}) \) and the force when the piston is at the other side \( (Fspr_{\text{max}}) \). The spring constant \( (kspr) \) and initial spring position \( (x_0) \) are calculated out of these parameters by:

\[ kspr = \frac{(Fspr_{\text{max}} - Fspr_{\text{min}})}{\text{stroke}} \]
\[ x_0 = -\frac{Fspr_{\text{min}}}{kspr} \]

The travel of the piston is restricted. At the cylinder heads two collision models prevent the piston from traveling any further. The friction between the piston and the cylinder walls is modeled by static and viscous friction.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa</td>
<td>hydraulic port</td>
</tr>
<tr>
<td>p_barrel, p_rod</td>
<td>translation ports</td>
</tr>
</tbody>
</table>

**Causality**
preferred pressure out pa
preferred force out pm

**Parameters**

- **Vdead**: rest volume of oil in cylinder chamber when closed [m$^3$]
- **stroke**: stroke length [m]
- **x_initial**: starting position of piston [m]
- **dp**: piston diameter [m]
- **m_barrel**: barrel mass [kg]
- **m_rod**: rod and piston mass [kg]
- **kc**: stiffness during collision with cylinder heads [N/m]
- **dc**: damping during collision with cylinder heads [N.s/m]
- **Fc**: static friction [N]
- **dv**: viscous friction coefficient [N.s/m]
- **slope**: steepness of the static friction curve [\]
- **Fspr_min**: minimum return spring force (at x = 0)
- **Fspr_max**: maximum return spring force (at x = stroke)

**Note**

When the cylinder piston collides with the cylinder heads, simulation may get very slow or even become unstable. In these cases you are advised to use the BDF-method with default settings. Try to change the absolute integration error until a stable simulation is obtained!

**CylinderSingle**

**Library**

- Iconic Diagrams\Hydraulics\Cylinders

**Use**

- **Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics/Translational).

**Description**

![Cylinder Diagram](image)

This is the extended model of a single acting cylinder with mass, friction and end stops.
The volume of the chamber is given by:

\[ V = V_{\text{dead}} + A_a \cdot (x + x_{\text{initial}}) \]

with \( A_a \) the piston area, \( x \) the piston position and \( V_{\text{dead}} \) the initial volume when piston position is zero. The piston area \( A_a \) is related to the piston diameter \( dp \) by:

\[ A_a = \pi \cdot dp^2 / 4 \]

The travel of the piston is restricted. At the cylinder heads two collision models prevent the piston from traveling any further. The friction between the piston and the cylinder walls is modeled by static and viscous friction.

**Interface**

**Ports**

- \( \text{pa} \) hydraulic port
- \( \text{p_barrel, p_rod} \) translation ports

**Causality**

- preferred pressure out \( \text{pa} \)
- preferred force out \( \text{pm} \)

**Parameters**

- \( V_{\text{dead}} \) rest volume of oil in cylinder chamber when closed [m³]
- \( \text{stroke} \) stroke length [m]
- \( x_{\text{initial}} \) starting position of piston [m]
dp  
  piston diameter [m]

m_barrel  
  barrel mass [kg]

m_rod  
  rod and piston mass [kg]

kc  
  stiffness during collision with cylinder heads [N/m]

dc  
  damping during collision with cylinder heads [N.s/m]

Fc  
  static friction [N]

dv  
  viscous friction coefficient [N.s/m]

slope  
  steepness of the static friction curve []

**Note**

When a the cylinder piston collides with the cylinder heads, simulation may get very slow or even become unstable. In these cases you are advised to use the BDF-method with default settings. Try to change the absolute integration error until a stable simulation is obtained!

**Fluids**

**FluidProperties**

The fluid properties model, contains the properties of hydraulic fluids with the following parameters:

- kinematic viscosity {m2/s}
- density {kg/m3}
- bulk modulus {Pa}
- vapour pressure {Pa}

You can drag and drop the FluidProperties model in the Editor and use all these parameters automatically in all other hydraulic components of your model.

**Fluids**

Every fluid is stored as an implementation of the FluidProperties model. When you drag and drop the FluidProperties model in the Editor, you will be asked which implementation you want to use. Currently the following fluids are supported:

Default
Diesel
Gasoline
ISO VG 100
ISO VG 150
ISO VG 22
ISO VG 32
ISO VG 46
ISO VG 68
Kerosene
SAE 10W-30
SAE 10W-40
SAE 15W-40
SAE 75W-140
Sea Water
Skydrol 500B-4
VW13
Water

**Default Fluid**
The default fluid is meant for use in hydraulic cylinders and hydraulic motors for (heavy) machines. The properties of the default fluid were used in 20-sim 4.8 and previous versions:

- \( \text{kin\_viscosity} = 2.7e-5 \ \text{m}^2/\text{s}; // \text{kinematic viscosity} \)
- \( \rho = 865.0 \ \text{kg/m}^3; // \text{density} \)
- \( B = 1.6e9 \ \text{Pa}; // \text{effective bulk modulus} \)
- \( p_{\text{vapour}} = -99900.0 \ \text{Pa}; // \text{vapour pressure} \)

**Custom Fluid**
You can change the parameters of a fluid in the Parameters Editor.

**Multiple Fluids**
The fluid properties are valid at the level where the FluidProperties model is inserted. If you have multiple hydraulic circuits and you want to use multiple fluids, you have to put every circuit in a submodel and insert FluidProperties model into that submodel.

**Parameters**

**Kinematic Viscosity (kin\_viscosity)**
The kinematic viscosity is defined in SI units: m^2/s. It is used in the line model to calculate the pressure drop over a hydraulic line because of friction.

**Density (rho)**
The density of a fluid is defined in SI units: kg/m^3. It is used to derive the mass of a fluid in the hydraulic inertia model and line models and for the pressure drop over an orifice in the orifice and valve models.

The density of a fluid is defined in SI units: kg/m^3.

**Bulk modulus (B)**
No liquid is fully incompressible. The compliance characteristics of the oil in a hydraulic system is a vital parameters affecting the response. The effect of compressibility is incorporated by entering the bulk modulus of the fluid:

\[
dp = -B*dV/V
\]

Here \( dp \) is the pressure, \( V \) the volume and \( B \) the bulk modulus. For small pressure variations the compressibility effect my be rewritten as:

\[
p = B/V*\text{int(flow)}
\]

The bulk modulus is a very uncertain parameter. It depends on the percentage of air dissolved in the fluid, the pressure and the temperature. In most textbooks a values of 1.5 to 1.75 [GPa] is used. 20-sim uses a default value of 1.6 [GPa]. If fluid should be simulated at elevated temperatures or with a high percentage or air dissolved, you should use a smaller value for the bulk modulus.
**Vapour Pressure (p\_vapour)**

The 20-sim hydraulics library uses the common definition of pressure in Pa:

\[ 1 \text{ Pa} = 1 \text{ N/m}^2 = 1e-5 \text{ bar} \]

The air pressure at sea level is taken as the zero value:

\[ 0 \text{ Pa} = \text{air pressure} \]

Consequently the pressure for a hydraulic fluid that starts to vaporize is negative. In 20-sim the default value of the vapour pressure is:

\[ p\_vapour = -0.999e5 \text{ Pa} \]

The vapour pressure is the minimum pressure. Some models have a safeguard on the pressure to prevent it to become smaller. You can change the value of the vapour pressure but take care that always a value is chosen that is smaller than zero. Otherwise some of the models will not work correctly.

**Motors**

**Basic Motors**

**DisplacementMotor**

**Library**

Iconic Diagrams\Hydraulics\Pumps\Basic Pumps

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**

This model describes an ideal motor with an axial speed that is proportional to the input flow rate:

\[ pa.\phi = pb.\phi = i \times p\_rot.\omega; \]
\[ i = D / (2 \times \pi); \]

The torque is equal to:

\[ p.T = i \times (pa.p - pb.p); \]

If the port pressure is smaller than the vapour pressure \( p < p\_vapour \), the flow is zero. If the port pressure becomes larger than the vapour pressure the flow gradually grows to its normal value, until the atmospheric pressure \( p = 0 \) is reached.
**Interface**

**Ports**
- pa: inlet port (hydraulic)
- pb: outlet port (hydraulic)
- p_rot: axis (rotation)

**Description**
- pa.phi = pb.phi = i * p_rot.omega;
- i = D * c / (2*pi);

**Causality**
- fixed volume flow
  - out pa
  - fixed volume flow
  - out pb
  - fixed torque out
  - p_rot

**Parameters**
- D: displacement per revolution [m³]

### VariableDisplacementMotor

**Library**
Iconic Diagrams\Hydraulics\Pumps\Basic Pumps

**Use**
- Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**
This model describes an ideal motor with an axial speed that is proportional to the input flow rate:

\[
p_a.phi = p_b.phi = i \times p_rot.omega; \quad i = D \times c / (2\pi);\]

The torque is equal to:

\[
p.T = i(\text{pa.p} - \text{pb.p});\]

The displacement is controllable by the input signal \(c\). For a positive rotation of the driving axis the flow is:

- \(c >= 1\): maximum flow from port 1 to port 2
- \(c = 0\): zero flow
- \(c <= -1\): maximum flow from port 2 to port 1

If the port pressure is smaller than the vapour pressure (\(p < p_{vapour}\)), the flow is zero. If the port pressure becomes larger than the vapour pressure the flow gradually grows to its normal value, until the atmospheric pressure (\(p = 0\)) is reached.
11. Library

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa</td>
<td>inlet port (hydraulic)</td>
</tr>
<tr>
<td>pb</td>
<td>outlet port (hydraulic)</td>
</tr>
<tr>
<td>p_rot</td>
<td>axis (rotation)</td>
</tr>
</tbody>
</table>

**Causality**

fixed volume flow

out pa

fixed volume flow

out pb

fixed torque out

p_rot

**Input**

c relative displacement

**Parameters**

D displacement per revolution [m³]

**DisplacementMotor-Leakage**

**Library**

Iconic Diagrams\Hydraulics\Pumps

**Use**

Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**
This model describes an motor with internal leakage and an axial speed that is proportional to the input flow rate:

\[
\text{pa}.\text{phi} = \text{pb}.\text{phi} = i \times \text{p_rot}.\omega;
\]
\[
i = D / (2\pi);
\]

The actual flows at the inlet and outlet port may be slightly different because of the flow into the lumped volumes and the leakage flows. The leakage flows are modeled by laminar resistances. The torque is equal to:

\[
\text{p}.\text{T} = i(\text{pa}.\text{p} - \text{pb}.\text{p});
\]

If the port pressure is smaller than the vapour pressure (p < p_vapour), the flow is zero.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa</td>
<td>inlet port (hydraulic)</td>
</tr>
<tr>
<td>pb</td>
<td>outlet port (hydraulic)</td>
</tr>
<tr>
<td>p_rot</td>
<td>axis (rotation)</td>
</tr>
</tbody>
</table>

**Causality**

- preferred pressure out pa
- preferred pressure out pb
- preferred angular velocity out
- p_rot

**Parameters**

- **D** Displacement per revolution [m3]
- **J** Rotational inertia [kg.m2]
- **d_m** Viscous (rotational) friction [N.m.s/rad]
- **p_static** Start pressure, acts as Coulomb friction, set to 2% of max pressure if unknown [Pa]
- **G_int** Internal laminar leakage conductance, set to 1e-13 if unknown [m3/s.Pa]
- **V** Dead volume of the pump at each port [m3]
VariableDisplacementMotor-Leakage

Library
Iconic Diagrams\Hydraulics\Pumps

Use

Description
This model describes an motor with internal leakage and an axial speed that is proportional to input flow rate:

\[ pa.phi = pb.phi = i * p_rot.omega; \]
\[ i = D / (2*pi); \]

The actual flows at the inlet and outlet port may be slightly different because of the flow into the lumped volumes and the leakage flows. The leakage flows are modeled by laminar resistances. The torque is equal to:

\[ p.T = i*(pa.p - pb.p); \]

The displacement is controllable by the input signal \( c \). For a positive rotation of the driving axis the flow is:

\[ c >= 1 \quad \text{maximum flow from port 1 to port 2} \]
\[ c = 0 \quad \text{zero flow} \]
\[ c <= -1 \quad \text{maximum flow from port 2 to port 1} \]

If the port pressure is smaller than the vapour pressure (\( p < p_{\text{vapour}} \)), the flow is zero.
### Interface

#### Ports

<table>
<thead>
<tr>
<th>Port</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa</td>
<td>inlet port (hydraulic)</td>
</tr>
<tr>
<td>pb</td>
<td>outlet port (hydraulic)</td>
</tr>
<tr>
<td>p_rot</td>
<td>axis (rotation)</td>
</tr>
</tbody>
</table>

#### Causality

- preferred pressure out pa
- preferred pressure out pa
- preferred angular velocity out p_rot

#### Inputs

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>relative displacement</td>
</tr>
</tbody>
</table>

#### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Displacement per revolution [m(^3)]</td>
</tr>
<tr>
<td>J</td>
<td>Rotational inertia [kg.m(^2)]</td>
</tr>
<tr>
<td>d_m</td>
<td>Viscous (rotational) friction [N.m.s/rad]</td>
</tr>
<tr>
<td>p_static</td>
<td>start pressure, acts as Coulomb friction, set to 2% of max pressure if unknown [Pa]</td>
</tr>
<tr>
<td>G_int</td>
<td>Conductance of laminar resistance [m(^3)/s.Pa]</td>
</tr>
<tr>
<td>V</td>
<td>Dead volume of the pump at each port [m(^3)]</td>
</tr>
</tbody>
</table>

### Pumps

**Basic Pumps**

**DisplacementPump**

#### Library

Iconic Diagrams\Hydraulics\Pumps\Basic Pumps

#### Use

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

#### Description

This model describes an ideal pump with a displacement that is proportional to the speed of the input axis:

\[
p_a \phi = p_b \phi = i \times p_{_rot} \omega; \\
i = D / (2 \pi);
\]
The torque is equal to:

\[ p.T = i*(pa.p - pb.p); \]

If the inlet pressure is smaller than the vapour pressure \( p < p_{\text{vapour}} \), the flow is zero.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa</td>
<td>inlet port (hydraulic)</td>
</tr>
<tr>
<td>pb</td>
<td>outlet port (hydraulic)</td>
</tr>
<tr>
<td>p_rot</td>
<td>axis (rotation)</td>
</tr>
</tbody>
</table>

**Causality**

fixed volume flow
out pa
fixed volume flow
out pb
preferred angular velocity out p_rot

**Parameters**

D displacement per revolution \([m^3]\)

**FlowSource**

**Library**
Iconic Diagrams\Hydraulics\Pumps\Basic Pumps

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**
This model represents an ideal flow source with a fixed flow given by the parameter phi:

\[ p.phi = phi; \]

The model has no leakage.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

fixed volume flow
out p

**Parameters**
ModulatedFlowSource

Library
Iconic Diagrams\Hydraulics\Pumps\Basic Pumps

Use

Description
This model represents an ideal flow source with a variable flow that is given by input signal \( \phi \):

\[
p.\phi = \phi;
\]

The model has no leakage.

Interface

<table>
<thead>
<tr>
<th>Ports</th>
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</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td></td>
</tr>
</tbody>
</table>

Causality
fixed volume flow
out p

Input

| phi   | Volume flow [m3/s] |

ModulatedPressureSource

Library
Iconic Diagrams\Hydraulics\Pumps\Basic Pumps

Use

Description
This model represents an ideal pressure source with a fixed pressure given by the parameter pressure:

\[
p.p = \text{pressure};
\]

The model has no leakage.
Interface

Ports  Description
p

Causality
fixed pressure out

Input
pressure  Pressure [Pa]

PressureSource

Library
Iconic Diagrams\Hydraulics\Pumps\Basic Pumps

Use

Description
This model represents an ideal pressure source with a fixed pressure given by the parameter pressure:

\[ p.p = \text{pressure}; \]

The model has no leakage.

Interface

Ports  Description
p

Causality
fixed pressure out

Parameters
p  Pressure [Pa]

VariableDisplacementPump

Library
Iconic Diagrams\Hydraulics\Pumps\Basic Pumps

Use

Description
This model describes an ideal pump with a displacement that is proportional to the speed of the input axis:
\[ \text{pa} \cdot \phi = \text{pb} \cdot \phi = i \cdot \text{p_rot} \cdot \omega; \]
\[ i = \frac{D \cdot c}{(2 \pi)}; \]

The torque is equal to:
\[ p \cdot T = i \cdot (\text{pb} \cdot p - \text{pa} \cdot p); \]

The displacement is controllable by the input signal \( c \). For a positive rotation of the driving axis the flow is:
\[
\begin{align*}
    c \geq 1 & \quad \text{maximum flow from port 1 to port 2} \\
    c = 0 & \quad \text{zero flow} \\
    c \leq -1 & \quad \text{maximum flow from port 2 to port 1}
\end{align*}
\]

If the port pressure is smaller than the vapour pressure (\( p < p_{\text{vapour}} \)), the flow is zero.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa</td>
<td>inlet port (hydraulic)</td>
</tr>
<tr>
<td>pb</td>
<td>outlet port (hydraulic)</td>
</tr>
<tr>
<td>p_rot</td>
<td>axis (rotation)</td>
</tr>
</tbody>
</table>

**Causality**

fixed volume flow
out pa
fixed volume flow
out pb
fixed torque out
p_rot

**Input**

| c       | relative displacement   |

**Parameters**

| D       | displacement per revolution [m3] |

**CentrifugalPump**

**Library**

Iconic Diagrams\Hydraulics\Pumps

**Use**

Description

A centrifugal pump converts the input power of a rotating shaft into kinetic energy of a the liquid by accelerating the liquid through an impeller.

The pump is characterized by two curves:

1. The head \( H \) as function of the volume flow at a preset speed.
2. The efficiency \( n \) of the pump as a function of the fluid flow at a present speed. The efficiency is defined as the flow output power divided by rotational input power.

The pump curves are approximated by two second order polynomials:

\[
H = ha*q^2 + hb*q + hc
\]

\[
n = na*q^2 + nb*q + nc
\]

To fit the polynomial curves, the heads and efficiencies have to be specified at three
different flows. The first flow ($q0$) is zero. The other two flows ($q1$ and $q2$) can be chosen arbitrary.

Note: some pump flows extrapolate the efficiency curves to zero at zero fluid flow. This would mean that at a zero fluid flow no power can be transmitted and the pump can never start! Therefore in this model always use an efficiency that is non-zero at zero flow.

Some pump characteristics give multiple input speeds. This model automatically takes into account for varying input speeds of the input axis by transforming the pump curve using the affinity rules.

\[
H_a = H_b \left(\frac{v_b}{v_a}\right)^2 \\
Q_a = Q_b \left(\frac{v_b}{v_a}\right)
\]

Some pump characteristics give the efficiencies as regions. You have then have to estimate the efficiencies at the chosen flows $q0$, $q1$ and $q2$.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_t</td>
<td>inlet port, tank (hydraulic)</td>
</tr>
<tr>
<td>p_a</td>
<td>outlet port (hydraulic)</td>
</tr>
<tr>
<td>p_rot</td>
<td>axis (rotation)</td>
</tr>
</tbody>
</table>

**Causality**

velocity out p_rot

**Input**

phi Volume flow [m3/s]
Parameters

- q1: flow 1 (choose an arbitrary point between zero and nominal)
- q2: flow 2 (nominal flow)
- H0: head at zero flow
- H1: head at flow 1
- H2: head at flow 2 (nominal flow)
- n0: efficiency (0 < n < 1) at zero flow
- n1: efficiency (0 < n < 1) at flow 1
- n2: efficiency (0 < n < 1) at flow 2 (nominal flow)
- v_nom: nominal speed of the pump

Description

This model describes a pump with internal and external leakage and a displacement that is proportional to the speed of the input axis:

\[ i = \frac{D \cdot c}{2\pi}; \]
\[ pa.phi = pb.phi = i \cdot p\_rot.omega; \]
The actual flows at the inlet and outlet port may be slightly different because of the flow into the lumped volumes and the leakage flows. The leakage flows are modeled by laminar resistances. The torque of the pump is equal to:

\[ p.T = i*(p.a.p - p.b.p); \]

If the inlet pressure is smaller than the vapour pressure \( p < p_{\text{vapour}} \), the flow is zero. If the inlet pressure becomes larger than the vapour pressure the flow gradually grows to its normal value, until the atmospheric pressure \( p = 0 \) is reached.

**Interface**

<table>
<thead>
<tr>
<th><strong>Ports</strong></th>
<th><strong>Description</strong></th>
</tr>
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<tbody>
<tr>
<td>pa</td>
<td>inlet port (hydraulic)</td>
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<td>outlet port (hydraulic)</td>
</tr>
<tr>
<td>p_rot</td>
<td>axis (rotation)</td>
</tr>
</tbody>
</table>

**Causality**

preferred pressure out pa  
preferred pressure out pa  
preferred angular velocity out  
p_rot

**Parameters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Displacement per revolution ([m^3])</td>
</tr>
<tr>
<td>J</td>
<td>Rotational inertia ([kg.m^2])</td>
</tr>
<tr>
<td>d_m</td>
<td>Viscous (rotational) friction ([N.m.s/rad])</td>
</tr>
<tr>
<td>p_static</td>
<td>Start pressure, acts as Coulomb friction, set to 2% of max pressure if unknown ([\text{Pa}])</td>
</tr>
<tr>
<td>G_int</td>
<td>Internal laminar leakage conductance, set to 1e-13 if unknown ([m^3/s.Pa])</td>
</tr>
<tr>
<td>V</td>
<td>Dead volume of the pump at each port ([m^3])</td>
</tr>
</tbody>
</table>
FlowSource-Leakage

Library
Iconic Diagrams\Hydraulics\Pumps

Use

Description
This model represents a flow source with a fixed flow and leakage. The flow is given by the parameter \( \phi \):

\[
p \cdot \phi = \phi - G \cdot p
\]

At the output port of the flow source a parasitic volume is mounted. A parasitic volume is a tiny volume that can be added to elements to make them more easy to simulate.

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>fixed volume flow out</td>
</tr>
</tbody>
</table>

Input
phi Volume flow [m3/s]

Parameters
FlowSource\phi Volume flow [m3/s]
TankRes\p_nom Nominal pressure
TankRes\p_tank Tank pressure [Pa]
TankRes\Q_leak Leakage flow at nominal pressure [m3/s]
V\V Volume of oil under pressure [m3] (hidden)
V\p_initial The starting pressure of the volume [Pa] (hidden)
ModulatedFlowSource-Leakage

Library
Iconic Diagrams\Hydraulics\Pumps

Use

Description
This model represents a flow source with a variable flow and leakage. The variable flow is given by an input signal:

\[ p.phi = phi - G*p.p; \]

At the output port of the flow source a parasitic volume is mounted. A parasitic volume is a tiny volume that can be added to elements to make them more easy to simulate.

Interface

Ports

\( p \)

Causality
fixed volume flow out

\( p \)

Input

\( \phi \)

Description
Volume flow [m3/s]

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TankRes\p_nom</td>
<td>Nominal pressure</td>
</tr>
<tr>
<td>TankRes\p_tank</td>
<td>Tank pressure [Pa]</td>
</tr>
<tr>
<td>TankRes\Q_leak</td>
<td>Leakage flow at nominal pressure [m3/s]</td>
</tr>
<tr>
<td>V\V</td>
<td>Volume of oil under pressure [m3] (hidden)</td>
</tr>
<tr>
<td>V\p_initial</td>
<td>The starting pressure of the volume [Pa] (hidden)</td>
</tr>
</tbody>
</table>


VariableDisplacementPump-Leakage

**Library**
Iconic Diagrams\Hydraulics\Pumps

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Hydraulics).

**Description**

This model describes a pump with internal and external leakage and a displacement that is proportional to the speed of the input axis:

\[
i = \frac{D \cdot c}{2\pi};
\]

\[
pa.phi = pb.phi = i \cdot p_rot.omega;
\]

The actual flows at the inlet and outlet port may be slightly different because of the flow into the lumped volumes and the leakage flows. The leakage flows are modeled by laminar resistances. The torque of the pump is equal to:

\[
p.T = i*(pa.p - pb.p);
\]

The displacement is controllable by the input signal \(c\). For a positive rotation of the driving axis the flow is:

\[c \geq 1 \quad \text{maximum flow from port 1 to port 2}\]
\[ c = 0 \quad \text{zero flow} \]
\[ c \leq -1 \quad \text{maximum flow from port 2 to port 1} \]

If the port pressure is smaller than the vapour pressure \((p < p_{\text{vapour}})\), the flow is zero. If the port pressure becomes larger than the vapour pressure the flow gradually grows to its normal value, until the atmospheric pressure \((p = 0)\) is reached.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
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<tbody>
<tr>
<td>pa</td>
<td>inlet port (hydraulic)</td>
</tr>
<tr>
<td>pb</td>
<td>outlet port (hydraulic)</td>
</tr>
<tr>
<td>p_rot</td>
<td>axis (rotation)</td>
</tr>
</tbody>
</table>

**Causality**

preferred pressure out pa
preferred pressure out pa
preferred angular velocity out p_rot

**Input**

| c | relative displacement |

**Parameters**

<table>
<thead>
<tr>
<th>D</th>
<th>Displacement per revolution [m3]</th>
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<td>d_m</td>
<td>Viscous (rotational) friction [N.m.s/ rad]</td>
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<td>p_static</td>
<td>Start pressure, acts as Coulomb friction, set to 2% of max pressure if unknown [Pa]</td>
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<tr>
<td>G_int</td>
<td>Internal laminar leakage conductance, set to 1e-13 if unknown [m3/s.Pa]</td>
</tr>
<tr>
<td>V</td>
<td>Dead volume of the pump at each port [m3]</td>
</tr>
</tbody>
</table>
Restrictions

LaminarResistance

Library
Iconic Diagrams\Hydraulics\Restrictions

Use

Description
This model describes the laminar flow through a component:

\[ pa.phi = pb.phi = G \times (pa.p - pb.p) \]

with the conductance calculated out of the flow \( Q_{nom} \) at a nominal pressure drop \( p_{nom} \).

\[ G = \frac{Q_{nom}}{p_{nom}} \]

The pressure at both ports has a lower limit which is equal to the vapour pressure. Therefore the actual equations used in this component are:

\[ p1\_lim = \text{if } pa.p < p_{vapour} \text{ then } p_{vapour} \text{ else } pa.p \text{ end; } \]
\[ p2\_lim = \text{if } pb.p < p_{vapour} \text{ then } p_{vapour} \text{ else } pb.p \text{ end; } \]
\[ dp = p1\_lim - p2\_lim; \]
\[ pa.phi = G \times dp; \]
\[ pb.phi = pa.phi; \]

There is no check on the validity of laminar flow in this component!

Interface

Ports
pa, pb

Description
Both terminals of the hydraulic component.

Causality
fixed volume flow
out pa
fixed volume flow
out pb

Parameters
p_nom
nominal pressure drop [Pa]

Q_nom
flow at nominal pressure drop \{m3/s\}
**Orifice**

**Library**
Iconic Diagrams\Hydraulics\Restrictions

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**
This model describes the laminar/turbulent flow through an orifice if no cavitation occurs. The flow depends on the pressure difference:

\[
\begin{align*}
dp &= p_a - p_b \\
\phi &= \text{sign}(dp) \times C_d \times A \times \sqrt{\frac{2}{\rho}} \times \text{abs}(dp) + G_{\text{leak}} \times dp
\end{align*}
\]

Here \( C_d \) the discharge coefficient, \( A \) the orifice area, \( \rho \) the fluid density, \( G_{\text{leak}} \) the conductance of laminar flow and \( dp \) the pressure difference. The discharge coefficient depends on the shape of the orifice and is generally not listed in data sheets. Therefore we will write the turbulent flow with nominal parameters. Given a nominal pressure drop \( p_{\text{nom}} \) we find a nominal flow:

\[
Q_{\text{nom}} = C_d \times A \times \sqrt{\frac{2}{\rho}} \times p_{\text{nom}}
\]

we can use this to rewrite the flow equation as:

\[
\phi = Q_{\text{nom}} \times \sqrt{\frac{dp}{p_{\text{nom}}}}
\]

Similar we can write the laminar leakage flow as

\[
Q_{\text{leak}} = G \times p_{\text{nom}}
\]

we can use this to rewrite the complete orifice equation as:
\[
\phi = Q_{\text{nom}} \times \sqrt{\frac{dp}{p_{\text{nom}}}} + \frac{(Q_{\text{leak}}/p_{\text{nom}}) \times dp}{p_{\text{nom}}}
\]

The pressure at both ports has a lower limit that is equal to the vapour pressure. Therefore the actual equations used in this component are:

\[
\begin{align*}
    p1_{\text{lim}} &= \text{if } pa.p < p_{\text{vapour}} \text{ then } p_{\text{vapour}} \text{ else } pa.p \text{ end}; \\
    p2_{\text{lim}} &= \text{if } pb.p < p_{\text{vapour}} \text{ then } p_{\text{vapour}} \text{ else } pb.p \text{ end}; \\
    dp &= p1_{\text{lim}} - p2_{\text{lim}};
\end{align*}
\]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa, pb</td>
<td>Both terminals of the hydraulic component.</td>
</tr>
</tbody>
</table>

**Causality**

fixed volume flow

out pa

fixed volume flow

out pb

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_{\text{nom}}</td>
<td>Turbulent flow at nominal pressure drop [m3/s]</td>
</tr>
<tr>
<td>Q_{\text{leak}}</td>
<td>Leakage flow at nominal pressure drop, make 1e-8 if unknown [m3/s]</td>
</tr>
<tr>
<td>p_{\text{nom}}</td>
<td>Nominal pressure [Pa].</td>
</tr>
</tbody>
</table>
VariableLaminarResistance

Library
Iconic Diagrams\Hydraulics\Restrictions

Use

Description
This model describes the laminar flow through a component:

\[ \text{pa} \phi = \text{pb} \phi = G \times (\text{pa}.p - \text{pb}.p); \]

The variable conductance G is given by an input signal. The pressure at both ports has a lower limit that is equal to the vapour pressure. Therefore the actual equations used in this component are:

\[
\begin{align*}
\text{p1}_\text{lim} &= \text{if } \text{pa}.p < \text{p}_\text{vapour} \text{ then } \text{p}_\text{vapour} \text{ else } \text{pa}.p \text{ end;} \\
\text{p2}_\text{lim} &= \text{if } \text{pb}.p < \text{p}_\text{vapour} \text{ then } \text{p}_\text{vapour} \text{ else } \text{pb}.p \text{ end;} \\
\text{dp} &= \text{p1}_\text{lim} - \text{p2}_\text{lim}; \\
\text{pa}.\phi &= G \times \text{dp}; \\
\text{pb}.\phi &= \text{pa}.\phi;
\end{align*}
\]

There is no check on the validity of laminar flow in this component!

Interface

Ports
pa, pb

Description
Both terminals of the hydraulic component.

Causality
fixed volume flow
out pa
fixed volume flow
out pb

Input
G

Conductance of laminar resistance [m3/s.Pa], G >= 0.

VariableOrifice

Library
Iconic Diagrams\Hydraulics\Restrictions

Use

Description
This model describes the laminar/turbulent flow through an orifice if no cavitation occurs. The flow depends on the pressure difference:
\[ dp = pa.p - pb.p; \]
\[ \phi = \text{sign}(dp) \times Cd \times sp \times A \times \sqrt{\frac{2}{\rho} \times \text{abs}(dp)} + G_{\text{Leak}} \times dp; \]

Here \( Cd \) the discharge coefficient, \( sp \) the orifice opening, \( A \) the orifice area, \( \rho \) the fluid density, \( G_{\text{Leak}} \) the conductance of laminar flow and \( dp \) the pressure difference. The discharge coefficient depends on the shape of the orifice and is generally not listed in data sheets. Therefore we will write the turbulent flow with nominal parameters. Given a nominal pressure drop \( p_{\text{nom}} \) we find a nominal flow:

\[ Q_{\text{nom}} = Cd \times A \times \sqrt{\frac{2}{\rho} \times p_{\text{nom}}} \]

we can use this to rewrite the flow equation as:

\[ \phi = sp \times Q_{\text{nom}} \times \sqrt{\frac{dp}{p_{\text{nom}}}} \]

Similar we can write the laminar leakage flow as

\[ Q_{\text{leak}} = G \times p_{\text{nom}} \]

we can use this to rewrite the complete orifice equation as:

\[ \phi = sp \times Q_{\text{nom}} \times \sqrt{\frac{dp}{p_{\text{nom}}}} + \left( \frac{Q_{\text{leak}}}{p_{\text{nom}}} \right) \times dp \]

The orifice opening is determined with the input signal \( sp \) which can vary between 0 (orifice closed) to 1 (orifice open).

The pressure at both ports has a lower limit that is equal to the vapour pressure. Therefore the actual equations used in this component are:
\[
p1\_lim = \text{if } pa.p < p\_vapour \text{ then } p\_vapour \text{ else } pa.p \text{ end};
\]
\[
p2\_lim = \text{if } pb.p < p\_vapour \text{ then } p\_vapour \text{ else } pb.p \text{ end};
\]
\[
dp = p1\_lim - p2\_lim;
\]

**Interface**

<table>
<thead>
<tr>
<th><strong>Ports</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>pa, pb</td>
<td>Both terminals of the hydraulic component.</td>
</tr>
</tbody>
</table>

**Causality**

fixed volume flow
out pa
fixed volume flow
out pb

**Input**

| sp       | orifice opening, sp <= 0 -> closed, sp >= 1 -> open. |

**Parameters**

<table>
<thead>
<tr>
<th>Q_nom</th>
<th>Turbulent flow at nominal pressure drop [m3/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_leak</td>
<td>Leakage flow at nominal pressure drop, make 1e-8 if unknown [m3/s]</td>
</tr>
<tr>
<td>p_nom</td>
<td>Nominal pressure [Pa].</td>
</tr>
</tbody>
</table>

**Sensors**

**DifferentialPressure**

**Library**

Iconic Diagrams\Hydraulics\Sensors

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**

This model gives the measured pressure drop between two ports (plus and min) as an output signal:

\[
\text{pressure} = p\_plus.p - p\_min.p;
\]
\[
p\_plus.phi = p\_min.phi = 0;
\]

The model has no leakage.

**Interface**

<table>
<thead>
<tr>
<th><strong>Ports</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>p_plus</td>
<td>Both pressure terminals of the pressure sensor</td>
</tr>
<tr>
<td>p_min</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**
fixed volume flow
out p_plus
fixed volume flow
out p_min

**Output**
pressure Pressure drop between the two terminals (plus and min) [Pa]

**FlowSensor**

**Library**
Iconic Diagrams\Hydraulics\Sensors

**Use**

**Description**
This model gives the measured flow as an output signal. The port p of the model has separate high and low terminals. The equations are:

\[
\begin{align*}
    p,\phi & = p_{\text{high}},\phi = p_{\text{low}},\phi; \\
    p,\rho & = p_{\text{high}},\rho - p_{\text{low}},\rho; \\
    p,\rho & = 0; \\
    \phi & = p,\phi;
\end{align*}
\]

The model has no leakage.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**
fixed volume flow
out

**Output**
phi Volume flow [m3/s]
HeadSensor

Library
Iconic Diagrams\Hydraulics\Sensors

Use

Description
This sensor gives the pressure in head:

\[ H = \frac{p}{\rho \times g} \]

with \( \rho \) the density of the fluid and \( g \) the specific gravity. The head is the rise of fluid in meters if an open tube would be connected. The figure below shows an example for water at 1 bar and 20 degrees (\( \rho = 998 \text{ kg/m}^3 \)) giving a head of 10.2 m.

Interface

Ports  Description
\( p \)

Causality
indifferent

PowerSensor

Library
Iconic Diagrams\Hydraulics\Sensors

Use

Description
This model gives the power that is transferred over a hydraulic line:

\[
\begin{align*}
  p_{\text{high}}.p &= p_{\text{low}}.p; \\
  p_{\text{high}}.\phi &= p_{\text{low}}.\phi; \\
  P &= p_{\text{high}}.\phi \times p_{\text{high}}.p;
\end{align*}
\]

The model has no leakage.

Interface

Ports  Description
\( p \)
**Causality**
indifferent

**Output**
P Power [W].

**PressureSensor**

**Library**
Iconic Diagrams\Hydraulics\Sensors

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**
This model gives the measured pressure as an output signal:

\[
\text{pressure} = p.p; \\
p.phi = 0;
\]

The model has no leakage.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p Pressure terminals of the pressure sensor.</td>
</tr>
</tbody>
</table>

**Causality**
fixed volume flow

**out p**

**Output**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure Pressure [Pa].</td>
</tr>
</tbody>
</table>

**Valves**

**Basic Valves**

**CheckValve**

**Library**
Iconic Diagrams\Hydraulics\Valves\Basic Valves

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).
Description
This model describes a spring-loaded check valve. The resistance depends on the pressure difference:

\[\begin{align*}
\text{dp} < \text{pclosed} & \Rightarrow \text{valve closed, only leakage: } \text{pa}.\phi = \text{pb}.\phi = (\text{Q}_\text{leak}/\text{p}_\text{nom})*\text{dp} \\
\text{pclosed} < \text{dp} < \text{popen} & \Rightarrow \text{working range, i.e. valve partially opened} \\
\text{popen} < \text{dp} & \Rightarrow \text{valve wide open: } \text{pa}.\phi = \text{pb}.\phi = \text{Q}_\text{nom} \times \sqrt{\frac{\text{dp}}{\text{p}_\text{nom}}} + (\text{Q}_\text{leak}/\text{p}_\text{nom})*\text{dp}
\end{align*}\]

Interface

Ports
pa, pb
Both terminals of the hydraulic component.

Causality
fixed volume flow
out pa
fixed volume flow
out pb

Parameters
pclosed
Valve is closed under this pressure [Pa].

popen
Valve is fully open above this pressure [Pa].

Q_nom
Turbulent flow at nominal pressure drop [m3/s]

Q_leak
Leakage flow at nominal pressure drop, make 1e-12 if unknown [m3/s]

p_nom
Nominal pressure [Pa].
FlowControlValve

Library
Iconic Diagrams\Hydraulics\Valves\Basic Valves

Use

Description
Flow control valves have the purpose to provide a constant flow, independent of the downstream pressure. The flow is obtained by means of a pressure difference controller using the pressure drop over an orifice. Therefore flow control valves always need a certain pressure drop before the desired flow can be achieved.

In this model the flow is modeled by an tanh function. The pressure drop is defined as the pressure where 95% of the desired flow rate is achieved.

\[
dp = pa.p - pb.p
\]
\[
phi = \begin{cases} 
Q_set \cdot \text{tanh}\left( \frac{\arctan(0.95)}{p\_drop} \cdot dp \right) + GLeak \cdot dp; & \text{if } dp > 0 \\
GLeak \cdot dp & \text{else}
\end{cases}
\]

Here \( \phi \) is the desired flow and \( p\_drop \) is the 95% pressure drop. \( G\text{leak} \) is the conductance of laminar leakage flow when the valve is closed. The pressure at both ports has a lower limit that is equal to the vapour pressure. Therefore the actual equations used in this model are:
\[ \begin{align*}
p_{1\text{\_lim}} &= \text{if } p_{\text{a},p} < p_{\text{vapour}} \text{ then } p_{\text{vapour}} \text{ else } p_{\text{a},p} \text{ end}; \\
p_{2\text{\_lim}} &= \text{if } p_{\text{b},p} < p_{\text{vapour}} \text{ then } p_{\text{vapour}} \text{ else } p_{\text{b},p} \text{ end}; \\
dp &= p_{1\text{\_lim}} - p_{2\text{\_lim}}; 
\end{align*} \]

### Interface

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both terminals of the hydraulic component.</td>
<td>pa, pb</td>
</tr>
</tbody>
</table>

**Causality**

- fixed volume flow
- out pa
- fixed volume flow
- out pb

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired flow [ \text{[m3/s]} ]</td>
<td>Q_set</td>
</tr>
<tr>
<td>Pressure drop at 95% flow [ \text{[Pa]} ]</td>
<td>p_drop</td>
</tr>
<tr>
<td>Conductance of the laminar leakage flow [ \text{[m3/s.Pa]} ], GLeak ( \geq 0 )</td>
<td>GLeak</td>
</tr>
</tbody>
</table>

---

### FourThreeWayDirectionalValve

**Library**

Iconic Diagrams\Hydraulics\Valves\Basic Valves

**Use**

- **Domains**: Continuous
- **Size**: 1-D
- **Kind**: Iconic Diagrams (Hydraulics)

**Description**

This model is equal to the four three way proportional valve model, except for the spool position. The spool position is rounded to 0, 1 or -1:

\[-0.5 < \text{spoolpos} < 0.5 \Rightarrow \text{pos} = 0\]
\[\text{spoolpos} \geq 0.5 \Rightarrow \text{pos} = 1\]
\[\text{spoolpos} \leq -0.5 \Rightarrow \text{pos} = -1\]

The spool dynamics is modeled by a second order transfer function:

\[ sp = SO(f,d,\text{discrete(pos)}) \]

which is characterized by the bandwidth \( f \) and damping \( d \).

**Implementation**

The 4/3-way directional control valve is implemented with various spool centre configurations. The configurations are shown in the picture below:
When you drag and drop a model in the editor, you will be asked which implementation you want to choose. During modeling you can easily change the spool center configuration:

1. Select the valve model.
2. Click the right mouse button to open the right mouse menu.
3. Click *Edit Implementation* and choose another implementation.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp, pt, pa, pb</td>
<td>All terminals of the valve.</td>
</tr>
</tbody>
</table>

**Causality**

- fixed volume flow
  - out pp
- fixed volume flow
  - out pt
- fixed volume flow
  - out pa
- fixed volume flow
  - out pb

**Inputs**

- spoolpos: position of the spool valve: 0 = closed, 1 = open positive, -1 = open negative, -1 <= spoolpos <= 1

**Parameters**

- Q_nom: Nominal flow at nominal pressure per edge, spool in the open position [m3/s], Q_nom > 0
- Q_nom_central: Nominal flow at nominal pressure per edge with, spool in the closed position, Q_nom_central > 0
- Q_leak: Leakage flow at nominal pressure per edge [m3/s], Q_leak > 0
- p_nom: Nominal pressure per edge [Pa], p_nom > 0
- overlap: Valve overlap as percentage of full stroke, -1 < overlap < 1.
11. Library

Natural frequency, $f > 0$.

**FourThreeWayProportionalValve**

**Library**
Iconic Diagrams\Hydraulics\Valves\Basic Valves

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**

This model describes a 4/3-way proportional control valve with second order spool dynamics.

The spool position is indicated by the variable $sp$:

- $sp = -1$  
  Flow from $p$ to $b$ and $a$ to $t$
- $-1 < sp < 0$  
  Partial flow from $p$ to $b$ and $a$ to $t$
- $sp = 0$  
  No flow
- $0 < sp < 1$  
  Partial flow from $p$ to $a$ and $b$ to $t$
- $sp = 1$  
  Flow from $p$ to $a$ and $b$ to $t$
The flow through the valves is described as laminar/turbulent flow through an orifice. A detailed description of the flow equations can be found in the description of the model TwoTwoWayDirectionalValve.

In the neutral spool position \((sp = 0)\) all valves are closed. A positive overlap indicates that the spool must travel a certain distance before the valves open. A negative overlap indicates that the valves are already open in the neutral position. A 4/3-way directional control valve with negative overlap could therefore also be indicated by the figure below.

The overlap is indicated by the parameter overlap, which is given as a fraction of the spool position. Note that overlap is only active in the neutral position. For the spool position equal to 1 or -1 the valves are completely open or completely closed.

The spool position \(sp\) is a function of the input signal \(spoolpos\):

\[
sp = SO(f,d,\text{discrete}(spoolpos))
\]

where \(SO\) is a second order transfer function to model the spool dynamics. The function is characterized by the bandwidth \((f)\) and damping \((d)\). The valve input position \(spoolpos\) should be limited to the range between -1 and 1.

**Implementation**

The 4/3-way proportional control valve is implemented with various spool centre configurations. The configurations are shown in the picture below:

When you drag and drop a model in the editor, you will be asked which implementation you want to choose. During modeling you can easily change the spool center configuration:
1. Select the valve model.
2. Click the right mouse button to open the right mouse menu.
3. Click *Edit Implementation* and choose another implementation

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp, pt, pa, pb</td>
<td>All terminals of the valve.</td>
</tr>
</tbody>
</table>

**Causality**

- fixed volume flow
- out pp
- fixed volume flow
- out pt
- fixed volume flow
- out pa
- fixed volume flow
- out pb

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>spoolpos</td>
<td>position of the spool valve: 0 = closed, 1 = open</td>
</tr>
<tr>
<td></td>
<td>0 &lt;= spoolpos &lt;= 1</td>
</tr>
</tbody>
</table>

**Parameters**

- **Q_nom** Nominal flow at nominal pressure per edge, spool in the open position  
  \([\text{m}^3/\text{s}], \ Q_{\text{nom}} > 0\)
- **Q_nom_central** Nominal flow at nominal pressure per edge with, spool in the closed position,  
  \(Q_{\text{nom\_central}} > 0\)
- **Q_leak** Leakage flow at nominal pressure per edge \([\text{m}^3/\text{s}], \ Q_{\text{leak}} > 0\)
- **p_nom** Nominal pressure per edge \([\text{Pa}], \ p_{\text{nom}} > 0\)
- **overlap** Valve overlap as percentage of full stroke, \(-1 < \text{overlap} < 1\).
- **f** Natural frequency, \(f > 0\).
LoopFlushingValve

Library
Iconic Diagrams\Hydraulics\Valves\Basic Valves

Use

Description
Loop flushing valves are used to maintain a high quality working fluid in closed hydraulic circuits. In closed hydraulic circuits, the oil is continuously flowing from a pump to an actuator. A loop flushing valve allows the oil to leave the circuit for cooling and filtering. If one side ($p_a$) of the valve has a higher pressure, oil will flow from the other side ($p_b$) out of the closed circuit and vice versa.

The circuit is always equipped (not shown above) with a charge pump to keep the suction side of the pump on a pre-pressure to avoid cavitation and so damage to the pump, and to exchange the fluid that is flushed.

Loop flushing valves are spring operated. I.e. a certain pressure difference between port $a$ and $b$ is required to open the valve. This pressure can be adjusted and is indicated by the parameter $p_{sw}$. 
A small pressure difference is required to turn a valve from completely closed to completely opened. This overlap pressure is indicated by the parameter $p_o$.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa, pb</td>
<td>Input terminals of the valve.</td>
</tr>
<tr>
<td>p_out</td>
<td>Output terminal.</td>
</tr>
</tbody>
</table>

**Causality**

fixed volume flow

out pa

fixed volume flow

out pb

fixed volume flow

out p_out

**Parameters**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_o$</td>
<td>Overlap pressure [Pa].</td>
</tr>
<tr>
<td>$p_{sw}$</td>
<td>Switching pressure [Pa].</td>
</tr>
<tr>
<td>$Q_{nom}$</td>
<td>Turbulent flow at nominal pressure drop [m3/s]</td>
</tr>
<tr>
<td>$p_{nom}$</td>
<td>Nominal pressure [Pa].</td>
</tr>
<tr>
<td>$f$</td>
<td>Bandwidth of the spool dynamics [Hz], $f &gt; 0$, (hidden).</td>
</tr>
<tr>
<td>$d$</td>
<td>Damping of the spool dynamics [], $d &gt; 0$, (hidden).</td>
</tr>
<tr>
<td>$G_{Leak}$</td>
<td>Conductance of the laminar leakage flows [m3/s.Pa], $G_{Leak} &gt;= 0$. (hidden).</td>
</tr>
</tbody>
</table>
**PilotOperatedCheckValve**

**Library**
Iconic Diagrams\Hydraulics\Valves\Basic Valves

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**
A pilot operated check valve is a check valve that is normally closed but can be opened for reverse flow by a signal from an external pilot supply.

![Diagram of Pilot Operated Check Valve](image)

The figure above shows the standard design using a pilot piston with a stem to unseat the check valve poppet for reverse flow. The pilot piston has an area three to four times that of the poppet seat. This produces enough force to open the poppet against backpressure. Some pilot-operated check valves have area ratios up to 100:1, allowing a very low pilot pressure to open the valve against high backpressure.

The flow through a pilot operated check depends on the differential pressure \( dp \) between the inlet port \( pa \) and the outlet port \( pb \) and is equal to:

\[
flow = Q_{nom} \times \sqrt{\frac{dp}{p_{nom}}} + \left( \frac{Q_{leak}}{p_{nom}} \right) dp
\]

The variable \( valve \) indicates the valve opening and varies between zero (closed) and 1 (open). The opening depends on a force balance which depends on the pressures of the inlet and outlet port, the spring force and the pressure of the pilot port \( px \):

\[
valve = \text{limit}\left( \frac{pa.p - pb.p - pclosed + px.p \times kp}{(popen - pclosed)}, 0, 1 \right)
\]

The pilot ratio \( kp \) is ratio of the pilot piston area and the check valve area. For a large pilot ratio a relatively small pilot pressure is sufficient to open the valve against a large outlet pressure.
## Interface

### Ports

<table>
<thead>
<tr>
<th>Port</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa</td>
<td>Inlet port</td>
</tr>
<tr>
<td>pb</td>
<td>Outlet port</td>
</tr>
<tr>
<td>px</td>
<td>Pilot port</td>
</tr>
</tbody>
</table>

### Causality

- fixed volume flow out pa
- fixed volume flow out pb
- fixed volume flow out pt

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_nom</td>
<td>Nominal flow at nominal pressure per edge, spool in the open position [m3/s], Q_nom &gt; 0</td>
</tr>
<tr>
<td>Q_leak</td>
<td>Leakage flow (valve closed) at nominal pressure drop [m3/s], Q_leak &gt; 0.</td>
</tr>
<tr>
<td>p_nom</td>
<td>Nominal pressure drop [Pa], p_nom &gt; 0</td>
</tr>
<tr>
<td>pclosed</td>
<td>Valve is closed under this pressure [Pa] and zero pilot pressure.</td>
</tr>
<tr>
<td>open</td>
<td>Valve is fully open above this pressure [Pa] and zero pilot pressure.</td>
</tr>
<tr>
<td>kp</td>
<td>Pilot ratio []</td>
</tr>
</tbody>
</table>
**PressureCompensator**

**Library**
Iconic Diagrams\Hydraulics\Valves\Basic Valves

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description - Default**

A pressure compensator is a component that maintains a constant differential pressure across its sensing ports $px$ and $py$ by regulating the flow through the component from port $pa$ to port $pb$. A pressure compensator can be used to maintain a constant flow over a valve by keeping the pressure drop over the valve constant. The sensing ports $py$ and $px$ are then connected with the input and output of the valve.

![Diagram of PressureCompensator](image)

The flow through the element is laminar or turbulent depending on the pressure drop $p_{ab}$ over $pa$ and $pb$:

$$p_{ab} = pa.p - pb.p;$$

$$\phi = \text{sign}(p_{ab}) * Cd * A * \sqrt{(2/rho) * abs(dp)} + G\text{Leak} * p_{ab};$$

The opening $A$ depends on the pressure drop $p_{xy}$ over $pa$ and $pb$: 

...
The maximum opening $A_{\text{max}}$ is determined by the maximum flow $\phi_{\text{max}}$ at the maximum pressure drop $p_{\text{in\_max}}$ over the component:

$$A_{\text{max}} = \frac{\phi_{\text{max}}}{C_d \sqrt{\frac{2}{\rho} p_{\text{in\_max}}}};$$

The opening is at its maximum value when the differential pressure across it sensing ports $p_x$ and $p_y$ is below the pressure $\left(\frac{k-1}{k}\right)p_{\text{set}}$. If the differential pressure across it sensing ports $p_x$ and $p_y$ is too high, the opening is closed. In between it varies between fully open and fully closed. The speed of response of the components is determined by the proportional gain $k$ (typical choose $k = 2$ to 5). The proportional gain determines the slope of the valve opening. If $k$ is large the regulator will respond quickly but also induce oscillations in the circuit.

The valve is implemented with second order spool dynamics. I.e. the spool opening is characterized by the bandwidth ($f$) and damping ($d$).

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input and output terminals of the component.</td>
<td>pa, pb</td>
</tr>
<tr>
<td>Sensing terminals of the component. These are used to measure the pressure and have almost zero flow.</td>
<td>px, py</td>
</tr>
</tbody>
</table>

**Causality**

- fixed volume flow out pa
- fixed volume flow out pb
- fixed volume flow out px
- fixed volume flow out py

**Parameters**
**PressureReducingValve**

**Library**

Iconic Diagrams\Hydraulics\Valves\Basic Valves

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Hydraulics).

**Description**

Pressure reducing valves have the purpose to provide a constant pressure \( p_{\text{set}} \), independent of the upstream pressure. They are used to limit the pressure of a primary circuit to a desired pressure for a secondary circuit.

The desired pressure \( p_{\text{set}} \) is obtained by means of a flow over a valve between an input port \( pa \) and an output port \( pb \). The valve is modeled by a variable conductance. Depending on the pressure downstream \( pb.p \) the valve is opened (large conductance) or closed (zero conductance). Therefore pressure reducing valves always need a small flow to establish the correct downstream pressure.

![Diagram of pressure reducing valve](image)

When the downstream pressure \( pb.p \) increases over the desired pressure a second valve opens to allow flow from the downstream port which is connected to the tank. The speed of the valve is controlled by the parameter \( k \). If \( k \) is high (\( >> 10 \)) the valve will respond quickly but can also get into oscillation more quickly. When \( k \) is small (\( << 10 \)), the valve is stable but will react more slowly.
### Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa</td>
<td>Upstream port</td>
</tr>
<tr>
<td>pb</td>
<td>Downstream port</td>
</tr>
</tbody>
</table>

### Causality

- fixed volume flow
- out pa
- fixed volume flow
- out pb

### Parameters

- **p_set**: Desired pressure at port b [Pa], $p_{set} > 0$.
- **p_max**: Maximum input pressure at port a [Pa], $p_{max} > 0$.
- **phi_max**: Maximum flow at maximum input pressure and zero desired pressure [m3/s], $\phi_{max} > 0$.
- **k**: Valve gain, $k > 0$.

---

### PressureReliefValve

**Library**

Iconic Diagrams\Hydraulics\Valves\Basic Valves

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**

This model describes a pressure relief valve. The resistance depends on the pressure difference:
\[ dp = pa.p - pb.p \]

- \( dp < pclosed \Rightarrow \text{valve closed, only leakage: } pa.\phi = pb.\phi = dp \times G_{\text{Leak}} \)
- \( pclosed < dp < popen \Rightarrow \text{working range, i.e. valve partially opened} \)
- \( popen < dp \Rightarrow \text{valve wide open: } pa.\phi = pb.\phi = dp \times G_{\text{Open}} \)

### Interface

#### Ports
- **pa, pb**: Both terminals of the hydraulic component.

#### Causality
- fixed volume flow
  - out pa
  - fixed volume flow
  - out pb

#### Parameters
- **pclosed**: Valve is closed under this pressure [Pa].
- **popen**: Valve is fully open above this pressure [Pa].
- **G_{\text{Leak}}**: Conductance of closed valve [m3/s.Pa].
- **G_{\text{Open}}**: Conductance of open valve [m3/s.Pa].
ShuttleValve

Library
Iconic Diagrams\Hydraulics\Valves\Basic Valves

Use

Description - Default
A shuttle valve is a type of valve which allows fluid to flow through it from one of two sources. Shuttle valves accept flow from two different sources ($pa$) and ($pb$) and divert the highest pressure to a single outlet port ($p_{out}$). Shuttle valves are commonly used in Load Sensing circuits and at a cylinder to measure the working pressure, as well as Brake circuits. Normal shuttle valve are mostly ball and poppet types valves.

The default implementation of the shuttle valve assumes ideal behaviour:

\[
p_{out}.p = \text{maximum}(pa.p, pb.p) \\
p_{a}.phi = pb.phi = 0;
\]

This model sets the flows of the input ports to zero and assumes the output flow is zero as well. However the output flow is determined by the component that is connected with the output port. A warning is given when the output flow exceeds $1.0e^{-5}$ m$^3$. If flows are important in your model, use the Spool Dynamics implementation of this model (see below).

Interface - Default

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pa$, $pb$</td>
<td>Input terminals of the valve.</td>
</tr>
<tr>
<td>$p_{out}$</td>
<td>Output terminal.</td>
</tr>
</tbody>
</table>

Causality
fixed volume flow
out $pa$
fixed volume flow
out $pb$
fixed pressure out
p_out

**Description - BallDynamics**

This implementation is equal to the default implementation but with modeled dynamics. A small pressure difference between the inlet ports $pa$ and $pb$ is enough to make the ball switch from one side to the other. This pressure is called the overlap pressure $po$.

---

**Interface - BallDynamics**

**Ports**

- $pa$, $pb$
- $p_{out}$

**Description**

- Input terminals of the valve.
- Output terminal.

**Causality**

- fixed volume flow
  - out $pa$
- fixed volume flow
  - out $pb$
- fixed volume flow
  - out $p_{out}$

**Parameters**

- $Q_{max}$: flow at maximum pressure drop [m3/s], $Q_{max} > 0$.
- $p_{max}$: Maximum pressure drop over the valve [Pa], $p_{max} > 0$.
- $f$: Bandwidth of the valve dynamics [Hz], $f > 0$.
- $p_o$: Overlap pressure [Pa], $p_o >= 0$. 
TwoTwoWayDirectionalValve

Library
Iconic Diagrams\Hydraulics\Valves\Basic Valves

Use

Description

This model describes a 2/2-way directional control valve with second order spool dynamics. The flow through the valve is described as laminar/turbulent flow through an orifice:

\[
dp = pa.p - pb.p  
\]

\[
\phi = \text{sign}(dp) \times \text{Cd} \times A(sp) \times \sqrt{\frac{2}{\rho} \times \text{abs}(dp)} + G_{\text{Leak}} \times dp; 
\]

Here \( \text{Cd} \) is the discharge coefficient which normally has a value between 0.55 and 0.7. \( A(sp) \) is the area of the orifice opening. \( A(sp) \) depends linearly on the spool position \( sp \) and varies between 0 (\( sp = 0 \)) and the maximum area \( A_{\text{max}} \) (\( sp = 1 \)). \( G_{\text{Leak}} \) is the conductance of laminar leakage flow when the valve is closed. The relative opening of the spool valve is indicated by \( sp \). For a closed valve the spool position \( (sp) \) is equal to zero and for an open valve the spool position \( (sp) \) is equal to 1.

In the neutral spool position \( (sp = 0) \) the valve is just closed. A positive overlap indicates that the spool must travel a certain distance before the valve opens.
A negative overlap indicates that the valve is already open in the neutral position.

The overlap is indicated by the parameter overlap, which is given as a fraction of the spool position.

The spool position sp is a function of the input signal spoolpos:

\[ sp = SO(f,d,\text{discrete}(\text{spoolpos})) \]

where \( SO \) is a second order transfer function to model the spool dynamics. The function is characterized by the bandwidth \( f \) and damping \( d \). The model acts as a directional valve (a valve which is either open or closed) because the input signal \( \text{spoolpos} \) is rounded to 0 or 1:

- \( \text{spoolpos} < 0.5 \Rightarrow 0 \)
- \( \text{spoolpos} \geq 0.5 \Rightarrow 1 \)

The pressure at both ports has a lower limit which is equal to the vapour pressure. Therefore the actual equations used in this component are:

\[
\begin{align*}
\pa_{\text{lim}} &= \text{if } \pa.p < \text{p_vapour} \text{ then } \text{p_vapour} \text{ else } \pa.p \text{ end;} \\
\pb_{\text{lim}} &= \text{if } \pb.p < \text{p_vapour} \text{ then } \text{p_vapour} \text{ else } \pb.p \text{ end;}
\end{align*}
\]
### Interface

#### Ports

| Description | pa, pb | Both terminals of the valve. |

#### Causality

fixed volume flow

out pa

fixed volume flow

out pb

#### Inputs

| Description | spoolpos | position of the spool valve |
|            |         | spoolpos < 0.5 => valve is closed |
|            |         | spoolpos >= 0.5 => valve is open |

#### Parameters

| Description | Q_nom | Nominal flow at nominal pressure per edge, spool in the open position [m3/s], Q_nom > 0 |
|            | Q_leak | Leakage flow at nominal pressure per edge [m3/s], Q_leak > 0 |
|            | p_nom | Nominal pressure per edge [Pa], p_nom > 0 |
|            | overlap | Valve overlap as percentage of full stroke, -1 < overlap < 1. |
|            | f | Natural frequency, f > 0. |

### TwoTwoWayProportionalValve

#### Library

Iconic Diagrams\Hydraulics\Valves\Basic Valves

#### Use

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Hydraulics).
Description

This model describes a 2/2-way proportional control valve with second order spool dynamics. The flow through the valve is described as laminar/turbulent flow through an orifice:

\[
\begin{align*}
    dp &= pa.p - pb.p \\
    \phi &= \text{sign}(dp) \cdot Cd \cdot A(sp) \cdot \sqrt{\frac{2}{\rho} \cdot \text{abs}(dp)} + GLeak \cdot dp;
\end{align*}
\]

Here \(Cd\) is the discharge coefficient which normally has a value between 0.55 and 0.7. \(A(sp)\) is the area of the orifice opening. \(A(sp)\) depends linearly on the spool position \(sp\) and varies between 0 (\(sp = 0\)) and the maximum area \(A_{max}\) (\(sp = 1\)). \(G_{leak}\) is the conductance of laminar leakage flow when the valve is closed. The relative opening of the spool valve is indicated by \(sp\). For a closed valve the spool position (\(sp\)) is equal to zero and for an open valve the spool position (\(sp\)) is equal to 1.

In the neutral spool position (\(sp = 0\)) the valve is just closed. A positive overlap indicates that the spool must travel a certain distance before the valve opens.
A negative overlap indicates that the valve is already open in the neutral position.

The overlap is indicated by the parameter overlap, which is given as a fraction of the spool position.

The spool position $sp$ is a function of the input signal $spoolpos$:

$$sp = SO(f,d,spoolpos)$$

where $SO$ is a second order transfer function to model the spool dynamics. The function is characterized by the bandwidth ($f$) and damping ($d$). The valve input position $spoolpos$ should be limited to the range between 0 and 1.

The pressure at both ports has a lower limit which is equal to the vapour pressure. Therefore the actual equations used in this component are:

$$pa\_lim = \text{if } pa.p < p\_vapour \text{ then } p\_vapour \text{ else } pa.p \text{ end};$$
$$pb\_lim = \text{if } pb.p < p\_vapour \text{ then } p\_vapour \text{ else } pb.p \text{ end};$$

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa, pb</td>
<td>Both terminals of the valve.</td>
</tr>
</tbody>
</table>
**Causality**

fixed volume flow
out pa
fixed volume flow
out pb

**Inputs**

spoolpos  
position of the spool valve: 0 = closed, 1 = open
0 <= spoolpos <= 1

**Parameters**

Q_nom  
Nominal flow at nominal pressure per edge, spool in the open position [m³/s], Q_nom > 0
Q_leak  
Leakage flow at nominal pressure per edge [m³/s], Q_leak > 0
p_nom  
Nominal pressure per edge [Pa], p_nom > 0
overlap  
Valve overlap as percentage of full stroke, -1 < overlap < 1.
f  
Natural frequency, f > 0.

**Check Valve States**

**Library**

Iconic Diagrams\Hydraulics\Valves

**Use**


**Description**

This model describes a spring-loaded check valve with parasitic volumes. The resistance depends on the pressure difference:
\( dp < pclosed \Rightarrow \text{valve closed, only leakage: } pa.phi = pb.phi = dp \times G_{\text{Leak}} \)
\( pclosed < dp < popen \Rightarrow \text{working range, i.e. valve partially opened} \)
\( popen < dp \Rightarrow \text{valve wide open: } pa.phi = pb.phi = K \times \sqrt{dp - pclosed}; \)

**Interface**

**Ports**

- \( pa, pb \)

**Description**

Both terminals of the hydraulic component.

**Causality**

- preferred pressure out \( pa \)
- preferred pressure out \( pb \)

**Parameters**

- \( \text{CheckValve}\_pclosed \)
  - Valve is closed under this pressure [Pa].
- \( \text{CheckValve}\_popen \)
  - Valve is fully open above this pressure [Pa].
- \( \text{CheckValve}\_Q\_nom \)
  - Turbulent flow at nominal pressure drop [m3/s].
- \( \text{CheckValve}\_Q\_leak \)
  - Leakage flow at nominal pressure drop, make 1e-12 if unknown [m3/s]
- \( \text{CheckValve}\_p\_nom \)
  - Nominal pressure [Pa]
- \( V_a\_V \)
  - Volume of oil under pressure [m3] (hidden)
- \( V_a\_p\_initial \)
  - The starting pressure of the volume [Pa] (hidden)
- \( V_b\_V \)
  - Volume of oil under pressure [m3] (hidden)
- \( V_b\_p\_initial \)
  - The starting pressure of the volume [Pa] (hidden)
CounterbalanceValve

Library
Iconic Diagrams\Hydraulics\Valves

Use

Description
This model an externally piloted counter balance valve. The model consists of an externally piloted pressure relief valve with a check valve in parallel. The ports of the model are connected to parasitic volumes.

The Counterbalance valve is applied as a brake valve to get a positive control on a hydraulic cylinder or motor with a negative load. The check valve is used to get a free running actuator in one direction and the pressure relief valve is used to control the actuator in the other direction. The relief valve is controlled by the external pilot pressure.

Interface

Ports
pa, pb
pt.

Causality
fixed volume flow out pa
fixed volume flow out pb
fixed volume flow out pt

Description
Both terminals of the hydraulic component.
**Parameters**

- **CheckValve\pclosed**  
  Valve is closed under this pressure [Pa].
- **CheckValve\popen**  
  Valve is fully open above this pressure [Pa].
- **CheckValve\Q_nom**  
  Turbulent flow at nominal pressure drop [m3/s].
- **CheckValve\Q_leak**  
  Leakage flow at nominal pressure drop, make 1e-12 if unknown [m3/s].
- **PressureReliefValve\pclosed**  
  Valve is closed under this pressure [Pa].
- **PressureReliefValve\popen**  
  Valve is fully open above this pressure [Pa].
- **PressureReliefValve\G_Leak**  
  Conductance of closed valve [m3/s.Pa].
- **PressureReliefValve\G_Open**  
  Conductance of open valve [m3/s.Pa].
- **Va\V**  
  Volume of oil under pressure [m3] (hidden)
- **Va\p_initial**  
  The starting pressure of the volume [Pa] (hidden)
- **Vb\V**  
  Volume of oil under pressure [m3] (hidden)
- **Vb\p_initial**  
  The starting pressure of the volume [Pa] (hidden)
- **Vt\V**  
  Volume of oil under pressure [m3] (hidden)
- **Vt\p_initial**  
  The starting pressure of the volume [Pa] (hidden)

**FlowControlValve-States**

**Library**  
Iconic Diagrams\Hydraulics\Valves\Basic Valves

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**

This model describes a flow control valve with with parasitic volumes.
In this model the flow is modeled by a \(\text{tanh}\) function. The pressure drop is defined as the pressure where 95\% of the desired flow rate is achieved.

\[
\begin{align*}
\text{dp} &= pa.p - pb.p \\
\text{phi} &= \text{if } \text{dp} > 0 \text{ then} \\
&\quad \text{Q_set} \cdot \text{tanh}\left(\frac{\text{arctan}(0.95)}{\text{p_drop}} \cdot \text{dp}\right) + \text{GLeak} \cdot \text{dp} \\
&\quad \text{else} \\
&\quad \text{GLeak} \cdot \text{dp} \\
&\quad \text{end};
\end{align*}
\]

Here \(\text{phi}\) is the desired flow and \(\text{p_drop}\) is the 95\% pressure drop. \(\text{Gleak}\) is the conductance of laminar leakage flow when the valve is closed. The pressure at both ports has a lower limit that is equal to the vapour pressure. Therefore the actual equations used in this model are:

\[
\begin{align*}
\text{p1_lim} &= \text{if } pa.p < \text{p_vapour} \text{ then } \text{p_vapour} \text{ else } pa.p \text{ end}; \\
\text{p2_lim} &= \text{if } pb.p < \text{p_vapour} \text{ then } \text{p_vapour} \text{ else } pb.p \text{ end}; \\
\text{dp} &= \text{p1_lim} - \text{p2_lim};
\end{align*}
\]

**Interface**

**Ports**

- \(pa, pb\)

**Description**

Both terminals of the hydraulic component.

**Causality**

- fixed volume flow out \(pa\)
- fixed volume flow out \(pb\)

**Parameters**

- FlowControlValve\Q_set: Desired flow [m3/s]
- FlowControlValve\p_drop: Pressure drop at 95\% flow [Pa]
- FlowControlValve\GLeak: Conductance of the laminar leakage flow [m3/s.Pa], \(\text{GLeak} >= 0!\)
- Va\V
- Va\B: Volume of oil under pressure [m3] (hidden)
The starting pressure of the volume [Pa] (hidden)
Volume of oil under pressure [m3] (hidden)
Effective bulk modulus [Pa] (hidden)
Effective bulk modulus [Pa] (hidden)

**FourThreeWayDirectionalValve-States**

**Library**
Iconic Diagrams\Hydraulics\Valves

**Use**

**Description**

This model describes a 4/3-way directional control valve with second order spool dynamics and parasitic volumes. The flow through the valves is described as laminar/turbulent flow through an orifice. A detailed description of the valve can be found in FourThreeWayDirectionalValve.htm.

The spool position is indicated by the input spoolpos:

- $sp = -1 \quad Flow \ from \ p \ to \ b \ and \ a \ to \ t$
- $sp = 0 \quad No \ flow$
- $sp = 1 \quad Flow \ from \ p \ to \ a \ and \ b \ to \ t$

Values between -1 and 0 or between 0 and 1 are rounded to the nearest value.

**Implementation**
The 4/3-way proportional control valve is implemented with various spool center configurations. The configurations are shown in the picture below:
When you drag and drop a model in the editor, you will be asked which implementation you want to choose. During modeling you can easily change the spool center configuration:

1. Select the valve model.
2. Click the right mouse button to open the right mouse menu.
3. Click *Edit Implementation* and choose another implementation.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>All terminals of the valve.</td>
<td>pp, pt, pa, pb</td>
</tr>
</tbody>
</table>

**Causality**

<table>
<thead>
<tr>
<th>preferred effort out pp</th>
<th>preferred effort out pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferred effort out pa</td>
<td>preferred effort out pb</td>
</tr>
</tbody>
</table>

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>position of the spool valve</td>
<td>spoolpos</td>
</tr>
<tr>
<td>spoolpos &lt; 0.5 =&gt; valve is closed</td>
<td>spoolpos &gt;= 0.5 =&gt; valve is open</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal flow at nominal pressure per edge, spool in the open position [m3/s], Q_nom &gt; 0.</td>
<td>FourThreeWayDirectionalValve Q_nom</td>
</tr>
<tr>
<td>Nominal flow at nominal pressure per edge with, spool in the closed position, Q_nom_central &gt; 0.</td>
<td>FourThreeWayDirectionalValve Q_nom_central</td>
</tr>
<tr>
<td>Leakage flow at nominal pressure per edge [m3/s], Q_leak &gt; 0.</td>
<td>FourThreeWayDirectionalValve Q_leak</td>
</tr>
<tr>
<td>Nominal pressure per edge [Pa], p_nom &gt; 0.</td>
<td>FourThreeWayDirectionalValve p_nom</td>
</tr>
</tbody>
</table>
The valve overlap in closed position [], -1 < overlap < 1.

Bandwidth of the spool dynamics [Hz], \( f > 0 \).

Volume of oil under pressure [m³] (hidden).

The starting pressure of the volume [Pa] (hidden).

Volume of oil under pressure [m³] (hidden).

The starting pressure of the volume [Pa] (hidden).

Volume of oil under pressure [m³] (hidden).

The starting pressure of the volume [Pa] (hidden).

Volume of oil under pressure [m³] (hidden).

This model describes a 4/3-way proportional control valve with second order spool dynamics and parasitic volumes. The flow through the valves is described as laminar/turbulent flow through an orifice. A detailed description of the valve can be found in FourThreeWayProportionalValve.htm.

The spool position is indicated by the input \textit{spoolpos}:

\[ sp = -1 \quad \text{Flow from p to b and a to t} \]
-1 < \(sp\) < 0  Partial flow from \(p\) to \(b\) and \(a\) to \(t\)

\(sp = 0\)  No flow

0 < \(sp\) < 1  Partial flow from \(p\) to \(a\) and \(b\) to \(t\)

\(sp = 1\)  Flow from \(p\) to \(a\) and \(b\) to \(t\)

**Implementation**

The 4/3-way proportional control valve is implemented with various spool centre configurations. The configurations are shown in the picture below:

When you drag and drop a model in the editor, you will be asked which implementation you want to choose. During modeling you can easily change the spool center configuration:

1. Select the valve model.
2. Click the right mouse button to open the right mouse menu.
3. Click *Edit Implementation* and choose another implementation.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>pp, pt, pa, pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>All terminals of the valve.</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

<table>
<thead>
<tr>
<th>preferred effort out pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferred effort out pt</td>
</tr>
<tr>
<td>preferred effort out pa</td>
</tr>
<tr>
<td>preferred effort out pb</td>
</tr>
</tbody>
</table>

**Inputs**

<table>
<thead>
<tr>
<th>spoolpos</th>
<th>value of the spool position, -1 &lt;= spoolpos &lt;= 1.</th>
</tr>
</thead>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>FourThreeWayProportionalVal Nominal flow at nominal pressure per edge, spool in the open position ([m^3/s]), Q_nom &gt; 0.</th>
</tr>
</thead>
</table>
FourThreeWayProportionalVal Nominal flow at nominal pressure per edge with, spool in the closed position, $Q_{nom\_central} > 0$.

FourThreeWayProportionalVal Leakage flow at nominal pressure per edge [m3/s], $Q_{leak} > 0$.

FourThreeWayProportionalVal Nominal pressure per edge [Pa], $p_{nom} > 0$.

FourThreeWayProportionalVal The valve overlap in closed position [], $-1 < \text{overlap} < 1$.

FourThreeWayProportionalVal Bandwidth of the spool dynamics [Hz], $f > 0$.

FourThreeWayProportionalVal Volume of oil under pressure [m3], (hidden).

The starting pressure of the volume [Pa], (hidden).

Volume of oil under pressure [m3], (hidden).

The starting pressure of the volume [Pa], (hidden).

Volume of oil under pressure [m3], (hidden).

The starting pressure of the volume [Pa], (hidden).

LoopFlushingValve-States

Library
Iconic Diagrams\Hydraulics\Valves

Use

Description
This model describes a loop flushing valve with parasitic volumes.
Loop flushing valves are used to maintain a high quality working fluid in closed hydraulic circuits. In closed hydraulic circuits the oil is continuously flowing from a pump to an actuator. A loop flushing valve allows the oil to leave the circuit for cooling and filtering. If one side (pa) of the valve has a higher pressure, oil will flow from the other side (pb) out of the closed circuit and vice versa.

The circuit is always equipped (not shown above) with a charge pump to keep the suction side of the pump on a pre-pressure to avoid cavitation and so damage to the pump, and to exchange the fluid that is flushed.

Loop flushing valves are spring operated. I.e. a certain pressure difference between port a and b is required to open the valve. This pressure can be adjusted and is indicated by the parameter p_sw.
A small pressure difference is required to turn a valve from completely closed to completely opened. This overlap pressure is indicated by the parameter $p_o$.

**Interface**

- **LoopFlushingValve\p_o**: Overlap pressure [Pa].
- **LoopFlushingValve\p_sw**: Switching pressure [Pa].
- **LoopFlushingValve\Q_nom**: Turbulent flow at nominal pressure drop [m3/s].
- **LoopFlushingValve\p_nom**: Nominal pressure [Pa].
- **LoopFlushingValve\f**: Bandwidth of the spool dynamics [Hz], $f > 0$, (hidden).
- **LoopFlushingValve\d**: Damping of the spool dynamics [], $d > 0$, (hidden).
- **LoopFlushingValve\GLeak**: Conductance of the laminar leakage flows [m3/s.Pa], $G_{Leak} \geq 0$, (hidden).
- **V1\V**: Volume of oil under pressure [m3], (hidden).
- **V1\p_initial**: The starting pressure of the volume [Pa], (hidden).
- **V2\V**: Volume of oil under pressure [m3], (hidden).
- **V2\p_initial**: The starting pressure of the volume [Pa], (hidden).
- **V3\V**: Volume of oil under pressure [m3], (hidden).
- **V3\p_initial**: The starting pressure of the volume [Pa], (hidden).

**PilotOperatedCheckValve-States**

**Library**

Iconic Diagrams\Hydraulics\Valves\Basic Valves

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**

This model is a pilot operated check valve with parasitic volumes.
The flow through a pilot operated check depends on the differential pressure $dp$ between the inlet port $pa$ and the outlet port $pb$ and is equal to:

$$flow = Q_{\text{nom}} \times \sqrt{dp / p_{\text{nom}}} + (Q_{\text{leak}} / p_{\text{nom}}) \times dp$$

The variable $valve$ indicates the valve opening and varies between zero (closed) and 1 (open). The opening depends on a force balance which depends on the pressures of the inlet and outlet port, the spring force and the pressure of the pilot port $px$:

$$valve = \text{limit}( (pa.p - pb.p - pclosed + px.p \times kp )/(popen - pclosed) , 0 , 1 )$$

The pilot ratio $kp$ is ratio of the pilot piston area and the check valve area. For a large pilot ratio a relatively small pilot pressure is sufficient to open the valve against a large outlet pressure.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa</td>
<td>Inlet port</td>
</tr>
<tr>
<td>pb</td>
<td>Outlet port</td>
</tr>
<tr>
<td>px</td>
<td>Pilot port</td>
</tr>
</tbody>
</table>

**Causality**

fixed volume flow
out pa
fixed volume flow
out pb
Parameters

PilotOperatedCheckValve\ Q_nom
Nominal flow at nominal pressure per edge, spool in the open position [m3/s], Q_nom > 0

PilotOperatedCheckValve\ Q_leak
Leakage flow (valve closed) at nominal pressure drop [m3/s], Q_leak > 0.

PilotOperatedCheckValve\ p_nom
Nominal pressure drop [Pa], p_nom > 0

PilotOperatedCheckValve\ p_closed
Valve is closed under this pressure [Pa] and zero pilot pressure.

PilotOperatedCheckValve\ p_open
Valve is fully open above this pressure [Pa] and zero pilot pressure.

PilotOperatedCheckValve\ kp
Pilot ratio [].

Va\ V
Volume of oil under pressure [m3], (hidden).

Va\ p_initial
The starting pressure of the volume [Pa], (hidden).

Vb\ V
Volume of oil under pressure [m3], (hidden).

Vb\ p_initial
The starting pressure of the volume [Pa], (hidden).

Vx\ V
Volume of oil under pressure [m3], (hidden).

Vx\ p_initial
The starting pressure of the volume [Pa], (hidden).

PressureCompensator-States

Library

Iconic Diagrams\Hydraulics\Valves

Use


Description - Default

This model is a pressure compensator with parasitic volumes. A pressure compensator is an component that maintains a constant differential pressure across it sensing ports px and py by regulating the flow through the component from port pa to port pb. A pressure compensator can be used to maintain a constant flow over a valve by keeping the pressure drop over the valve constant. The sensing ports py and px are then connected with the input and output of the valve.
The flow through the element is laminar or turbulent depending on the pressure drop $p_{ab}$ over $pa$ and $pb$:

$$p_{ab} = pa.p - pb.p;$$
$$phi = \text{sign}(p_{ab}) \times Cd \times A \times \sqrt{ \frac{2}{rho} \times \text{abs}(dp) } + G\text{Leak} \times p_{ab};$$

The opening $A$ depends on the pressure drop $p_{xy}$ over $pa$ and $pb$:

[Diagram]

The maximum opening $A_{\text{max}}$ is determined by the maximum flow $\phi_{\text{max}}$ at the maximum pressure drop $p_{\text{in\_max}}$ over the component:

$$A_{\text{max}} = \phi_{\text{max}} / \left( Cd \times \sqrt{ \frac{2}{rho} \times p_{\text{in\_max}} } \right);$$
The opening is at its maximum value when the differential pressure across it sensing ports $px$ and $py$ is below the pressure $((k-1)/k)\cdot p_{set}$. If the differential pressure across it sensing ports $px$ and $py$ is too high, the opening is closed. In between it varies between fully open and fully closed. The speed of response of the components is determined by the proportional gain $k$ (typical choose $k = 2$ to 5). The proportional gain determines the slope of the valve opening. If $k$ is large the regulator will respond quickly but also induce oscillations in the circuit.

The valve is implemented with second order spool dynamics. I.e. the spool opening is characterized by the bandwidth ($f$) and damping ($d$).

### Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pa$, $pb$</td>
<td>Input and output terminals of the component.</td>
</tr>
<tr>
<td>$px$, $py$</td>
<td>Sensing terminals of the component. These are used to measure the pressure and have almost zero flow.</td>
</tr>
</tbody>
</table>

### Causality

<table>
<thead>
<tr>
<th>Causality</th>
<th>preferred pressure out $pa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferred pressure out $pb$</td>
<td></td>
</tr>
<tr>
<td>preferred pressure out $px$</td>
<td></td>
</tr>
<tr>
<td>preferred pressure out $py$</td>
<td></td>
</tr>
</tbody>
</table>

### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>Mass density of the fluid [kg/m$^3$].</td>
</tr>
<tr>
<td>$G_{\text{Leak}}$</td>
<td>Conductance of the laminar leakage flows [m$^3$/s.Pa], $G_{\text{Leak}}$ $\geq 0$.</td>
</tr>
<tr>
<td>$Cd$</td>
<td>Discharge coefficient [], $Cd &gt; 0$.</td>
</tr>
<tr>
<td>$\Delta p_{set}$</td>
<td>Desired differential pressure over $xy$ ($px.p - py.p$), [Pa].</td>
</tr>
<tr>
<td>$\Delta p_{in_max}$</td>
<td>Maximum flow at maximum inlet pressure ($pa.p$) and zero outlet pressure ($pb.p$), [m$^3$/s].</td>
</tr>
<tr>
<td>$\phi_{_max}$</td>
<td>Natural frequency of the second order spool dynamics [Hz].</td>
</tr>
<tr>
<td>$f$</td>
<td>Proportional gain [-].</td>
</tr>
<tr>
<td>$V_a$</td>
<td>Volume of oil under pressure [m$^3$], (hidden).</td>
</tr>
<tr>
<td>$p_{_initial}$</td>
<td>The starting pressure of the volume [Pa], (hidden).</td>
</tr>
<tr>
<td>$V_b$</td>
<td>Volume of oil under pressure [m$^3$], (hidden).</td>
</tr>
<tr>
<td>$p_{_initial}$</td>
<td>The starting pressure of the volume [Pa], (hidden).</td>
</tr>
<tr>
<td>$V_y$</td>
<td>Volume of oil under pressure [m$^3$], (hidden).</td>
</tr>
<tr>
<td>$p_{_initial}$</td>
<td>The starting pressure of the volume [Pa], (hidden).</td>
</tr>
</tbody>
</table>
PressureReducingValve-States

Library
Iconic Diagrams\Hydraulics\Valves

Use

Description

This model describes a pressure reducing valve with parasitic volumes. Pressure reducing valves have the purpose to provide a constant pressure ($p_{\text{nom}}$), independent of the upstream pressure. They are used to limit the pressure of a primary circuit to a desired pressure for a secondary circuit.

Interface

Ports

pa, pb
pt

Description
Both terminals of the hydraulic component.

Pilot

Causality

fixed volume flow out pa
fixed volume flow out pb

Parameters

PressureReducingValve
$p_{\text{set}}$ Desired pressure a port b [Pa], $p_{\text{set}} > 0$.
PressureReducingValve
$p_{\text{max}}$ Maximum input pressure at port a [Pa], $p_{\text{max}} > 0$.
PressureReducingValve
$\phi_{\text{max}}$ Maximum flow at maximum input pressure and zero desired pressure [m3/s], $\phi_{\text{max}} > 0$.
PressureReducingValve$k$ Valve gain, $k > 0$. 
PressureReliefValve-States

Library
Iconic Diagrams\Hydraulics\Valves

Use

Description

This model describes a pressure relief valve with parasitic volumes. The resistance depends on the pressure difference:
\[ dp = pa.p - pb.p \]
\[ dp < pclosed \Rightarrow \text{valve closed, only leakage: } pa.\phi = pb.\phi = dp \times G_{\text{Leak}} \]
\[ pclosed < dp < popen \Rightarrow \text{working range, i.e. valve partially opened} \]
\[ popen < dp \Rightarrow \text{valve wide open: } pa.\phi = pb.\phi = dp \times G_{\text{Open}} \]

### Interface

#### Ports
- **pa, pb**: Both terminals of the hydraulic component.

#### Causality
- **preferred pressure out pa**
- **preferred pressure out pb**

#### Parameters
- **PressureReliefValve\(pclosed\)**: Valve is closed under this pressure [Pa].
- **PressureReliefValve\(popen\)**: Valve is fully open above this pressure [Pa].
- **PressureReliefValve\(G_{\text{Leak}}\)**: Conductance of closed valve [m³/s·Pa].
- **PressureReliefValve\(G_{\text{Open}}\)**: Conductance of open valve [m³/s·Pa].
- **Va\(V\)**: Volume of oil under pressure [m³] (hidden)
- **Va\(B\)**: Effective bulk modulus [Pa] (hidden)
- **Va\(p\_initial\)**: The starting pressure of the volume [Pa] (hidden)
- **Vb\(V\)**: Volume of oil under pressure [m³] (hidden)
- **Vb\(B\)**: Effective bulk modulus [Pa] (hidden)
- **Vb\(p\_initial\)**: The starting pressure of the volume [Pa] (hidden)
ShuttleValve-States

Library
Iconic Diagrams\Hydraulics\Valves

Use

Description - Default
This model describes a loop shuttle valve with parasitic volumes. A shuttle valve is a type of valve which allows fluid to flow through it from one of two sources. Shuttle valves accept flow from two different sources (\(pa\)) and (\(pb\)) and divert the highest pressure to a single outlet port (\(p_{out}\)). Shuttle valves are commonly used in Load Sensing circuits and at a cylinder to measure the working pressure, as well as Brake circuits. Normal shuttle valve are mostly ball and poppet types valves.

\[
p_{out}.p = \text{maximum}(pa.p, pb.p) \\
p_{a}.\phi = p_{b}.\phi = 0;
\]

This model sets the flows of the input ports to zero and assumes the output flow is zero as well. However the output flow is determined by the component that is connected with the output port. A warning is given when the output flow exceeds 1.0e-5 m3. If flows are important in your model, use the Spool Dynamics implementation of this model (see below).

Interface - Default

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pa, pb</td>
<td>Input terminals of the valve.</td>
</tr>
<tr>
<td>p_out</td>
<td>Output terminal.</td>
</tr>
</tbody>
</table>

Causality
preferred
pressure out pa
preferred
pressure out pb
Description - BallDynamics

This model describes a loop shuttle valve with parasitic volumes. This implementation is equal to the default implementation but with modeled dynamics. A small pressure difference between the inlet ports \( p_a \) and \( p_b \) is enough to make the ball switch from one side to the other. This pressure is called the overlap pressure \( p_o \).

\[
\begin{array}{c}
\text{valve a} \\
A_0 \\
\text{valve b}
\end{array}
\]

\[
\begin{array}{c}
p_o \\
p_o \\
p_a - p_o
\end{array}
\]

Interface - BallDynamics

<table>
<thead>
<tr>
<th><strong>Ports</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>pa, pb</td>
<td>Input terminals of the valve.</td>
</tr>
<tr>
<td>p_out</td>
<td>Output terminal.</td>
</tr>
</tbody>
</table>

Causality

- preferred pressure out pa
- preferred pressure out pb
- preferred pressure out p_out

Parameters

- \( \text{ShuttleValve\Q_max} \) flow at maximum pressure drop [m3/s], \( \Q_max > 0 \).
- \( \text{ShuttleValve\p_max} \) Maximum pressure drop over the valve [Pa], \( \p_max > 0 \).
- \( \text{ShuttleValve\f} \) Bandwidth of the valve dynamics [Hz], \( f > 0 \).
- \( \text{ShuttleValve\p_o} \) Overlap pressure [Pa], \( p_o >= 0 \).
V1\V  Volume of oil under pressure [m3], (hidden).
V1\p_initial  The starting pressure of the volume [Pa], (hidden).
V2\V  Volume of oil under pressure [m3], (hidden).
V3\p_initial  The starting pressure of the volume [Pa], (hidden).
V3\V  Volume of oil under pressure [m3], (hidden).
V3\p_initial  The starting pressure of the volume [Pa], (hidden).

**TwoTwoWayValve-States**

**Library**
Iconic Diagrams\Hydraulics\Valves

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**

This model describes a 2/2-way directional control valve with second order spool dynamics and parasitic volumes. The flow through the valve is described as laminar/turbulent flow through an orifice. A detailed description of the valve can be found in TwoTwoWayDirectionalValve.htm.

**Interface**

**Ports**

- pa, pb  Both terminals of the valve.

**Causality**

- preferred effort out pa
- preferred effort out pb

**Inputs**

- spoolpos  position of the spool valve
  spoolpos < 0.5 => valve is closed
spoolpos >= 0.5 => valve is open

**Parameters**

TwoTwoWayDirectionalValve

\( Q_{nom} \)

Nominal flow at nominal pressure per edge, spool in the open position [m3/s], \( Q_{nom} > 0 \).

TwoTwoWayDirectionalValve

\( Q_{Leak} \)

Leakage flow at nominal pressure per edge [m3/s], \( Q_{Leak} > 0 \).

TwoTwoWayDirectionalValve

\( p_{nom} \)

Nominal pressure per edge [Pa], \( p_{nom} > 0 \).

TwoTwoWayDirectionalValve

\( \text{overlap} \)

Valve overlap as percentage of full stroke, \(-1 < \text{overlap} < 1\).

TwoTwoWayDirectionalValve

\( f \)

Bandwidth of the spool dynamics [Hz], \( f > 0 \).

TwoTwoWayProportionalValve

\( V_a \)

Volume of oil under pressure [m3] (hidden)

\( V_a \)

Effective bulk modulus [Pa] (hidden)

\( p_{initial} \)

The starting pressure of the volume [Pa] (hidden)

\( V_b \)

Volume of oil under pressure [m3] (hidden)

\( V_b \)

Effective bulk modulus [Pa] (hidden)

\( p_{initial} \)

The starting pressure of the volume [Pa] (hidden)

**TwoTwoWayProportionalValve-States**

**Library**

Iconic Diagrams\Hydraulics\Valves

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Hydraulics).
**Description**

This model describes a 2/2-way proportional control valve with second order spool dynamics and parasitic volumes. The flow through the valve is described as laminar/turbulent flow through an orifice. A detailed description of the valve can be found in TwoTwoWayProportionalValve.htm.

**Interface**

**Ports**
- pa, pb

**Causality**
- preferred effort out pa
- preferred effort out pb

**Inputs**
- spoolpos
  - position of the spool valve: 0 = closed, 1 = open
  - 0 <= spoolpos <= 1

**Parameters**
- Q_nom: Nominal flow at nominal pressure per edge, spool in the open position [m3/s], Q_nom > 0.
- Q_leak: Leakage flow at nominal pressure per edge [m3/s], Q_leak > 0.
- p_nom: Nominal pressure per edge [Pa], p_nom > 0.
- overlap: Valve overlap as percentage of full stroke, -1 < overlap < 1.
- f: Bandwidth of the spool dynamics [Hz], f > 0.
- Va\V: Volume of oil under pressure [m3] (hidden)
- Va\B: Effective bulk modulus [Pa] (hidden)
- Va\p_initial: The starting pressure of the volume [Pa] (hidden)
Vb\V
Vb\B
Vb\p_initial

Volumes

Accumulator

Library
Iconic Diagrams\Hydraulic\Volumes

Use

Description
Accumulators consist of a gas filled chamber, pressurized by an oil filled chamber. The chambers are separated by a bladder or piston. If oil enters the chamber the gas chamber will reduce in size and the pressure will rise. If the oil pressures sinks, the gas chamber will expand and drive oil out of the oil chamber. The accumulator thus acts as a storage of hydraulic energy. Most accumulators are filled with nitrogen gas which is also used in this model. You can change to other gasses by changing the gas parameters.
Use
When preparing an accumulator for use with the oil at ambient pressure, the gas is pre-charged to a certain pressure $p_{pr}$. The gas chamber will expand its maximum size which is called the accumulator volume $V$. During operation, oil will flow into the chamber and the gas chamber will change size. The oil and gas pressure will be in balance and indicated with the gas pressure $p_{gas}$. The resulting gas volume is name $V_{gas}$. We assume that during pre-charging the gas temperature is constant and equal to the ambient temperature $T_{amb}$. During operation, the gas temperature may change but the ambient temperature is assumed constant.

Thermal Model
Due to compression, the gas temperature will increase and the accumulator will heat up. This heat may be lost to the environment. In this model the heat loss is modeled by a first order transfer function using a thermal time constant $tau$. If the accumulator is heated up and the gas keeps its volume, an exponential temperature decrease will be found. The thermal time constant is the time where the temperature is decreased by 63%. However, the gas will be compressed if the temperature sinks. As a rule of thumb take for the thermal time constant the time it takes for the temperature to sink by 50%. By making $tau$ infinite, the accumulator does not convert heat to the environment. The change in gas volume is then called adiabatic expansion or compression. By making $tau$ very small, the accumulator instantly convert all heat to the environment. The change in gas volume is then called isothermal expansion or compression.
**Gas Laws**

The accumulator model is based on the Van der Waals equation for a real gas. This model takes into account that gas gas particles have finite size and attractive forces. The Van der Waals model uses the critical gas temperature $T_{cr}$ and the critical gas pressure $p_{cr}$ as parameters. By taking the parameter $T_{cr} = 0$ the Van der Waals model changes into the ideal gas model.

By changing the parameters, the accumulator model can represent various gas models:

1) Ideal Gas: set $T_{cr} = 0$
2) Ideal Gas, Adiabatic Expansion: set $T_{cr} = 0$ and $tau$ very large (i.e. $1.0e9$)
3) Ideal Gas, Isothermal Expansion: set $T_{cr} = 0$ and $tau$ very small (i.e. $1.0e-9$)
4) Real Gas: set the critical temperature of the gas (i.e. nitrogen: $T_{cr} = 126.2$ [K]) and set the thermal time constant to a specific value

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>hydraulic port</td>
</tr>
</tbody>
</table>

**Causality**

fixed volume flow

**out**

**Parameters**

- $G$: conductance of the accumulator input [m3/s.Pa].
- $V$: max gas volume of the accumulator [m3]
- $p_{pr}$: pre-charge pressure [Pa]
- $p_{oil}$: oil pressure at the start [Pa]
- $T_{amb}$: ambient temperature [K]
- $tau$: thermal time constant [s]
- $R_s$: specific gas constant [J/kg.K]
- $c_v$: specific heat of the gas at constant volume [J/kg.K]
- $T_{cr}$: critical gas temperature [K]
- $p_{cr}$: critical gas pressure [Pa]

**External Leakage**

**Library**

Iconic Diagrams\Hydraulic\Volumes

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Hydraulics).

**Description**

This model represents a leakage path to the tank with the leakage is modeled as laminar flow. The tank has a preload pressure against atmosphere. The default preload pressure of 0 [Pa] means that the tank has atmospheric pressure.
## Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Causality: fixed volume flow out p</td>
</tr>
</tbody>
</table>

### Parameters

- `p_tank`: tank pressure [Pa], `p_tank` $\geq 0$.
- `Q_leak`: Leakage flow at nominal pressure drop [m³/s·Pa], `Q_nom` > 0.
- `p_nom`: Nominal pressure drop [Pa], `p_nom` > 0.

## ParasiticVolume

### Library

Iconic Diagrams\Hydraulic\Volumes

### Use

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Hydraulics).

### Description

This model represents a tiny volume (default: 1 ml) if the causality of the port is pressure out, and a zero flow, if the causality is flow out:

- **Pressure out:** Volume of 1 ml
- **Flow out:** flow source with 0 {m³/s} flow.

A parasitic volume is a tiny volume that can be added to elements to make them more easy to simulate. Some elements require a pressure as input variable. Coupling two such elements leads to a mathematical problem: both yield a volume flow as function of the input pressure. Adding a parasitic volume in between will solve the mathematical problem (the parasitic volume calculates the pressure) without changing the dynamics much (the volume is small).

The parasitic element has a likes causality. If two parasitic volumes are coupled, one of them will get a pressure out causality (representing a tiny volume) and the other will get a flow out causality (representing a zero flow). I.e only one of them is a volume and the other becomes ineffective.

**Note:** If you want an element to have a specific volume, do not use the parasitic volume! In case of a flow out causality it will be replaced by a 0 flow (e.g. ero volume). Use the volume element instead.

### Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
</table>
p

Causality
likes pressure out

Parameters (hidden)
V Volume of oil under pressure [m3].
p_initial The starting pressure of the volume [Pa], (hidden).

Tank

Library
Iconic Diagrams\Hydraulic\Volumes
Use
Description
This model represents a tank with a preload pressure against atmosphere. A default tank pressure of 0 [Pa] means that the tank has atmospheric pressure.

Interface

Ports Description
p

Causality
fixed pressure out
Parameters
p_tank tank pressure [Pa], p_tank >= 0.

Volume

Library
Iconic Diagrams\Hydraulic\Volumes
Use
Description
This model represents a lumped volume with a constant bulk modulus. If the calculated pressure falls below the vapour pressure the pressure is NOT limited to the vapour pressure.

Interface

Ports Description
\( p \)

**Causality**  
preferred  
pressure out

**Parameters**

\( V \)  
Volume of oil under pressure \([\text{m}^3]\)

\( p_{\text{initial}} \)  
The starting pressure of the volume \([\text{Pa}]\)

### 11.2.4 Mechanical

**Mechanical**

The Mechanical library contains components which are very useful for modeling mechanical systems. The library contains the following sections:

- Mechanics
  - Rotation
    - Actuators
    - Components
  - Friction
    - Gears
    - Sensors
  - Translation
    - 2D Small Rotation
    - 3D Small Rotation
    - Actuators
    - Components
    - Friction
    - Sensors
    - Transmission
**Rotation**

**Actuators**

**AccelerationActuator-Relative**

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**
Domains: Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Rotation), Block Diagrams.

**Description**
This model represents an ideal actuator. An angular acceleration input signal is integrated to an angular velocity difference between its two terminals:

\[
p_{\text{high}}.\omega = p_{\text{low}}.\omega + \text{int}(\alpha,\omega_{\text{initial}}); \\
\]

\[
p_{\text{low}}.T = p_{\text{high}}.T = \text{indifferent};
\]

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>p_high, p_low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both terminals of the Rotation port p.</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

fixed angular velocity out

**Input**

<table>
<thead>
<tr>
<th>alpha</th>
<th>Angular acceleration [rad/s²].</th>
</tr>
</thead>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>omega_initial</th>
<th>Initial angular velocity output of the integration [rad/s].</th>
</tr>
</thead>
</table>

**AccelerationActuator**

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**
Domains: Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Rotation), Block Diagrams.

**Description**
This model represents an ideal actuator. An angular acceleration input signal is integrated to an angular velocity at the rotation port. The actuator is mounted to the fixed world:
\[ p.\omega = \text{int}(\alpha, \omega_{\text{initial}}); \]
\[ p.T = \text{indifferent}; \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed angular velocity out

**Input**

| alpha     | Angular acceleration $[\text{rad/s}^2]$. |

**Parameters**

| omega_initial | Initial angular velocity at the port $[\text{rad/s}]$. |

---

**ACMotor-TorqueLoop.em**

**Note**

This model was named ServoMotor.emx in previous versions of 20-sim!

**Library**

Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation).

**Description**

Industrial servo motors in the medium to high power range generally consist of an AC-electric and drive (the digital controlled current supply of the motor). The drive takes care of the correct supply of current to let the motor follow every desired path. Unfortunately the exact implementation and performance of drives and motors is one of the trade secrets of the commercial motor suppliers. Fortunately modern servo-motors are designed well enough to be described by general parameters that can be found in every data sheet.
The servo motor model describes a digitally controlled AC-motor that is described by general parameters. The model is suited for modeling machine dynamics, i.e. models where the machine behavior is the topic of interest and not the motor itself. For studying the exact motor behavior (temperature, wear, vibration etc.) other motor models should be used. A complete description of the motor is given in the second part of this topic.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**

<table>
<thead>
<tr>
<th>Preferred angular velocity out p</th>
</tr>
</thead>
</table>

**Inputs**

<table>
<thead>
<tr>
<th>velocity setpoint [rad/s]</th>
</tr>
</thead>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Maximum motor speed (&gt;0) [rad/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum allowed acceleration (&gt;0) [rad/s²]</td>
</tr>
<tr>
<td>Bandwidth drive (half of the sample frequency, &gt;0) [Hz]</td>
</tr>
<tr>
<td>Proportional gain []</td>
</tr>
<tr>
<td>Integral time constant (&gt;0) [s]</td>
</tr>
<tr>
<td>Tracking time constant (&gt;0) [s]</td>
</tr>
<tr>
<td>Maximum motor torque (&gt;0) [Nm]</td>
</tr>
<tr>
<td>Motor speed where torque gain starts to drop (&gt;0) [rad/s]</td>
</tr>
<tr>
<td>Torque gain at zero motor speed (&gt;0, choose equal to 1 to turn off torque gain drop [])</td>
</tr>
<tr>
<td>Bandwidth drive and motor electronics [Hz]</td>
</tr>
<tr>
<td>Motor inertia [kg.m²/rad]</td>
</tr>
</tbody>
</table>

**Variables**

There are some variables that can be of interest when inspecting the servo performance:

| The error between setpoint and motor velocity [rad/s]. |
| Motor Angle [rad] |
| Motor Speed [rad/s] |
| Motor Acceleration [rad/s²] |
| Output Torque [Nm]. |
| Output Power [W]. |
Model

The complete servo motor model is shown below. Every block that is used to form this model will be explained in the next sections. The model has a velocity input signal \( v \) and a rotary output port \( p \).

```
<table>
<thead>
<tr>
<th>y</th>
<th>VelocityLimit</th>
<th>AccelerationLimit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>PI</td>
<td>TorqueSensor</td>
</tr>
<tr>
<td>MV</td>
<td>Op</td>
<td>TorqueActuator</td>
</tr>
<tr>
<td>PI</td>
<td>PowerSensor</td>
<td></td>
</tr>
</tbody>
</table>
```

The servo motor model can be used in a machine model as shown in the example below.

```
<table>
<thead>
<tr>
<th>SP</th>
<th>ServoMotor</th>
<th>Load</th>
<th>Bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>setpoint</td>
<td>rotary output port</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

Blocks

Velocity Limit

Most servo motors have a velocity limit to prevent the motor from damage. This limit can be set in the velocity VelocityLimit block. If no limit is known choose twice the nominal velocity.

Acceleration Limit

To prevent the motor from damage, most servos have a maximum acceleration limit. This limit is very important in a model because it can seriously degrade the system's performance.

To find the acceleration, the derivative of the input must be calculated. This is done by means of a first order differentiation with bandwidth \( f_c \). The bandwidth is equal to one half the of the sample frequency of the velocity control loop. Older drives may have loops that run on sample frequencies ranging from 100 Hz to 500 Hz. Modern drives can run the velocity control loop on sample frequencies of 2 kHz or more.
To switch the maximum acceleration limit off, choose the maximum acceleration parameter high enough and choose the bandwidth sufficiently high, preferably 10 times as large as the bandwidth $f_e$ of the motor electronics (specified in the motor dynamics block).

**PI-Controller**

Most servos will use velocity as the setpoint signal. To calculate the desired torque out of the velocity setpoint, PI-controllers are widely used. For many servos, the controller parameters can be changed by the user, but this is not a very easy task. Therefore these servos often offer automatic tuning facilities.

In 20-sim you can use the Optimization toolbox for automatic tuning. A good starting point is to take the error variable of the PI-controller and minimize it by changing the controller parameters $K_p$, $T_i$ and $T_a$. It is important to realize that automatic tuning will tune the controller parameters for a certain task. If you run another task, i.e. perform a simulation with another setpoint, the results may degrade. For varying tasks it is better to use parameters the give a good response over a wide area of loads. To help the user find good starting values, the table below shows some motors, loads and corresponding starting value for the controller parameters.

<table>
<thead>
<tr>
<th>Motor Power</th>
<th>Nominal Torque [Nm]</th>
<th>Nominal Speed [rpm]</th>
<th>Peak Torque [Nm]</th>
<th>Load + Motor Inertia [kg.m²]</th>
<th>Kp</th>
<th>Ti</th>
<th>Ta</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>1.2</td>
<td>3000</td>
<td>4.6</td>
<td>0.005</td>
<td>250</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>1.13</td>
<td>3.6</td>
<td>3000</td>
<td>14</td>
<td>0.002</td>
<td>1000</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>7.54</td>
<td>24</td>
<td>3000</td>
<td>134</td>
<td>0.1</td>
<td>5000</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.1</td>
<td>36</td>
<td>3000</td>
<td>90</td>
<td>0.4</td>
<td>15000</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>55</td>
<td>177</td>
<td>3000</td>
<td>631</td>
<td>2</td>
<td>750000</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>560</td>
<td>1792</td>
<td>3000</td>
<td>6092.8</td>
<td>25</td>
<td>7500000</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

The user has to find the load that should be driven in terms of the rotational inertia. If there is a gear that changes the rotary motion to a linear motion this means the load has to be divided by the square of the gear ratio to get the corresponding load in the rotational domain. Do not forget to add the inertia of the motor itself! For many gear ratios the load in terms of rotational inertia will be of the same magnitude as the motor inertia.

In this model PI-controller with an anti-windup facility is used. This controller is the heart of the servo motor model. It is therefore important to know something about PI-control. More information can be found in the PID controllers section of the library.

AC-motors have a limited output torque which is a complex function of the controller settings, the applied speed, duty cycle, temperature and more. In the servo motor model simply the torque limit of the PI-controller $T_{\text{max}}$ is used which limits the generated torque to a maximum. Because this is a simplification of the real behavior, the maximum torque limit should only be used to inspect what happens to the system when the motor torque is approaching its maximum value. For a proper evaluation of its system, the user should also look at the unconstrained torque. Run a simulation and note the amount of time that the motor runs at a maximum torque. This is called the duty cycle. Every motor manual will have tables showing duty cycles and the corresponding chances of overheating.
Torque Gain

Standard AC-motors, normally designed to run at base speeds between 850 to 3500 rpm, are not particularly well suited for low-speed operation, as their efficiency drops with the reduction in speed. They may also be unable to deliver sufficient smooth torque at low speeds.

An ideal motor will always have a torque gain of 1, i.e. an input signal of 1 Nm will always result in an output torque of 1 Nm. Most industrial motors have a torque gain that is only equal to 1 for higher speeds. At low speeds the torque gain will drop due to electronic limitations. This behavior is represented by the graph below. At speeds below a drop-off speed $v_d$ the torque gain drops linearly to a user defined zero speed torque gain $g_0$. If no torque gain drop is desired, choose $g_0$ equal to 1.

Motor Dynamics

The electrical circuits of the drive and wiring of the motor have a limited bandwidth. This is modeled with a first order low-pass filter with a bandwidth $f_e$. Typical motor bandwidths vary from 3 kHz to 20 kHz.

Torque source

In the torque source block the torque signal is converted to an iconic diagram port $p$.

Inertia

This block describes the rotor inertia. The equations of motion of the inertia are used to get the angular acceleration without needing derivatives.

Sensors
Finally four sensors are available to plot the position, velocity, acceleration and output power.

**Variables**
There are some variables in the model that may be of special interest

- **PI\(\text{error}\)**: The error between setpoint and motor velocity [rad/s].
- **PositionSensor\(\phi\)**: Motor Angle [rad].
- **VelocitySensor\(\omega\)**: Motor Speed [rad/s].
- **Inertia\(\alpha\)**: Motor Acceleration [rad/s²].
- **PowerSensor\(T\)**: Output Torque [Nm].
- **PowerSensor\(P\)**: Output Power [W].

All these variables are output signals of their respective blocks. By inserting extra outputs in the servo motor model you can use as output signals for usage in other parts of your model. In the pictures below is shown how to define signals for the torque and power.

---

In the servo model define a torque and a power output and connect them.

---

One level higher you can use these signals for modeling, for example in a high level control unit.
ACMotor

Library
Iconic Diagrams\Mechanical\Rotation\Actuators

Use

Description
This is a model of an industrial AC electric motor with squirrel cage rotor. The motor is not controlled by a power electric convertor. Instead its performance is directly defined by a torque speed curve.

The torque speed curve is fully defined by the parameters shown in the picture. The synchronous speed is defined as:

\[ n = 2 \times \text{voltage frequency} / \text{no. of poles} \]

Interface

Ports
p
Output axis (Rotation)

Parameters
Ts
start torque (zero speed) [Nm]
n
synchronous speed (zero torque) [rad/s]
Tm
maximum torque [Nm]
nm
speed at maximum torque [rad/s]
Tf
full load torque [Nm]
nf
speed at full load torque [rad/s]
J
motor inertia [kgm^2/rad]
DCMotor

Library
Iconic Diagrams\Electric\Actuators
Iconic Diagrams\Mechanical\Electric

Implementations
Default
IR

Use

Description - Default
This models represents an ideal DC-motor with no energy loss. The electric port has separate high and low terminals. The equations are

\[
p1.i = p1\_high.i = p1\_low.i; \\
p1.u = p1\_high.u - p1\_low.u;
\]

The model can have mixed forms of causality

\[
p1.u = k \ast p2.omega; \\
p2.T = k \ast p1.i;
\]

or:

\[
p2.omega = p1.u / k; \\
p1.i = p2.T / k;
\]

Interface - Default

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1_high, p1_low</td>
<td>Both terminals of the Electric port p1.</td>
</tr>
<tr>
<td>p2</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

Causality
mixed

Parameters
k
motor constant [Nm/A]

Description - IR
This models represents an ideal DC-motor with inductance and resistance.
The electric port has separate high and low terminals. The equations are

\[ p1.i = p1\_high.i = p1\_low.i; \]
\[ p1.u = p1\_high.u - p1\_low.u; \]

**Interface - IR**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1_high, p1_low</td>
<td>Both terminals of the Electric port p1.</td>
</tr>
<tr>
<td>p2</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**

mixed

See equations above.

**Parameters**

<table>
<thead>
<tr>
<th>k</th>
<th>motor constant [Nm/A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>motor inductance [H]</td>
</tr>
<tr>
<td>R</td>
<td>motor resistance [Ohm]</td>
</tr>
</tbody>
</table>

**PositionActuator-Relative**

**Library**

Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**

*Domains*: Continuous. *Size*: 1-D. *Kind*: Iconic Diagrams (Rotation), Block Diagrams.

**Description**

This model represents an ideal actuator. An angle input signal is differentiated by a state variable filter to an angular velocity difference between its two terminals:

\[ p\_high.omega = p\_low.omega + dphi/dt; \]
\[ p\_low.T = p\_high.T = indifferent; \]

Differentiation is performed by a state variable filter:
The S-domain function of this filter is equal to:

\[
output = \frac{s}{s + f} \cdot input
\]

where \( f \) is the cut-off frequency. For very high values of \( f \), the output becomes the pure derivative of the input. High values of \( f \), however, increase simulations times. A good trade-off is a starting value of 1e5.

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Rotation port p.</td>
</tr>
</tbody>
</table>

Causality

fixed angular velocity out

Input

phi Angle [rad].

Parameters

f Cut-off frequency of the differentiation [Hz].

omega_initial Initial angular velocity output of the differentiation [rad/s].
**ServoMotor**

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Electric).

**Description**
This is a masked model which opens the Servo Motor Editor when edited. The servo Motor Editor is a tool that can shows the torque speed plots numerous permanent magnet motors and can generate a dynamic model from any motor that you select. The following motor types are supported:

1. Brush DC
2. Brushless DC (trapezoidal EMC and square wave currents)
3. AC synchronous (sinusoidal EMC and sinusoidal currents)
4. AC synchronous linear (sinusoidal EMC and sinusoidal currents)

**Interface**
Depending on the type of motor that you have selected, the interface can vary:

**DC Brush**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**
fixed rotational velocity out

**Input**
i The input current [A]

**DC Brushless**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**
fixed rotational velocity out

**Input**
i The maximum input current [A]
AC Synchronous

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed rotational velocity out

**Input**

i_rms The rms phase current [A]

AC Synchronous Linear

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed velocity out

**Input**

i_rms The rms phase current [A]

For more information on the parameters and variables of this model is referred to the Mechatronic Toolbox.

PositionActuator

**Library**

Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation), Block Diagrams.

**Description**

This model represents an ideal actuator. An angle input signal is differentiated by a state variable filter to an angular velocity at the rotation port. The actuator is mounted to the fixed world:

\[
p.\omega = d\phi/dt; \quad p.T = \text{indifferent};
\]

Differentiation is performed by a state variable filter:
The S-domain function of this filter is equal to:

\[
output = \frac{s}{s + f} \cdot input
\]

where \(f\) is the cut-off frequency. For very high values of \(f\), the output becomes the pure derivative of the input. High values of \(f\), however, increase simulations times. A good trade-off is a starting value of 1e5.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed angular velocity out

**Input**

phi Angle [rad].

**Parameters**

f Cut-off frequency of the differentiation [Hz].

omega_initial Initial angular velocity at the port [m/s].
**Stepper Motor**

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**

**Description**
A stepper motor is a device used to convert electrical pulses into discrete mechanical rotational movements. The minimum movement, invoked by one pulse, is called the step angle. The electrical pulses are mostly generated by a pulse generator that converts a setpoint change in a corresponding amount of pulses. This model describes a combination of a pulse generator and stepper motor.

At standstill the torque required to deflect the motor a full step is called the holding torque. The holding torque normally is much higher than required to drive the load, and thus acts as a strong brake to hold the load. The holding torque as function of the output angle is shown in the graph below. Around zero angle the curves shows the behavior of a spring. By changing the input by one step, the force will increase to its maximum and move the the load.

![Holding Torque Graph](image)

Motor torque as function of the angle (holding torque = 1 [N], step angle = [10°]).

If the subsequent steps are generated fast enough the holding torque will start to decrease. The maximum holding torque as function of the rotation speed is shown in the figure below. This force curve is commonly describe as the pull out curve.
Pull out curve: maximum generated torque as a function of the rotational speed.

**Ports**
- **input**: Desired output angle.
- **p_out**: Rotation port.

**Causality**
- fixed current out
- **p_in**: preferred angular velocity out p_out

**Inputs**
- **input**: Stepper motor input

**Parameters**
- **step_angle**: Minimum change of the output axis [deg].
- **tau**: Time constant coil [s].
- **Th**: Holding torque [Nm].
- **J**: Inertia rotor [Nm^2].
- **B**: Relative damping at the stepper motor resonance [].
- **fmax**: Maximum frequency motor (frequency at which the torque gets zero) [rad/s].
11. Library

**Torque-Relative**

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**

**Description**
This model represents an ideal actuator. The actuator applies a torque between its two terminals. This torque can be set to a certain constant value, the angular velocity is indifferent.

\[ p_{\text{high}}.T = p_{\text{low}}.T = T \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Rotational port p.</td>
</tr>
</tbody>
</table>

**Causality**
fixed torque out

**Input**

| T | Torque [Nm]. |

---

**Torque**

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**

**Description**
This model represents an ideal actuator. The actuator is mounted to the fixed world and applies a torque. The torque can be set to a certain constant value, the angular velocity is indifferent.

\[ p.T = T; \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**
**Parameters**

T \( \text{Torque \ [Nm]} \).
**TorqueActuator**

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**
Domains: Continuous. Size: 1-D. Kind: Iconic Diagrams (Rotation), Block Diagrams.

**Description**
This model represents an ideal actuator. The actuator is mounted to the fixed world and applies a torque. The torque can be set to a (fluctuating) value given by the input signal $T$, the angular velocity is indifferent.

$$p.T = T;$$

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation port.</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

fixed torque out

**Input**

<table>
<thead>
<tr>
<th>Description</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque [Nm].</td>
<td></td>
</tr>
</tbody>
</table>

**Velocity-Relative**

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**

**Description**
This model represents an ideal actuator. The actuator applies an angular velocity difference between its two terminals. This angular velocity can be set to a constant value $\omega$, the force is indifferent.

$$p\_low.\omega = p\_high.\omega + \omega$$

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
</table>

---
p_high, p_low    Both terminals of the Rotation port p.

**Causality**
fixed    angular
velocity out

**Parameter**

\( v \)    Angular velocity \([\text{rad/s}]\).

---

### Velocity

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**
- **Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation).

**Description**
This model represents an ideal actuator. The actuator is mounted to the fixed world and applies an angular velocity. This angular velocity can be set to a certain constant value, the torque is indifferent.

\[ p.\omega = \omega; \]

**Interface**

<table>
<thead>
<tr>
<th><strong>Ports</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**
fixed    angular
velocity out

**Parameters**

\( \omega \)    Angular velocity \([\text{rad/s}]\).

---

### VelocityActuator-Relative

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**
- **Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation), Block Diagrams.
**Description**
This model represents an ideal actuator. The actuator applies an angular velocity difference between its two terminals. This angular velocity can be set to a (fluctuating) value given by the input signal $v$, the force is indifferent.

$$p_{low}.\omega = p_{high}.\omega + \omega$$

**Interface**

**Ports**
- **Description**
  - $p_{high}, p_{low}$: Both terminals of the Rotation port $p$.

**Causality**
- **fixed angular velocity out**

**Input**
- **omega**: Angular velocity [rad/s].

**VelocityActuator**

**Library**
Iconic Diagrams\Mechanical\Rotation\Actuators

**Use**
- **Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation), Block Diagrams.

**Description**
This model represents an ideal actuator. The actuator is mounted to the fixed world and applies an angular velocity. This angular velocity can be set to a (fluctuating) value given by the input signal $omega$, the torque is indifferent.

$$p.\omega = \omega;$$

**Interface**

**Ports**
- **Description**
  - $p$: Rotation port.

**Causality**
- **fixed angular velocity out**

**Input**
omega  Angular velocity [rad/s].

**Components**

**Backlash**

**Library**
Iconic Diagrams\Mechanical\Rotation\Components

**Use**

**Description**
This model represents backlash by a spring damper system equivalent to the translational backlash model. The port p of this model has separate high and low terminals. The equations are:

\[
\begin{align*}
  p.T &= p_{\text{high}}.T = p_{\text{low}}.T \\
  p.\omega &= p_{\text{high}}.\omega - p_{\text{low}}.\omega
\end{align*}
\]

**Interface**

**Ports**

**Description**
Both terminals of port p (Rotation).

**Causality**
fixed torque out

**Parameters**

<table>
<thead>
<tr>
<th>s</th>
<th>Interval of the play [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>k1</td>
<td>Stiffness in the play [Nm/rad]</td>
</tr>
<tr>
<td>k2</td>
<td>Stiffness outside the play [Nm/rad]</td>
</tr>
<tr>
<td>d1</td>
<td>Damping inside the play [Nms/rad]</td>
</tr>
<tr>
<td>d2</td>
<td>Damping outside the play [Nms/rad]</td>
</tr>
<tr>
<td>ep</td>
<td>Relative round off (1e-6 -&gt; sharp edges, 1e-2 -&gt; smoother)</td>
</tr>
</tbody>
</table>

| x_initial | Initial position in the play [rad], -s/2 < x_initial < s/2 |
Bearing

Library
Iconic Diagrams\Mechanical\Rotation\Components

Use

Description
In this model bearing friction is represented as linear viscous friction. The model has only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc. 20-sim will automatically create equations such that the resulting torque $p.T$ is equal to the sum of the torques of all connected ports p1 .. pn. The angular velocities of all connected ports are equal to $p.omega$. The model can have an torque out as well as an angular velocity out causality. In the last case the constitutive equation, as shown below, is simply inverted:

$$p.T = \text{sum}(p1.T, p2.T, \ldots)$$
$$p.omega = p1.omega = p2.omega = \ldots$$

Torque out causality:

$$p.T = d \times p.omega;$$

Angular velocity out causality:

$$p.omega = p.T / d;$$

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Rotation).</td>
</tr>
</tbody>
</table>

Causality
indifferent

Parameters

d   Damping [Nms/rad]

Brake

Library
Iconic Diagrams\Mechanical\Rotation\Components

Implementations
C
11. Library

Use

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Rotation).

**Introduction**

The brake models represent a disk brake or other type of brake where a rotation is stopped by applying a friction force. The amount of friction depends on the normal force that is applied and the friction function that is used. The normal force is given by the input signal $F_n$. The brake is mounted to the fixed world.

![Diagram](image)

The model has only one initial port $p$ defined. Because any number of connections can be made, successive ports are named $p1$, $p2$, $p3$ etc. 20-sim will automatically create equations such that the resulting torque $p.T$ is equal to the sum of the torques of all connected ports $p1 .. pn$. The angular velocities of all connected ports are equal to $p.omega$.

$$p.T = \text{sum}(p1.T, p2.T, ....)$$

$$p.omega = p1.omega = p2.omega = ....$$

Due to the use of normal force, the brake models all have a fixed torque out causality. The constitutive equations are therefore described as:

$$p.T = F_n * f(p.omega);$$

with $f$ the friction function.

**Description - C**

This model represents a brake with braking force described as coulomb friction. The brake is mounted to the fixed world. The amount of friction depends on the normal force that is applied:

$$p.T = F_n*mu_c*tanh(slope*p.omega);$$

$F_n$: normal force (given by the input signal $F_n$)
$mu_c$: the coulomb friction coefficient
$slope$: the steepness of the coulomb friction curve.
Interface - C

Ports       Description
p[any]      Any number of connections can be made (Rotation).

Causality
Fixed torque out

Input
Fn          Normal force [N]

Parameters
mu_c        Coulomb friction coefficient [m]
slope       Steepness of Coulomb friction curve [s/rad]

Description - V
This model represents a brake with braking force described as viscous friction. The brake is mounted to the fixed world. The amount of friction depends on the normal force that is applied:

\[ p.T = F_n \times \mu_v \times p.\omega; \]

\( F_n \): normal force (given by the input signal \( F_n \))
\( \mu_v \): the viscous friction coefficient
Interface - V

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Rotation).</td>
</tr>
</tbody>
</table>

Causality
Fixed torque out

Input

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fn</td>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu_v</td>
<td>Viscous friction coefficient [m.s/rad]</td>
</tr>
</tbody>
</table>

Description - CV

This model represents a brake with braking force described as coulomb plus viscous friction. The brake is mounted to the fixed world. The amount of friction depends on the normal force that is applied:

\[ p.T = Fn*(mu_c*tanh(slope*p.omega) + mu_v*p.omega); \]

*Fn*: normal force (given by the input signal Fn)
*mu_v*: the viscous friction coefficient
*mu_c*: the coulomb friction coefficient
*slope*: the steepness of the coulomb friction curve.
Interface - CV

Ports

<table>
<thead>
<tr>
<th>Port</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Rotation).</td>
</tr>
</tbody>
</table>

Causality

Fixed torque out

Input

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fn</td>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu_v</td>
<td>Viscous friction coefficient [ms/rad]</td>
</tr>
<tr>
<td>mu_c</td>
<td>Coulomb friction coefficient [m]</td>
</tr>
<tr>
<td>slope</td>
<td>Steepness of Coulomb friction curve [s/rad]</td>
</tr>
</tbody>
</table>

Description - SCVS

This model represents a brake with braking force described as static plus coulomb plus viscous plus Stibeck friction. The brake is mounted to the fixed world. The amount of friction depends on the normal force that is applied:

\[
p.T = Fn \times ((mu_c + (mu_st*abs(tanh(slope*p.omega))) - mu_c) \\
* exp((-((p.omega / v_st)^2)) * sign(p.omega)) \\
+ mu_v * p.omega)\
\]

\(Fn\): normal force (given by the input signal Fn)
\(mu_s\): the static friction coefficient
\(mu_v\): the viscous friction coefficient
\(mu_c\): the coulomb friction coefficient
\(slope\): the steepness of the coulomb and static friction curve.
\(v_st\): the characteristic Stribeck velocity.
Interface - SCVS

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
</tr>
</tbody>
</table>

**Causality**

Fixed torque out

**Input**

| Fn          | Normal force [N] |

**Parameters**

| mu_s        | Static friction coefficient [m] |
| mu_v        | Viscous friction coefficient [m.s/rad] |
| mu_c        | Coulomb friction coefficient [m] |
| slope       | Steepness of Coulomb friction curve [s/rad] |
| v_st        | Characteristic Striebeck velocity [rad/s] |

**Description - LuGre**

This model represents a brake with braking force described by the LuGre friction model. The brake is mounted to the fixed world. The amount of friction depends on the normal force that is applied:

\[ p.T = FN*f_{lg}(p.omega); \]

*Fn*: normal force (given by the input signal Fn)

*f_{lg}*: the LuGre friction model

**Interface - LuGre**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
</tr>
</tbody>
</table>

**Causality**

Fixed Torque out
11. Library

**Input**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fn</td>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu_c</td>
<td>Coulomb friction coefficient</td>
</tr>
<tr>
<td>mu_s</td>
<td>Static friction coefficient [m]</td>
</tr>
<tr>
<td>mu_v</td>
<td>Viscous friction coefficient [ms/rad]</td>
</tr>
<tr>
<td>v_st</td>
<td>Characteristic Striebeck velocity [rad/s]</td>
</tr>
<tr>
<td>mu_k</td>
<td>Rotational stiffness coefficient at zero speed [m/rad]</td>
</tr>
</tbody>
</table>

**Clutch**

Iconic Diagrams\Mechanical\Rotation\Components

**Implementations**

C
V
CV
SCVS
LuGre

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Rotation).

**Introduction**

The clutch models model represent friction relative to other objects. The amount of friction depends on the normal force that is applied and the friction function that is used. The normal force is given by the input signal *FN*.

![Diagram](image)

The port *p* of the clutch model has separate high and low terminals. The equations are:

\[
    p.T = p_{high}.T = p_{low}.T \\
    p.\omega = p_{high}.\omega - p_{low}.\omega
\]

Due to the use of normal force, the clutch models all have a fixed torque out causality. The constitutive equations are therefore described as:

\[
    p.T = F_n * f(p.\omega);
\]

with *f* the friction function.
Description - C
This model represents bearing with friction force described as coulomb friction. The amount of friction depends on the normal force that is applied and the friction function that is used:

\[ p.T = Tc \cdot \tanh(\text{slope} \cdot p.\omega) \]

*Tc*: coulomb friction  
*slope*: the steepness of the coulomb friction curve.

Interface - C

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>p</em></td>
<td>Both terminals of port <em>p</em> (Rotation).</td>
</tr>
</tbody>
</table>

**Causality**

Fixed torque out

**Input**

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Fn</em></td>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Tc</em></td>
<td>Coulomb friction [N.m]</td>
</tr>
<tr>
<td><em>slope</em></td>
<td>Steepness of Coulomb friction curve [s/rad]</td>
</tr>
</tbody>
</table>

Description - V

This model represents a clutch with friction force described as viscous friction. The amount of friction depends on the normal force that is applied and the friction function that is used:

\[ p.T = Fn \cdot \mu_v \cdot p.\omega \]

*Fn*: normal force (given by the input signal *Fn*)  
*\mu_v*: the viscous friction coefficient
### Interface - V

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of port p (Rotation).</td>
</tr>
</tbody>
</table>

**Causality**

Fixed torque out

**Input**

<table>
<thead>
<tr>
<th>Fn</th>
<th>Normal force [N]</th>
</tr>
</thead>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>mu_v</th>
<th>Viscous friction coefficient [m.s/rad]</th>
</tr>
</thead>
</table>

**Description - CV**

This model represents a clutch with friction force described as coulomb plus viscous friction. The amount of friction depends on the normal force that is applied and the friction function that is used:

\[
p.T = Fn*(Tc*\tanh(slope*p.omega) + mu_v*p.omega);
\]

*Fn*: normal force (given by the input signal Fn)
*mu_v*: the viscous friction coefficient
*Tc*: the coulomb friction coefficient
*slope*: the steepness of the coulomb friction curve.
Interface - CV

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of port p (Rotation).</td>
</tr>
</tbody>
</table>

Causality
Fixed torque out

Input
Fn Normal force [N]

Parameters
mu_v Viscous friction coefficient [m.s/rad]
Tc Coulomb friction [N.m]
slope Steepness of Coulomb friction curve [s/rad]

Description - SCVS
This model represents a clutch with friction force described as static plus coulomb plus viscous plus Stribeck friction. The amount of friction depends on the normal force that is applied and the friction function that is used:

\[ p.T = Fn * \]
\[ (T_c + (mu_st*abs(tanh( slope*p.omega )) - T_c) * exp( -(p.omega / v_st)^2 )) * sign(p.omega) + mu_v * p.omega); \]

Fn: normal force (given by the input signal Fn)
mu_s: the static friction coefficient
mu_v: the viscous friction coefficient
Tc: the coulomb friction coefficient
slope: the steepness of the coulomb and static friction curve.
v_st: the characteristic Stribeck velocity.
Interface - SCVS

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of port p (Rotation).</td>
</tr>
</tbody>
</table>

Causality

Fixed torque out

Input

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fn</td>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu_s</td>
<td>Static friction coefficient [m]</td>
</tr>
<tr>
<td>mu_v</td>
<td>Viscous friction coefficient [m.s/rad]</td>
</tr>
<tr>
<td>Tc</td>
<td>Coulomb friction [N.m]</td>
</tr>
<tr>
<td>slope</td>
<td>Steepness of Coulomb friction curve [s/rad]</td>
</tr>
<tr>
<td>v_st</td>
<td>Characteristic Striebeck velocity [rad/s]</td>
</tr>
</tbody>
</table>

Description - LuGre

This model represents a clutch with friction force described by the LuGre friction model. The amount of friction depends on the normal force that is applied and the friction function that is used:

\[ p.T = FN \times f_{\text{lg}}(p.\omega); \]

Fn: normal force (given by the input signal Fn)
f_{lg}: the LuGre friction model

Interface - LuGre

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of port p (Rotation).</td>
</tr>
</tbody>
</table>

Causality

Fixed torque out
Input
Fn   Normal force [N]

Parameters
Tc   Coulomb friction coefficient
mu_s Static friction coefficient [m]
mu_v Viscous friction coefficient [m.s/rad]
v_st Characteristic Strubeck velocity [rad/s]
mu_k rotational stiffness coefficient at zero speed [m/rad]

Damper

Library
Iconic Diagrams\Mechanical\Rotation\Components

Use

Description
This model represents a linear damper. It can have an torque out as well as an angular velocity out causality. In the last case the constitutive equation, as shown below, is simply inverted. The port $p$ of the damper model has separate high and low terminals. The equations are:

\[
 p.T = p_{high}.T = p_{low}.T \\
 p.\omega = p_{high}.\omega - p_{low}.\omega
\]

Torque out causality:

\[
 p.T = d \times p.\omega;
\]

Angular velocity out causality:

\[
 p.\omega = p.T / d;
\]

Interface

Ports    Description
p_high, p_low Both terminals of the Rotation port $p$.

Causality
indifferent

Parameters
d   damping [Nms/rad]
FixedWorld

Library
Iconic Diagrams\Mechanical\Rotation\Components

Use

Description
This model represents the fixed world (angular velocity = 0). The model has only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc. which gives the constitutive equations:

\[ p1.\omega = p2.\omega = \ldots = pn.\omega = 0; \]
\[ p1.T = \text{free}; p2.T = \text{free}; \ldots; pn.T = \text{free}; \]

Interface

Ports Description
p [any] Any number of connections can be made.

Causality
Fixed angular All ports have a fixed angular velocity out causality.
velocity out

Friction

Library
Iconic Diagrams\Mechanical\Rotation\Components

Implementations
C
V
CV
SCVS
LuGre

Use

Introduction
The friction model represent bearing friction with various friction models. The model have only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc. 20-sim will automatically create equations such that the resulting force \( p.F \) is equal to the sum of the forces of all connected ports \( p1 \ldots pn \). The velocities of all connected ports are equal to \( p.v \).
\[ p.F = \text{sum}(p1.F, p2.F, \ldots) \]
\[ p.v = p1.v = p2.v = \ldots \]

**Description - C**

This model represents a bearing with friction torque described as coulomb friction:

\[ p.T = Tc*tanh(slope*p.omega); \]

*Tc*: the coulomb friction

*slope*: the steepness of the coulomb friction curve.

**Interface - C**

**Ports**

*p*[any] Any number of connections can be made (Rotation).

**Causality**

Fixed torque out

**Parameters**

*Tc* Coulomb friction [N.m]

*slope* Steepness of Coulomb friction curve [s/rad]

**Description - V**

This model represents a bearing with friction force described as viscous friction:

\[ p.T = d*p.omega; \]

*d*: the viscous damping
Interface - V

Ports
p[any]  Any number of connections can be made (Rotation).

Causality
Fixed torque out

Input
Fn  Normal force [N]

Parameters
d  Viscous friction torque or damping [N.m.s/rad]

Description - CV
This model represents a bearing with friction force described as coulomb plus viscous friction:

\[ p.T = T_c \tanh(slope \cdot p.\omega) + d \cdot p.\omega; \]

\( d \): the viscous damping
\( T_c \): the coulomb friction
\( slope \): the steepness of the coulomb friction curve.
Interface - CV

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>p[any]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any number of connections can be made (Rotation).</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

Fixed torque out

**Input**

<table>
<thead>
<tr>
<th>Description</th>
<th>Fn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal force [N]</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>mu_v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscous damping [N.m.s/rad]</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Tc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coulomb friction [N.m]</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steepness of Coulomb friction curve [s/rad]</td>
<td></td>
</tr>
</tbody>
</table>

**Description - SCVS**

This model represents a bearing with friction force described as static plus coulomb plus viscous plus Stribeck friction:

\[
p.T = (( Tc + (Tst\cdot\text{abs}(\tanh(\text{slope}\cdot p.\omega))) - Tc) \cdot \exp(-((p.\omega / v.st)^2)) \cdot \text{sign}(p.\omega) + d \cdot p.\omega);\]

- **Tst**: the static friction
- **d**: the viscous damping
- **Tc**: the coulomb friction
- **slope**: the steepness of the coulomb and static friction curve.
- **v_st**: the characteristic Stribeck velocity.

![Friction force vs Sliding velocity graph]
Fixed torque out

**Input**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fn</td>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tst</td>
<td>Static friction torque [N.m]</td>
</tr>
<tr>
<td>d</td>
<td>Viscous friction torque or damping [N.m.s/rad]</td>
</tr>
<tr>
<td>Tc</td>
<td>Coulomb friction [N.m]</td>
</tr>
<tr>
<td>slope</td>
<td>Steepness of Coulomb friction curve [s/rad]</td>
</tr>
<tr>
<td>v_st</td>
<td>Characteristic Stribeck velocity [rad/s]</td>
</tr>
</tbody>
</table>

**Description - LuGre**

This model represents a bearing with friction force described by the LuGre friction model:

\[ p.T = f_{lg}(p.omega); \]

*f_{lg}*: the LuGre friction model

**Interface - LuGre**

**Ports**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Rotation).</td>
</tr>
</tbody>
</table>

**Causality**

Fixed torque out

**Input**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fn</td>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tc</td>
<td>Coulomb friction [N.m]</td>
</tr>
<tr>
<td>Tst</td>
<td>Static friction torque [m]</td>
</tr>
<tr>
<td>d</td>
<td>Viscous damping [N.m.s/rad]</td>
</tr>
<tr>
<td>v_st</td>
<td>Characteristic Stribeck velocity [rad/s]</td>
</tr>
<tr>
<td>c</td>
<td>Stiffness at zero speed [N.m/rad]</td>
</tr>
</tbody>
</table>
Inertia

Library
Iconic Diagrams\Mechanical\Rotation\Components

Use

Description
This model represents an ideal rotational inertia. The element has a preferred angular velocity out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred torque out causality. The constitutive equations then contain a derivation. The model has only one initial port \( p \) defined. Because any number of connections can be made, successive ports are named \( p_1, p_2, p_3 \) etc. 20-sim will automatically create equations such that the resulting torque \( p.T \) is equal to the sum of the torques of all connected ports \( p_1..p_n \) and that the angular velocities of all connected ports is equal to \( p.omega \).

\[
p.T = \text{sum}(p_1.T, p_2.T, ....)
p.omega = p_1.omega = p_2.omega = ....
\]

angular velocity out causality (preferred):

\[
alpha = \frac{p.T}{J};
p.omega = \text{int}(alpha);
phi = \text{int}(p.omega);
\]

torque out causality:

\[
alpha = \text{ddt}(p.omega);
p.T = J*alpha;
phi = \text{int}(p.omega);
\]

Interface

Ports
\( p[\text{any}] \) Any number of connections can be made (Rotation).

Causality
preferred angular velocity out An torque out causality results in a derivative constitutive equation.

Variables
\( \phi \) angle [rad]
\( \alpha \) angular acceleration [rad/s^2]

Parameters
\( J \) moment of inertia [kgm^2]
**Initial Values**

- p.omega_initial  
  The initial velocity of the inertia [rad/s].
- phi_initial  
  The initial angle of the inertia [rad].

**Node**

**Library**

Iconic Diagrams\Mechanical\Rotation\Components

**Use**

- **Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation).

**Description**

This node model represents a structural connection between two (or more) shafts, where the velocity of all connected shafts is equal. The model has only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p [any]</td>
<td>Any number of connections can be made (Rotation).</td>
</tr>
</tbody>
</table>

**Spring**

**Library**

Iconic Diagrams\Mechanical\Rotation\Components

**Use**

- **Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation).

**Description**

This model represents an ideal rotational spring. The element has a preferred torque out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred angular velocity out causality. The constitutive equations then contain a derivation. The port p of the spring model has separate high and low terminals. The equations are:

\[
p.T = p\_high.T = p\_low.T \]
\[
p.omega = p\_high.omega - p\_low.omega \]

Torque out causality (preferred):
\[ \phi = \text{int}(p.\omega); \]
\[ p.T = c \times \phi; \]

angular velocity out causality:

\[ p.\omega = \text{ddt}(\phi); \]
\[ \phi = \frac{p.T}{k}; \]

**Interface**

**Ports**

p\_high, p\_low

Both terminals of the Rotational port p.

**Causality**

preferred torque out

An angular velocity out causality results in a derivative constitutive equation.

**Variables**

phi
torsion of the spring [rad]

**Parameters**

c
Stiffness [Nm/rad]

**Initial Values**

phi\_initial
The initial torsion of the spring [rad].

**SpringDamper**

**Library**

Iconic Diagrams\Mechanical\Rotation\Components

**Implementations**

Default
Stiffness
Frequency

**Use**


**Description - Default**

This model represents an ideal rotational spring with damper. The element has a preferred torque out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred angular velocity out causality. The constitutive equations then contain a derivation. The port p of the spring model has separate high and low terminals. The equations are:

\[ p.T = p\_high.T = p\_low.T \]
\[ p.\omega = p\_high.\omega - p\_low.\omega \]

Torque out causality (preferred):
\[
\begin{align*}
\phi &= \text{int}(p.\omega); \\
p.T &= c \times \phi + d*p.\omega;
\end{align*}
\]
Angular velocity out causality:

\[
\begin{align*}
p.\omega &= \text{ddt}(\phi); \\
\phi &= (p.T - d*p.\omega)/c;
\end{align*}
\]

**Interface - Default**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high</td>
<td>Two ports of the spring (Rotation).</td>
</tr>
<tr>
<td>p_low</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

preferred torque out

An angular velocity out causality results in a derivative constitutive equation.

**Variables**

| phi  | torsion of the spring [rad] |

**Parameters**

| c     | Rotational stiffness [Nm /rad] |
| d     | Damping [Nms/rad] |

**Initial Values**

| phi_initial | The initial torsion of the spring [rad]. |

**Description - Stiffness**

This model represents an ideal rotational spring with damper. The damping value \(d\) is calculated on the basis of a known stiffness \(c\), relative damping \(b\) and reference inertia \(J\). The inertia is only used to compute the damping (no actual mass is used in this component).

The element has a preferred torque out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred angular velocity out causality. The constitutive equations then contain a derivation. The port \(p\) of the spring model has separate high and low terminals. The equations are:

\[
\begin{align*}
p.T &= p\text{\_high}.T = p\text{\_low}.T \\
p.\omega &= p\text{\_high}.\omega - p\text{\_low}.\omega
\end{align*}
\]

Torque out causality (preferred):

\[
\begin{align*}
\phi &= \text{int}(p.\omega); \\
p.F &= c \times \phi + d*p.\omega; \\
d &= 2*b*\text{sqrt}(c*J);
\end{align*}
\]

Angular velocity out causality:
\[
p.\omega = ddt(\phi);
\]
\[
\phi = (p.T - d*p.\omega)/c;
\]
\[
d = 2*b*sqrt(c*J);
\]

**Interface - Stiffness**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high</td>
<td>Two ports of the spring (Rotation).</td>
</tr>
<tr>
<td>p_low</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

- preferred torque out
  - An angular velocity out causality results in a derivative constitutive equation.

**Variables**

- \(\phi\): torsion of the spring [rad]
- \(d\): damping [Nms/rad]

**Parameters**

- \(c\): Rotational stiffness [Nm /rad]
- \(b\): Relative damping []
- \(J\): Moment of inertia [kgm^2]

**Initial Values**

- \(\phi_{\text{initial}}\): The initial torsion of the spring [rad].

**Description - Frequency**

This model represents an ideal rotational spring with damper. The stiffness \((c)\) is calculated on basis of a known resonance frequency \((f)\). The damping value \((d)\) is calculated on the basis of the stiffness, relative damping \((b)\) and reference inertia \((J)\). The inertia is only used to compute the damping (no actual mass is used in this component).

The element has a preferred torque out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred angular velocity out causality. The constitutive equations then contain a derivation. The port \(p\) of the spring model has separate high and low terminals. The equations are:

\[
p.T = p\_\text{high}.T = p\_\text{low}.T
\]
\[
p.\omega = p\_\text{high}.\omega - p\_\text{low}.\omega
\]

Torque out causality (preferred):

\[
\begin{align*}
\phi &= \text{int}(p.\omega); \\
p.T &= c \times \phi + d*p.\omega; \\
c &= J*(2*pi*f)^2; \\
d &= 2*b*sqrt(c*J);
\end{align*}
\]

Angular velocity out causality:
\[ p.\omega = ddt(\phi); \]
\[ \phi = (p.T - d*p.\omega)/c; \]
\[ c = J*(2*pi*f)^2; \]
\[ d = 2*b*sqrt(c*J); \]

**Interface - Frequency**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high</td>
<td>Two ports of the spring (Rotation).</td>
</tr>
<tr>
<td>p_low</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

- preferred torque out

An angular velocity out causality results in a derivative constitutive equation.

**Variables**

- \( \phi \): torsion of the spring [rad]
- \( c \): rotational stiffness [Nm/rad]
- \( d \): damping [Nms/rad]

**Parameters**

- \( f \): Resonance frequency [Hz]
- \( b \): Relative damping []
- \( J \): Moment of inertia [kgm^2]

**Initial Values**

- \( \phi_{\text{initial}} \): The initial torsion of the spring [rad].

---

**Unbalance**

**Library**

Iconic Diagrams\Mechanical\Rotation\Components

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation).

**Description**

This model represents an unbalanced mass with an offset \( r \) to the axis of rotation and a starting angle \( \phi_{\text{initial}} \).
The mass will act as an inertia $J$ with a gravity induced disturbance torque:

$$J = r^2 \times m;$$

$$\alpha = (p.T + m \times r \times g_n \times \sin(\phi))/ J;$$

$$p.\omega = \text{int} (\alpha);$$

$$\phi = \text{int} (p.\omega, \phi_{\text{initial}});$$

The element has a preferred angular velocity out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred torque out causality. The constitutive equations then contain a derivation. The model has only one rotation port $p$ defined. Because any number of connections can be made, successive ports are named $p1$, $p2$, $p3$ etc. 20-sim will automatically create equations such that the resulting torque $p.T$ is equal to the sum of the torques of all connected ports $p1 .. pn$ and that the angular velocities of all connected ports is equal to $p.\omega$.

$$p.T = \text{sum}(p1.T, p2.T, ....)$$

$$p.\omega = p1.\omega = p2.\omega = ....$$

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any number of connections can be made (Rotation).</td>
<td>p[any]</td>
</tr>
</tbody>
</table>

**Causality**

| An torque out causality results in a derivative constitutive equation. | preferred angular velocity out |

**Variables**

| moment of inertia [kgm^2] | J |
| angle [rad] | phi |
| angular acceleration [rad/s^2] | alpha |

**Parameters**
m mass [kg]
r distance of mass from center line of rotation [m]

Initial Values
p.omega_initial The initial velocity of the inertia [rad/s].
phi_initial The starting angle of the mass [rad].

ZeroTorque

Library
Iconic Diagrams\Mechanical\Rotation\Components

Use

Description
This model can be used to connect any open end of another model that is not connected to the fixed world. It generates a fixed torque of 0 N while the angular velocity is free:

\[ p.\omega = \text{indifferent}; \]
\[ p.T = 0; \]

Interface

Ports Description
p rotation port

Causality
Fixed torque out
Gears

BeltPulley

Library
Iconic Diagrams\Mechanical\Rotation\Gears

Use

Description
This models represents a belt and pulley. The connection to the pulley is through the rotation port \( p_{rot} \). The connection to the belt is through the translation port \( p_{trans} \). The model is ideal, i.e. there are no compliances or inertias. The causality of this model is always mixed: torque out & velocity out or angular velocity out & force out:

\[
\begin{align*}
    p_{rot}.T &= \text{radius} \times p_{trans}.F \\
    p_{trans}.v &= \text{radius} \times p_{rot.\omega}
\end{align*}
\]
or:

\[
\begin{align*}
    p_{trans}.F &= 1/\text{radius} \times p_{rot}.T \\
    p_{rot.\omega} &= 1/\text{radius} \times p_{trans}.v
\end{align*}
\]

Interface

Ports

<table>
<thead>
<tr>
<th>Port</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{rot} )</td>
<td>Rotation port.</td>
</tr>
<tr>
<td>( p_{trans} )</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

Causality

\( p_{rot} \) notequal \( p_{trans} \)

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{radius} )</td>
<td>pulley radius [m]</td>
</tr>
</tbody>
</table>

Cam-Wizard

Library
Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Transmission\Transmission

Use

Description
This is a masked model which opens the Cam Wizard when edited. Depending on the selections entered, various cam motion profiles can be generated.
Interface

**Ports**

<table>
<thead>
<tr>
<th>Port</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
<td>Driving axis (Rotation)</td>
</tr>
<tr>
<td>p_out</td>
<td>Output port with resulting motion (Rotation or Translation)</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>stroke</td>
<td>amplitude of resulting motion</td>
</tr>
<tr>
<td>start_angle</td>
<td>start angle motion</td>
</tr>
<tr>
<td>stop_angle</td>
<td>angle when the maximum is reached</td>
</tr>
<tr>
<td>return_angle</td>
<td>start angle of the return motion</td>
</tr>
<tr>
<td>end_angle</td>
<td>finish angle of the return motion</td>
</tr>
</tbody>
</table>

CamRod

**Library**

Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

**Use**


**Description**

This models represents a cam and rod mechanism. If the input shaft is rotating with a constant speed, the output motion is a pure sinusoidal. The mechanism starts with the carriage in the most left position. The arm length is half of the stroke:
The mechanism is ideal, i.e., it does not have inertia, friction or geometrical limitations. It has one rotation port \((p_{\text{in}})\) and one translation port \((p_{\text{out}})\). The causality of this model is always mixed: one port has a force out causality while the other has a velocity out causality:

\[
\begin{align*}
    p_{\text{in}}.T &= i \cdot p_{\text{out}}.F \\
    p_{\text{out}}.v &= i \cdot p_{\text{in}}.\omega
\end{align*}
\]

The transmission ratio \((i)\) is the ratio of the velocities of both ports (in fact a sinusoidal function of the shaft angle).

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_{\text{in}})</td>
<td>Driving axis (Rotation)</td>
</tr>
<tr>
<td>(p_{\text{out}})</td>
<td>Output port with resulting motion (Translation)</td>
</tr>
</tbody>
</table>

**Causality**

| fixed torque out | \(p_{\text{in}}\) |
| fixed velocity out | \(p_{\text{out}}\) |

**Parameters**

| stroke | Stroke of the translation port (is equal to half the length of the rod). |
CrankRod

Library
Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

Use

Description

This model represents a crank and rod mechanism. The mechanism is ideal, i.e., it does not have inertia, friction or geometrical limitations. It has one rotation port (p_in) and one translation port (p_out). The causality of this model is always mixed: one port has a force out causality while the other has a velocity out causality:

\[ p_{in}.T = i \times p_{out}.F \]
\[ p_{out}.v = i \times p_{in}.\omega \]

The transmission ratio (i) is the ratio of the velocities of both ports. It is a function of the shaft angle, the crank length and the rod length.

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
<td>Driving axis (Rotation)</td>
</tr>
<tr>
<td>p_out</td>
<td>Output port with resulting motion (Translation)</td>
</tr>
</tbody>
</table>

Causality

<table>
<thead>
<tr>
<th>fixed</th>
<th>torque out p_in</th>
</tr>
</thead>
<tbody>
<tr>
<td>fixed</td>
<td>velocity out p_out</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>crank_length</td>
<td>Crank length [m]</td>
</tr>
<tr>
<td>rod_length</td>
<td>Rod length [m]</td>
</tr>
</tbody>
</table>
**DifferentialGear**

**Library**
Iconic Diagrams\Mechanical\Rotation\Gears

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Rotation).

**Description**
A differential gear is well known for its use in automotive mechanics. It transfers power from the engine to the wheels, dividing the force equally between them but permitting them to follow paths of different lengths when turning a corner.

When p3 is the drive-shaft and p1 and p3 the shafts connected to the wheels, the constitutive equations for this model are:

\[
p3.omega*2*i = p1.omega + p2.omega; \\
p1.T = p2.T = p3.T/(2*i);
\]

with i the gear ratio. The gear ratio is equal to the diameter of the drive shaft pinion divided by the diameter of the ring gear, which makes it equivalent to the angular velocity of the drive shaft divided by the average angular velocity of the wheel shafts:

\[
i = p3.omega / ((p1.omega + p2.omega)/2);
\]

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>drive shaft port (Rotation)</td>
</tr>
</tbody>
</table>
Differential

Library
Iconic Diagrams\Mechanical\Rotation\Gears

Use

Description

This model is equivalent to the fork model of the Translation library. It represents a special type of node where the torques are equal and the angular velocities are added:

\[ p3.\omega = p1.\omega + p2.\omega; \]
\[ p1.T = p2.T = p3.T; \]

This model can for example be used for actuators that generate a torque difference. With the differential model an equivalent model can be found with the actuator attached to the fixed world:

Interface

Ports

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
</table>

p2, p3 driven shafts ports (Rotation)

Parameters

<table>
<thead>
<tr>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>gear ratio</td>
</tr>
</tbody>
</table>

[Diagram of differential model]
p1,p2,p3  Rotation ports.

**Gear**

**Library**
Iconic Diagrams\Mechanical\Rotation\Gears

**Implementations**
Ideal
Lossy

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation).

**Description - Ideal**
This models represents any type of gearbox with two counter rotating shafts. The gear is ideal, i.e., it does not have inertia or friction. The gear has one fast moving shaft and one slow moving shaft. The gearbox has a reduction of i : 1 and thus a transmission ratio of 1/i.

The causality of this model is always mixed: one port has a torque out causality while the other has an angular velocity out causality:

\[
p_{\text{in}.T} = -\frac{1}{i} * p_{\text{out}.T} \\
p_{\text{out}.\omega} = -\frac{1}{i} * p_{\text{in}.\omega}
\]

or:

\[
p_{\text{out}.T} = -i * p_{\text{in}.T} \\
p_{\text{in}.\omega} = -i * p_{\text{out}.\omega}
\]

**Interface - Ideal**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
<td>Input port</td>
</tr>
<tr>
<td>p_out</td>
<td>Output port</td>
</tr>
</tbody>
</table>

**Causality**

p_in not equal p_out

**Parameters**

i  gearbox reduction, i > 1

**Description - Efficiency**
This models represents any type of gearbox with two counter rotating shafts. The gearbox has a reduction of i : 1 and thus a transmission ratio of 1/i.
Unlike the model of an ideal gearbox, this model includes power loss. The power loss is represented by the efficiency, where the efficiency is defined as the output power divided by the input power:

$$\text{eff} = \frac{P_{out}}{P_{in}}$$

The efficiency is a value between zero and one and given by the gearbox manufacturer. If you do not know the value, a good guess is a power loss of 3% per stage ($\text{eff} = 0.97$). If your gearbox for example contains three stages, you can set the efficiency as:

$$\text{eff} = 0.97 \times 0.97 \times 0.97 = 0.91$$

### Interface - Efficiency

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
<td>Input port</td>
</tr>
<tr>
<td>p_out</td>
<td>Output port</td>
</tr>
</tbody>
</table>

#### Causality

$p_{in}$ not equal $p_{out}$

#### Parameters

- $i$: gearbox reduction [-], $i > 1$
- $\text{eff}$: gearbox efficiency [-]

### Description - Lossy

This model represents any type of gearbox with two counter rotating shafts. The gearbox has a reduction of $i:1$ and thus a transmission ratio of $1/i$.

$$p_{in.omega} = -i \times p_{out.omega}$$

Unlike the model of an ideal gearbox, this model includes rotational inertia and power loss. The inertia is defined at the input axis. If the gearbox manufacturer gives the inertia at the output axis you can calculate the inertia at input axis as:

$$J_{input} = \frac{J_{output}}{i^2}$$

The power loss is represented by the efficiency, where the efficiency is defined as the output power divided by the input power:

$$\text{eff} = \frac{P_{out}}{P_{in}}$$

The efficiency is a value between zero and one and given by the gearbox manufacturer. If you do not know the value, a good guess is a power loss of 3% per stage ($\text{eff} = 0.97$). If your gearbox for example contains three stages, you can set the efficiency as:
\[ \text{eff} = 0.97 \times 0.97 \times 0.97 = 0.91 \]

**Interface - Lossy**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
<td>Input port</td>
</tr>
<tr>
<td>p_out</td>
<td>Output port</td>
</tr>
</tbody>
</table>

**Causality**

- preferred angular velocity out \( p_{\text{in}} \)
- preferred angular velocity out \( p_{\text{out}} \)

**Parameters**

- \( i \) : gearbox reduction [-], \( i > 1 \)
- \( J \) : moment of inertia [kgm^2]
- \( \text{eff} \) : gearbox efficiency [-]

**PlanetaryGear**

**Library**
Iconic Diagrams\Mechanical\Rotation\Gears

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation).

**Description**
A planetary gear is well known for its use in automotive mechanics. It transfers power from a sun wheel to the planet wheels and the ring. In standard planetary gears, the planet wheels are connected by a carriage. I.e the gear has three rotation ports: the sun, the carriage and the ring.
The model that is used here is ideal. I.e. there is only power flow between the three axes. No internal dynamics or friction are incorporated. If the inertia cannot be neglected, you can easily add inertia models to the ports of the planetary gear model.

The number of teeth of the planet wheels are uniquely defined by the number of teeth of the sun wheel and the ring by:

\[zp = (z_r - z_s)/2;\]

Therefore the ratio between the sun teeth and the ring teeth:

\[z = z_r / z_s;\]

determine the transmission ratio of the gearbox and therefore the dynamic equations of the gearbox:

\[
\begin{align*}
carriage.\omega &= sun.\omega \ast (1/(1 + z)) + ring.\omega \ast (z/(1 + z)); \\
ring.T &= carriage.T \ast (z/(1 + z)); \\
sun.T &= carriage.T \ast (1/(1 + z));
\end{align*}
\]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sun</td>
<td>shaft attached to the sun wheel (Rotation)</td>
</tr>
<tr>
<td>carriage</td>
<td>shaft attached to the carriage (Rotation)</td>
</tr>
<tr>
<td>ring</td>
<td>shaft attached to the ring (Rotation)</td>
</tr>
</tbody>
</table>

**Parameters**

| z     | number of ring teeth divided by the number of sun teeth [] |
RackPinionGear

Library
Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

Implementations
FixedPinion
FixedRack

Use

Description - FixedPinion
This models represents a rack and pinion gear. The connection to the pinion gear is through the rotation port $p_{rot}$. The connection to the rack is through the translation port $p_{trans}$. The model is ideal, i.e. there is no compliance nor inertia nor backlash.

In this model the pinion bearing is connected to the fixed world and the rack is free to move. This in contrary to the model FixedRackPinionGear where the pinion bearing is free to move and the rack is connected to the fixed world.

The causality of this model is always mixed: torque out & velocity out or angular velocity out & force out:

\[ p_{rot}.T = \text{radius} \times p_{trans}.F \]
\[ p_{trans}.v = \text{radius} \times p_{rot}.\omega \]

or:

\[ p_{trans}.F = 1/\text{radius} \times p_{rot}.T \]
\[ p_{rot}.\omega = 1/\text{radius} \times p_{trans}.v \]

The rack position is determined by the internal variable $x$. For $x = 0$, the pinion gear is at the middle of the rack. When the pinion crosses the end of the rack, i.e.
abs(x) > rack_length/2

A warning is given, "WARNING: rack length has been exceeded at the rack and pinion gear!", and the simulation is stopped.

**Interface - FixedPionion**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_rot</td>
<td>Rotation port.</td>
</tr>
<tr>
<td>p_trans</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>p_rot</td>
<td>notequal</td>
</tr>
<tr>
<td>p_trans</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>radius</td>
<td>pinion gear pitch radius [m]</td>
</tr>
<tr>
<td>rack_length</td>
<td>rack length [m]</td>
</tr>
</tbody>
</table>

**Variables**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>Internal variable which denotes the rack position, abs(x) &lt; rack_length/2 else simulation halted.</td>
</tr>
</tbody>
</table>

**Initial values**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x_initial</td>
<td>Initial rack position, abs(x_initial) &lt; rack_length/2</td>
</tr>
</tbody>
</table>

**Description - FixedRack**

This models represents a fixed rack and pinion gear. The connection to the pinion gear is through the rotation port \( p_{rot} \). The connection to the rack is through the translation port \( p_{trans} \). The model is ideal, i.e. there is no compliance nor inertia nor backlash.

In this model the pinion bearing is free to move and the rack is connected to the fixed world. This in contrary to the model RackPinionGear where the pinion bearing is connected to the fixed world and the rack is free to move.
The causality of this model is always mixed: torque out & velocity out or angular velocity out & force out:

\[
p_{\text{rot}}.T = \text{radius} \times p_{\text{trans}}.F \\
p_{\text{trans}}.v = \text{radius} \times p_{\text{rot}}.\omega
\]

or:

\[
p_{\text{trans}}.F = \frac{1}{\text{radius}} \times p_{\text{rot}}.T \\
p_{\text{rot}}.\omega = \frac{1}{\text{radius}} \times p_{\text{trans}}.v
\]

The rack position is determined by the internal variable \(x\). For \(x = 0\) the pinion gear is at the middle of the rack. When the pinion crosses the end of the rack, i.e.

\[
\text{abs}(x) > \text{rack}_\text{length}/2
\]
a warning is given, "WARNING: rack length has been exceeded at the rack and pinion gear!", and the simulation is stopped.

**Interface - FixedRack**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_{\text{rot}})</td>
<td>Rotation port.</td>
</tr>
<tr>
<td>(p_{\text{trans}})</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

\(p_{\text{rot}}\) notequal \(p_{\text{trans}}\)

**Parameters**

- \(\text{radius}\): pinion gear pitch radius [m]
- \(\text{rack}_\text{length}\): rack length [m]

**Variables**

- \(x\): Internal variable which denotes the rack position, \(\text{abs}(x) < \text{rack}_\text{length}/2\) else simulation halted.

**Initial values**

- \(x_{\text{initial}}\): Initial rack position, \(\text{abs}(x_{\text{initial}}) < \text{rack}_\text{length}/2\)
Spindle

Library
Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

Use

Introduction
This model represents a spindle and nut. It transfers an angular motion of the spindle into a translational motion of the nut. The model is ideal, i.e., it does not have inertia or friction. The causality of this model is always mixed: one port has a torque out causality while the other has an angular velocity out causality:

\[
p_{\text{spindle}}.T = i \times p_{\text{nut}}.F \\
p_{\text{nut}}.v = i \times p_{\text{spindle}}.omega
\]

or:

\[
p_{\text{nut}}.F = \frac{1}{i} \times p_{\text{spindle}}.T \\
p_{\text{spindle}}.omega = \frac{1}{i} \times p_{\text{nut}}.v
\]

The model has two implementations which calculate the transform ratio \(i\) out of different parameters.

Description - Pitch
In this implementation the transform ratio is calculated using the pitch (the advance of the nut during one revolution of the spindle):

\[
i = \frac{\text{pitch}}{2 \times \pi};
\]

Interface - Pitch

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_spindle</td>
<td>Port at the spindle shaft (Rotation).</td>
</tr>
<tr>
<td>p_nut</td>
<td>Port at the wheel (Translation).</td>
</tr>
</tbody>
</table>

Causality
p_spindle
notequal p_nut

Parameters
pitch translation of the nut during one revolution of the spindle [m]

Description - LeadAngle
This implementation calculates the transform ratio out of the lead angle \(\alpha\) and the radius \(r_{\text{spindle}}\) of the spindle:

\[
i = \tan(\alpha) \times r_{\text{spindle}};
\]
The pitch angle is shown in the figure below. $r_{spindle}$ is the effective radius of the spindle, i.e. the radius from the center of the spindle to the pitch point $p$.

![Diagram showing the pitch angle and effective radius of the spindle.]

**Interface - LeadAngle**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{spindle}$</td>
<td>Port at the spindle shaft (Rotation).</td>
</tr>
<tr>
<td>$p_{nut}$</td>
<td>Port at the wheel (Translation).</td>
</tr>
</tbody>
</table>

**Causality**

$p_{spindle}$

$notequal p_{nut}$

**Parameters**

- $r_{spindle}$: effective radius of the spindle [m]
- $alpha$: lead angle of the spindle [rad]

**TimingBelt**

**Library**

Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation/Translation).

**Introduction**

This model represents a timing belt, used for linear positioning.
It has a rotating pulley which drives the belt and clamp. The timing belt is modeled by a series of spring damper elements that convey the rotation of the pulley to a clamp translation. Because the output position is moving, stiffness and damping values are not constant.

The stiffness for a piece of belt can be expressed as:

\[ k = \frac{E \cdot A}{l} \]

with

- \( E \) = Modulus of elasticity \( \text{N/m}^2 \)
- \( A \) = Belt area \( \text{m}^2 \)
- \( l \) = Belt length \( \text{m} \)

If the belt is sufficiently pre-tensioned, the stiffness experienced at the clamp can be expressed as the combination of three individual belt parts:

\[ k = \frac{E \cdot A}{(0.5 \cdot l + x)} + \frac{1}{\frac{1}{\frac{E \cdot A}{(0.5 \cdot l - x)}} + \frac{1}{\frac{E \cdot A}{l}} } \]

which can be rewritten to:

\[ k = \frac{E \cdot A \cdot (1/(0.5 \cdot l + x) + 1/(1.5 \cdot l - x))}{1} \]

The stiffness approaches infinity as the clamp moves to the driven pulley \((x = -l/2)\) and has a minimum value when the clamp moves to the other pulley \((x = 0.5 \cdot l)\). The minimum stiffness is equal to:

\[ k = \frac{2 \cdot E \cdot A}{l} \]

The belt position is determined by the internal variable \( x \). For \( x = 0 \) the clamp is in the middle. When the position crosses the driven pulley, i.e.
The simulation is stopped: "Error: clamp position larger than belt end!". When the position crosses the other pulley, i.e.

\[ x < - \frac{\text{belt_length}}{2} \]

the simulation is also stopped, "Error: clamp position smaller than belt start!".

**Description - Default**

In this model the minimum stiffness is used, based on an output position at a length \( L \) of the driven pulley.

\[ k = \frac{2 \times E \times A}{l} \]

**Description - Variable Stiffness**

In this model a variable stiffness is used equal to:

\[ k = E \times A \times \left( \frac{1}{0.5 \times l + x} + \frac{1}{1.5 \times l - x} \right) \]

Take care not to let the clamp get too close to the driven pulley, because the stiffness will then grow to infinity!

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation port.</td>
<td>p_rot</td>
</tr>
<tr>
<td>Translation port.</td>
<td>p_trans</td>
</tr>
</tbody>
</table>

**Causality**

<table>
<thead>
<tr>
<th></th>
<th>p_rot</th>
<th>p_trans</th>
</tr>
</thead>
<tbody>
<tr>
<td>notequal</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>pinion gear pitch radius [m]</td>
<td>radius</td>
</tr>
<tr>
<td>damping N.s/m</td>
<td>d</td>
</tr>
<tr>
<td>Modulus of elasticity [N/m²]</td>
<td>E</td>
</tr>
<tr>
<td>Belt area [m²]</td>
<td>A</td>
</tr>
<tr>
<td>Belt length [m]</td>
<td>l</td>
</tr>
</tbody>
</table>

**Variables**

<table>
<thead>
<tr>
<th>Description</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>clamp position, abs(x) &lt; belt length/2</td>
<td>x</td>
</tr>
</tbody>
</table>

**Initial values**

<table>
<thead>
<tr>
<th>Description</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial clamp position, abs(x_initial) &lt; belt length/2</td>
<td>x_initial</td>
</tr>
</tbody>
</table>
Transmission

Library
Iconic Diagrams\Mechanical\Rotation\Gears

Implementations
Ideal
Lossy

Use

Description - Ideal
This models represents any type of gearbox with two shafts rotating in the same direction. The gear is ideal, i.e., it does not have inertia or friction. The gear has one fast moving shaft and one slow moving shaft. The gearbox has a reduction of i : 1 and thus a transmission ratio of 1/i.

The causality of this model is always mixed: one port has a torque out causality while the other has an angular velocity out causality:

\[
p_{\text{in}}.T = \frac{1}{i} * p_{\text{out}}.T
\]
\[
p_{\text{out}}.\omega = \frac{1}{i} * p_{\text{in}}.\omega
\]
or:

\[
p_{\text{out}}.T = i * p_{\text{in}}.T
\]
\[
p_{\text{in}}.\omega = i * p_{\text{out}}.\omega
\]

Interface - Ideal

Ports | Description
--- | ---
p_{\text{in}} | Input port
p_{\text{out}} | Output port

Causality
p_{\text{in}} not equal p_{\text{out}}

Parameters
i | gearbox reduction, i > 1

Description - Efficiency
This models represents any type of gearbox with two shafts rotating in the same direction. The gearbox has a reduction of i : 1 and thus a transmission ratio of 1/i.

\[
p_{\text{in}}.\omega = i * p_{\text{out}}.\omega
\]

Unlike the model of an ideal gearbox, this model includes power loss. The power loss is represented by the efficiency, where the efficiency is defined as the output power divided by the input power:
The efficiency is a value between zero and one and given by the gearbox manufacturer. If you do not know the value, a good guess is a power loss of 3% per stage (eff = 0.97). If your gearbox for example contains three stages, you can set the efficiency as:

\[
\text{eff} = 0.97 \times 0.97 \times 0.97 = 0.91
\]

**Interface - Efficiency**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
<td>Input port</td>
</tr>
<tr>
<td>p_out</td>
<td>Output port</td>
</tr>
</tbody>
</table>

**Causality**

p_in not equal p_out

**Parameters**

i \quad \text{gearbox reduction [-], } i > 1

\text{eff} \quad \text{gearbox efficiency [-]}

**Description - Lossy**

This model represents any type of gearbox with two shafts rotating in the same direction. The gearbox has a reduction of \(i:1\) and thus a transmission ratio of \(1/i\).

\[
p_{\text{in.omega}} = i \times p_{\text{out.omega}}
\]

Unlike the model of an ideal gearbox, this model includes rotational inertia and power loss. The inertia is defined at the input axis. If the gearbox manufacturer gives the inertia at the output axis you can calculate the inertia at input axis as:

\[
J_{\text{input}} = J_{\text{output}} / i^2
\]

The power loss is represented by the efficiency, where the efficiency is defined as the output power divided by the input power:

\[
\text{eff} = P_{\text{out}} / P_{\text{in}}
\]

The efficiency is a value between zero and one and given by the gearbox manufacturer. If you do not know the value, a good guess is a power loss of 3% per stage (eff = 0.98). If your gearbox for example contains three stages, you can set the efficiency as:

\[
\text{eff} = 0.97 \times 0.97 \times 0.97 = 0.91
\]

**Interface - Lossy**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
<td>Input port</td>
</tr>
</tbody>
</table>
p_out  

**Causality**
preferred angular velocity out p_in
preferred angular velocity out p_out

**Parameters**
- i  
gearbox reduction [-], i > 1
- J  
moment of inertia [kgm^2]
- eff  
gearbox efficiency [-]

---

**UniversalCoupling**

**Library**
Iconic Diagrams\Mechanical\Rotation\Gears

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation).

**Description**

Universal Joint couplings are used to couple axes which are not aligned. They can be used in single or double set-up. Consider the single Universal Joint coupling, shown in the picture below.
Due to the nature of the coupling, the output angular velocity $w_1$ will show a sinusoidal ripple, compared to the input angular velocity $w_2$:

$$\omega_2 = \frac{\cos(\alpha)}{1 - \cos^2(\varphi_1) \sin^2(\alpha)} \cdot \omega_1$$

with $\alpha$ the angle between the two axes and $\varphi_1$ the initial rotation of the input axis. The initial rotation $\varphi_1$ is defined with respect to a plane that is spanned by the axes (1 and 2).

When two Universal Joint couplings are combined, the angular velocity of the output axis will be equal to the angular velocity of the input axis (e.g. no ripple) when two conditions are met. When the output axis of the first coupling is connected to the input axis of the second coupling, these conditions are:

1. For both couplings the absolute value of the angle $\alpha$ should be equal.
2. The difference in initial rotation of both couplings ($\varphi_1 - \varphi_2$) should be equal to $+\pi/2$ [rad] or $-\pi/2$ [rad].

Two alignments are shown in the figure below.

$\alpha = 0.35, \alpha' = -0.35, \varphi_1 = 0, \varphi_1' = \pi/2$ [rad]  
$\alpha = 0.35, \alpha' = 0.35, \varphi_1 = 0, \varphi_1' = \pi/2$ [rad]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1, p2</td>
<td>The input and output axes (Rotation)</td>
</tr>
</tbody>
</table>

**Causality**
Input
p1 not equal p2

Parameters
alpha The angle between the two axes (\( \alpha \)).

Initial Values
phi1_initial The initial rotation of the input axis (\( \phi 1 \)).

Wormgear

Library
Iconic Diagrams\Mechanical\Rotation\Gears

Implementations
Ideal
Backlash

Use

Description - Ideal

This models represents a worm gear with spindle (also referred to as worm) and wheel (also referred to as gear). The gear is ideal, i.e., it does not have inertia or friction. The causality of this model is always mixed: one port has a torque out causality while the other has an angular velocity out causality:

\[
p_{\text{spindle}.T} = i \times p_{\text{wheel}.T} \\
p_{\text{wheel}.omega} = i \times p_{\text{spindle}.omega}
\]

or:

\[
p_{\text{wheel}.T} = 1/i \times p_{\text{spindle}.T} \\
p_{\text{spindle}.omega} = 1/i \times p_{\text{wheel}.omega}
\]

with
\[ i = \tan(\alpha) \frac{r_{\text{spindle}}}{r_{\text{wheel}}}; \]

\( \alpha \) is the pitch angle as shown in the figure below. \( r_{\text{wheel}} \) and \( r_{\text{spindle}} \) are the effective radii of the wheel and spindle, i.e. the radii from the center of the wheel and spindle to the pitch point \( p \).

**Interface - Ideal**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{\text{spindle}} )</td>
<td>Port at the spindle shaft (Rotation).</td>
</tr>
<tr>
<td>( p_{\text{wheel}} )</td>
<td>Port at the wheel (Rotation).</td>
</tr>
</tbody>
</table>

**Causality**

\( p_{\text{wheel}} \) notequal \( p_{\text{spindle}} \)

**Parameters**

<table>
<thead>
<tr>
<th>parameter</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{\text{spindle}} )</td>
<td>pitch radius spindle [m]</td>
</tr>
<tr>
<td>( r_{\text{wheel}} )</td>
<td>pitch radius wheel [m]</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>lead angle of the spindle [rad]</td>
</tr>
</tbody>
</table>
Description - Backlash

This models represents a worm gear with spindle (also referred to as worm) and wheel (also referred to as gear). Between spindle and wheel, backlash and friction is modelled. The causality of this model is always fixed: both ports have a torque out causality.

Analysis

The spindle and wheel have one or more pair of teeth contacting each other. The effective point of contact is called the pitch point \( P \). At the pitch point a frame is defined, with an \( x \)- and \( y \)-direction. During rotation of the wheel and spindle, the teeth will experience a normal force \( F_n \) in the \( x \)-direction and a friction force \( F_f \) in the \( y \)-direction.

Between each pair of teeth, a clearance exists (\( y \)-direction), causing backlash. This effect is time-dependent, because of the tooth pairs coming in and out of contact. During normal operation this is a high frequency effect, which is filtered out by the damping of the construction. We therefore only use an average backlash at the pitch point. Using the same reasoning as backlash, an average friction is used at the pitch point.

To define both backlash and friction a frame is used at the pitch point (see picture above) to indicate velocities. The velocity in \( x \)-direction is the sliding velocity between the teeth and used to calculate the friction force. The position in \( y \)-direction is the position in the clearance and used to calculate the backlash force.
Backlash

The backlash is described by the standard formula that is also used in the Backlash.emx model. The normal force is modelled by a spring-damper system. Inside the clearance a low damping and stiffness is used \((k1 \text{ and } d1)\), while a high stiffness and damping \((k2 \text{ and } d2)\) is used at both ends of the clearance. This yields a normal force \(Fn\) of:

\[
p.F = 0.5 \cdot k_2 \cdot \left( x - \sqrt{-x - \frac{s}{2}} + (ep \cdot s)^2 + x + \sqrt{x - \frac{s}{2}} + (ep \cdot s)^2 \right) + k_1 \cdot x + d_{1\text{or2}} \cdot p.v
\]

Friction

Friction is described as static plus coulomb plus viscous plus Stribeck friction:

\[
p.F = Fn \cdot \left( \mu_c + (\mu_s \cdot \text{abs(tanh(slope \cdot p.v)}) - \mu_c) \right) \cdot \exp(-((p.v / v_st)^2)) \cdot \text{sign(p.v)} + \mu_v \cdot p.v;
\]

with:

\(Fn\): the normal force (given by the backlash formula)

\(\mu_s\): the static friction coefficient

\(\mu_v\): the viscous friction coefficient

\(\mu_c\): the coulomb friction coefficient

\(\text{slope}\): the steepness of the coulomb and static friction curve.

\(v_st\): the characteristic Stribeck velocity.

Self-Locking

A worm gear is said to be self-locking, or irreversible when the wheel cannot drive the spindle. This condition is obtained, if the lead angle of the worm is small and the friction force between the teeth is high enough. Then the friction force becomes larger than the driving force on the teeth. Suppose we only consider static and Coulomb friction and both friction coefficients are equal. Then self locking is obtained when the following condition holds:

\[
\mu_s > \tan(alpha) \\
\mu_c > \tan(alpha)
\]

Interface - Backlash

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_spindle</td>
<td>Port at the spindle shaft (Rotation).</td>
</tr>
<tr>
<td>p_wheel</td>
<td>Port at the wheel (Rotation).</td>
</tr>
</tbody>
</table>

Causality

fixed torque out

Parameters
11. Library

r_spindle   pitch radius spindle [m]
r_wheel     pitch radius wheel [m]
alpha       lead angle of the spindle [rad]
s           Interval of the play [m]
k1          Stiffness in the play [N/m]
k2          Stiffness outside the play [N/m]
d1          Damping inside the play [Ns/m]
d2          Damping outside the play [Ns/m]
ep          Relative round off (1e-6 -> sharp edges, 1e-2 -> smoother)
mu_s        Static friction coefficient []
mu_v        Viscous friction coefficient [s/m]
mu_c        Coulomb friction coefficient []
slope       Steepness of Coulomb friction curve [s/m]
v_st        Characteristic Stribeck velocity [m/s]

Interesting Variables
Fn           Average normal force between teeth [N]
Ff           Average friction force between teeth [N]
v_x          Velocity in x-direction at the pitch frame [m/s] (used in friction formula)
v_y          Velocity in y-direction at the pitch frame [m/s] (used in backlash formula)
x_x          Position in x-direction at the pitch frame [m/s] (used in friction formula)
x_y          Position in y-direction at the pitch frame [m/s] (used in backlash formula)

Sensors

AccelerationSensor-Absolute

Library
Iconic Diagrams\Mechanical\Rotation\Sensors

Use
Domains: Continuous. Size: 1-D. Kind: Iconic Diagrams (Rotation), Block Diagrams.

Description
This model describes an acceleration sensor which derives an angular acceleration output out of a port angular velocity by differentiation. Differentiation is performed by a state variable filter:
The S-domain function of this filter is equal to:

\[
\text{output} = \frac{s}{s + \frac{1}{f}} \cdot \text{input}
\]

where \( f \) is the cut-off frequency. For very high values of \( f \), the output becomes the pure derivative of the input. High values of \( f \), however, increase simulations times. A good trade-off is a starting value of 1e5.

The equations of this model are:

\[
\begin{align*}
\alpha &= \frac{d(p.\omega)}{dt}; \\
p.T &= \text{indifferent};
\end{align*}
\]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port p.</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out

**Output**

alpha Absolute angular acceleration \([\text{rad/s}^2]\)

**Parameters**

f Cut-off frequency of the differentiation \([\text{Hz}]\).
alpha_initial Initial angular acceleration \([\text{m/s}]\).

**AccelerationSensor-Relative**

**Library**

Iconic Diagrams\Mechanical\Rotation\Sensors

**Use**

Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation), Block Diagrams.
**Description**

This model describes an acceleration sensor which derives an angular acceleration output out of a angular velocity difference (between high and low terminals) by differentiation. Differentiation is performed by a state variable filter:

\[
\text{output} = \frac{s}{s + \frac{1}{f}} \cdot \text{input}
\]

where \( f \) is the cut-off frequency. For very high values of \( f \), the output becomes the pure derivative of the input. High values of \( f \), however, increase simulation times. A good trade-off is a starting value of \( 1e5 \).

The equations of this model are:

\[
\begin{align*}
\alpha &= \frac{d}{dt}(p_{\text{high}}\omega - p_{\text{low}}\omega); \\
p_{\text{low}}.T &= p_{\text{high}}.T = \text{indifferent};
\end{align*}
\]

**Interface**

**Ports**

- **p_high, p_low**: Both terminals of the Mechanical port \( p \).

**Causality**

- fixed force out

**Output**

- **alpha**: Angular acceleration (measured as the difference between both terminals) \([\text{rad/s}^2]\)

**Parameters**

- **f**: Cut-off frequency of the differentiation \([\text{Hz}]\).
- **alpha_initial**: Initial angular acceleration \([\text{m/s}]\).
Encoder

Library
Iconic Diagrams\Mechanical\Rotation\Sensors

Implementations
Ideal
Absolute
Incremental

Use

Description - Ideal
This is a model of an optical encoder combined with sampling. The Encoder has no internal friction. The output signal is equal to the sampled shaft angle (in radians).

Example
The shaft angle is equal to a sine with amplitude 2*pi (one revolution forward and one back), the sampling rate is 5 Hz.

Interface - Ideal

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Causality</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fixed torque out</td>
<td>(The output torque is zero)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>sampled shaft angle (rad)</td>
</tr>
</tbody>
</table>
**Description - Absolute**

This is a model of an optical encoder combined with counting logic and analog to digital conversion. The encoder has no internal friction. Counting is absolute. The shaft angle is measured with an accuracy of a given number of counts per revolution.

**Example**

An encoder has an accuracy of 10 counts per revolution. This means an input signal with value 6.283185307 gives an output of 10. This is illustrated in the figure below. The input is a sine with amplitude 2*pi (one revolution forward and one back).

![Encoder (12 bits, 10 counts per revolution)](image)

**Overflow**

This model has no overflow.

**Interface - Absolute**

<table>
<thead>
<tr>
<th><strong>Ports</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port</td>
</tr>
</tbody>
</table>

**Causality**

fixed torque out  (The output torque is zero)

**Outputs**

<table>
<thead>
<tr>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
<tr>
<td>number of counts</td>
</tr>
</tbody>
</table>

**Parameters**

| **counts** | counts per revolution. |

**Description - Incremental**

This is a model of an optical encoder combined with counting logic and analog to digital conversion. The encoder has no internal friction. Counting is incremental. The shaft angle is measured with an accuracy of a given number of counts per revolution and a window defined by the number of bits.
Example
An encoder has an accuracy of 2000 counts per revolution. This means an input signal with value 6.283185307 gives an output of 2000.

Example
An encoder has an accuracy of 10 counts per revolution and a 5 bits counter. This means an input signal with value 6.283185307 gives an output of 10 and the output is clipping between +15 and -16. This is illustrated in the figure below. The input is a sine with amplitude 2*pi (one revolution forward and one back).

The next figure shows the same settings but only 4 bits are used. This means the output is clipping between +7 and -8.
Overflow
The maximum and minimum number of counts are equal to \(2^{(\text{bits}-1)} - 1\) and \(-2^{(\text{bits}-1)}\). If the number of counts passes \(2^{(\text{bits}-1)} - 1\), counting continues at \(-2^{(\text{bits}-1)}\) and vice versa.

Interface - Incremental

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p)</td>
<td>Rotation port</td>
</tr>
</tbody>
</table>

Causality
fixed torque out (The output torque is zero)

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>number of counts</td>
</tr>
</tbody>
</table>

Parameters
counts counts per revolution.
bits maximum counting interval is between \(2^{(\text{bits}-1)} - 1\) and \(-2^{(\text{bits}-1)}\).

Limitations
The output of this model is a discrete signal. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sample time. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).

PositionSensor-Absolute

Library
Iconic Diagrams\Mechanical\Rotation\Sensors

Use

Description
This model translates a angular position to an output signal. It has a force out causality. The equations are:

\[
p.T = 0; \\
\phi = \text{int}(p.\omega);
\]

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_\text{high}, p_\text{low})</td>
<td>Rotation port (p).</td>
</tr>
</tbody>
</table>
fixed force out

**Output**
phi Absolute angular position [rad]

**Initial Values**
phi_initial Initial angular position [rad]

---

**PositionSensor-Relative**

**Library**
Iconic Diagrams\Mechanical\Rotation\Sensors

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Rotation), Block Diagrams.

**Description**
This model translates an angular position difference to an output signal. It has a force out causality. The port $p$ of the model has separate high and low terminals. The equations are:

\[
\begin{align*}
    p.T &= p_{\text{high}}.T = p_{\text{low}}.T; \\
    p.\omega &= p_{\text{high}}.\omega - p_{\text{low}}.\omega; \\
    p.T &= 0; \\
    \phi &= \text{int}(p.\omega);
\end{align*}
\]

**Interface**

**Ports**
- **p_high, p_low** Both terminals of the Rotation port $p$.

**Causality**
fixed force out

**Output**
phi Relative angular position [rad]

**Initial Values**
phi_initial Initial angular position [rad]
**Potentiometer**

**Library**
Iconic Diagrams \ Mechanical \ Rotation \ Sensors

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation / Electric).

**Description**
Potentiometers have a variable resistance according to a certain rotation. By establishing a voltage (see picture below) across the resistor it is possible to get a proportional relation between the angle and the output voltage.

\[ U_{\text{out}} = U_{\text{max}} \times \frac{\text{angle}}{(\text{turns} \times 2 \pi)} \]

Here \( U_{\text{max}} \) is the maximum voltage and \( \text{turns} \) is the maximum number of turns.

**Interface**

**Ports**
- **p1**: Rotation port.
- **p2**: Electric port.

**Causality**
- fixed torque out (The output torque is zero)
- fixed voltage out

**Parameters**
- \( U_{\text{max}} \): Maximum output voltage [V]
- \( \text{turns} \): maximum allowed number of turns []
PowerSensor

Library
Iconic Diagrams\Mechanical\Rotation\Sensors

Use
Domains: Continuous. Size: 1-D. Kind: Iconic Diagrams (Rotation), Block Diagrams.

Description
This is an ideal sensor (no dissipation or other effects) that yields the power that flows through the model as output signal. The equations are:

\[
\begin{align*}
p_{\text{high}}.T &= p_{\text{low}}.T \\
p_{\text{high}}.\omega &= p_{\text{low}}.\omega \\
P &= p_{\text{high}}.T \times p_{\text{high}}.\omega;
\end{align*}
\]

Interface

Ports Description
p_high, p_low Both rotation ports.

Causality
p_high not equal p_low

Output
P Power [w].

Tachometer

Library
Iconic Diagrams\Mechanical\Rotation\Sensors

Use

Description
A tachometer is a transducer for measuring the rotation speed. It is normally mounted at the shaft of a motor and gives a voltage signal proportional to the rotation speed:

\[
V = K_v \cdot \nu
\]

with \(K_v\) the tachometer gradient [V / rad/s] and \(\nu\) the shaft velocity [rad/s]. This equation represents the ideal case. Due to the slots and commutator segments of the tachometer, a noise ripple will exists:
with \( N \) the ripple frequency [cycles per turn] and \( Kn \) the peak to peak noise Ripple [in % of the output voltage]. To convert the Voltage Gradient parameter from RPM units \([V / RPM]\) to radian units \([V / rad/s]\), use the conversion formula:

\[
K_{v_{rad/s}} = K_{v_{RPM}} \cdot \frac{2 \cdot \pi}{60}
\]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**

- fixed torque out
  - \((\text{The output torque is zero})\)

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{output} )</td>
<td>Output voltage [V]</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Kv )</td>
<td>Voltage Gradient ([V / \text{rad/s}]).</td>
</tr>
<tr>
<td>( Kn )</td>
<td>Noise Ripple, relative to output voltage [%].</td>
</tr>
<tr>
<td>( N )</td>
<td>Ripple frequency in cycles per turn [().</td>
</tr>
</tbody>
</table>

**TorqueSensor**

**Library**

Iconic Diagrams\Mechanical\Rotation\Sensors

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Rotation), Block Diagrams.

**Description**

This model translates an applied torque to an output signal. It has an angular velocity output causality. The port \( p \) of the model has separate high and low terminals. The equations are:

\[
\begin{align*}
p.T &= p_{\text{high}}.T = p_{\text{low}}.T; \\
p.omega &= p_{\text{high}}.omega - p_{\text{low}}.omega; \\
p.omega &= 0; \\
T &= p.T;
\end{align*}
\]
### Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Rotation port p.</td>
</tr>
</tbody>
</table>

**Causality**

| fixed angular velocity out |

**Output**

| T         | Applied torque [N/m] |

### VelocitySensor-Absolute

**Library**

Iconic Diagrams\Mechanical\Rotation\Sensors

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation), Block Diagrams.

**Description**

This model translates an angular velocity to an output signal. It has a force out causality. The equations are:

\[
p.T = 0; \\
\text{omega} = p.\text{omega};
\]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Mechanical port p.</td>
</tr>
</tbody>
</table>

**Causality**

| fixed force out |

**Output**

| omega     | Absolute angular velocity [rad/s] |
VelocitySensor-Relative

Library
Iconic Diagrams\Mechanical\Rotation\Sensors

Use
Domains: Continuous. Size: 1-D. Kind: Iconic Diagrams (Rotation), Block Diagrams.

Description
This model translates a velocity difference to an output signal. It has a force out causality. The port $p$ of the model has separate high and low terminals. The equations are:

\[
\begin{align*}
p.T &= p\_high.T = p\_low.T; \\
p.\omega &= p\_high.\omega - p\_low.\omega; \\
p.T &= 0; \\
\omega &= p.\omega;
\end{align*}
\]

Interface

Ports

<table>
<thead>
<tr>
<th>Description</th>
<th>p_high, p_low</th>
</tr>
</thead>
</table>

Causality

fixed force out

Output

<table>
<thead>
<tr>
<th>Description</th>
<th>omega</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative angular velocity [rad/s]</td>
<td></td>
</tr>
</tbody>
</table>

Translation

2DSmallRotation

2D Library (Small Rotations)

Introduction

The 2DSmallRotation library contains models that describe 2-D planar motion and are valid for small rotations. Due to these small rotations, the dynamic equations that describe the various models are simple and can be linearized symbolically. The library is therefore suited for modeling mechanical systems that experience small rotations and must be thoroughly analyzed in the frequency domain.
Consider the guidance system below. Due to the limited stiffness of the guidance wheels, the central body will experience a small rotation that results in a movement in the x-direction at the end-effector. To properly model the end-effector movement as a function of the driven force, this rotation has to be incorporated. To inspect the resulting resonance frequencies in a bode plot, the model must be linearized. If linearization is performed symbolically, the effect of parameter changes \((a_f, b, J)\) can be inspected directly in the bode plot, which is very useful when the system is still in the design phase.

To perform symbolic linearization, the example system should be modeled using the models of the 2DSmallAngles library.

**2D**

When we speak of **2D motion** we often mean all planar motion. However, to describe this motion, **three degrees of freedom** (displacement \(x\) and \(y\) and rotation \(\theta\)) are used. In 20-sim we keep to the common naming standard of 2D for planar motion (3 degrees of freedom) and 3D for spatial motion (6 degrees of freedom). In 20-sim the three degrees of freedom for planar motion are combined in a vector notation:

<table>
<thead>
<tr>
<th>d.o.f.</th>
<th>identity</th>
<th>forces</th>
<th>velocities</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>position</td>
<td>(P.F[1] \text{ [N]})</td>
<td>(P.v[1] \text{ [m/s]})</td>
</tr>
<tr>
<td>(y)</td>
<td>position</td>
<td>(P.F[2] \text{ [N]})</td>
<td>(P.v[2] \text{ [m/s]})</td>
</tr>
<tr>
<td>(\theta)</td>
<td>angle</td>
<td>(P.F[3] \text{ [Nm]})</td>
<td>(P.v[3] \text{ [rad/s]})</td>
</tr>
</tbody>
</table>

**Note**

It is not possible in 20-sim to use vector elements with mixed units. Therefore element number 3 will be displayed with units [m/s] and [N] although it really is [rad/s] and [Nm]!
Ports

1D
The models in the 2DSmallRotation library have two types of connection ports: 1D and 2D. The 1D ports can represent movement and force (x- or y-direction) or an angular displacement and torque.

The models of the standard translation and rotation libraries can be used connect to these 1D ports as is shown in the picture below.

![Diagram of 1D connection](image)

2D
The 2D connection port is a vector that represents three degrees of freedom. The vector notation that is used in 20-sim is:

<table>
<thead>
<tr>
<th>d.o.f.</th>
<th>identity</th>
<th>forces</th>
<th>velocities</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>position</td>
<td>P.F[1] [N]</td>
<td>P.v[1] [m/s]</td>
</tr>
<tr>
<td>y</td>
<td>position</td>
<td>P.F[2] [N]</td>
<td>P.v[2] [m/s]</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle</td>
<td>P.F[3] [Nm]</td>
<td>P.v[3] [rad/s]</td>
</tr>
</tbody>
</table>

In 20-sim it is not possible to use vector ports with mixed units. This means that element number 3 will be always be displayed with the units [m/s] and [N] although it should be interpreted as [rad/s] and [Nm].

To connect 2D ports, only other models with 2D ports can be used. A double line indicates this vector connection.
Small Rotations

Consider the body below:

![Diagram of a body with a force Fx in x-direction acting upon it at an offset y1 from the center.](image)

Given a force $F_x$ in $x$-direction acting upon the body at an offset $y_1$ from the center, the resulting force at the center of the body is:

$$F_{1x} = F_x \cdot \cos(q)$$
$$F_{1y} = F_x \cdot \sin(q)$$
$$F_{1q} = F_x \cdot -y_1$$

For small angles this can be simplified to:

$$F_{1x} = F_x$$
$$F_{1y} = 0$$
$$F_{1q} = F_x \cdot -y_1$$

A force acting upon a body at a certain offset is rewritten to a force at the center of the body. This is common in multibody dynamics and called a transformation. A force acting at a certain point can be transformed to see its effect at another point.

Consider two frames which have an arbitrary offset as shown in the picture below. We want to know how a force in frame 0 is transformed to a force in frame 1. We assume that frame 1 has an offset of $x_1$ and $y_1$ with respect to frame 0 and a rotation $q_1$ with respect to frame 0. In order to make clear that the offsets are given with respect to frame 0 we will write the with extra indices ($x_{1,0}$, $y_{1,0}$ and $\theta_{1,0}$).
Given an arbitrary force $F_{1,0}$ at frame 0 the resulting force $F_{1,1}$ at frame 1 is equal to:

$$F_{1,1} = R_0^1 \cdot F_{1,0} \quad \text{with} \quad R_0^1 = \begin{bmatrix} \cos(\theta_{1,0}) & \sin(\theta_{1,0}) & 0 \\ -\sin(\theta_{1,0}) & \cos(\theta_{1,0}) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

For small angles this can be simplified to:

$$F_{1,1} = R_{01} \cdot F_{1,0} \quad \text{with} \quad R_{01} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -\gamma_{1,0} & x_{1,0} & 1 \end{bmatrix}$$

The accuracy of this simplification depends on the angle $\theta$. For an angle of 0.5 degrees (0.009 rad) this results in an almost 1% error in the calculation of $F_{1,1}$. Considering the cumulative effects of this error when multiple models are used, an angle of maximum 0.05 degrees (<1 mrad) is an upper bound for the models of the 2DSmallRotation library.

The simplification of the equations has two advantages. First because of the small rotations there is no frame rotation any more. Therefore all frames have the same direction (there is only an offset in x-direction and y-direction). Interpreting results is therefore much easier. But the biggest advantage is the simplification of equations which allows us to linearize models symbolically and thus perform tasks in the frequency like parameter sweeps!

**Connections**

**Degrees of Freedom**

As described in the previous topic, the models in 2DSmallRotation library have two types of connection ports: 1D and 2D. The 1D port can represent movement in the x-direction, the y-direction or an angular displacement $\theta$. 
The 2D port is a vector that contains all three degrees of freedom. The vector notation that is used in 20-sim is:

<table>
<thead>
<tr>
<th>d.o.f.</th>
<th>identity</th>
<th>forces</th>
<th>velocities</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>position</td>
<td>P.F[1] [N]</td>
<td>P.v[1] [m/s]</td>
</tr>
<tr>
<td>y</td>
<td>position</td>
<td>P.F[2] [N]</td>
<td>P.v[2] [m/s]</td>
</tr>
<tr>
<td>θ</td>
<td>angle</td>
<td>P.F[3] [Nm]</td>
<td>P.v[3] [rad/s]</td>
</tr>
</tbody>
</table>

The vector element number (1, 2 or 3) denotes the identity of the degree of freedom (x, y and θ). To create meaningful models, we have to define the positive direction of each degree of freedom:

<table>
<thead>
<tr>
<th>d.o.f.</th>
<th>positive direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>from left to right</td>
</tr>
<tr>
<td>y</td>
<td>from bottom to top</td>
</tr>
<tr>
<td>θ</td>
<td>counter clockwise</td>
</tr>
</tbody>
</table>

This definition is arbitrary. We could as well define it any other way. In the 2DSmallRotation library we have chosen the definition above. It will help us define new models and interpret simulation results.

**Orientation Independent**

The connections between models only indicate how variables (forces and velocities) are transferred from one model to the other and vice versa. The orientation of the models in the Graph Editor (how they are drawn) is therefore not important. Flipping, rotating or moving a model does not change the model! All four representations in the figure below are the same although their individual models are oriented differently.

The figure above shows a point model in x-direction connected to a 2D body. The point indicates a force in x-direction that is applied to the body. Since we defined that the positive x-direction is from the left to the right, intuitively figure b leads to the correct interpretation.
This indicates a problem. Although all models describe the same behavior, we would intuitively interpret them differently. It is therefore useful to impose some rules to prevent misinterpretation of a model by other users.

**Drawing Rules**

1. Preferably leave the orientation of the models of the 2DSmallRotation library as they pop up on the screen.
2. If necessary, only flip or rotate models in a direction that does not lead to misinterpretations.
3. If possible, draw 1D connections in the following direction:

<table>
<thead>
<tr>
<th>d.o.f.</th>
<th>positive direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>from left to right</td>
</tr>
<tr>
<td>y</td>
<td>from bottom to top</td>
</tr>
<tr>
<td>( \theta )</td>
<td>from left bottom to right top</td>
</tr>
</tbody>
</table>

An example is shown in the figure below:

![TwoDBody Diagram](attachment:TwoDBody.png)

**TwoDBody**

**Library**

Iconic Diagrams\Mechanical\Translation\2DSmallAngles

**Use**

**Domains:** Continuous. **Size:** 2-D. **Kind:** Iconic Diagrams (2D Planar).
**Description**

The central model in the 2DSmallRotation library is the TwoDBody model. It describes a body with three degrees of freedom: $x$, $y$ and $\theta$. The TwoDBody is a point mass with rotational inertia. The constitutive equations are therefore very simple:

$$P.v = I \cdot int(P.F);$$

With

$$I = [1/M; 1/M; 1/J];$$

Any number of connections can be made to the TwoDBody model. All forces acting upon the body are added.

Because any number of connections can be made, successive ports are named $P1$, $P2$, $P3$ etc. 20-sim will automatically create equations such that the resulting force $P.F$ is equal to the sum of the forces of all connected ports $P1$ to $Pn$. The velocities of all connected ports are equal to $P.v$. The model has a preferred velocity out causality. The corresponding constitutive equations then contain an integration. The model can also have the non-preferred force out causality. The constitutive equations then contain a differentiation.

$$P.F = sum(P1.F, P2.F, ....)$$
$$P.v = P1.v = P2.v = ....$$

velocity out causality (preferred):

$$I = [1/M; 1/M; 1/J]$$
$$P.v = I*int(P.F);$$

force out causality:

$$I = [1/M; 1/M; 1/J]$$
$$P.F = I-1*ddt(P.v);$$

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
</table>

---

20-sim 5.1 Reference Manual 883
Port with three degrees of freedom \((x, y, \theta)\). Any number of connections can be made.

**Causality**

preferred velocity

out

**Parameters**

\(M\)  
Mass [kg].

\(J\)  
Moment of inertia [kgm\(^2\)/rad]

**Note**

- A TwoDBody model can be connected to any other element of the 2D-library except other 2D-bodies. Two bodies can always be simplified to one TwoDBody model with the combined mass and inertia of both single bodies.

- TwoDBody models can be connected to 1D models using the TwoDPoint models as intermediate. If a TwoDPoint is connected to a body, it constrains the movement of the body in one direct

**TwoDPoint Models**

TwoDPoint models are used to connect 1D models to TwoDBodies. They indicate a 1D force or torque that is applied in a certain direction, onto a body.

A point model forms the connection between the single degree of freedom part of a system and the center of mass of a body. Consider the example below, where force \(F\) in \(x\)-direction (single degree of freedom) is pushing upon a body (three degrees of freedom) at an offset \(YP\) from the body center of mass.

To create such a construct, the TwoDPoint-X model is used:
The TwoDPoint-X model describes the translation of a 1D force (x-direction) to a 2D-force (x-, y- and \(\theta\)-direction) and vice versa the translation of a 2D-velocity (x-, y- and \(\theta\)-direction) to a 1D velocity (x-direction).

There are four point models. Three point models transform from x-direction, y-direction and \(\theta\)-direction to 2D. One point models transforms from direction with arbitrary orientation to 2D.

**Fixation of bodies**

If a TwoDBody model is used in combination with TwoDPoint models, at least three non-coinciding, unequal (i.e. not having the same offsets) TwoDPoints must be connected to prevent the body from free motion. This is obvious when we interpret the point models physically. Point models can be interpreted as constraints on motion in one direction. The motion in the other two directions is free.

To show that two points are not sufficient to constrain all motions look at the figure below.

---

11. Library
**TwoDPoint**

**Library**
Iconic Diagrams\Mechanical\Translation\2DSmallAngles

**Implementations**
X
Y
theta
XY

**Use**

**Domains:** Continuous. **Size:** 1-D/2-D. **Kind:** Iconic Diagrams (1D Translation, 2D Planar).

**Description - X**

TwoDPoint models are used to connect 1D models to TwoDBodies. They indicate a 1D force or torque that is applied in a certain direction, onto a body. The TwoDPoint-X model forms the connection between the single degree of freedom in x-direction and the center of mass of a body. Consider the example below, where force $F$ in x-direction (single degree of freedom) is pushing upon a body (three degrees of freedom) at an offset $YP$ from the body center of mass.

![Diagram of TwoDPoint-X model](image)

To create such a construct the TwoDPoint-X model is used:

The TwoDPoint-X model describes the transformation of force in x-direction to a force in three degrees of freedom. The single degree of freedom port $p\_in$ describes the connection in x-direction and the three three degree of freedom port $P\_out$ describes connection with the 2D-body (x, y and $\theta$).

\[
P\_out.F[1] = p\_in.F; \quad \text{// x-direction}
\]
\[
P\_out.F[2] = 0; \quad \text{// y-direction}
\]
\[
P\_out.F[3] = -p\_in.F \times YP; \quad \text{// rotation}
\]
\[
p\_in.v = P\_out.v[1] - YP \times \text{// x-direction}
\]
\[
P\_out.v[3];
\]
### Interface - X

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
<td>1D Translation port (x).</td>
</tr>
<tr>
<td>P_out[3]</td>
<td>2D Port with three degrees of freedom (x, y, θ).</td>
</tr>
</tbody>
</table>

**Causality**
- fixed force out
- P_out
- fixed velocity out
- p_in

**Parameters**
- YP: Distance (y-direction) between connection and center of mass [m].

### Description - Y

TwoDPoint models are used to connect 1D models to TwoDBodies. They indicate a 1D force or torque that is applied in a certain direction, onto a body. The TwoDPoint-Y model forms the connection between the single degree of freedom in y-direction and the center of mass of a body. Consider the example below, where force F in y-direction (single degree of freedom) is pushing upon a body (three degrees of freedom) at an offset XP from the body center of mass.

![Diagram of TwoDPoint-Y model](image)

To create such a construct the 2D-point-Y model is used:
The 2D-point-Y model describes the transformation of force in y-direction to a force in three degrees of freedom. The single degree of freedom port \( p_{in} \) describes the connection in y-direction and the three three degree of freedom port \( P_{out} \) describes connection with the 2D-body \((x, y, \theta)\).

\[
\begin{align*}
P_{out}[1] &= 0; & \text{\textit{\# x-direction}} \\
P_{out}[2] &= p_{in}.F; & \text{\textit{\# y-direction}} \\
P_{out}[3] &= p_{in}.F \times XP; & \text{\textit{\# rotation}} \\
p_{in}.v &= P_{out}.v[2] + XP \times P_{out}.v[3]; & \text{\textit{\# y-direction}} \\
\end{align*}
\]

**Interface - Y**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{in} )</td>
<td>1D Translation port (y).</td>
</tr>
<tr>
<td>( P_{out}[3] )</td>
<td>2D Port with three degrees of freedom ((x, y, \theta)).</td>
</tr>
</tbody>
</table>

**Causality**

- fixed force out \( P_{out} \)
- fixed velocity out \( p_{in} \)

**Parameters**

- \( XP \) Distance (x-direction) between connection and center of mass [m].
Description - theta

TwoDPoint models are used to connect 1D models to TwoDBodies. They indicate a 1D force or torque that is applied in a certain direction, onto a body. The TwoDPoint-Theta model forms the connection between the single degree of freedom rotation and the center of mass of a body. Consider the example below, where torque (single degree of freedom) is acting on a body (three degrees of freedom).

![Diagram of TwoDPoint-Theta model](image)

To create such a construct the TwoDPoint-Theta model is used:

```
P_out.F[1] = 0;  // x-direction
P_out.F[2] = 0;  // y-direction
p_in.omega = P_out.v[3];  // rotation
```

Interface - theta

### Ports

<table>
<thead>
<tr>
<th>Description</th>
<th>1D Rotation port ((\theta)).</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
<td>2D Port with three degrees of freedom (x, y, (\theta)).</td>
</tr>
<tr>
<td>P_out[3]</td>
<td></td>
</tr>
</tbody>
</table>

### Causality

- fixed force out
- \(P\_out\)
- fixed velocity out
- \(p\_in\)
**Description - XY**

TwoDPoint models are used to connect 1D models to TwoDBodies. They indicate a 1D force or torque that is applied in a certain direction, onto a body. The TwoDPoint-XY model forms the connection between a single degree of freedom in arbitrary direction and the center of mass of a body. Consider the example below, where force $F$ (single degree of freedom) is pushing upon a body (three degrees of freedom) with an arbitrary angle $\theta$ at an offset $XP$ and $YP$ from the body center of mass.

![Diagram of TwoDPoint-XY model](image)

To create such a construct the TwoDPoint-XY model is used:

\[
Fx = \cos(\theta) \times p_{\text{in}}.F; \quad \text{// arbitrary-direction}
\]
\[
Fy = \sin(\theta) \times p_{\text{in}}.F; \quad \text{// arbitrary-direction}
\]
\[
P_{\text{out}}.F[1] = Fx; \quad \text{// x-direction}
\]
\[
P_{\text{out}}.F[2] = Fy; \quad \text{// y-direction}
\]
\[
P_{\text{out}}.F[3] = Fy \times XP - Fx \times YP; \quad \text{// rotation}
\]
\[ p_{\text{in}}.v = \cos(\theta) \cdot P_{\text{out}}.v[1] + \sin(\theta) \cdot P_{\text{out}}.v[2] + \ XP \cdot \sin(\theta) \cdot P_{\text{out}}.v[3] - \ YP \cdot \cos(\theta) \cdot P_{\text{out}}.v[3]; \]

\textit{// arbitrary-direction}

\textbf{Interface - XY}

\textbf{Ports} \quad \textbf{Description}
\begin{tabular}{ll}
p_{\text{in}} & 1D Translation port in arbitrary direction. \\
P_{\text{out}}[3] & 2D Port with three degrees of freedom (x, y, \theta). \\
\end{tabular}

\textbf{Causality}
\begin{tabular}{ll}
fixed & force out \\
P_{\text{out}} & fixed velocity out \\
p_{\text{in}} & \\
\end{tabular}

\textbf{Parameters}
\begin{tabular}{ll}
YP & Distance (y-direction) between connection and center of mass [m]. \\
XP & Distance (x-direction) between connection and center of mass [m]. \\
\theta & Angle of impact of the single degree of freedom port [rad]. \\
\end{tabular}

\textbf{Note}
- A TwoDBody has to be connected to at least three unequal TwoDPoint models to prevent it from free motion (rotation & translation).
- Flipping or rotating the model does not change the direction of applied forces or measured directions. Preferably leave the orientation as it pops up on the screen.

\textbf{TwoDFixedWorld}

\textbf{Library}
Iconic Diagrams\Mechanical\Translation\2DSmallAngles

\textbf{Use}
\textbf{Domains:} Continuous. \textbf{Size:} 2-D. \textbf{Kind:} Iconic Diagrams (2D Planar).

\textbf{Description}
The TwoDFixedWorld represents the fixed world in 3 degrees of freedom. It can be connected to other 2D models to freeze their motion. Models that can be connected to the fixed world are:
1. TwoDSprings
2. TwoDLinearSlides
3. TwoDLinearActuators

Although other models like the TwoDBody can also be connected to the TwoDFixedWorld model, it makes no sense because it completely fixates all equations of motion.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Port with three degrees of freedom (x, y, θ).</td>
</tr>
</tbody>
</table>

**Causality**

fixed velocity out

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Port with three degrees of freedom (x, y, θ).</td>
</tr>
</tbody>
</table>

**TwoDZeroForce**

**Library**

Iconic Diagrams\Mechanical\Translation\2DSmallAngles

**Use**


**Description**

This model can be used to connect any open end of another 2D model that is not connected to the fixed world. It generates a three degree of freedom zero force while the velocity is free.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Port with three degrees of freedom (x, y, θ).</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out P

**Sensors**

To inspect the model behavior you can plot variables. Sometimes not all variables are available. Then sensor model can be used.

**1D**

To use the 1D sensor models from the standard library, connect them to the 2D models using the TwoDPoint models.
2D
To measure variables directly from the 2D models, three absolute sensors are available showing the absolute position, velocity and acceleration. Also two relative sensors are available showing the force and powerflow between two elements.

TwoDPositionSensor

Library
Iconic Diagrams\Mechanical\Translation\2DSmallAngles

Use
Domains: Continuous. Size: 1-D/2-D. Kind: Iconic Diagrams (1D Translation, 1D Rotation, 2D Planar).

Description
This model is used to find the absolute position of a TwoDBody model. It has a port $P$ which can be connected to the body and it has three output signals that denotes the $x$- and $y$-position and the angle of the body. The model has a force out causality. The equations are:

\[
P.F = 0; \\
x = \text{int}(P.v[1]); \\
y = \text{int}(P.v[2]); \\
theta = \text{int}(P.v[3]);
\]

Interface

Ports
<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P[3]$</td>
</tr>
</tbody>
</table>

Causality
fixed force out $P$

Output
\begin{align*}
x & \quad \text{Absolute position [m].} \\
y & \quad \text{Absolute position [m].} \\
theta & \quad \text{Absolute angle [rad].}
\end{align*}

Initial Values

\begin{align*}
x_{\text{initial}} & \quad \text{Initial position [m]} \\
y_{\text{initial}} & \quad \text{Initial position [m]} \\
\theta_{\text{initial}} & \quad \text{Initial angle [rad]} \\
\end{align*}
**TwoDVelocitySensor**

**Library**

Iconic Diagrams\Mechanical\Translation\2DSmallAngles

**Use**

**Domains:** Continuous. **Size:** 1-D/2-D. **Kind:** Iconic Diagrams (1D Translation, 1D Rotation, 2D Planar).

**Description**

This model is used to find the absolute velocity of a TwoDBody model. It has a port $P$ which can be connected to the body and it has three output signals that denotes the $x$- and $y$-velocity and the angular velocity of the body. The model has a force out causality. The equations are:

\[
P.F = 0; \\
v_x = P.v[1]; \\
v_y = P.v[2]; \\
omega = P.v[3];
\]

**Interface**

**Ports**

- **P[3]**: Port with three degrees of freedom $(x, y, \theta)$.

**Causality**

- fixed force out $P$

**Output**

- $v_x$: Absolute velocity [m].
- $v_y$: Absolute velocity [m].
- $omega$: Absolute angular velocity [rad].

---

**TwoDAccelerationSensor**

**Library**

Iconic Diagrams\Mechanical\Translation\2DSmallAngles

**Use**

**Domains:** Continuous. **Size:** 1-D/2-D. **Kind:** Iconic Diagrams (1D Translation, 1D Rotation, 2D Planar).

**Description**

This model is used to find the absolute acceleration of a TwoDBody model. It has a port $P$ which can be connected to the body and it has three output signals that denotes the $x$- and $y$-acceleration and the angular acceleration of the body. The acceleration output is calculated out of the velocity by differentiation. Differentiation is performed by a state variable filter:
The S-domain function of this filter is equal to:

\[
\text{output} = \frac{s}{s + \frac{1}{f}} \cdot \text{input}
\]

where \( f \) is the cut-off frequency. For very high values of \( f \), the output becomes the pure derivative of the input. High values of \( f \), however, increase simulations times. A good trade-off is a starting value of 1e5.

The equations of this model are:

\[
\begin{align*}
P.F &= 0; \\
ax &= 2\pi f (P.v[1] - \text{int}(ax, 0)); \\
ay &= 2\pi f (P.v[2] - \text{int}(ay, 0)); \\
alpha &= 2\pi f (P.v[3] - \text{int}(alpha, 0));
\end{align*}
\]

### Interface

#### Ports

<table>
<thead>
<tr>
<th>Description</th>
<th>Port with three degrees of freedom (x, y, ( \theta )).</th>
</tr>
</thead>
<tbody>
<tr>
<td>P[3]</td>
<td>Port</td>
</tr>
</tbody>
</table>

#### Causality

fixed force out P

#### Outputs

<table>
<thead>
<tr>
<th>Description</th>
<th>Absolute acceleration [m].</th>
</tr>
</thead>
<tbody>
<tr>
<td>ax</td>
<td></td>
</tr>
<tr>
<td>ay</td>
<td></td>
</tr>
<tr>
<td>alpha</td>
<td>Absolute acceleration [rad].</td>
</tr>
</tbody>
</table>

#### Initial Values

<table>
<thead>
<tr>
<th>Description</th>
<th>Initial acceleration [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ax_initial</td>
<td></td>
</tr>
<tr>
<td>ay_initial</td>
<td></td>
</tr>
<tr>
<td>alpha_initial</td>
<td>Initial angular acceleration [m]</td>
</tr>
</tbody>
</table>
**TwoDForceSensor**

**Library**  
Iconic Diagrams\Mechanical\Translation\2DSmallAngles

**Use**  
**Domains**: Continuous. **Size**: 1-D/2-D. **Kind**: Iconic Diagrams (1D Translation, 1D Rotation, 2D Planar).

**Description**  
This model can be used to measure the forces and torque between two components. It has a high and a low terminal to connect to both components. The equations are:

\[
\begin{align*}
  P.F &= P_{\text{high}}.F = P_{\text{low}}.F; \\
  P.v &= P_{\text{high}}.v - P_{\text{low}}.v; \\
  P.v &= 0; \\
  Fx &= P.F[1]; \\
  Fy &= P.F[2]; \\
  T &= P.F[3];
\end{align*}
\]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P[3]</td>
<td>Port with three degrees of freedom ((x, y, \theta)).</td>
</tr>
</tbody>
</table>

**Causality**  
fixed velocity out

**Outputs**  
- Fx: Force [N].  
- Fy: Force [N].  
- T: Torque [Nm].

---

**TwoDPowerSensor**

**Library**  
Iconic Diagrams\Mechanical\Translation\2DSmallAngles

**Use**  
**Domains**: Continuous. **Size**: 1-D/2-D. **Kind**: Iconic Diagrams (1D Translation, 1D Rotation, 2D Planar).

**Description**  
This model can be used to measure the powerflow between two models. It has two ports to both models. The equations are:
\[ P.F = P_{\text{high}.F} = P_{\text{low}.F}; \]
\[ P_{\text{high}.F} = P_{\text{low}.F}; \]
\[ P_{\text{high}.v} = P_{\text{low}.v}; \]
\[ P = P_{\text{high}.v} \cdot P_{\text{high}.F}; \]
\[ Px = P[1]; \]
\[ Py = P[2]; \]
\[ P\theta = P[3]; \]

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P[3]</td>
</tr>
</tbody>
</table>

**Ports Description**

- **P[3]**: Port with three degrees of freedom \((x, y, \theta)\).

**Causality**

<table>
<thead>
<tr>
<th>Causality</th>
</tr>
</thead>
<tbody>
<tr>
<td>fixed velocity out</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Px</td>
</tr>
<tr>
<td>Py</td>
</tr>
<tr>
<td>P\theta</td>
</tr>
</tbody>
</table>

- **Px**: Power [W].
- **Py**: Power [W].
- **P\theta**: Power [W].

**Springs and other Flexible Components**

**2D Springs**

A TwoDSpring model represents a flexible spring between two bodies. The center of stiffness is located relative to the two bodies. The offsets from the bodies to the center of stiffness are indicated by \(x_1, y_1, x_2\) and \(y_2\) as shown in the picture below (left).

![A 2-D spring in rest (left) and stretched (right).](image-url)
Note that $x_1$, $y_1$, $x_2$ and $y_2$ are defined with respect to the spring coordinate frame which is at the center of the spring. This means in the picture above $x_1$ and $y_1$ have a negative value and $x_2$ and $y_2$ have a positive value.

When the spring is stretched the offsets will change by the spring elongations $x$, $y$ and $\theta$ as indicated in the picture (right). The center of stiffness is always located precisely in the middle of the spring elongations. Because all spring equations will be calculated from the center of stiffness this means that the offsets for a stretched spring are $(x_1 - x/2)$, $(y_1 - y/2)$, $(x_2 + x/2)$ and $(y_2 + y/2)$.

For a realistic representation of vibration behavior, every 2D spring has a damper in parallel. If you want to turn off the effects of this damper, choose the damping parameters equal to zero. If you want to damp out unwanted vibrations, choose the damping parameters equal to 0.1% to 10% of the spring parameters.

**Linear Slides**

Take a look at the TwoDSpring model in the picture below. If we replace the spring in $x$-direction by a zero force we have created a linear slide.

![Linear slide diagram](image)

*Linear slide: $x = \text{free}$, $y = \text{stiff}$, $\theta = \text{stiff}$.*

Consider a carriage that is clamped with four wheels to a slide. In the $x$-direction the carriage is free to move, which is equal to a zero force. The limited stiffness of the wheels is represented by springs. If there is a force with equal sign on both wheels, the carriage will slightly move in the $y$-direction. If there is a force with opposite sign on both wheels, the carriage will only rotate. This can be represented by two independent springs: one in the $y$-direction and $\theta$-direction.

If we repeat the same experiment and replace the spring in $x$-direction by a zero force and the spring in $\theta$-direction by a zero torque, we have created a linear slide with rotational freedom. In practice this can be found with carriages that are clamped with a limited set of wheels as shown below.
The TwoDLibrary contains four Linear Slide models:

1. TwoDLinearSlide-X  \( x = \text{free}, \ y = \text{stiff}, \ \theta = \text{stiff} \)
2. TwoDLinearSlide-Y  \( x = \text{stiff}, \ y = \text{free}, \ \theta = \text{stiff} \)
3. TwoDLinearSlide-XTheta  \( x = \text{free}, \ y = \text{stiff}, \ \theta = \text{free} \)
4. TwoDLinearSlide-YTheta  \( x = \text{free}, \ y = \text{stiff}, \ \theta = \text{free} \)

**Linear Actuators**

Instead of replacing the spring in \( x \)-direction with a zero force as with the linear slides, we can replace it by a 1D power port to allow all kind of connections with the models from the standard library. In this way we have created a linear actuator, that allows every kind of actuation.

Like the linear slides, for the linear actuators we can also replace the spring in \( \theta \)-direction by a zero torque, which makes the total number of linear actuator models equal to four:
With the port connection ever possible form of actuation can be created. Two examples are shown below.

\textbf{TwoDSpring}

\textbf{Library}
Iconic Diagrams\Mechanical\Translation\2DSmallAngles

\textbf{Use}

\textbf{Description}
A TwoDSpring model represents a flexible connection between two bodies. The bodies are located relative to the center of stiffness. The offsets from the bodies to the center of stiffness are indicated by \(x1, y1, x2\) and \(y2\) as shown in the picture below (left).
Note that $x_1$, $y_1$, $x_2$ and $y_2$ are defined with respect to the spring coordinate frame which is at the center of the spring. This means in the picture above $x_1$ and $y_1$ have a negative value and $x_2$ and $y_2$ have a positive value.

When the spring is stretched the offsets will change by the spring elongations $x$, $y$ and $\theta$ as indicated in the picture (right). The center of stiffness is always located precisely in the middle of the spring elongations. Because all spring equations will be calculated from the center of stiffness this means that the offsets for a stretched spring are $(x_1 - x/2)$, $(y_1 - y/2)$, $(x_2 + x/2)$ and $(y_2 + y/2)$.

For a realistic representation of vibration behavior, every 2D spring has a damper in parallel. If you want to turn off the effects of this damper, choose the damping parameters equal to zero. If you want to damp out unwanted vibrations, choose the damping parameters equal to 0.1% to 10% of the spring parameters.

**Interface**

**Ports**

- **P[3]**: Port with three degrees of freedom ($x$, $y$, $\theta$).

**Description**

- Port with three degrees of freedom ($x$, $y$, $\theta$).

**Causality**

- fixed force out P

**Parameters**

- **x1**: distance in x-direction from center of stiffness to port 1 [m]
- **y1**: distance in y-direction from center of stiffness to port 1 [m]
- **x2**: distance in x-direction from center of stiffness to port 2 [m]
- **y2**: distance in y-direction from center of stiffness to port 2 [m]
- **kx**: stiffness in x-direction [N/m]
- **ky**: stiffness in y-direction [N/m]
- **kth**: rotational stiffness [N.m/rad]
- **dx**: damping in x-direction [N.s/m]
dy damping in y-direction [N.s/m]
dth rotational damping [N.m.s/rad]

**Initial Values**
- x_initial: The initial extension of the spring [m].
- y_initial: The initial extension of the spring [m].
- theta_initial: The initial rotation of the spring [rad].

**TwoDLinearSlide**

**Library**
Iconic Diagrams\Mechanical\Translation\2DSmallAngles

**Implementations**
- X
- Y
- XTheta
- YTheta

**Use**
**Domains**: Continuous. **Size**: 2-D. **Kind**: Iconic Diagrams (2D Planar).

**Description - X**
The TwoDLinearSlide-X model represents a flexible connection between two bodies in y- and θ-direction. The bodies are located relative to the center of stiffness. The offsets from the bodies to the center of stiffness are indicated by the parameters x1, y1, x2 and y2 as shown in the picture below.

The TwoDLinearSlide-X model is based on the TwoDSpring model by replacing the spring and damper in x-direction by a zero force. Consider a carriage that is clamped with four wheels to a slide. In the x-direction the carriage is free to move, which is equal to a zero force. The limited stiffness of the wheels is represented by springs. If there is a force with equal sign on both wheels, the carriage will slightly move in the y-direction. If there is a force with opposite sign on both wheels, the carriage will only rotate. This can be represented by two independent springs: one in the y-direction and θ-direction.
Linear slide: $x = \text{free, } y = \text{stiff, } \theta = \text{stiff}$.

For a realistic representation of vibration behavior, every spring has a damper in parallel. If you want to turn off the effects of this damper, choose the damping parameters equal to zero. If you want to damp out unwanted vibrations, choose the damping parameters equal to 0.1% to 10% of the spring parameters.

**Interface - X**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P[3]</td>
<td>Port with three degrees of freedom ($x$, $y$, $\theta$).</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out P

**Parameters**

- $x_1$, distance in $x$-direction from center of stiffness to port 1 [m]
- $y_1$, distance in $y$-direction from center of stiffness to port 1 [m]
- $x_2$, distance in $x$-direction from center of stiffness to port 2 [m]
- $y_2$, distance in $y$-direction from center of stiffness to port 2 [m]
- $k_y$, stiffness in $y$-direction [N/m]
- $k_{th}$, rotational stiffness [N.m/rad]
- $d_y$, damping in $y$-direction [N.s/m]
- $d_{th}$, rotational damping [N.m.s/rad]

**Initial Values**

- $y_{\text{initial}}$, The initial extension of the spring [m].
- $\theta_{\text{initial}}$, The initial rotation of the spring [rad].

**Description - Y**

The TwoDLinearSlide-Y model is equal to the TwoDLinearSlide-X model except that here the movement is free in the $y$-direction.
11. Library

Interface - Y

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P[3]</td>
<td>Port with three degrees of freedom (x, y, θ).</td>
</tr>
</tbody>
</table>

Causality
fixed force out P

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x1</td>
<td>distance in x-direction from center of stiffness to port 1 [m]</td>
</tr>
<tr>
<td>y1</td>
<td>distance in y-direction from center of stiffness to port 1 [m]</td>
</tr>
<tr>
<td>x2</td>
<td>distance in x-direction from center of stiffness to port 2 [m]</td>
</tr>
<tr>
<td>y2</td>
<td>distance in y-direction from center of stiffness to port 2 [m]</td>
</tr>
<tr>
<td>kx</td>
<td>stiffness in x-direction [N/m]</td>
</tr>
<tr>
<td>kth</td>
<td>rotational stiffness [N.m/rad]</td>
</tr>
<tr>
<td>dx</td>
<td>damping in x-direction [N.s/m]</td>
</tr>
<tr>
<td>dth</td>
<td>rotational damping [N.m.s/rad]</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x_initial</td>
<td>The initial extension of the spring [m].</td>
</tr>
<tr>
<td>theta_initial</td>
<td>The initial rotation of the spring [rad].</td>
</tr>
</tbody>
</table>

Description - XTheta

The TwoDLinearSlide-XTheta model represents a flexible connection between two bodies in y-direction. The bodies are located relative to the center of stiffness. The offsets from the bodies to the center of stiffness are indicated by the parameters x1, y1, x2 and y2 as shown in the picture below.

The TwoDLinearSLide-X model is based on the TwoDSpring model by replacing the spring and damper in x- and θ-direction by a zero force. Consider a carriage that is clamped with two wheels to a slide. In the x-direction the carriage is free to move, which is equal to a zero force. The carriage is also free to rotate, which is equal to a zero torque. The limited stiffness of the wheels is represented by springs. If there is a force on the wheels, the carriage will slightly move in the y-direction.
Linear slide: $x =$ free, $y =$ stiff, $\theta =$ stiff.

For a realistic representation of vibration behavior, every spring has a damper in parallel. If you want to turn off the effects of this damper, choose the damping parameters equal to zero. If you want to damp out unwanted vibrations, choose the damping parameters equal to 0.1\% to 10\% of the spring parameters.

**Interface - XTheta**

**Ports**

- **P[3]**: Port with three degrees of freedom ($x$, $y$, $\theta$).

**Causality**

- Fixed force out P

**Parameters**

- **x1**: distance in $x$-direction from center of stiffness to port 1 [m]
- **y1**: distance in $y$-direction from center of stiffness to port 1 [m]
- **x2**: distance in $x$-direction from center of stiffness to port 2 [m]
- **y2**: distance in $y$-direction from center of stiffness to port 2 [m]
- **ky**: stiffness in $y$-direction [N/m]
- **dy**: damping in $y$-direction [N.s/m]

**Initial Values**

- **y_initial**: The initial extension of the spring [m].

**Description - YTheta**

The TwoDLinearSlide-YTheta model is equal to the TwoDLinearSlide-XTheta model except that here the movement is free in the $y$ and $\theta$-direction.

**Interface - YTheta**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
</table>
Port with three degrees of freedom \((x, y, \theta)\).

**Causality**
fixed force out \(P\)

**Parameters**

- \(x_1\): distance in \(x\)-direction from center of stiffness to port 1 [m]
- \(y_1\): distance in \(y\)-direction from center of stiffness to port 1 [m]
- \(x_2\): distance in \(x\)-direction from center of stiffness to port 2 [m]
- \(y_2\): distance in \(y\)-direction from center of stiffness to port 2 [m]
- \(k_x\): stiffness in \(x\)-direction [N/m]
- \(d_x\): damping in \(x\)-direction [N.s/m]

**Initial Values**

- \(x_{\text{initial}}\): The initial extension of the spring [m].

---

**TwoDLinearActuator**

**Library**
Iconic Diagrams\Mechanical\Translation\2DSmallAngles

**Implementations**

- \(X\)
- \(Y\)
- \(X\Theta\)
- \(Y\Theta\)

**Use**
Domains: Continuous. **Size**: 1-D / 2-D. Kind: Iconic Diagrams (1D Translation, 2D Planar).

**Description - X**

The TwoDLinearActuator-X model represents a flexible connection between two bodies in \(y\)- and \(\theta\)-direction. The TwoDLinearActuator-X model is based on the TwoDLinearSlide-X model. Instead of using a zero force in the \(x\)-direction, there is a coupling with a 1D translation port for the actuator force.
Consider a carriage that is clamped with four wheels to a slide. In the x-direction the carriage can be moved by a certain force. The limited stiffness of the wheels is represented by springs. If there is a force with equal sign on both wheels, the carriage will slightly move in the y-direction. If there is a force with opposite sign on both wheels, the carriage will only rotate. This can be represented by two independent springs: one in the y-direction and θ-direction.

*Linear slide: x = free, y = stiff, θ = stiff.*

For a realistic representation of vibration behavior, every spring has a damper in parallel. If you want to turn off the effects of this damper, choose the damping parameters equal to zero. If you want to damp out unwanted vibrations, choose the damping parameters equal to 0.1% to 10% of the spring parameters.

With the 1D port connection every possible form of actuation can be created using the models from the standard library. Two examples are shown below.

**Interface - X**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P[3]</td>
<td>Port with three degrees of freedom (x, y, θ).</td>
</tr>
</tbody>
</table>
11. Library


\[ p \]

1D translation port

**Causality**

fixed force out P

**Parameters**

- **x1** distance in x-direction from center of stiffness to port 1 [m]
- **y1** distance in y-direction from center of stiffness to port 1 [m]
- **x2** distance in x-direction from center of stiffness to port 2 [m]
- **y2** distance in y-direction from center of stiffness to port 2 [m]
- **ky** stiffness in y-direction [N/m]
- **kth** rotational stiffness [N.m/rad]
- **dy** damping in y-direction [N.s/m]
- **dth** rotational damping [N.m.s/rad]

**Initial Values**

- **y_initial** The initial extension of the spring [m].
- **theta_initial** The initial rotation of the spring [rad].

**Description - Y**

The TwoDLinearActuator-Y model is equal to the TwoDLinearActuator-X model except that here the force acts in the y-direction.

**Interface - Y**

**Ports**

- **P[3]** Port with three degrees of freedom (x, y, \( \theta \)).
- **p** 1D translation port

**Causality**

fixed force out P

**Parameters**

- **x1** distance in x-direction from center of stiffness to port 1 [m]
- **y1** distance in y-direction from center of stiffness to port 1 [m]
- **x2** distance in x-direction from center of stiffness to port 2 [m]
- **y2** distance in y-direction from center of stiffness to port 2 [m]
- **kx** stiffness in x-direction [N/m]
- **kth** rotational stiffness [N.m/rad]
- **dx** damping in x-direction [N.s/m]
- **dth** rotational damping [N.m.s/rad]

**Initial Values**

- **x_initial** The initial extension of the spring [m].
- **theta_initial** The initial rotation of the spring [rad].
**Description - XTheta**

The TwoDLinearActuator-XTheta model represents a flexible connection between two bodies in $y$-direction. The TwoDLinearActuator-XTheta model is based on the TwoDLinearSlide-XTheta model. Instead of using a zero force in the $x$-direction, there is a coupling with a 1D translation port for the actuator force.

Consider a carriage that is clamped with two wheels to a slide. In the $x$-direction the carriage can be moved by a certain force. The carriage is free to rotate, which is equal to a zero torque. The limited stiffness of the wheels is represented by springs. If there is a force acting on both wheels, the carriage will slightly move in the $y$-direction. If there is a force acting on the wheels, the carriage will slightly move in the $y$-direction.

![Diagram](image)

*Linear slide: $x = \text{free}$, $y = \text{stiff}$, $\theta = \text{stiff}$.*

For a realistic representation of vibration behavior, the spring has a damper in parallel. If you want to turn off the effects of this damper, choose the damping parameters equal to zero. If you want to damp out unwanted vibrations, choose the damping parameter equal to 0.1% to 10% of the spring parameter.

With the 1D port connection every possible form of actuation can be created using the models from the standard library. For example see the TwoDLinearActuator-X model.

**Interface - XTheta**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P[3]</td>
<td>Port with three degrees of freedom ($x$, $y$, $\theta$).</td>
</tr>
<tr>
<td>p</td>
<td>1D translation port</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out P

**Parameters**

- $x_1$: distance in $x$-direction from center of stiffness to port 1 [m]
- $y_1$: distance in $y$-direction from center of stiffness to port 1 [m]
- $x_2$: distance in $x$-direction from center of stiffness to port 2 [m]
- $y_2$: distance in $y$-direction from center of stiffness to port 2 [m]
ky

stiffness in y-direction [N/m]

dy

damping in y-direction [N.s/m]

**Initial Values**

y_initial

The initial extension of the spring [m].

**Description - YTheta**

The TwoDLinearActuator-YTheta model is equal to the TwoDLinearActuator-XTheta model except that here the force acts in the y-direction.

**Interface - YTheta**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P[3]</td>
<td>Port with three degrees of freedom (x, y, θ).</td>
</tr>
<tr>
<td>p</td>
<td>1D translation port</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out P

**Parameters**

x1
distance in x-direction from center of stiffness to port 1 [m]

y1
distance in y-direction from center of stiffness to port 1 [m]

x2
distance in x-direction from center of stiffness to port 2 [m]

y2
distance in y-direction from center of stiffness to port 2 [m]

kx

stiffness in x-direction [N/m]

kth

rotational stiffness [N.m/rad]

dx
damping in x-direction [N.s/m]

dth

rotational damping [N.m.s/rad]

**Initial Values**

x_initial

The initial extension of the spring [m].

theta_initial

The initial rotation of the spring [rad].
**Tips**

When you are working with the 2D-Library for small angles, it is good to keep the following tips in mind:

- The 2DSmallRotations library is very well suited for frequency domain analysis through linearization.
- The 2DSmallRotations library is not suited for large rotations. Consider a rotation of 0.05 degrees or 1 mrad as an upper bound for every model part.
- It is not possible in 20-sim to use vector elements with mixed units. Therefore element number 3 will be displayed with units $[\text{m/s}]$ and $[\text{N}]$ although it really is $[\text{rad/s}]$ and $[\text{Nm}]$!
- The vector element number (1, 2 or 3) denotes the degree of freedom. Flipping or rotating of a model does not change this degree (e.g. a rotation does not change from $x$ into $y$). Preferably leave the orientation of the models as they pop up on the screen.
- To create intuitive models, the positive direction of each degree of freedom is defined as: $x$ from left to right, $y$ from bottom to top, $\theta$ counter clockwise.
- To prevent misinterpretation of a model by other users, stick to the drawing rules that are given.
- A TwoDBody model can be connected to any other element of the 2D-library except other 2D-bodies.
- A TwoDBody model can be connected to 1D models using the TwoDPoint models as intermediate.
- TwoDPoint models can only be connected to TwoDBody models.
- If a TwoDBody model is connected to TwoDPoint models only, it has to be connected to at least three non-coinciding, unequal (i.e. not having the same offsets) TwoDPoints to prevent it from free motion.

**3DSmallRotation**

**ThreeDLibrary**

**Library**

The 3DSmallRotation library contains 3D models that are only suited for small rotations. The library is comparable to the 2DSmallRotation library and suited for modeling systems that, due to limited stiffness, experience rotation that should be accounted for.

**Degrees of Freedom**

All models in 3DSmallRotation library contain one or more ports with 6 degrees of freedom. The first three degrees of freedom denote the $x$-, $y$- and $z$-position and the last three degrees of freedom denote the rotation around the $x$-, $y$- and $z$-axes. A vector notation is used to denote the forces and velocities for these degrees of freedom. For a model with a port $P$ the notation is:

<table>
<thead>
<tr>
<th>degree</th>
<th>identity</th>
<th>forces</th>
<th>velocities</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>position</td>
<td>$P.F[1]$ [N]</td>
<td>$P.v[1]$ [m/s]</td>
</tr>
</tbody>
</table>
11. Library

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit 1</th>
<th>Unit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>y</td>
<td>position</td>
<td>P.F[2] [N]</td>
<td>P.v[2] [m/s]</td>
</tr>
<tr>
<td>z</td>
<td>position</td>
<td>P.F[3] [N]</td>
<td>P.v[3] [m/s]</td>
</tr>
<tr>
<td>θ_x</td>
<td>angle</td>
<td>P.F[4] [Nm]</td>
<td>P.v[4] [rad/s]</td>
</tr>
<tr>
<td>θ_y</td>
<td>angle</td>
<td>P.F[5] [Nm]</td>
<td>P.v[5] [rad/s]</td>
</tr>
<tr>
<td>θ_z</td>
<td>angle</td>
<td>P.F[6] [Nm]</td>
<td>P.v[6] [rad/s]</td>
</tr>
</tbody>
</table>

Note

- It is not possible in 20-sim to use vector elements with mixed units. Therefore element number 4 to 6 will be displayed with units [m/s] and [N] although it really is [rad/s] and [Nm]!
- The vector element number (1 to 6) denotes the identity of the degree of freedom. Flipping or rotating of a model does not change this identity (e.g. a rotation does not change x into y). Preferably leave the orientation of the models as they pop up on the screen.

3D-body

![3D-body diagram](image)

The central model in the 3DSmallRotation library is the 3D-body model which describes a body with 6 degrees of freedom.

3D-mass

The 3D-mass model is a body with only mass and zero rotational inertia.

Points

![Points diagram](image)

The 3D-body model is nothing more than a center of mass. To connect a 3D-body with the outside (single degree of freedom) world, 3D-points are used. A 3D-point describes the offset between the center of mass and the connection point.

- A 3D-body has to be connected to 3D-points with at least three orthogonal nonzero offsets to prevent it from free rotation.
- A 3D-body has to be connected to at least three orthogonal 3D-point models to prevent it from free motion.

Sensors

The velocities of bodies can be inspected directly in the body models. To find positions sensor models are available.
ThreeDBody

Library
Iconic Diagrams\Mechanical\Translation\3DSmallAngles

Use

Description
This is a model of a 6 degree of freedom body. It is the equivalent of the 2D-body model. The first three degrees of freedom in this model are represented by a single mass and the last three degrees of freedom by a rotational inertia. The 3D-body has to be connected to at least three orthogonal 3D-points, which define the reaction forces.

The model has a preferred velocity out causality. The corresponding constitutive equations then contain an integration. The model can also have the non-preferred force out causality. The constitutive equations then contain a differentiation. Because any number of connections can be made, successive ports are named P1, P2, P3 etc. 20-sim will automatically create equations such that the resulting force \( P.F \) is equal to the sum of the forces of all connected ports \( P1 .. Pn \). The velocities of all connected ports are equal to \( P.v \)

\[
P.F = \text{sum}(P1.F, P2.F, ....)
\]
\[
P.v = P1.v = P2.v = ....
\]

velocity out causality (preferred):

\[
I = [1/M;1/M;1/M;1/J[1];1/J[2];1/J[3]];
\]
\[
P.v = I.*\text{int}(P.F);
\]

force out causality:

\[
I = [1/M;1/M;1/M;1/J[1];1/J[2];1/J[3]];
\]
\[
P.F = I-1.*\text{ddt}(P.v);
\]

Interface

Ports

P[6] Port with 6 degrees of freedom. Any number of connections can be made.

Causality
preferred velocity out

Parameters

M Mass [kg].

Note

- A body has to be connected to 3D-points with at least three orthogonal nonzero offsets to prevent it from free rotation.
- A 3D-body has to be connected to at least three orthogonal 3D-point models to prevent it from free motion.
- Flipping or rotating the model does not change the direction of applied forces or measured directions. Preferably leave the orientation as it pops up on the screen.
- It is not possible in 20-sim to use vector elements with mixed units. Therefore element number 4 to 6 will be displayed with units [m/s] and [N] although it really is [rad/s] and [Nm]!

ThreeDFixedWorld

Library
Iconic Diagrams\Mechanical\Translation\3DSmallAngles

Use

Description
This model represents the fixed world in 6 degrees of freedom. It can be connected to a 3D-body model to freeze its motion.

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Port with 6 degrees of freedom.</td>
</tr>
</tbody>
</table>

Causality
fixed velocity out

P

ThreeDForceActuator-Relative

Library
Iconic Diagrams\Mechanical\Translation\3DSmallAngles

Use
Domains: Continuous. Size: 1-D/6-D. Kind: Iconic Diagrams (Translation,Rotation).

Description
This model represents an ideal actuator. The actuator applies a force between its two terminals. This force can be set to a (fluctuating) value given by the input signal $F$, the velocity is indifferent.
This model is the equivalent of the 1 degree of freedom model ForceActuator-Relative.emx. It model represents an ideal actuator. The actuator applies a force between its two terminals. The force can be set to a (fluctuating) value given by a vector \( K \) multiplied by a signal \( F \), the velocity is indifferent. By setting the elements of the vector \( K \) equal to zero or one, specific elements of the 6 degrees of freedom output force can set equal to the input signal \( F \).

\[
\]

**Interface**

**Ports**

- **P_high[6]**, Both terminals of the port with 6 degrees of freedom.
- **P_low[6]**

**Causality**

fixed force out \( P \)

**Parameters**

- **K[6]**, Vector with 6 elements to set the 6 force elements on or off.

---

### ThreeDForceActuator

**Library**

Iconic Diagrams\Mechanical\Translation\3DSmallAngles

**Use**

Domains: Continuous. Size: 1-D/6-D. Kind: Iconic Diagrams (Translation,Rotation).

**Description**

This model is the equivalent of the 1 degree of freedom model ForceActuator.emx. It model represents an ideal actuator. The actuator is mounted to the fixed world and applies a force. The force can be set to a (fluctuating) value given by a vector \( K \) multiplied by a signal \( F \), the velocity is indifferent. By setting the elements of the vector \( K \) equal to zero or one, specific elements of the 6 degrees of freedom output force can set equal to the input signal \( F \).

\[
\]

**Interface**

**Ports**

- **P**, Port with 6 degrees of freedom.

**Causality**

fixed force out \( P \)

**Parameters**

- **K[6]**, Vector with 6 elements to set the 6 force elements on or off.
ThreeDMass

Library

Iconic Diagrams\Mechanical\Translation\3DSmallAngles

Use


Description

This is a model of a 6 degree of freedom body without rotational inertia. The 3D-mass has to be connected to at least three orthogonal 3D-points, which define the reaction forces.

The model has a fixed velocity out causality. Because any number of connections can be made, successive ports are named $P_1$, $P_2$, $P_3$ etc. 20-sim will automatically create equations such that the resulting force $P.F$ is equal to the sum of the forces of all connected ports $P_1 .. P_n$. The velocities of all connected ports are equal to $P.v$

$$
P.F = \text{sum}(P_1.F, P_2.F, ....)\\
P.v = P_1.v = P_2.v = ....\\
I = [1/M;1/M;1/M];\\
P.v[1..3] = I.*\text{int}(P.F);\\
P.v[4..6] = 0;
$$

Interface

Ports

<table>
<thead>
<tr>
<th>Description</th>
<th>Port with 6 degrees of freedom. Any number of connections can be made.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P[6]$</td>
<td></td>
</tr>
</tbody>
</table>

Causality

fixed velocity out

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mass [kg].</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td></td>
</tr>
</tbody>
</table>

Note

- A 3D-body has to be connected to 3D-points with at least three orthogonal nonzero offsets to prevent it from free rotation.
- A 3D-body has to be connected to at least three orthogonal 3D-point models to prevent it from free motion.
- Flipping or rotating the model does not change the direction of applied forces or measured directions. Preferably leave the orientation as it pops up on the screen.
- It is not possible in 20-sim to use vector elements with mixed units. Therefore element number 4 to 6 will be displayed with units [m/s] and [N] although it really is [rad/s] and [Nm]!
### ThreeDPoint

**Library**
Iconic Diagrams\Mechanical\Translation\3DSmallAngles

**Implementations**
X
Y
Z
XYZ

**Use**

**Domains**: Continuous. **Size**: 1-D/6-D. **Kind**: Iconic Diagrams (Translation, Rotation).

**Description - X**
A point model forms the connection between the single degree of freedom part of a system and the center of mass of a 3D-body. The 3D-point-X model is the equivalent of the 2D-point-X model. It describes the translation of force in x-direction to a force in 6 degrees of freedom. Because there are three rotational degrees of freedom, the 3D-point-X model has two offsets, $YP$ and $ZP$.

The single degree of freedom port $p_{in}$ describes the connection in x-direction and the 6 degree of freedom port $P_{out}$ describes connection with the 3D-body.

\[
\begin{align*}
P_{out}.F[1] &= p_{in}.F; & \text{ // x-direction} \\
P_{out}.F[2] &= 0; & \text{ // y-direction} \\
P_{out}.F[3] &= 0; & \text{ // z-direction} \\
P_{out}.F[4] &= 0; & \text{ // x-rotation} \\
P_{out}.F[5] &= ZP*p_{in}.F; & \text{ // y-rotation} \\
P_{out}.F[6] &= -YP*p_{in}.F; & \text{ // z-rotation} \\
p_{in}.v &= P_{out}.v[1] - YP*P_{out}.v[6] \quad \text{ // x-direction} \\
+ ZP*P_{out}.v[5]; & \\
\end{align*}
\]

As can be seen from the equations, a nonzero offset $YP$ or $ZP$ (distance from center of mass) in a 3D-point will result in a momentum. Therefore a 3D-body has to be connected to 3D-points with at least three orthogonal nonzero offsets to prevent it from free rotation.

The equations also show that the y-direction and z-direction are not affected by the 3D-point-X model. Therefore each 3D-body has to be connected to at least three orthogonal 3D-point models to prevent it from free motion.

**Interface - X**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
</table>

20-sim 5.1 Reference Manual 917
p_in Translation port with one degree of freedom (x [m]).

Causality
fixed force out
P_out
fixed velocity out
p_in

Parameters
YP Distance (y-direction) between connection and center of mass [m].
ZP Distance (z-direction) between connection and center of mass [m].

Description - Y
A point model forms the connection between the single degree of freedom part of a system and the center of mass of a 3D-body.
The 3D-point-Y model is the equivalent of the 2D-point-Y model. It describes the translation of force in x-direction to a force in 6 degrees of freedom. Because there are three rotational degrees of freedom, the 3D-point-Y model has two offsets, XP and ZP.

The single degree of freedom port p_in describes the connection in x-direction and the 6 degree of freedom port P_out describes connection with the 3D-body.

\[
\begin{align*}
P_{\text{out}.F[1]} &= 0; & \text{// x-direction} \\
P_{\text{out}.F[2]} &= p_{\text{in}.F;} & \text{// y-direction} \\
P_{\text{out}.F[3]} &= 0; & \text{// z-direction} \\
P_{\text{out}.F[4]} &= -ZP*p_{\text{in}.F;} & \text{// x-rotation} \\
P_{\text{out}.F[5]} &= 0; & \text{// y-rotation} \\
P_{\text{out}.F[6]} &= XP*p_{\text{in}.F;} & \text{// z-rotation} \\
p_{\text{in}.v} &= p_{\text{out}.v[2]} + XP*p_{\text{out}.v[6]} & \text{// y-direction} \\
- ZP *p_{\text{out}.v[4]};
\end{align*}
\]

As can bee seen from the equations, a nonzero offset XP or ZP (distance from center of mass) in a 3D-point will result in a momentum. Therefore a 3D-body has to be connected to 3D-points with at least three orthogonal nonzero offsets to prevent it from free rotation.

The equations also show that the x-direction and z-direction are not affected by the 3D-point-Y model. Therefore each 3D-body has to be connected to at least three orthogonal 3D-point models to prevent it from free motion.

Interface - Y

Ports Description
The single degree of freedom port \( p_{\text{in}} \) describes the connection in \( x \)-direction and the 6 degree of freedom port \( P_{\text{out}} \) describes connection with the 3D-body.

\[
\begin{align*}
P_{\text{out}}.F[1] &= 0; & \text{// x-direction} \\
P_{\text{out}}.F[2] &= 0; & \text{// y-direction} \\
P_{\text{out}}.F[3] &= p_{\text{in}}.F; & \text{// z-direction} \\
P_{\text{out}}.F[4] &= YP*p_{\text{in}}.F; & \text{// x-rotation} \\
P_{\text{out}}.F[5] &= -XP*p_{\text{in}}.F; & \text{// y-rotation} \\
P_{\text{out}}.F[6] &= 0; & \text{// z-rotation} \\
p_{\text{in}}.v &= P_{\text{out}}.v[3] - XP*P_{\text{out}}.v[5] & \text{// y-direction} \\
+ YP *P_{\text{out}}.v[4];
\end{align*}
\]

As can be seen from the equations, a nonzero offset \( XP \) or \( YP \) (distance from center of mass) in a 3D-point will result in a momentum. Therefore a 3D-body has to be connected to 3D-points with at least three orthogonal nonzero offsets to prevent it from free rotation.

The equations also show that the \( x \)-direction and \( y \)-direction are not affected by the 3D-point-Z model. Therefore each 3D-body has to be connected to at least three orthogonal 3D-point models to prevent it from free motion.

**Interface - Z**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{\text{in}} )</td>
<td>Translation port with one degree of freedom (( x ) [m]).</td>
</tr>
</tbody>
</table>

**Causality**
fixed force out
P_out
fixed velocity out
p_in

**Parameters**
XP Distance (x-direction) between connection and center of mass [m].
YP Distance (y-direction) between connection and center of mass [m].

**Description - XYZ**
A point model forms the connection between the single degree of freedom part of a system and the center of mass of a 3D-body.

The 3D-point-XYZ model is a combination of the 3D-point-X model, the 3D-point-Y model and the 3D-point-Z model. It describes the translation of force in x-direction, y-direction and z-direction to a force in 6 degrees of freedom. Because there are three rotational degrees of freedom, the model has three offsets, XP, YP and ZP.

The single degree of freedom ports p_inx, p_iny and p_inz describes the connection in x-direction, y-direction and z-direction and the 6 degree of freedom port P_out describes connection with the 3D-body.

\[
P_{out}.F[1] = p_{inx}.F; \quad \text{ // x-direction}
\]
\[
P_{out}.F[2] = p_{iny}.F; \quad \text{ // y-direction}
\]
\[
P_{out}.F[3] = p_{inz}.F; \quad \text{ // z-direction}
\]
\[
P_{out}.F[4] = YP*p_{inz}.F - ZP*p_{iny}.F; \quad \text{ // x-rotation}
\]
\[
P_{out}.F[5] = -XP*p_{inz}.F + ZP*p_{inx}.F; \quad \text{ // y-rotation}
\]
\[
P_{out}.F[6] = XP*p_{iny}.F - YP*p_{inx}.F; \quad \text{ // z-rotation}
\]

\[
p_{inx}.v = P_{out}.v[1] - YP*P_{out}.v[6] + ZP; \quad \text{ // x-direction}
\]
\[
*P_{out}.v[5]; \quad \text{ // y-direction}
\]
\[
p_{iny}.v = P_{out}.v[2] + XP*P_{out}.v[6] - ZP; \quad \text{ // z-direction}
\]
\[
*P_{out}.v[4];
\]
\[
\]

As can bee seen from the equations, a nonzero offset XP, YP or ZP (distance from center of mass) in a 3D-point will result in a momentum. **Therefore a 3D-body has to be connected to 3D-points with at least three orthogonal nonzero offsets to prevent it from free rotation.**
Interface - XYZ

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_inx</td>
<td>Translation port with one degree of freedom [m].</td>
</tr>
<tr>
<td>p_iny</td>
<td>Translation port with one degree of freedom [m].</td>
</tr>
<tr>
<td>p_inz</td>
<td>Translation port with one degree of freedom [m].</td>
</tr>
</tbody>
</table>

Causality
fixed force out
P_out
fixed velocity out
p_in

Parameters
YP       Distance (y-direction) between connection and center of mass [m].
XP       Distance (x-direction) between connection and center of mass [m].
theta    Angle of impact of the single degree of freedom port [rad].

Note
- A body has to be connected to 3D-points with at least three orthogonal nonzero offsets to prevent it from free rotation.
- A 3D-body has to be connected to at least three orthogonal 3D-point models to prevent it from free motion.
- Flipping or rotating the model does not change the direction of applied forces or measured directions. Preferably leave the orientation as it pops up on the screen.
- It is not possible in 20-sim to use vector elements with mixed units. Therefore element number 4 to 6 will be displayed with units [m/s] and [N] although it really is [rad/s] and [Nm]!

ThreeDPositionSensor

Library
Iconic Diagrams\Mechanical\Translation\3DSmallAngles

Use

Description
This model is used to find the positions of a 3D-body model. It has a port P which can be connected to the body and an output signal pos that denotes the positions \((x,y,z,\theta_x,\theta_y,\theta_z)\) of the body.
Interface

Ports  Description

Causality
fixed force out P

Output
Pos(6)  Absolute positions [m].

Initial Values
Pos_initial[6]  Initial positions [m]

Note
- The sensor model yields an absolute position starting at 0. Set the initial values to yield a position starting at other values.
- It is not possible in 20-sim to use vector elements with mixed units. Therefore element number 4 to 6 will be displayed with units [m] although it really is [rad]!

ThreeDSpringDamper

Library
Iconic Diagrams\Mechanical\Translation\3DSmallAngles

Use
Domains: Continuous. Size: 1-D/6-D. Kind: Iconic Diagrams (Translation,Rotation).

Description
This model is the equivalent of the 1 degree of freedom model SpringDamper.emx. It model represents an ideal spring-damper. The model has a preferred force out causality. The corresponding constitutive equations then contain integrations. The element can also have the non-preferred velocity out causality. The constitutive equations then contain derivatives. The spring-damper model has separate high and low ports. The equations are

\[
P.F = P\_high.F = P\_low.F \\
P.v = P\_high.v - P\_low.v
\]

Force out causality (preferred):

\[
X = int(P.v); \\
P.F = S*X + D*P.v;
\]

Velocity out causality:
\[P.v = ddt(X);\]
\[X = S^{-1}(P.F - D*P.v);\]

### Interface

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both terminals of a port with 6 degrees of freedom.</td>
<td>P_high[6], P_low[6]</td>
</tr>
</tbody>
</table>

**Causality**

| preferred force out P |

**Variables**

<table>
<thead>
<tr>
<th>Description</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector with 6 spring extension values [m].</td>
<td>X</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness vector [N/m]</td>
<td>S[6]</td>
</tr>
<tr>
<td>Damping vector [N.s/m]</td>
<td>D[6]</td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
<th>Initial Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector with 6 initial extension values of the spring [m].</td>
<td>X_initial[6]</td>
</tr>
</tbody>
</table>

**Note**

It is not possible in 20-sim to use vector elements with mixed units. Therefore element number 4 to 6 will be displayed with units [m/s] and [N] although it really is [rad/s] and [Nm] etc.!

### ThreeDZeroForce

**Library**

| Iconic Diagrams\Mechanical\Translation\3DSmallAngles |

**Use**


**Description**

This model can be used to connect any open end of another 3D model that is not connected to the fixed world. It generates a three degree of freedom zero force while the velocity is free.

**Interface**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port with 6 degrees of freedom.</td>
<td>P</td>
</tr>
<tr>
<td>fixed force out P</td>
<td></td>
</tr>
</tbody>
</table>
Note
It is not possible in 20-sim to use vector elements with mixed units. Therefore element number 4 to 6 will be displayed with units [m/s] and [N] although it really is [rad/s] and [Nm] etc.!!

Actuators

AccelerationActuator-Relative

Library
Iconic Diagrams\Mechanical\Translation\Actuators

Use

Description
This model represents an ideal actuator. An acceleration input signal is integrated to a velocity difference between its two terminals:

\[
\begin{align*}
    p_{\text{high}}.v &= p_{\text{low}}.v + \text{int}(a,v_{\text{initial}}); \\
    p_{\text{low}}.F &= p_{\text{high}}.F = \text{indifferent};
\end{align*}
\]

Interface

Ports

Description
p_high, p_low Both terminals of the Translation port p.

Causality
fixed velocity out

Input

a Acceleration [m/s^2].

Parameters

v_initial Initial velocity output of the integration [m/s].

AccelerationActuator

Library
Iconic Diagrams\Mechanical\Translation\Actuators

Use

Description
This model represents an ideal actuator. An acceleration input signal is integrated to a velocity at the translation port. The actuator is mounted to the fixed world:
\[ p.v = \text{int}(a,v_{\text{initial}}); \]
\[ p.F = \text{indifferent}; \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed velocity out

**Input**

a

Acceleration [\(\text{m/s}^2\)].

**Parameters**

v_initial

Initial velocity at the port [\(\text{m/s}\)].

---

**CMABender**

**Library**

Iconic Diagrams\Electric\Actuators
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**

Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation), Block Diagrams.

**Description**

This model represents a piezo actuator. The actuator translates a voltage difference at port \(p1\) to a mechanical position difference between the base at port \(p2\) and the end effector at port \(p3\).

Although the underlying equations of this model are equal to the equations of the CMAStrecher.emx model, the default parameter values are typical for bending.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out

**Input**

C

Capacitance [\(\text{F}\)]

K\(F\)

Voltage to force conversion factor [\(\text{N/V}\)]

m

Equivalent mass [\(\text{kg}\)]

k

Stiffness [\(\text{N/m}\)]

B

Relative damping ratio [\(\text{}\)]
**CMAStretcher**

**Library**
Iconic Diagrams\Electric\Actuators
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation), Block Diagrams.

**Description**
This model represents a piezo actuator. The actuator translates a voltage difference at port $p_1$ to a mechanical position difference between the base at port $p_2$ and the end effector at port $p_3$.

Although the underlying equations of this model are equal to the equations of the CMABender.emx model, the default parameter values are typical for stretching.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**
fixed force out

**Input**

<table>
<thead>
<tr>
<th>C</th>
<th>Capacitance [F]</th>
</tr>
</thead>
<tbody>
<tr>
<td>KF</td>
<td>Voltage to force conversion factor [N/V]</td>
</tr>
<tr>
<td>m</td>
<td>Equivalent mass [kg]</td>
</tr>
<tr>
<td>k</td>
<td>Stiffness [N/m]</td>
</tr>
<tr>
<td>B</td>
<td>Relative damping ratio []</td>
</tr>
<tr>
<td>KB</td>
<td>Force to voltage conversion factor [V/N]</td>
</tr>
</tbody>
</table>


**Force-Relative**

**Library**
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**
Domains: Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation), Block Diagrams.

**Description**
This model represents an ideal actuator. The actuator applies a force between its two terminals. This force can be set to a constant value $F$, the velocity is indifferent.

$$p_{\text{high}}.F = p_{\text{low}}.F = F$$

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{\text{high}}, p_{\text{low}}$</td>
</tr>
<tr>
<td>Both terminals of the Translation port $p$.</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
</tr>
<tr>
<td>Force [N]</td>
</tr>
</tbody>
</table>

**Force**

**Library**
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**
Domains: Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation).

**Description**
This model represents an ideal actuator. The actuator is mounted to the fixed world and applies a force. The force can be set to a certain constant value, the velocity is indifferent.

$$p.F = F;$$

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
</tr>
<tr>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out

**Parameters**
**ForceActuator-Relative**

**Library**
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation), Block Diagrams.

**Description**
This model represents an ideal actuator. The actuator applies a force between its two terminals. This force can be set to a (fluctuating) value given by the input signal $F$, the velocity is indifferent.

$$p_{\text{high}}.F = p_{\text{low}}.F = F$$

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{\text{high}}, p_{\text{low}}$</td>
<td>Both terminals of the Translation port $p$.</td>
</tr>
</tbody>
</table>

**Causality**
fixed force out

**Input**

$F$  
Force [N]

---

**ForceActuator**

**Library**
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation), Block Diagrams.

**Description**
This model represents an ideal actuator. The actuator is mounted to the fixed world and applies a force. The force can be set to a (fluctuating) value given by the input signal $F$, the velocity is indifferent.

$F$  
Force [N].


\[ p.F = F; \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out

**Input**

F  
Force [N].

### PositionActuator-Relative

**Library**

Iconic Diagrams\Mechanical\Translation\Actuators

**Use**

Domains: Continuous.  
Size: 1-D.  
Kind: Iconic Diagrams (Translation), Block Diagrams.

**Description**

This model represents an ideal actuator. A position input signal is differentiated by a state variable filter to a velocity difference between its two terminals:

\[
\begin{align*}
    p_{\text{high}}.v &= p_{\text{low}}.v + \frac{dx}{dt}; \\
    p_{\text{low}}.F &= p_{\text{high}}.F = \text{indifferent};
\end{align*}
\]

Differentiation is performed by a state variable filter:

![Filter Diagram]

The S-domain function of this filter is equal to:

\[
\text{output} = \frac{s}{s + 1} \cdot \text{input}
\]

where \( f \) is the cut-off frequency. For very high values of \( f \), the output becomes the pure derivative of the input. High values of \( f \), however, increase simulations times. A good trade-off is a starting value of 1e5.
### Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Translation port p.</td>
</tr>
</tbody>
</table>

**Causality**

fixed velocity out

**Input**

x  
Position [m].

**Parameters**

f  
Cut-off frequency of the differentiation [Hz].

v_initial  
Initial velocity output of the differentiation [m/s].

### PositionActuator

**Library**

Iconic Diagrams\Mechanical\Translation\Actuators

**Use**

Domains: Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation), Block Diagrams.

**Description**

This model represents an ideal actuator. A position input signal is differentiated by a state variable filter to a velocity at the translation port. The actuator is mounted to the fixed world:

\[
p.v = \frac{dx}{dt};
\]

\[
p.F = \text{indifferent};
\]

Differentiation is performed by a state variable filter:

![State variable filter diagram]

The S-domain function of this filter is equal to:
where $f$ is the cut-off frequency. For very high values of $f$, the output becomes the pure derivative of the input. High values of $f$, however, increase simulations times. A good trade-off is a starting value of $1e5$.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

fixed velocity out

**Input**

| x     | Position [m]. |

**Parameters**

| f     | Cut-off frequency of the differentiation [Hz]. |
| v_initial | Initial velocity at the port [m/s]. |

**ServoMotor**

**Library**

Iconic Diagrams\Mechanical\Rotation\Actuators
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Electric).

**Description**

This is a masked model which opens the Servo Motor Editor when edited. The servo Motor Editor is a tool that can shows the torque speed plots numerous permanent magnet motors and can generate a dynamic model from any motor that you select. The following motor types are supported:

1. Brush DC
2. Brushless DC (trapezoidal EMC and square wave currents)
3. AC synchronous (sinusoidal EMC and sinusoidal currents)
4. AC synchronous linear (sinusoidal EMC and sinusoidal currents)
Interface
Depending on the type of motor that you have selected, the interface can vary:

**DC Brush**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**
fixed rotational velocity out

**Input**
i The input current [A]

**DC Brushless**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**
fixed rotational velocity out

**Input**
i The maximum input current [A]

**AC Synchronous**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>

**Causality**
fixed rotational velocity out

**Input**
i_rms The rms phase current [A]

**AC Synchronous Linear**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**
fixed velocity out

**Input**
The rms phase current [A]

For more information on the parameters and variables of this model is referred to the Mechatronic Toolbox.

**Velocity-Relative**

**Library**
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description**
This model represents an ideal actuator. The actuator applies a velocity difference between its two terminals. This velocity can be set to a constant value $v$, the force is indifferent.

\[ p_{low}.v = p_{high}.v + v \]

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
</tr>
</tbody>
</table>

**Causality**
fixed velocity out

**Parameter**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v$</td>
</tr>
</tbody>
</table>

**Velocity**

**Library**
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description**
This model represents an ideal actuator. The actuator is mounted to the fixed world and applies a velocity. This velocity can be set to a certain constant value, the force is indifferent.
\[ p.v = v; \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>Translation port</td>
</tr>
</tbody>
</table>

**Causality**

fixed velocity out

**Parameters**

| \( v \)     | velocity [m/s]   |

**VelocityActuator-relative**

**Library**

Iconic Diagrams\Mechanical\Translation\Actuators

**Use**


**Description**

This model represents an ideal actuator. The actuator applies a velocity difference between its two terminals. This velocity can be set to a (fluctuating) value given by the input signal \( v \), the force is indifferent.

\[ p._{\text{high}}.v = p._{\text{low}}.v + v \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p.<em>{\text{high}}, p.</em>{\text{low}} )</td>
<td>Both terminals of the Translation port ( p ).</td>
</tr>
</tbody>
</table>

**Causality**

fixed velocity out

**Input**

| \( v \) | Velocity [m/s] |

**VelocityActuator**

**Library**
Iconic Diagrams\Mechanical\Translation\Actuators

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation), Block Diagrams.

**Description**
This model represents an ideal actuator. The actuator is mounted to the fixed world and applies a velocity. This velocity can be set to a (fluctuating) value given by the input signal $v$, the force is indifferent.

$$p.v = v;$$

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translation port.</td>
<td>p</td>
</tr>
</tbody>
</table>

**Causality**
fixed velocity out

**Input**

<table>
<thead>
<tr>
<th>Description</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity [m/s].</td>
<td>v</td>
</tr>
</tbody>
</table>

**Components**

**Backlash**

**Library**
Iconic Diagrams\Mechanical\Translation\Components

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description**
This model represents backlash by a spring damper system. Inside an outside the play, spring and damping can be set separately. Discontinuities are avoided by adding a round off. The model can has a force out causality. The port $p$ of this model has separate high and low terminals. The equations are:
\[
p.F = p_{\text{high}}.F = p_{\text{low}}.F \\
p.v = p_{\text{high}}.v - p_{\text{low}}.v \\
p.F = 0.5 \cdot k_2 \left( x - \sqrt{\left(-x - \frac{s}{2}\right) + (ep \cdot s)^2} + x + \sqrt{\left(x - \frac{s}{2}\right) + (ep \cdot s)^2} \right) + k_1 \cdot x + d_{1or2} \cdot p.v \\
\]

with \(x\) the position within the play. Real backlash behavior is obtained by choosing low stiffness and damping values inside the play and choosing high stiffness and damping values outside the play.

The parameter \(ep\) determines the smoothness of the force curve that is obtained. A larger value (> 0.01) makes the force change gradually when the position reaches the play boundaries. A smaller value (< 0.001) makes the force change abruptly. This is shown in the figure below. A good starting value for \(ep\) is \(1e^{-4}\).

![Graph showing the effect of different values of \(ep\) on the force curve.](image)

**Interface**

**Ports**
- \(p_{\text{high}}, p_{\text{low}}\)
  - Both terminals of port p (Translation).

**Causality**
- fixed force out

**Parameters**
- \(s\)
  - Interval of the play [m]
- \(c_1\)
  - Stiffness in the play [N/m]
- \(c_2\)
  - Stiffness outside the play [N/m]
11. Library

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>d1</td>
<td>Damping inside the play [Ns/m]</td>
</tr>
<tr>
<td>d2</td>
<td>Damping outside the play [Ns/m]</td>
</tr>
<tr>
<td>ep</td>
<td>Relative round off (1e-6 -&gt; sharp edges, 1e-2 -&gt; smoother)</td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x_initial</td>
<td>Initial position in the play [m], -s/2 &lt; x_initial &lt; s/2</td>
</tr>
</tbody>
</table>

**Collision-Relative**

**Library**

Iconic Diagrams\Mechanical\Translation\Components

**Implementations**

Right
Left

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description - Right**

This model represents an collision of an object with another object. It can be used to indicate a possible collision to the right of an object.

The collision force is modeled by a spring and damper:

\[
p.F = \text{if } x > x0 \text{ then } k*(x-x0) + d*\text{limit}(p.v,0,1e20) \text{ else } 0 \text{ end};
\]

with a stiffness \( k \) and damping \( d \). The \( \text{limit} \) function is used to prevent the damper force to become negative. The initial position of the spring is indicated by \( x0 \) (see the figure above). Note that the positive direction is to the right. If \( x \) is larger than \( x0 \), the two sides have collided and are in contact. The collision model has separate high and low ports. The equations are

\[
p.F = p_{high}.F = p_{low}.F \\
p.v = p_{high}.v - p_{low}.v
\]

**Interface - Right**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high</td>
<td>Two ports of the collision model.</td>
</tr>
</tbody>
</table>
p_low

**Causality**
fixed force out

**Variables**

- x: extension of the spring [m]

**Parameters**

- x0: unstretched spring position
- k: stiffness [N/m]
- d: damping [N.s/m]

**Initial Values**

- x_initial: The initial extension of the spring [m].

**Description - Left**

This model represents a collision of an object with another object. It can be used to indicate a possible collision to the left of an object.

The collision force is modeled by a spring and damper. Note that the positive direction is to the right, so the initial position of the spring $x_0$ has a negative value in the figure above. If $x$ is smaller than $x_0$, the two sides have collided and are in contact.

**Interface - Left**

**Ports**

- p_high
- p_low

**Causality**
fixed force out

**Variables**

- x: extension of the spring [m]

**Parameters**

- x0: unstretched spring position
k  stiffness [N/m]  
d  damping [N.s/m]  

**Initial Values**  
\( x_{\text{initial}} \) The initial extension of the spring [m].

**Collision**  

**Library**  
Iconic Diagrams\Mechanical\Translation\Components

**Implementations**  
Right  
Left

**Use**  
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation).

**Description - Right**  
This model represents an collision of an object with the ground.

The collision force is modeled by a spring and damper:

\[
p.F = \text{if } x > x0 \text{ then } k*(x-x0) + d*\text{limit}(p.v,0,1e20) \text{ else } 0 \text{ end};
\]

with a stiffness \(k\) and damping \(d\). The \textit{limit} function is used to prevent the damper force to become negative. The initial position of the spring is indicated by \(x0\) (see the figure above). Note that the positive direction is to the right. If \(x\) is larger that \(x0\), the two sides have collided and are in contact. The collision model has separate high and low ports. The equations are

\[
p.F = p_{\text{high}}.F = p_{\text{low}}.F  
p.v = p_{\text{high}}.v - p_{\text{low}}.v
\]

**Interface - Right**  

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high</td>
<td>Two ports of the collision model.</td>
</tr>
<tr>
<td>p_low</td>
<td></td>
</tr>
</tbody>
</table>

11. Library
**Causality**
fixed force out

**Variables**
x extension of the spring [m]

**Parameters**
x0 unstretched spring position
k stiffness [N/m]
d damping [N.s/m]

**Initial Values**
x_initial The initial extension of the spring [m].

**Description - Left**
This model represents a collision of an object with the ground.

The collision force is modeled by a spring and damper. Note that the positive direction is to the right, so the initial position of the spring $x_0$ has a negative value in the figure above. If $x$ is smaller than $x_0$, the two sides have collided and are in contact.

**Interface - Left**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high</td>
<td>Two ports of the collision model.</td>
</tr>
<tr>
<td>p_low</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**
fixed force out

**Variables**
x extension of the spring [m]

**Parameters**
x0 unstretched spring position
k stiffness [N/m]
d damping [N.s/m]
Initial Values

\[ x_{\text{initial}} \quad \text{The initial extension of the spring [m].} \]

**Damper**

**Library**

Iconic Diagrams\Mechanical\Translation\Components

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description**

This model represents a linear damper. It can have an force out as well as an velocity out causality. In the last case the constitutive equation, as shown below, is simply inverted. The port \( p \) of the damper model has separate high and low terminals. The equations are:

\[
\begin{align*}
p.F &= p\_high.F = p\_low.F \\
p.v &= p\_high.v - p\_low.v
\end{align*}
\]

Force out causality:

\[ p.F = d \times p.v; \]

Velocity velocity out causality:

\[ p.v = p.F / d; \]

**Interface**

**Ports**

\( p\_high, \ p\_low \) Both terminals of the Translation port \( p \).

**Causality**

indifferent

**Parameters**

\( d \) damping [Ns/m]
**FixedWorld**

**Library**
Iconic Diagrams\Mechanical\Translation\Components

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation).

**Description**
This model represents the fixed world (velocity = 0). The model has only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc. which gives the constitutive equations:

\[ p1.v = p2.v = .. = pn.v = 0; \]
\[ p1.F = free; p2.F = free; ..; pn.F = free; \]

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any number of connections can be made (Translation).</td>
<td>p [any]</td>
</tr>
</tbody>
</table>

**Causality**

Fixed angular All ports have a fixed velocity out causality.

velocity out

**Friction**

**Library**
Iconic Diagrams\Mechanical\Translation\Components

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation).

**Implementations**
C
V
CV
SCVS
LuGre

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation).

**Introduction**
These models represents friction with the fixed world. The amount of friction depends on the normal force that is applied and the friction function that is used. The normal force is given by the input signal \( F_n. \)
The models have only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc. 20-sim will automatically create equations such that the resulting force \( p.F \) is equal to the sum of the forces of all connected ports p1..pn. The velocities of all connected ports are equal to \( p.v \).

\[
p.F = \text{sum}(p1.F, p2.F, ....) \\
p.v = p1.v = p2.v = ....
\]

Due to the use of normal force, the friction models all have a fixed force out causality. The constitutive equations are therefore described as:

\[
p.F = Fn \times f(p.v);
\]

with \( f \) the friction function.

**Description - C**

This model represents friction with the fixed world described as coulomb friction:

\[
p.F = Fn \times mu_c \times \tanh(slope \times p.v);
\]

\( Fn \): normal force (given by the input signal Fn)  
\( mu_c \): the coulomb friction coefficient  
\( slope \): the steepness of the coulomb friction curve.

**Interface - C**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Translation).</td>
</tr>
</tbody>
</table>

**Causality**

Fixed force out

**Input**
**Parameters**

- **mu_c**  : Coulomb friction coefficient [\[\]
- **slope** : Steepness of Coulomb friction curve [s/m]

**Description - V**

This model represents friction with the fixed world described as viscous friction:

\[
p.F = Fn*mu_v*p.v;
\]

*Fn*: normal force (given by the input signal Fn)

*mu_v*: the viscous friction coefficient

![Friction force vs Sliding velocity graph](image)

**Interface - V**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Translation).</td>
</tr>
</tbody>
</table>

**Causality**

Fixed force out

**Input**

- **Fn**  : Normal force [N]

**Parameters**

- **mu_v**  : Viscous friction coefficient [s/m]

**Description - CV**

This model represents friction with the fixed world described as coulomb plus viscous friction:
\[ p.F = F_n*( \mu_c \cdot \tanh(slope \cdot p.v) + \mu_v \cdot p.v); \]

- **\( F_n \)**: normal force (given by the input signal \( F_n \))
- **\( \mu_v \)**: the viscous friction coefficient
- **\( \mu_c \)**: the coulomb friction coefficient
- **\( slope \)**: the steepness of the coulomb friction curve.

**Interface - CV**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p[\text{any}] )</td>
<td>Any number of connections can be made (Translation)</td>
</tr>
</tbody>
</table>

**Causality**

Fixed force out

**Input**

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_n )</td>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_v )</td>
<td>Viscous friction coefficient [s/m]</td>
</tr>
<tr>
<td>( \mu_c )</td>
<td>Coulomb friction coefficient []</td>
</tr>
<tr>
<td>( slope )</td>
<td>Steepness of Coulomb friction curve [s/m]</td>
</tr>
</tbody>
</table>

**Description - SCVS**

This model represents friction with the fixed world described as static plus coulomb plus viscous plus Strubeck friction:

\[
p.F = F_n * \\
(( \mu_c + ( \mu_s \cdot \text{abs}( \tanh(\ slope \cdot p.v )) - \mu_c) \\
* \exp( -((p.v / v_st)^2 )) ) * \text{sign}(p.v) \\
+ \mu_v \cdot p.v); \\
\]

- **\( F_n \)**: normal force (given by the input signal \( F_n \))
- **\( \mu_s \)**: the static friction coefficient
- **\( \mu_v \)**: the viscous friction coefficient
- **\( \mu_c \)**: the coulomb friction coefficient
slope: the steepness of the coulomb and static friction curve.

\( v_{st} \): the characteristic Stribeck velocity.

\[ p.F = FN*F_{lg}(p.v); \]

\( Fn \): normal force (given by the input signal \( Fn \))

\( F_{lg} \): the LuGre friction model

**Interface - SCVS**

**Ports**

- p[any]
  - Any number of connections can be made (Translation).

**Causality**

- Fixed force out

**Input**

- Fn
  - Normal force [N]

**Parameters**

- mu_s
  - Static friction coefficient []

- mu_v
  - Viscous friction coefficient [s/m]

- mu_c
  - Coulomb friction coefficient []

- slope
  - Steepness of Coulomb friction curve [s/m]

- v_st
  - Characteristic Stribeck velocity [m/s]

**Description - LuGre**

This model represents friction with the fixed world described by the LuGre friction model:

\[ p.F = FN*F_{lg}(p.v); \]

\( Fn \): normal force (given by the input signal \( Fn \))

\( F_{lg} \): the LuGre friction model

**Interface - LuGre**

**Ports**

- p[any]
  - Any number of connections can be made (Translation).

**Causality**
Fixed force out

**Input**

<table>
<thead>
<tr>
<th>Fn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>mu_c</th>
<th>Coulomb friction coefficient []</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu_s</td>
<td>Static friction coefficient []</td>
</tr>
<tr>
<td>mu_v</td>
<td>Viscous friction coefficient [s/m]</td>
</tr>
<tr>
<td>v_st</td>
<td>Characteristic Strubeck velocity [m/s]</td>
</tr>
<tr>
<td>mu_k</td>
<td>Stiffness coefficient at zero speed []</td>
</tr>
</tbody>
</table>

**Friction-Relative**

**Library**

Iconic Diagrams\Mechanical\Translation\Components

**Implementations**

<table>
<thead>
<tr>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
</tr>
<tr>
<td>CV</td>
</tr>
<tr>
<td>SCVS</td>
</tr>
<tr>
<td>LuGre</td>
</tr>
</tbody>
</table>

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation).

**Introduction**

These models represent friction relative to other objects. The amount of friction depends on the normal force that is applied and the friction function that is used. The normal force is given by the input signal $Fn$.

The port $p$ of the friction models have separate high and low terminals. The equations are:

\[
\begin{align*}
p.F &= p._{high}.F = p._{low}.F \\
p.v &= p._{high}.v - p._{low}.v
\end{align*}
\]

Due to the use of normal force, the friction models all have a fixed torque out causality. The constitutive equations are therefore described as:

\[
p.F = Fn * f(p.v);
\]

with $f$ the friction function.

**Description - C**

This model represents friction between two terminals described as coulomb friction:
\[ p.F = Fn*mu_c*tanh(slope*p.v); \]

*Fn*: normal force (given by the input signal Fn)

*mu_c*: the coulomb friction coefficient

*slope*: the steepness of the coulomb friction curve.

**Interface - C**

**Ports**
- p_high, p_low: Both terminals of port p (Translation).

**Causality**
- Fixed force out

**Input**
- fn: Normal force [N]

**Parameters**
- mu_c: Coulomb friction coefficient []
- slope: Steepness of Coulomb friction curve [s/m]

**Description - V**

This model represents friction between two terminals described as viscous friction:

\[ p.F = Fn*mu_v*p.v; \]

*Fn*: normal force (given by the input signal Fn)

*mu_v*: the viscous friction coefficient
Interface -V

Ports Description

p_high, p_low Both terminals of port p (Translation).

Causality
Fixed force out

Input

Fn Normal force [N]

Parameters

mu_v Viscous friction coefficient [s/m]

Description - CV
This model represents friction between two terminals described as coulomb plus viscous friction:

\[ p.F = F_n*(\mu_c*tanh(slope*p.v) + \mu_v*p.v); \]

\( F_n \): normal force (given by the input signal Fn)
\( \mu_v \): the viscous friction coefficient
\( \mu_c \): the coulomb friction coefficient
\( slope \): the steepness of the coulomb friction curve.
11. Library

Interface - CV

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of port p (Translation).</td>
</tr>
</tbody>
</table>

**Causality**

Fixed force out

**Input**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fn</td>
<td>Normal force [N]</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu_v</td>
<td>Viscous friction coefficient [s/m]</td>
</tr>
<tr>
<td>mu_c</td>
<td>Coulomb friction coefficient []</td>
</tr>
<tr>
<td>slope</td>
<td>Steepness of Coulomb friction curve [s/m]</td>
</tr>
</tbody>
</table>

**Description - SCVS**

This model represents friction between two terminals described as static plus coulomb plus viscous plus Stribeck friction:

\[
p.F = Fn \times \\
\left( (mu_c + (mu_st*abs(tanh(slope*p.v)) - mu_c) \right) * exp( -((p.v/v_st)^2)) ) * sign(p.v) \\
+ mu_v * p.v) \\
\]

*Fn*: normal force (given by the input signal Fn)

*mu_s*: the static friction coefficient

*mu_v*: the viscous friction coefficient

*mu_c*: the coulomb friction coefficient

*slope*: the steepness of the coulomb and static friction curve.

*v_st*: the characteristic Stibeck velocity.
Interface - SCVS

Ports | Description
--- | ---
p_high, p_low | Both terminals of port p (Translation).

Causality
Fixed force out

Input
Fn | Normal force [N]

Parameters
mu_s | Static friction coefficient []
mu_v | Viscous friction coefficient [s/m]
mu_c | Coulomb friction coefficient []
slope | Steepness of Coulomb friction curve [s/m]
v_st | Characteristic Striebeck velocity [m/s]

Description - LuGre
This model represents friction between two terminals described by the LuGre friction model:

\[ p.F = FN*f_{lg}(p.v); \]

Fn: normal force (given by the input signal Fn)
f_{lg}: the LuGre friction model

Interface - LuGre

Ports | Description
--- | ---
p_high, p_low | Both terminals of port p (Translation).

Causality
**Fixed force out**

**Input**

| Fn | Normal force [N] |

**Parameters**

<table>
<thead>
<tr>
<th>mu_c</th>
<th>Coulomb friction coefficient [ ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu_s</td>
<td>Static friction coefficient [ ]</td>
</tr>
<tr>
<td>mu_v</td>
<td>Viscous friction coefficient [s/m]</td>
</tr>
<tr>
<td>v_st</td>
<td>Characteristic Striebeck velocity [m/s]</td>
</tr>
<tr>
<td>mu_k</td>
<td>Stiffness coefficient at zero speed [ ]</td>
</tr>
</tbody>
</table>

**FrictionSimple**

**Library**

Iconic Diagrams\Mechanical\Translation\Components

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation).

**Implementations**

C  
V  
CV  
SCVS  
LuGre

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation).

**Introduction**

These models represent friction with the fixed world. The amount of friction does not depend on the normal force but determined by parameters directly. The models have only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc. 20-sim will automatically create equations such that the resulting force $p.F$ is equal to the sum of the forces of all connected ports p1 .. pn. The velocities of all connected ports are equal to $p.v$.

$$p.F = \text{sum}(p1.F, p2.F, ....)$$
$$p.v = p1.v = p2.v = ....$$

**Description - C**

This model represents friction with the fixed world described as coulomb friction:

$$p.F = Fc*tanh(slope*p.v);$$

$Fc$: the coulomb friction  
$slope$: the steepness of the coulomb and static friction curve.
Interface - C

Ports | Description
---|---
p[any] | Any number of connections can be made (Translation).

Causality
Fixed force out

Parameters
- Fc: Coulomb friction [N]
- slope: Steepness of Coulomb friction curve [s/m]

Description - V
This model represents friction with the fixed world described as viscous friction:

\[ p.F = d*p.v; \]

\( d \): the viscous friction or damping
Interface - V

**Ports** | **Description**
--- | ---
*p[any]* | Any number of connections can be made (Translation).

**Causality**
Fixed force out

**Parameters**
- *d* | Viscous friction or damping [N.s/m]

**Description - CV**
This model represents friction with the fixed world described as coulomb plus viscous friction:

\[ p.F = Fc \cdot \tanh(slope \cdot p.v) + d \cdot p.v; \]

- *d*: the viscous friction or damping
- *Fc*: the coulomb friction
- *slope*: the steepness of the coulomb and static friction curve.

![Friction force vs Sliding velocity graph](image)

Interface - CV

**Ports** | **Description**
--- | ---
*p[any]* | Any number of connections can be made (Translation)

**Causality**
Fixed force out

**Parameters**
- *Fc* | Coulomb friction [N]
- *d* | Viscous friction or damping [N.s/m]
- *slope* | Steepness of Coulomb friction curve [s/m]
Description - SCVS
This model represents friction with the fixed world described as static plus coulomb plus viscous plus Stribeck friction:

\[ p.F = (( Fc + (Fst*\text{abs}(\text{tanh}(slope*p.v)) - Fc) * \exp(-((p.v / v_st)^2))) * \text{sign}(p.v) + d * p.v); \]

\[ Fst \]: the static friction
\[ d \]: the viscous friction or damping
\[ Fc \]: the coulomb friction
\[ slope \]: the steepness of the coulomb and static friction curve.
\[ v_st \]: the characteristic Stribeck velocity.

Interface - SCVS

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Translation).</td>
</tr>
</tbody>
</table>

Causality
Fixed force out

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fc</td>
<td>Coulomb friction [N]</td>
</tr>
<tr>
<td>Fst</td>
<td>Static friction [N]</td>
</tr>
<tr>
<td>d</td>
<td>Viscous friction or damping [N.s/m]</td>
</tr>
<tr>
<td>v_st</td>
<td>Characteristic Stribeck velocity [m/s]</td>
</tr>
<tr>
<td>slope</td>
<td>Steepness of Coulomb friction curve [s/m]</td>
</tr>
</tbody>
</table>

Description - LuGre
This model represents friction with the fixed world described by the LuGre friction model:

\[ p.F = f_{lg}(p.v); \]

\[ f_{lg} \]: the LuGre friction model
Interface - LuGre

Ports
p[any] Any number of connections can be made (Translation).

Causality
Fixed force out

Parameters
Fc Coulomb friction [N]
Fst Static friction [N]
d Viscous friction or damping [N.s/m]
v_st Characteristic Strubeck velocity [m/s]
k Stiffness at zero speed [N/m]

FrictionSimple-Relative

Library
Iconic Diagrams\Mechanical\Translation\Components

Use

Implementations
C
V
CV
SCVS
LuGre

Use

Introduction
These models represent friction with the fixed world. The amount of friction does not
depend on the normal force but determined by parameters directly. The models have
only one initial port p defined. The port p of the friction models have separate high and
low terminals. The equations are:

\[ p.F = p._{\text{high}}.F = p._{\text{low}}.F \]
\[ p.v = p._{\text{high}}.v - p._{\text{low}}.v \]

Description - C
This model represents friction with the fixed world described as coulomb friction:

\[ p.F = Fc*\text{tanh}(\text{slope}*p.v); \]

Fc: the coulomb friction
slope: the steepness of the coulomb and static friction curve.
Interface - C

**Ports**

- p[any]  
  Any number of connections can be made (Translation).

**Causality**

Fixed force out

**Parameters**

- Fc  
  Coulomb friction [N]
- slope  
  Steepness of Coulomb friction curve [s/m]

**Description - V**

This model represents friction with the fixed world described as viscous friction:

\[ p.F = d*p.v; \]

\( d \): the viscous friction or damping
Interface - V

<table>
<thead>
<tr>
<th>Ports</th>
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</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Translation).</td>
</tr>
</tbody>
</table>

Causality
Fixed force out

Parameters
d                  Viscous friction or damping [N.s/m]

Description - CV
This model represents friction with the fixed world described as coulomb plus viscous friction:

\[ p.F = Fc \tanh(slope \times p.v) + d \times p.v; \]

d: the viscous friction or damping
Fc: the coulomb friction
slope: the steepness of the coulomb and static friction curve.

![Friction force vs Sliding velocity graph]

Interface - CV

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Translation)</td>
</tr>
</tbody>
</table>

Causality
Fixed force out

Parameters
Fc                  Coulomb friction [N]
d                  Viscous friction or damping [N.s/m]
slope              Steepness of Coulomb friction curve [s/m]
Description - SCVS

This model represents friction with the fixed world described as static plus coulomb plus viscous plus Striebeck friction:

\[ p.F = (( Fc + (Fst*\text{abs(tanh}(slope*p.v))) - Fc) \times \exp(-(p.v / v_st)^2)) \times \text{sign}(p.v) + d \times p.v); \]

- \( Fst \): the static friction
- \( d \): the viscous friction or damping
- \( Fc \): the coulomb friction
- \( slope \): the steepness of the coulomb and static friction curve.
- \( v_st \): the characteristic Striebeck velocity.

\[ \text{Friction force} \]
\[ \text{Sliding velocity} \]

Interface - SCVS

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Translation).</td>
</tr>
</tbody>
</table>

Causality

Fixed force out

Parameters

- \( Fc \): Coulomb friction [N]
- \( Fst \): Static friction [N]
- \( d \): Viscous friction or damping [N.s/m]
- \( v_st \): Characteristic Striebeck velocity [m/s]
- \( slope \): Steepness of Coulomb friction curve [s/m]

Description - LuGre

This model represents friction with the fixed world described by the LuGre friction model:

\[ p.F = f_{lg}(p.v); \]

\( f_{lg} \): the LuGre friction model
Interface - LuGre

Ports                              Description
p[any]                            Any number of connections can be made (Translation).

Causality
Fixed force out

Parameters
Fc                                 Coulomb friction [N]
Fst                                Static friction [N]
d                                  Viscous friction or damping [N.s/m]
v_st                               Characteristic Stribeck velocity [m/s]
k                                  Stiffness at zero speed [N/m]

Mass

Library
Iconic Diagrams\Mechanical\Translation\Components

Use

Description-Default
This model represents an ideal mass (no gravity). The element has a preferred velocity out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred force out causality. The constitutive equations then contain a derivation. Because any number of connections can be made, successive ports are named p1, p2, p3 etc. 20-sim will automatically create equations such that the resulting force p.F is equal to the sum of the forces of all connected ports p1 .. pn. The velocities of all connected ports are equal to p.v.

\[ p.F = \text{sum}(p1.F, p2.F, \ldots) \]
\[ p.v = p1.v = p2.v = \ldots \]

velocity out causality (preferred):

\[ a = p.F/m; \]
\[ p.v = \text{int}(a); \]
\[ x = \text{int}(p.omega); \]

force out causality:
\[ a = ddt(p.v); \]
\[ p.F = m*a; \]
\[ x = int(p.v); \]

**Description-Gravity**

This model represents an ideal mass with gravity. It is equal to the default model with a gravitational acceleration \( g \) added:

\[ a = p.F/m - g; \]
\[ p.v = int(a); \]
\[ x = int(p.omega); \]

The gravitational acceleration \( g \) acts in the negative direction. E.g. a free fall will give the model a negative acceleration, negative velocity and negative position.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p[any]</td>
<td>Any number of connections can be made (Translation).</td>
</tr>
</tbody>
</table>

**Causality**

<table>
<thead>
<tr>
<th>Causality</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferred velocity out</td>
<td>An torque out causality results in a derivative constitutive equation.</td>
</tr>
</tbody>
</table>

**Variables**

| x  | position [m] |
| a  | acceleration [m/s^2] |
| p  | impulse [Ns] |

**Parameters**

| m  | mass [kg] |
| g  | acceleration of gravity [m/s^2] |

**Initial Values**

| p.v_initial | The initial velocity of the mass. |
| x_initial   | The initial position of the mass. |
Modal

Library
Iconic Diagrams\Mechanical\Translation\Components

Implementations
Stiffness
Frequency

Use

Description - Stiffness
This model represents a spring-damper-mass system that can be used for modal analysis. The springdamper is equivalent to the SpringDamper-Stiffness.emx model. The mass is equivalent to the Mass.emx model. The model has one output that can be connected to the modal-summer.emx model.

Interface - Stiffness

Ports  Description
---  ----
p  Translation port.

Causality
preferred velocity out

Parameters
- k  Stiffness [N/m]
- b  Relative damping []
- m  Equivalent mass [kg]

Description - Frequency
This model represents a spring-damper-mass system that can be used for modal analysis. The springdamper is equivalent to the SpringDamper-Frequency model. The mass is equivalent to the Mass model. The model has one output that can be connected to the Modal-Summer model.

Interface - Frequency

Ports  Description
---  ----
p  Translation port.

Causality
preferred velocity out

Parameters
- b  Relative damping []
- f  Resonance frequency [Hz]
m Equivalent mass [kg]

**ModalSummer**

**Library**
Iconic Diagrams\Mechanical\Translation\Components

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description**
This model combines the results from all modal.emx models to one resulting output. The model has 8 input ports and one output port that shows the combined result. If more or less input ports are needed, you have to adapt the model (Choose Go Down and alter the internal description).

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1 .. p8</td>
<td>Input ports for modal.emx models (Translation).</td>
</tr>
<tr>
<td>p_out</td>
<td>Port with the modal result (Translation)</td>
</tr>
</tbody>
</table>

**Causality**
preferred force out p1..p8
preferred velocity out p_out

**Parameters**
A1 .. A8 Gains for each input port.

**Node**

**Library**
Iconic Diagrams\Mechanical\Translation\Components

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description**
This node model represents a structural connection between two or more parts, where the velocity of all connected parts is equal. The model has only one initial port p defined. Because any number of connections can be made, successive ports are named p1, p2, p3 etc.
11. Library

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p [any]</td>
<td>Any number of connections can be made (Translation).</td>
</tr>
</tbody>
</table>

**ShockAbsorber**

**Library**
Iconic Diagrams\Mechanical\Translation\Components

**Implementations**
Right
Left

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Introduction**
This model represents a shock absorber with an open end. This type of shock absorbers is used to protect equipment from large impacts when reaching the end of a line.

The damper has an internal piston which can travel a certain length (i.e. the stroke \( l \)) until it collides with the end cap. The shock absorber is modeled by a damper for the active damping part and a spring damper to model the impact with the end cap. The position of the damper is indicated by the parameter \( x_0 \). Two implementations are available: one with the impact at the right and one with the impact at the left.

The damper is modeled by viscous damping, where the damping force is proportional with the velocity:

\[
p.F = d \times v;
\]

After a stroke of length \( l \), the end caps are reached which are modeled by a spring damper:

\[
p.F = k \times x;
\]
To get the damper back in its original position a return force is added.

**Description - Right**
The *ShockAbsorber-Right* models a shock absorber with impact at the right of the system.

![Shock absorber model with impact at the right.](image)

**Description - Right**
The *ShockAbsorber-Left* models a shock absorber with impact at the left of the system.

![Shock absorber model with impact at the left.](image)

**Interface**

**Ports**
- p_high
- p_low

**Causality**
- fixed force out

**Parameters**
- k: stiffness at the end cap [N/m]
- d: damping [N.s/m]
- l: shock absorber stroke [m]
- x0: position of the damper [m]
SkyHookDamper

Library
Iconic Diagrams\Mechanical\Translation\Components

Use

Description
This model represents a skyhook damper. It can have an force out as well as an velocity
out causality. In the last case the constitutive equation, as shown below, is simply
inverted. The model has a fixed force out causality. The equations are:

**Force out causality:**

\[
\begin{align*}
    p\_high.F &= d \times p\_high.v; \\
    p\_low.F &= p\_high.F
\end{align*}
\]

As the equations point out, the force of the skyhook damper only depends on the
velocity at the port \( p\_high \). The position of \( p\_high \) is indicated by an arrow, as shown in
the figure below.

In this figure two models are shown. In the top model, the damping force of the skyhook
damper is zero because the velocity at \( p\_high \) is zero. Consequently the mass is free to
move.

In the lower model, the damping force is proportional to the velocity of the mass. Here
the skyhook damper acts as a normal damper.

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_high ), ( p_low )</td>
<td>Both Translation ports of the skyhook damper.</td>
</tr>
</tbody>
</table>
**Causality**
fixed force out

**Parameters**
d damping [Ns/m]

**Spring**

**Library**
Iconic Diagrams\Mechanical\Translation\Components

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description**
This model represents an ideal translational spring. The element has a preferred force out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred velocity out causality. The constitutive equations then contain a derivation. The spring model has separate high and low ports. The equations are

\[
p.F = p\_high.F = p\_low.F \\
p.v = p\_high.v - p\_low.v
\]

Force out causality (preferred):

\[
x = int(p.v);
\]

\[
p.F = k \times x;
\]

Velocity out causality:

\[
p.v = ddt(x);
\]

\[
x = p.F/k;
\]

A positive force will compress the spring. The length x is positive when the spring is compressed. It is negative when the spring is stretched.

**Interface**

**Ports**
p\_high
p\_low

**Description**
Two ports of the spring (Translation).

**Causality**
pREFERRED
preferred force out

An velocity out causality results in a derivative constitutive equation.

**Variables**
x compression of the spring [m]

Parameters

k Stiffness [N/m]

Initial Values

x_initial The initial extension of the spring [m].

SpringDamper

Library Iconic Diagrams\Mechanical\Translation\Components

Implementations

Default Stiffness Frequency


Description - Default

This model represents an ideal translational spring with damper. The element has a preferred force out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred velocity out causality. The constitutive equations then contain a derivation. The spring-damper model has separate high and low ports. The equations are

\[
\begin{align*}
p.F &= p\_high.F = p\_low.F \\
p.v &= p\_high.v - p\_low.v
\end{align*}
\]

Force out causality (preferred):

\[
\begin{align*}
x &= \text{int}(p.v); \\
p.F &= k*x + d*p.v;
\end{align*}
\]

Velocity out causality:

\[
\begin{align*}
p.v &= \text{ddt}(x); \\
x &= (p.F - d*p.v)/k;
\end{align*}
\]

A positive force will compress the spring damper. The length \(x\) is positive when the spring damper is compressed. It is negative when the spring damper is stretched.

Interface - Default

Ports Description
p_high
p_low

Causality
preferred force out

Variables
x
compression of the spring [m]

Parameters
k
Stiffness [N/m]
d
damping [N.s/m]

Initial Values
x_initial
The initial extension of the spring [m].

Description - Stiffness
This model represents another implementation of the ideal translational spring with damper. The damping value (\(d\)) is calculated on the basis of a known stiffness (\(k\)), relative damping (\(b\)) and mass reference (\(m\)). The mass is only used to compute the damping (no actual mass is used in this component).

The element has a preferred force out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred velocity out causality. The constitutive equations then contain a derivation. The spring-damper model has separate high and low ports. The equations are

\[
\begin{align*}
p.F &= p_{high}.F = p_{low}.F \\
p.v &= p_{high}.v - p_{low}.v
\end{align*}
\]

Force out causality (preferred):

\[
\begin{align*}
x &= \text{int}(p.v) \\
p.F &= k * x + d*p.v \\
d &= 2*b*\sqrt{k*m}
\end{align*}
\]

Velocity out causality:

\[
\begin{align*}
p.v &= ddt(x) \\
x &= (p.F - d*p.v)/k \\
d &= 2*b*\sqrt{k*m}
\end{align*}
\]

A positive force will compress the spring damper. The length \(x\) is positive when the spring damper is compressed. It is negative when the spring damper is stretched.

Interface - Stiffness

Ports
p_high
Description
Two ports of the spring (Translation).
Causality
preferred force out

Variables
x  compression of the spring [m]
d  damping [N.s/m]

Parameters
k  Stiffness [N/m]
b  Relative damping []
m  Reference mass [kg]

Initial Values
x_initial  The initial extension of the spring [m].

Description - Frequency
This model represents another implementation of the ideal translational spring with damper. The stiffness \((k)\) is calculated on basis of a known resonance frequency. The damping value \((d)\) is calculated on the basis of the calculated stiffness \((k)\), relative damping \((b)\) and mass reference \((m)\). The mass is only used to compute the damping (no actual mass is used in this component).

The element has a preferred force out causality. The corresponding constitutive equations then contain an integration. The element can also have the non-preferred velocity out causality. The constitutive equations then contain a derivation. The spring-damper model has separate high and low ports. The equations are

\[
P.F = p\_high.F = p\_low.F \\
P.v = p\_high.v - p\_low.v
\]

Force out causality (preferred):

\[
x = int(p.v); \\
p.F = k * x + d*p.v; \\
k = m*(2*pi*f)^2; \\
d = 2*b*sqrt(k*m);
\]

Velocity out causality:

\[
p.v = ddt(x); \\
x = (p.F - d*p.v)/k; \\
k = m*(2*pi*f)^2; \\
d = 2*b*sqrt(k*m);
\]

A positive force will compress the spring damper. The length \(x\) is positive when the spring damper is compressed. It is negative when the spring damper is stretched.
Interface - Frequency

Ports

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high</td>
</tr>
<tr>
<td>p_low</td>
</tr>
</tbody>
</table>

Causality

preferred force out

Variables

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
</tr>
<tr>
<td>k</td>
</tr>
<tr>
<td>d</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>compression of the spring [m]</td>
</tr>
<tr>
<td>stiffness [N/m]</td>
</tr>
<tr>
<td>damping [N.s/m]</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
</tr>
<tr>
<td>f</td>
</tr>
<tr>
<td>m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative damping []</td>
</tr>
<tr>
<td>Resonance frequency [Hz]</td>
</tr>
<tr>
<td>Reference mass [kg]</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x_initial</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>The initial extension of the spring [m].</td>
</tr>
</tbody>
</table>

ZeroForce

Library

Iconic Diagrams\Mechanical\Translation\Components

Use


Description

This model can be used to connect any open end of another model that is not connected to the fixed world. It generates a fixed force of 0 N while the velocity is free:

\[ p.v = \text{indifferent}; \]
\[ p.F = 0; \]

Interface

Ports

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translation port</td>
</tr>
</tbody>
</table>
Sensors

AccelerationSensor-Absolute

Library
Iconic Diagrams\Mechanical\Translation\Sensors

Use

Description
This model describes an acceleration sensor which derives an acceleration output out of a port velocity by differentiation. Differentiation is performed by a state variable filter:

\[
\text{input} \rightarrow f \rightarrow \text{output}
\]

The S-domain function of this filter is equal to:

\[
\text{output} = \frac{s}{s + \frac{1}{f}} \cdot \text{input}
\]

where \( f \) is the cut-off frequency. For very high values of \( f \), the output becomes the pure derivative of the input. High values of \( f \), however, increase simulations times. A good trade-off is a starting value of 1e5.

The equations of this model are:

\[
a = \frac{d}{dt}(p.v); \\
p.F = \text{indifferent};
\]

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Translation port p.</td>
</tr>
</tbody>
</table>

Causality
fixed force out

Output
alpha

Parameters

f Cut-off frequency of the differentiation [Hz].
a_initial Initial acceleration [m/s].

AccelerationSensor-Relative

Library
Iconic Diagrams\Mechanical\Translation\Sensors

Use

Description
This model describes an acceleration sensor which derives an acceleration output out of a velocity difference (between high and low terminals) by differentiation. Differentiation is performed by a state variable filter:

\[
\text{output} = \frac{s}{s + \frac{1}{f}} \cdot \text{input}
\]

where \( f \) is the cut-off frequency. For very high values of \( f \), the output becomes the pure derivative of the input. High values of \( f \), however, increase simulations times. A good trade-off is a starting value of 1e5.

The equations of this model are:

\[
a = \frac{d(p_{\text{high}.v} - p_{\text{low}.v})}{dt}; \\
p_{\text{low}.F} = p_{\text{high}.F} = \text{indifferent};
\]

Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Translational port p.</td>
</tr>
</tbody>
</table>
**Causality**
fixed force out

**Output**
a Acceleration (measured as the difference between both terminals) [m/s^2]

**Parameters**
f Cut-off frequency of the differentiation [Hz].
a_initial Initial acceleration [m/s].

---

**ForceSensor**

**Library**
Iconic Diagrams\Mechanical\Translation\Sensors

**Use**

**Description**
This model translates an applied force to an output signal. It has a velocity out causality. The port \( p \) of the model has separate high and low terminals. The equations are:

\[
\begin{align*}
p.F &= p\text{\_high}.F = p\text{\_low}.F; \\
p.v &= p\text{\_high}.v - p\text{\_low}.v; \\
F &= p.F; \\
p.v &= 0;
\end{align*}
\]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_high, p_low )</td>
<td>Both terminals of the Translation port ( p ).</td>
</tr>
</tbody>
</table>

**Causality**
fixed velocity out

**Output**
F Applied force [N].
**PositionSensor-Absolute**

**Library**
Iconic Diagrams\Mechanical\Translation\Sensors

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation), Block Diagrams.

**Description**
This model translates a position to an output signal. It has a force out causality. The equations are:

\[
p.F = 0; \\
x = \text{int}(p.v);
\]

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translation port p.</td>
<td>p_high, p_low</td>
</tr>
</tbody>
</table>

**Causality**
fixed force out

**Output**

<table>
<thead>
<tr>
<th>Description</th>
<th>x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute position [m].</td>
<td></td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
<th>x_initial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial position [m]</td>
<td></td>
</tr>
</tbody>
</table>

**PositionSensor-Relative**

**Library**
Iconic Diagrams\Mechanical\Translation\Sensors

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation), Block Diagrams.

**Description**
This model translates a position difference to an output signal. It has a force out causality. The port \( p \) of the model has separate high and low terminals. The equations are:

\[
p.F = p\_high.F = p\_low.F; \\
p.v = p\_high.v - p\_low.v; \\
p.F = 0; \\
x = \text{int}(p.v);
\]
## Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Translation port p.</td>
</tr>
</tbody>
</table>

### Causality

fixed force out

### Output

| x       | Relative position [m].                                                     |

### Initial Values

| x_initial | Initial position [m].                                                     |

## PowerSensor

### Library

Iconic Diagrams\Mechanical\Translation\Sensors

### Use

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation), Block Diagrams.

### Description

This is an ideal sensor (no dissipation or other effects) that yields the power that flows through the model as output signal. The equations are:

\[
\begin{align*}
p_{\text{high}}.F & = p_{\text{low}}.F \\
p_{\text{high}}.v & = p_{\text{low}}.v \\
P & = p_{\text{high}}.F \times p_{\text{high}}.v;
\end{align*}
\]

### Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both translation ports.</td>
</tr>
</tbody>
</table>

### Causality

p_high not equal p_low

### Output

| P       | Power [w].                                                                 |

**VelocitySensor-Absolute**

**Library**
Iconic Diagrams\Mechanical\Translation\Sensors

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation), Block Diagrams.

**Description**
This model translates a velocity to an output signal. It has a force out causality. The equations are:

\[
p \cdot F = 0; \\
v = p \cdot v;
\]

**Interface**

**Ports**
- **p**
  - Description: Translation port p.

**Causality**
- fixed force out

**Output**
- **v**
  - Absolute velocity [m/s].

---

**VelocitySensor-Relative**

**Library**
Iconic Diagrams\Mechanical\Translation\Sensors

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation), Block Diagrams.

**Description**
This model translates a velocity difference to an output signal. It has a force out causality. The port \( p \) of the model has separate high and low terminals. The equations are:
\[ p.F = p_{\text{high}}.F = p_{\text{low}}.F; \]
\[ p.v = p_{\text{high}}.v - p_{\text{low}}.v; \]
\[ p.F = 0; \]
\[ v = p.v; \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both terminals of the Translation port p.</td>
</tr>
</tbody>
</table>

**Causality**

fixed force out

**Output**

| \( v \) | Relative velocity [m/s]. |

**Transmission**

**BeltPulley**

**Library**

Iconic Diagrams\Mechanical\Rotation\Gears

**Use**


**Description**

This models represents a belt and pulley. The connection to the pulley is through the rotation port \( p_{\text{rot}} \). The connection to the belt is through the translation port \( p_{\text{trans}} \). The model is ideal, i.e. there are no compliances or inertias. The causality of this model is always mixed: torque out & velocity out or angular velocity out & force out:

\[ p_{\text{rot}}.T = \text{radius} \times p_{\text{trans}}.F \]
\[ p_{\text{trans}}.v = \text{radius} \times p_{\text{rot}}.\omega \]

or:

\[ p_{\text{trans}}.F = 1/\text{radius} \times p_{\text{rot}}.T \]
\[ p_{\text{rot}}.\omega = 1/\text{radius} \times p_{\text{trans}}.v \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_rot</td>
<td>Rotation port.</td>
</tr>
</tbody>
</table>
p_trans  Translation port.

**Causality**

p_rot  notequal
p_trans

**Parameters**

radius  pulley radius [m]

**Cam-Wizard**

**Library**

Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

**Use**

Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation/Translation).

**Description**

This is a masked model which opens the Cam Wizard when edited. Depending on the selections entered, various cam motion profiles can be generated.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_in</td>
</tr>
<tr>
<td>p_out</td>
</tr>
</tbody>
</table>

**Description**

Driving axis (Rotation)
Output port with resulting motion (Rotation or Translation)

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>stroke</td>
</tr>
<tr>
<td>start_angle</td>
</tr>
<tr>
<td>stop_angle</td>
</tr>
<tr>
<td>return_angle</td>
</tr>
<tr>
<td>end_angle</td>
</tr>
</tbody>
</table>

amplitude of resulting motion
start angle motion
angle when the maximum is reached
start angle of the return motion
finish angle of the return motion

**CamRod**

**Library**

Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

**Use**

Domains: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description**

This models represents a cam and rod mechanism. If the input shaft is rotating with a constant speed, the output motion is a pure sinusoidal.
The mechanism starts with the carriage in the most left position. The arm length is half of the stroke:

\[ p_{in}.T = i \times p_{out}.F \]
\[ p_{out}.v = i \times p_{in}.\omega \]

The mechanism is ideal, i.e., it does not have inertia, friction or geometrical limitations. It has one rotation port \((p_{in})\) and one translation port \((p_{out})\). The causality of this model is always mixed: one port has a force out causality while the other has a velocity out causality:

The transmission ratio \((i)\) is the ratio of the velocities of both ports (in fact a sinusoidal function of the shaft angle).

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_{in})</td>
<td>Driving axis (Rotation)</td>
</tr>
<tr>
<td>(p_{out})</td>
<td>Output port with resulting motion (Translation)</td>
</tr>
</tbody>
</table>
Causality
fixed torque out
p_in
fixed velocity out
p_out
Parameters
stroke Stroke of the translation port (is equal to half the length of the rod).

CrankRod

Library
Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

Use

Description

This models represents a crank and rod mechanism. The mechanism is ideal, i.e., it does not have inertia, friction or geometrical limitations. It has one rotation port (p_in) and one translation port (p_out). The causality of this model is always mixed: one port has a force out causality while the other has a velocity out causality:

\[ p_{in}.T = i \times p_{out}.F \]
\[ p_{out}.v = i \times p_{in}.omega \]

The transmission ratio (i) is the ratio of the velocities of both ports. It is a function of the shaft angle, the crank length and the rod length.

Interface

Ports Description
p_in Driving axis (Rotation)
p_out Output port with resulting motion (Translation)
fixed torque out
p_in
fixed velocity out
p_out

**Parameters**
crank_length Crank length [m]
rod_length Rod length [m]

**Fork**

**Library**
Iconic Diagrams\Mechanical\Translation\Transmission

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Translation).

**Description**

This model is equivalent to the differential model of the Rotation library. It represents a special type of node where the forces are equal and the velocities are added:

\[
p3.v = p1.v + p2.v;
\]

This model can for example be used for actuators that generate a force difference. With the fork model an equivalent model can be found with the actuator attached to the fixed world:
11. Library

Interface

Ports          Description
p1,p2,p3       Translation ports.

Lever

Library
Iconic Diagrams\Mechanical\Translation\Transmission

Use

Description

This models represents any type of lever with two counter-moving ports. The lever is ideal, i.e., it does not have inertia, friction or geometrical limitations. The lever has one fast moving port and one slow moving port. The lever ratio is the (absolute) ratio of the velocities of both ports. The causality of this model is always mixed: one port has a force out causality while the other has an velocity out causality:

\[ p_{fast}.F = -i \times p_{slow}.F \]
\[ p_{slow}.v = -i \times p_{fast}.v \]

or:

\[ p_{slow}.F = -1/i \times p_{fast}.F \]
\[ p_{fast}.v = -1/i \times p_{slow}.v \]
Interface

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_fast</td>
<td>Fast moving translation port.</td>
</tr>
<tr>
<td>p_slow</td>
<td>Slow moving translation port.</td>
</tr>
</tbody>
</table>

**Causality**

p_slow  notequal  p_fast  

**Parameters**

\[i \quad \text{lever ratio } p\_slow.v / p\_fast.v [, 0 < i < 1\]

**Note**

Keep the lever ratio \(i\) between 0 and 1. Confusion might otherwise exist:
- \(i > 1\): the fast moving port is slower than the slow moving port (you better interchange the connections of the lever model).
- \(i < 0\): the ports are not counter-moving (use the transmission model instead).

**RackPinionGear**

**Library**

Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

**Implementations**

FixedPinion
FixedRack

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Rotation/Translation).

**Description - FixedPinion**

This model represents a rack and pinion gear. The connection to the pinion gear is through the rotation port \(p\_rot\). The connection to the rack is through the translation port \(p\_trans\). The model is ideal, i.e. there is no compliance nor inertia nor backlash.
In this model the pinion bearing is connected to the fixed world and the rack is free to move. This is contrary to the model FixedRackPinionGear where the pinion bearing is free to move and the rack is connected to the fixed world.

The causality of this model is always mixed: torque out & velocity out or angular velocity out & force out:

\[
\begin{align*}
    p_{\text{rot}}.T &= \text{radius} \times p_{\text{trans}}.F \\
    p_{\text{trans}}.v &= \text{radius} \times p_{\text{rot}}.\omega
\end{align*}
\]

or:

\[
\begin{align*}
    p_{\text{trans}}.F &= \frac{1}{\text{radius}} \times p_{\text{rot}}.T \\
    p_{\text{rot}}.\omega &= \frac{1}{\text{radius}} \times p_{\text{trans}}.v
\end{align*}
\]

The rack position is determined by the internal variable \(x\). For \(x = 0\), the pinion gear is at the middle of the rack. When the pinion crosses the end of the rack, i.e. \( \text{abs}(x) > \text{rack\_length}/2 \) a warning is given, "WARNING: rack length has been exceeded at the rack and pinion gear!", and the simulation is stopped.

**Interface - FixedPionion**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_rot</td>
<td>Rotation port.</td>
</tr>
<tr>
<td>p_trans</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**

<table>
<thead>
<tr>
<th>p_rot</th>
<th>notequal</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_trans</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>radius</th>
<th>pinion gear pitch radius [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>rack_length</td>
<td>rack length [m]</td>
</tr>
</tbody>
</table>

**Variables**
x Internal variable which denotes the rack position, abs(x) < rack_length/2 else simulation halted.

**Initial values**

x_initial Initial rack position, abs(x_initial) < rack_length/2

**Description - FixedRack**

This models represents a fixed rack and pinion gear. The connection to the pinion gear is through the rotation port \( p_{rot} \). The connection to the rack is through the translation port \( p_{trans} \). The model is ideal, i.e. there is no compliance nor inertia nor backlash.

In this model the pinion bearing is free to move and the rack is connected to the fixed world. This in contrary to the model RackPinionGear where the pinion bearing is connected to the fixed world and the rack is free to move.

The causality of this model is always mixed: torque out & velocity out or angular velocity out & force out:

\[
\begin{align*}
  p_{rot}.T &= radius \times p_{trans}.F \\
  p_{trans}.v &= radius \times p_{rot}.\omega
\end{align*}
\]

or:

\[
\begin{align*}
  p_{trans}.F &= 1/radius \times p_{rot}.T \\
  p_{rot}.\omega &= 1/radius \times p_{trans}.v
\end{align*}
\]

The rack position is determined by the internal variable x. For x = 0 the pinion gear is at the middle of the rack. When the pinion crosses the end of the rack, i.e.

\[
abs(x) > rack\_length/2
\]

a warning is given, "**WARNING: rack length has been exceeded at the rack and pinion gear!**", and the simulation is stopped.
### Interface - FixedRack

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_rot</td>
<td>Rotation port.</td>
</tr>
<tr>
<td>p_trans</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>

**Causality**
- p_rot: notequal
- p_trans

**Parameters**
- radius: pinion gear pitch radius [m]
- rack_length: rack length [m]

**Variables**
- x: Internal variable which denotes the rack position, abs(x) < rack_length/2 else simulation halted.

**Initial values**
- x_initial: Initial rack position, abs(x_initial) < rack_length/2

---

### Spindle

**Library**
- Iconic Diagrams\Mechanical\Rotation\Gears
- Iconic Diagrams\Mechanical\Translation\Transmission

**Use**
- **Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Rotation).

**Introduction**
This model represents a spindle and nut. It transfers an angular motion of the spindle into a translational motion of the nut. The model is ideal, i.e., it does not have inertia or friction. The causality of this model is always mixed: one port has a torque out causality while the other has an angular velocity out causality:

\[
p_{\text{spindle}}.T = i \times p_{\text{nut}}.F \\
p_{\text{nut}}.v = i \times p_{\text{spindle}}.\omega
\]

or:

\[
p_{\text{nut}}.F = \frac{1}{i} \times p_{\text{spindle}}.T \\
p_{\text{spindle}}.\omega = \frac{1}{i} \times p_{\text{nut}}.v
\]

The model has two implementations which calculate the transform ratio \(i\) out of different parameters.
Description - Pitch
In this implementation the transform ratio is calculated using the *pitch* (the advance of the nut during one revolution of the spindle):

\[ i = \frac{\text{pitch}}{2 \times \pi}; \]

Interface - Pitch

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_spindle</td>
<td>Port at the spindle shaft (Rotation).</td>
</tr>
<tr>
<td>p_nut</td>
<td>Port at the wheel (Translation).</td>
</tr>
</tbody>
</table>

Causality

<table>
<thead>
<tr>
<th>p_spindle</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>notequal p_nut</td>
<td></td>
</tr>
</tbody>
</table>

Parameters

| pitch       | translation of the nut during one revolution of the spindle [m] |

Description - LeadAngle
This implementation calculates the transform ratio out of the lead angle *alpha* and the radius *r_spindle* of the spindle:

\[ i = \tan(\alpha) \times r_{\text{spindle}}; \]

The pitch angle is shown in the figure below. *r_spindle* is the effective radius of the spindle, i.e. the radius from the center of the spindle to the pitch point *p*.

Interface - LeadAngle

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_spindle</td>
<td>Port at the spindle shaft (Rotation).</td>
</tr>
<tr>
<td>p_nut</td>
<td>Port at the wheel (Translation).</td>
</tr>
</tbody>
</table>
**Causality**

\[ \text{p\_spindle} \neq \text{p\_nut} \]

**Parameters**

- \text{r\_spindle}  
  effective radius of the spindle [m]
- \text{alpha}  
  lead angle of the spindle  [rad]

---

**TimingBelt**

**Library**

Iconic Diagrams\Mechanical\Rotation\Gears
Iconic Diagrams\Mechanical\Translation\Transmission

**Use**


**Introduction**

This model represents a timing belt, used for linear positioning.

It has a rotating pulley which drives the belt and clamp. The timing belt is modeled by a series of spring damper elements that convey the rotation of the pulley to a clamp translation. Because the output position is moving, stiffness and damping values are not constant.

The stiffness for a piece of belt can be expressed as:

\[ k = \frac{E \cdot A}{l} \]
with

\[ E = \text{Modulus of elasticity \{N/m}^2\} \]
\[ A = \text{Belt area \{m}^2\} \]
\[ l = \text{belt length \{m\}} \]

If the belt is sufficiently pre-tensioned, the stiffness experienced at the clamp can be expressed as the combination of three individual belt parts:

\[ k = \frac{E \cdot A}{0.5 \cdot l + x} + \frac{1}{\frac{1}{E \cdot A/(0.5 \cdot l - x)} + \frac{1}{E \cdot A / l}} \]

which can be rewritten to:

\[ k = E \cdot A \left( \frac{1}{0.5 \cdot l + x} + \frac{1}{1.5 \cdot l - x} \right) \]

The stiffness approaches infinity as the clamp moves to the driven pulley (\(x = -l/2\)) and has a minimum value when the clamp moves to the other pulley (\(x = 0.5 \cdot l\)). The minimum stiffness is equal to:

\[ k = 2 \cdot E \cdot A / l \]

The belt position is determined by the internal variable \(x\). For \(x = 0\) the clamp is in the middle. When the position crosses the driven pulley, i.e.

\[ x < - \frac{\text{belt length}}{2} \]

the simulation is stopped: "Error: clamp position larger than belt end!". When the position crosses the other pulley, i.e.

\[ x > \frac{\text{belt length}}{2} \]

the simulation is also stopped, "Error: clamp position smaller than belt start!".

**Description - Default**

In this model the minimum stiffness is used, based on an output position at a length \(L\) of the driven pulley.

\[ k = 2 \cdot E \cdot A / l \]

**Description - VariableStiffness**

In this model a variable stiffness is used equal to:

\[ k = E \cdot A \left( \frac{1}{0.5 \cdot l + x} + \frac{1}{1.5 \cdot l - x} \right) \]

Take care not to let the clamp get too close to the driven pulley, because the stiffness will then grow to infinity!

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_rot</td>
<td>Rotation port.</td>
</tr>
<tr>
<td>p_trans</td>
<td>Translation port.</td>
</tr>
</tbody>
</table>
Causality
p_rot not equal
p_trans

Parameters
radius pinion gear pitch radius [m]
d damping N.s/m
E Modulus of elasticity [N/m2]
A $A = \text{Belt area} \ [\text{m}^2]$
l belt length [m]

Variables
x clamp position, abs(x) < belt length/2

Initial values
x_initial Initial clamp position, abs(x_initial) < belt length/2

Transmission

Library
Iconic Diagrams\Mechanical\Translation\Transmission

Use

Description

This models represents any type of lever with ports moving in the same direction. The lever is ideal, i.e., it does not have inertia, friction or geometrical limitations. The lever has one fast moving port and one slow moving port. The transmission ratio is the ratio of the velocities of both ports. The causality of this model is always mixed: one port has a force out causality while the other has an velocity out causality:

\[ p_{\text{fast}}.F = i \times p_{\text{slow}}.F \]
\[ p_{\text{slow}}.v = i \times p_{\text{fast}}.v \]

or:

\[ p_{\text{slow}}.F = \frac{1}{i} \times p_{\text{fast}}.F \]
\[ p_{\text{fast}}.v = \frac{1}{i} \times p_{\text{slow}}.v \]

Interface

Ports Description
p_fast  Fast moving rotation port.

p_slow  Slow moving rotation port.

**Causality**

p_slow  notequal

p_fast

**Parameters**

i  transmission ratio \( \frac{p_{\text{slow}.v}}{p_{\text{fast}.v}} \), \( 0 < i < 1 \)

**Note**

Keep the transmission ratio \( i \) between 0 and 1. Confusion might otherwise exist:

- \( i > 1 \): the fast moving port is slower than the slow moving port (you better interchange the connections of the transmission model).
- \( i < 0 \): the ports are counter-moving (use the lever model instead).

**UniversalLever**

**Library**

Iconic Diagrams\Mechanical\Translation\Transmission

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Iconic Diagrams (Translation).

**Description**

This model represents an ideal transmission with a free pivot point. The relations are:

\[
\begin{align*}
p3.v &= \frac{i}{(1+i)}p1.v + \frac{1}{(1+i)}p2.v; \\
p2.F &= \frac{1}{(1+i)}p3.F; \\
p1.F &= \frac{i}{(1+i)}p3.F;
\end{align*}
\]

**Ground**

Although each of the three ports may be connected to the ground, it is more efficient to use other models. When \( p1 \) or \( p2 \) is connected to the ground, this model is equal to the Transmission.emx model. When \( p3 \) is connected to the ground, this model is equal to the Lever.emx model.
11. Library

The Thermal library contains components which are very useful for modeling thermal systems. The following libraries are available.

- Components
- Generators
- Sensors

**Note**

- For domains that have port variables that do not multiply to power the name `pseudo` is used. This model has pseudo-thermal ports. The port variables of a pseudo-thermal port are the heat flow, p.dQ [W], and the temperature, p.T [K], which do not multiply to power.
- The base unit of temperature is degrees Kelvin. You can select degrees Celsius in the Parameters Editor or Variables Chooser desired. 20-sim will take care that internally always SI units (Kelvin) are used for calculations.

### Interface

**Ports**

| p1, p2, p3 | Translation ports. |

**Parameters**

| i | Transmission ratio [ ] |
Components

Convection

Library

Iconic Diagrams\Mechanical\Thermal\Components

Use


Description

This model describes linear heat convection between a material surface and gas or fluid flow. The basic equation is:

\[ p.dQ = (p1.T - p2.T) \cdot G_c; \]

where \( p1.T \) is the temperature at the surface and \( p2.T \) the gas or fluid temperature. \( G_r \) is the thermal conductance which is function of the surface area \( A \) and the convection coefficient \( h \):

\[ G_r = A \cdot h; \]

In most cases \( h \) is not constant but a non-analytical function of the gas or fluid speed and other properties. In most cases \( G_r \) is experimentally defined. Therefore \( G \) is given as an input signal.

Interface

Ports

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1</td>
</tr>
<tr>
<td>p2</td>
</tr>
</tbody>
</table>

Causality

indifferent

Input

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
</tr>
</tbody>
</table>

Ground

Library

Iconic Diagrams\Mechanical\Thermal\Components
Use

Description
This is a general model for the heat storage that is so large that is can be considered constant (e.g. the environment). It is comparable to the ground in the electrical domain.

\[ T_0 = 25 \text{\,\degree C}; \]
\[ p.T = T_0; \]

Interface

Ports
p[any]
Any number of connections can be made (pseudothermal).

Causality
fixed temperature out
An torque out causality results in a derivative constitutive equation.

Parameters
T0
temperature [K]

HeatCapacity

Library

Iconic Diagrams\Mechanical\Thermal\Components

Use

Description
This is a general model for the heat storage in a specific material. A constant temperature distribution in the material is assumed and a constant heat capacity:

\[ E = \text{int}(p.dQ) + C*T_0; \]
\[ p.T = E/C; \]

T0 is the initial temperature of the material, E the internal energy \{J\} and C the thermal capacity \{J/K\}. Because any number of connections can be made, successive ports are named p1, p2, p3 etc. 20-sim will automatically create equations such that the resulting heat flow p.dQ is equal to the sum of the heatflows of all connected ports p1 .. pn. The temperatures of all connected ports are equal to element temperature p.T.

\[ p.dQ = \text{sum}(p1.dQ, p2.dQ, \ldots) \]
\[ p.T = p1.T = p2.T = \ldots. \]
The thermal capacity can be calculated with the specific heat capacity $c_p$ and material mass $m$:

$$ C = c_p \cdot m; $$

Typical values for $c_p$ are:

- water: 4186
- granite: 790
- glass: 840
- aluminium: 900
- concrete: 840
- copper: 387
- silver: 235
- iron / steel: 452
- wood: 1674
- air (50 °C): 1046

**Interface**

**Ports**

$p[\text{any}]$ 

Any number of connections can be made (pseudothermal).

**Causality**

preferred temperature out

An torque out causality results in a derivative constitutive equation.

**Variables**

$E$ 

internal energy [J]

$C$ 

thermal capacity [J/K]

$T0$ 

initial temperature [K]

**Radiation**

**Library**

Iconic Diagrams\Mechanical\Thermal\Components
Use


Description

This model describes the heat transfer between two bodies through radiation:

\[ p.dQ = Gr*\sigma*(T_1^4 - T_2^4); \]

where \( T_1 \) and \( T_2 \) are the temperatures of the body surfaces and \( \sigma \) is the Stefan-Boltzmann constant. For simple cases, \( Gr \) may be analytically computed. The analytical equations use \( \epsilon \), the surface emissivity of a body which is in the range 0..1. \( \epsilon = 1 \), if the body absorbs all radiation (= black body). \( \epsilon = 0 \), if the body reflects all radiation and does not absorb any.

Typical values for \( \epsilon \) are:

- aluminium, polished: 0.04
- copper, polished: 0.04
- gold, polished: 0.02
- paper: 0.09
- rubber: 0.95
- wood: 0.85..0.9

Analytical Equations for \( Gr \)

Small convex object in large enclosure (e.g., a hot machine in a room):

\[ Gr = e*A; \]

where

- \( e \): Emission value of object (0..1)
- \( A \): Surface area of object where radiation heat transfer takes place

Two parallel plates:

\[ Gr = A/(1/e1 + 1/e2 - 1); \]

where

- \( e1 \): Emission value of plate1 (0..1)
- \( e2 \): Emission value of plate2 (0..1)
- \( A \): Area of plate1 (= area of plate2)

Interface

Ports

- \( p1 \)  
  Description: Material port
- \( p2 \)  
  Description: Fluid port

Causality

indifferent
Input

G  thermal conductance [W/K]

**ThermalConductance**

**Library**
Iconic Diagrams\Mechanical\Thermal\Components

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Pseudo-thermal).

**Description**
When a temperature difference exists in a material, heat will flow from the high temperature part to the low temperature part. This model describes the transport of heat through a block of material with a temperature difference on both sides of the block. The heat conducting capacity of the material is indicated by the parameter $G$ (thermal conductance):

$$\rho \cdot dQ = \rho \cdot T \cdot G;$$

This model is the dual form of the thermal resistor where the insulation capacity of the block is indicated by the parameter $R$ (thermal resistance):

$$\rho \cdot dQ = \rho \cdot T \cdot R;$$

The heat flow through the material is ideal. I.e. there is no heat storage modeled. The thermal resistance model has separate high and low ports. The equations are

$$p \cdot dQ = p_{\text{high}} \cdot dQ = p_{\text{low}} \cdot dQ$$

$$p \cdot T = p_{\text{high}} \cdot T - p_{\text{low}} \cdot T$$

**Block**
The thermal conductance of a block can be calculated with the specific thermal conductivity $k$, the length $L$ of the block, and the area $A$ of both sides of the block:

$$G = k \cdot A / L$$

Typical values of the thermal conductivity [W.m⁻¹.K⁻¹] are:

<table>
<thead>
<tr>
<th>Material</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>0.6</td>
</tr>
<tr>
<td>granite</td>
<td>2.1</td>
</tr>
<tr>
<td>glass</td>
<td>1.0</td>
</tr>
<tr>
<td>aluminium</td>
<td>210</td>
</tr>
<tr>
<td>concrete</td>
<td>1.28</td>
</tr>
<tr>
<td>copper</td>
<td>390</td>
</tr>
<tr>
<td>silver</td>
<td>430</td>
</tr>
<tr>
<td>iron / steel</td>
<td>40-70</td>
</tr>
</tbody>
</table>


### Interface

#### Ports
- **p_high, p_low**
  - Description: Both terminals of the pseudothermal port p

#### Causality
- indifferent

#### Parameters
- **G**
  - thermal conductance [W/K]

---

### ThermalResistor

**Library**

- **Iconic Diagrams\Mechanical\Thermal\Components**

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Pseudothermal).

**Description**

When a temperature difference exists in a material, heat will flow from the high temperature part to the low temperature part. This model describes the transport of heat through a block of material with a temperature difference on both sides of the block. The insulation capacity of the block is indicated by the parameter $R$ (thermal resistance):

$$p.dQ = p.T/R;$$

This model is the dual form of the thermal conductor where the heat conducting capacity of the material is indicated by the parameter $G$ (thermal conductance):

$$p.dQ = p.T*G;$$

The heat flow through the material is ideal. I.e. there is no heat storage modeled. The thermal resistance model has separate high and low ports. The equations are:

$$p.dQ = p_{high}.dQ = p_{low}.dQ$$

$$p.T = p_{high}.T - p_{low}.T$$

**Block**

The thermal resistance of a block can be calculated with the specific thermal conductivity $k$, the length $L$ of the block, and the area $A$ of both sides of the block:

$$R = \frac{kA}{L}$$
\[ R = \frac{L}{k \cdot A} \]

Typical values of the thermal conductivity \([W.m^{-1}.K^{-1}]\) are:

- water: 0.6
- granite: 2.1
- glass: 1.0
- aluminium: 210
- concrete: 1.28
- copper: 390
- silver: 430
- iron / steel: 40-70
- wood: 0.13
- air: 0.026

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
</tr>
</tbody>
</table>

**Causality**

indifferent

**Parameters**

| R | thermal resistance \([K/W]\) |

**Generators**

**HeatFlow**

**Library**
Iconic Diagrams\Mechanical\Thermal\Generators

**Use**


**Description**
This model yields a heat flow that is set to a constant value. The temperature is indifferent. The model can represent any heat generating object with a constant heat flow.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
</tr>
</tbody>
</table>
**Causality**
fixed heat flow out

**Parameters**
dQ Heat flow [J/s]

**ModulatedHeatFlow**

**Library**
Iconic Diagrams\Mechanical\Thermal\Generators

**Use**

**Description**
This model yields a heat flow that is equal to a (fluctuating) value given by the input signal $dQ$. The temperature is indifferent. The model can represent any heat generating object with a fluctuating heat flow.

**Interface**

**Ports**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
</tr>
</tbody>
</table>

**Causality**
fixed heat flow out

**Parameters**

dQ Heat flow [J/s]

**ModulatedTemperatureSource**

**Library**
Iconic Diagrams\Mechanical\Thermal\Generators

**Use**

**Description**
This model has a temperature that is equal to a (fluctuating) value given by the input signal $T$. The heat flow is indifferent. This model can represent an object that has a heat capacity which is so much larger than the rest of the system, that its temperature can be seen as an independant variable.
11. Library

Interface

Ports |
| Description |
|---|---|
| p |

Causality
fixed temperature out

Input
T |
| Variable temperature signal [K] |

Resistor

Library
Iconic Diagrams\Thermal\Generators\Generators

Use

Description
This is a model of a resistor with a temperature coefficient. The resistance and voltage equation can be written as:

\[
R = R_{\text{ref}}(1 + \alpha(p_{\text{th}.T} - T_{\text{ref}}));
\]
\[
p_{\text{el}.u} = p_{\text{el}.i} \times R;
\]

where \(R_{\text{ref}}\) is the reference resistance at reference temperature \(T_{\text{ref}}\) and \(\alpha\) the temperature coefficient of resistance. The actual temperature of the resistor is given by the pseudothermal port of the model, \(p_{\text{el}.T}\). The heat generated by the resistor is equal to

\[
p_{\text{th}.dQ} = p_{\text{el}.u} \times p_{\text{el}.i};
\]

The electrical port \(p\) of the resistor model has separate high and low terminals. The equations are:

\[
p_{\text{el}.i} = p_{\text{high}.el}.i = p_{\text{low}.el}.i;
\]
\[
p_{\text{el}.u} = p_{\text{el}.high}.u - p_{\text{el}.low}.u;
\]

Interface

Ports |
| Description |
|---|---|
| p_{\text{el}.high} |
| Both terminals of the Electric port. |
| p_{\text{el}.low} |
| The pseudothermal port |
| p_{\text{th}} |

Causality
indifferent \(p_{\text{el}}\)
fixed heat flow
out p_th

Parameters
R_ref Reference resistance [Ohm].
T_ref Reference temperature [K].
alpha Temperature coefficient of the resistance []

TemperatureSource

Library

Iconic Diagrams\Mechanical\Thermal\Generators
Use
Description
This model has a temperature that is set to a certain constant value. The heat flow is indifferent. The model can represent a piece of material which is so large that its temperature variation is neglectable (e.g. the environment) and thus can be seen as an ideal temperature source

Interface

Ports Description
p

Causality
fixed temperature out

Parameters
T Fixed temperature [K]

Thermistor

Library

Iconic Diagrams\Thermal\Generators
Use
Description
This is a model of a linear thermistor. Thermistors are thermally sensitive resistors and have, according to type, a negative (NTC), or positive (PTC) resistance/temperature coefficient. For linear thermistors the resistance and voltage equation can be written as:
\[ R = R_{\text{ref}}(1 + \alpha(p_{\text{th}}.T - T_{\text{ref}})); \]
\[ p_{\text{el}}.u = p_{\text{el}}.i \times R; \]

where \( R_{\text{ref}} \) is the reference resistance at reference temperature \( T_{\text{ref}} \) and \( \alpha \) the temperature coefficient of resistance. The actual temperature of the thermistor is given by the pseudothermal port of the model, \( p_{\text{el}}.T \). The heat generated by the thermistor is equal to

\[ p_{\text{th}}.dQ = p_{\text{el}}.u \times p_{\text{el}}.i; \]

The electrical port \( p \) of the thermistor model has separate high and low terminals. The equations are:

\[ p_{\text{el}}.i = p_{\text{high}}_{\text{el}}.i = p_{\text{low}}_{\text{el}}.i; \]
\[ p_{\text{el}}.u = p_{\text{el}}_{\text{high}}.u - p_{\text{el}}_{\text{low}}.u; \]

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{\text{el}}_{\text{high}} )</td>
<td>Both terminals of the Electric port.</td>
</tr>
<tr>
<td>( p_{\text{el}}_{\text{low}} )</td>
<td></td>
</tr>
<tr>
<td>( p_{\text{th}} )</td>
<td>The pseudothermal port</td>
</tr>
</tbody>
</table>

**Causality**

indifferent \( p_{\text{el}} \)
fixed heat flow
out \( p_{\text{th}} \)

**Parameters**

- \( R_{\text{ref}} \) Reference resistance [Ohm].
- \( T_{\text{ref}} \) Reference temperature [K].
- \( \alpha \) Temperature coefficient of the resistance []

**Sensors**

**HeatFlowSensor**

**Library**

Iconic Diagrams\Mechanical\Thermal

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Iconic Diagrams (Pseudothermal).
**Description**
This is a model of an ideal heat flow sensor with an output signal $dQ$ that is equal to the measured heat flow. The sensor is ideal which means that it does not store, loses or adds heat.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_high, p_low</td>
<td>Both ports of the sensor</td>
</tr>
</tbody>
</table>

**Causality**

$p\_high$ not equal $p\_low$

**Parameters**

dQ Measured heat flow [J/s]

---

**TemperatureSensor**

**Library**

Iconic Diagrams\Mechanical\Thermal

**Use**


**Description**
This is a model of an ideal temperature sensor with an output signal $T$ that is equal to the measured temperature. The heat flow into the model is zero to assure zero power loss.

**Interface**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td></td>
</tr>
</tbody>
</table>

**Causality**

fixed heat flow out

**Parameters**

$T$ Measured temperature [K]
11.3 Signal

11.3.1 Block Diagram

**Attenuate**

**Library**
Signal\Block Diagram

**Use**
Domains: Continuous, Discrete. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model divides an input signal by a constant value.
\[ output = \frac{input}{K} \]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Division parameter</td>
</tr>
</tbody>
</table>

**Delay-Pade**

**Library**
Signal\Block Diagram

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
This model delays the input signal by "T" seconds using a 4th order Pade approximation. The model is linear which means that it can be used in models that should be linearized.

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Delay time.</td>
</tr>
</tbody>
</table>
**Delay-Step**

**Library**  
Signal\Block Diagram

**Use**  
**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**  
This model delays its input signal one simulation step.

\[
\begin{align*}
  \text{output} &= \text{initial}; \ (\text{time} = 0) \\
  \text{output} &= \text{inp}(\text{time} - \text{hk}); \ (\text{time} > 0)
\end{align*}
\]

where \(\text{hk} = \) simulation step size.

**Note**  
To correctly use models with constant delays, simulation runs must be performed using integration algorithms with a constant time-step. Otherwise the model Delay-Time.emx should be used!

**Interface**

**Inputs**  
- input

**Outputs**  
- output

**Parameters**  
- initial  
  The initial output value.

**Note**

- To correctly use models with constant delays, simulation runs must be performed using integration algorithms with a constant time-step. Otherwise the model Delay-Time.emx should be used!
- The delay-step.emx submodel is non-linear: i.e. models which include the delay-step.emx submodel cannot be linearized. Use the linear time delay Delay-Pade.emx if you want to perform linearization.

**Delay-Time**

**Library**  
Signal\Block Diagram

**Use**  
**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.
Description
This model stores the input signal and corresponding time in a buffer. After "delay" seconds the stored values are retrieved. When the simulation time step does not coincide with the delay time "delay", the output is calculated by first order interpolation.

\[
\begin{align*}
output &= initial; \ (time < delay) \\
output &= inp(time - delay); \ (time \geq delay)
\end{align*}
\]

Interface

Inputs
- Description
- input

Outputs
- output

Parameters
- initial: The initial output value.
- delay: Delay time.

Delay-VariableTime

Library
Signal\Block Diagram

Use

Description
This model stores the input signal and corresponding time in a buffer. After "delay" seconds the stored values are retrieved. This delay is a variable input signal. When the simulation time step does not coincide with the delay time "delay", the output is calculated by first order interpolation.

\[
\begin{align*}
output &= initial; \ (time < delay) \\
output &= inp(time - delay); \ (time \geq delay) \\
output &= inp(time); \ (delay < 0)
\end{align*}
\]

Interface

Inputs
- Description
- input

Outputs
- output

Parameters
- initial: The initial output value.
- delay: Delay time.
Note
- The maximum storage capacity of the buffer is 58254 input values. When many input values are stored the simulation speed may slow down considerably!
- The delay-variabletime.emx submodel is non-linear: i.e. models which include the delay-variabletime.emx submodel cannot be linearized. Use the linear time delay Delay-Pade.emx if you want to perform linearization.

Demux

Library
Signal\Block Diagram

Use

Description
You can use the Mux model to combine multiple input signals into one multi-dimensional signal. This model can be used to spit the multi-dimensional signal again into single signals.

Interface

Inputs

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>inputs</td>
<td>Default 2 signals can be connected. Use the right mouse menu and choose Edit Implementation to change the number of signals.</td>
</tr>
</tbody>
</table>

Outputs

| output[any] | real | The output signal size is equal to the number of inputs. |
DemuxBoolean

Library
Signal\Block Diagram

Use

Description
You can use the Mux model to combine multiple input signals into one multi-dimensional signal. This model can be used to split the multi-dimensional signal again into single signals.

Interface

Inputs
inputs

Type
boolean

Description
Default 2 signals can be connected. Use the right mouse menu and choose Edit Implementation to change the number of signals.

Outputs
output[any]

boolean

The output signal size is equal to the number of inputs.

DemuxInteger

Library
Signal\Block Diagram

Use

Description
You can use the Mux model to combine multiple input signals into one multi-dimensional signal. This model can be used to split the multi-dimensional signal again into single signals.
### Interface

#### Inputs

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>inputs</td>
<td>integer</td>
</tr>
</tbody>
</table>

Default 2 signals can be connected. Use the right mouse menu and choose *Edit Implementation* to change the number of signals.

#### Outputs

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output[any]</td>
<td>integer</td>
</tr>
</tbody>
</table>

The output signal size is equal to the number of inputs.

### DemuxString

**Library**

Signal\Block Diagram

**Use**

*Domains*: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

You can use the Mux model to combine multiple input signals into one multi-dimensional signal.

This model can be used to spit the multi-dimensional signal again into single signals.
Differentiate-Calculus

Library
Signal\Block Diagram

Use

Description
This model approximates the differentiation of an input signal by the equation:

\[ y = \frac{2}{3} \cdot \frac{u(t) - u(t - h)}{h} + \frac{1}{3} \cdot y(t - h) \]

where \( h \) = simulation step size. The initial value of the output is equal to the parameter "initial". When the simulation step size is zero (time event, state event) the output value will be equal to the previous output value (the simulation step size part is not calculated to prevent a division by zero).

Interface

Inputs

<table>
<thead>
<tr>
<th>Input</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>string</td>
<td>Default 2 signals can be connected. Use the right mouse menu and choose Edit Implementation to change the number of signals.</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Output</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output[any]</td>
<td>string</td>
<td>The output signal size is equal to the number of inputs.</td>
</tr>
</tbody>
</table>
**Parameters**

- **initial**: The initial value of the output.

---

**Differentiate-FO**

**Library**

Signal\Block Diagram

**Use**

- **Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This model is a first order approximation of a differentiation. The transfer function is:

\[ Y(s) = k_d \cdot \frac{2 \cdot \pi \cdot f_h \cdot s}{s + 2 \cdot \pi \cdot f_h} \cdot U(s) \]

As shown in the figure below, the model behaves as a differentiator for frequencies below \( f_l \).

---

**Interface**

**Inputs**

- **input**: Description

**Outputs**

- **output**: Description
Parameters

kd Differentiation gain [ ]
fl Differentiation limit [Hz]

Initial Values

output_initial The initial value of the integral.

Differentiate-SVF

Library
Signal\Block Diagram

Use

Description
This model approximates the differentiation of an input with a state variable filter:

As can be seen, no differentiation is used in this model and consequently all integration algorithms can be used. In the S-domain the output of this model is equal to:

\[ \frac{s}{s + 1} \cdot \text{input} \]

For very high values of N, the output becomes the pure derivative of the input. High values of N, however, increase simulations times. A good trade-off is a starting value of 10. If more accuracy is needed, this value can be increased.

Interface

Inputs
input

Outputs
output

Parameters
N Derivative Gain Limitation.
initial The initial value of the output.
### Differentiate

**Library**
Signal\Block Diagram

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
This model differentiates an input signal. The initial value of the output is equal to the parameter "initial".

\[
output = ddt(input, initial);
\]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>The initial value of the output.</td>
</tr>
</tbody>
</table>

### Filter

**Library**
Signal\Block Diagram

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
When you select this model and click Go Down a special editor opens (Filter Editor), allowing you to choose a filter:
11. Library

Interface

**Inputs**
- input

**Outputs**
- output

**Initial Values**

- The model has internal states that are not accessible.

**Parameters**

- Parameters are entered by the Filter Editor.

**Gain**

**Library**
Signal\Block Diagram

**Use**

**Description**

This model multiplies an input signal with a constant value.

\[
output = K * input
\]

**Interface**

**Inputs**

**Description**
Integrate-ExpWindow

Library
Signal\Block Diagram

Use

Description
This model integrates an input signal over an exponential window with time constant T0 [s].

\[
output(t) = \int_{0}^{t} \text{input}(\tau) \cdot e^{(t-\tau)/T0} \, d\tau
\]

The model behaves as a signal averager, with an effective window of T0 [s].

Interface

Inputs
input

Outputs
output

Initial Values
state(0) The initial value of the integral.

Parameters
T0 Window constant [s].
## Integrate-FO

### Library
Signal\Block Diagram

### Use
**Domains:** Continuous. **Size:** 1-D. **Kind:** Block Diagrams.

### Description
This model is a first order approximation of an integration. The transfer function is:

\[
Y(s) = \frac{k_i}{2\pi f_l + s} \cdot U(s)
\]

As shown in the figure below, the model behaves as an integrator for frequencies above the \( f_l \)

### Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ki</td>
<td>Integration gain []</td>
</tr>
<tr>
<td>fl</td>
<td>Integration limit [Hz]</td>
</tr>
<tr>
<td>output_initial</td>
<td>Initial value.</td>
</tr>
</tbody>
</table>
**Integrate-FOLimited**

**Library**
Signal\Block Diagram

**Use**
**Domains:** Continuous. **Size:** 1-D. **Kind:** Block Diagrams.

**Description**
This model is a first order approximation of an integration with an output value limited to a minimum and maximum value. The model checks the output value to see if the maximum of minimum values have been crossed. If so the input value is set to zero to prevent the integral from winding-up. Between the bounds the transfer function is:

\[
Y(s) = \frac{ki}{2\cdot\pi\cdot f_l + s} \cdot U(s)
\]

As shown in the figure below, the model behaves as an integrator for frequencies above the \( f_l \).

![Graph showing the behavior of Integrate-FOLimited](image)

**Interface**

**Inputs**
- **input**

**Description**

**Integrate-Limited**

**Library**
Signal\Block Diagram

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
This model integrates an input signal. The output of this integral is limited between a maximum and minimum bound. If the integral is in saturated condition and the input changes sign, the output wanders away from the bounds immediately.

\[
output = \text{int}(inp) + \text{state}(0); \ (\text{minimum} \leq output \leq \text{maximum})
\]

**Interface**

**Inputs**
\begin{itemize}
  \item \textbf{input}
\end{itemize}

**Outputs**
\begin{itemize}
  \item \textbf{output}
\end{itemize}

**Initial Values**
\begin{itemize}
  \item \textbf{state}(0) The initial value of the integral.
\end{itemize}

**Parameters**
\begin{itemize}
  \item \textbf{minimum}
  \item \textbf{maximum}
\end{itemize}

- **ki**: Integration gain [\( \right \)]
- **fl**: Integration limit [Hz]
- **output_initial**: Initial value.
- **maximum**: Maximum output value
- **minimum**: Minimum output value
**Integrate-RectWindow**

**Library**
Signal\Block Diagram

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Block Diagrams.

**Description**
This model integrates an input signal over a limited time interval which is $T_0$ [s] wide.

$$ output = \int_{t-T_0}^{t} \text{input} \cdot dt $$

The model behaves as a signal averager, with a rectangular window of $T_0$ [s].

**Interface**

**Inputs**
- input

**Outputs**
- output

**Initial Values**
- state(0) The initial value of the integral.

**Parameters**
- $T_0$ Integration interval.

---

**Integrate-Reset**

**Library**
Signal\Block Diagram

**Use**

**Domains:** Continuous. **Size:** 1-D. **Kind:** Block Diagrams.

**Description-Default**
This model integrates an input signal. The output of this integral may be reset to any desired value each time the reset signal is unequal to zero.

\[
output = \text{int}(\text{inp}) + \text{state}(0); \text{ (reset} = 0) \\
output = \text{reset to newoutput}; \text{ (reset} \neq 0)
\]
This implementation uses a normal integrator. That is why the model will also work when c-code is generated.

**Interface-Default**

**Inputs**
- input
- reset
- newoutput

**Outputs**
- output

**Initial Values**
- state(0)

**Description**

Input signal

When reset <> 0, the output changes to newoutput.

New output.

This model integrates an input signal. The output of this integral may be reset to any desired value each time the reset signal is unequal to zero.

\[
\text{output} = \text{int}(\text{inp}) + \text{state}(0); \ (\text{reset} = 0) \\
\text{output} = \text{reset to newoutput}; \ (\text{reset} <> 0)
\]

This implementation uses the function \( \text{resint} \). This function forces the integration method with a state event to search for the exact time where the integral is reset. The result is more accurate than the Default implementation, but this implementation will not work when c-code is generated.

**Interface-Pure**

**Inputs**
- input
- reset
- newoutput

**Outputs**
- output

**Initial Values**
- state(0)

**Description**

Input signal

When reset <> 0, the output changes to newoutput.

New output.

This model integrates an input signal:

**Integrate**

**Library**

Signal\Block Diagram

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This model integrates an input signal:
output = int(input) + state(0)

### Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>state(0)</td>
<td>The initial value of the integral.</td>
</tr>
</tbody>
</table>

### Inverse

**Library**

Signal\Block Diagram

**Use**

**Domains**: Continuous, Discrete. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**

This model yields the inverse of the input signal.

\[
output = \frac{1}{input}
\]

### Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

### Linear System

**Library**

Signal\Block Diagram

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

When you select this model and click Go Down a special editor opens (Linear System Editor), allowing you to enter a linear system in State Space form, as a Transfer Function or by adding poles and zeros:
### Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

### Initial Values

The model has internal states that are not accessible.

### Parameters

Parameters are entered by the Linear System Editor.
**MultiplyDivide**

**Library**
Signal\Block Diagram , System

**Use**
**Domains**: Continuous, Discrete. **Size**: [n,m]. **Kind**: Block Diagrams.

**Description**
This model yields a multiplication and/or division of one or more input signals. While connecting input signals, 20-sim will ask whether the signals should be multiplied or divided. The signals may have either size, but the size of all connected signals should be equal.

For example the MultiplyDivide model can have 2 signals connected that are multiplied and 2 signals that must be divided. 20-sim treats them as an array multiply and an array divide with:

\[
\text{multiply} = [\text{multiply1};\text{multiply2}];
\]

and

\[
\text{divide} = [\text{divide1};\text{divide2}];
\]

The output will then be equal to:

\[
\text{output} = (\text{multiply1} \times \text{multiply2}) / (\text{divide1} \times \text{divide2});
\]

**Interface**

**Inputs**
- **multiply[any]**
- **divide[any]**

**Description**
Any number of input signals (each of the same size) may be connected to be multiplied (multiply) or divided (divide).

**Outputs**
- **output**

**Limitations**
The signals connected to this model should all have the same size.
Mux

Library
Signal\Block Diagram

Use

Description
You can use this model to combine multiple input signals into one multi-dimensional signal.
The Demux model can be used to split the multi-dimensional signal again into single signals.

Interface

Inputs
inputs
Type
real
Description
Default 2 signals can be connected.
Use the right mouse menu and choose Edit Implementation to change the number of signals.

Outputs
output[any]
real
The output signal size is equal to the number of inputs.

MuxBoolean

Library
Signal\Block Diagram

Use
**Description**
You can use this model to combine multiple input signals into one multi-dimensional signal. The Demux model can be used to spit the multi-dimensional signal again into single signals.

**Interface**

**Inputs**
- **inputs**
  - **Type**: boolean
  - **Description**: Default 2 signals can be connected. Use the right mouse menu and choose *Edit Implementation* to change the number of signals.

**Outputs**
- **output[any]**
  - **Type**: boolean
  - **Description**: The output signal size is equal to the number of inputs.

**MuxInteger**

**Library**
Signal\Block Diagram

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
You can use this model to combine multiple input signals into one multi-dimensional signal. The Demux model can be used to spit the multi-dimensional signal again into single signals.
### Interface

<table>
<thead>
<tr>
<th><strong>Inputs</strong></th>
<th><strong>Type</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>inputs</td>
<td>integer</td>
<td>Default 2 signals can be connected. Use the right mouse menu and choose <em>Edit Implementation</em> to change the number of signals.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Outputs</strong></th>
<th><strong>Type</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>output[any]</td>
<td>integer</td>
<td>The output signal size is equal to the number of inputs.</td>
</tr>
</tbody>
</table>

### MuxString

#### Library

Signal\Block Diagram

#### Use

**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

#### Description

You can use this model to combine multiple input signals into one multi-dimensional signal. The Demux model can be used to split the multi-dimensional signal again into single signals.
Interface

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>inputs</td>
<td>string</td>
</tr>
</tbody>
</table>

Default 2 signals can be connected. Use the right mouse menu and choose *Edit Implementation* to change the number of signals.

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>output[any]</td>
<td>string</td>
</tr>
</tbody>
</table>

The output signal size is equal to the number of inputs.

Negate

**Library**

Signal\Block Diagram

**Use**

**Domains**: Continuous, Discrete. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**

This model yields the negative of the input signal.

\[ output = -input \]

**Interface**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
<tr>
<td>output</td>
</tr>
</tbody>
</table>
PlusMinus

Library
Signal\Block Diagram , System

Use
Domains: Continuous, Discrete. Size: [n,m]. Kind: Block Diagrams.

Description
This model yields a subtraction and/or summation of one or more input signals. While connecting input signals, 20-sim will ask whether the signals should be added or subtracted. The signals may have either size, but the size of all connected signals should be equal.

For example the PlusMinus model can have 2 signals connected that are added and 2 signals that must be subtracted. 20-sim treats them as an array plus and an array minus with:

\[
plus = [plus1;plus2];
\]

and

\[
minus = [minus1;minus2];
\]

The output will then be equal to:

\[
output = plus1 + plus2 - minus1 - minus2;
\]

Interface

Inputs
plus[any] minus[any]

Description
Any number of input signals (each of the same size) may be connected to be added (plus) or subtracted (minus).

Outputs
output

Limitations
The signals connected to this model should all have the same size.
**SignalMonitor**

**Library**
Signal\Block Diagram , Signal\Sources

**Use**
**Domains:** Continuous, Discrete. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This model shows the value of its input in the Simulator. When you open the Simulator (select Properties and Plot) the input of this model is automatically selected as plotvariable. As label for this variable the local name of the SignalMonitor model is chosen. It is therefore advised to give each SignalMonitor model a useful name (select the model, click the right mouse button and select Attributes from the right mouse menu).

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

The value of the input is shown in the Simulator using the local name of the model as label.

**Splitter**

**Library**
Signal\Block Diagram , System

**Use**
**Domains:** Continuous, Discrete. **Size:** \([n,m]\). **Kind:** Block Diagrams.

**Description**
This model can split one output signal into two or more output signals. The signals may have either size, but the size of all connected signals should be equal.
### Interface

**Inputs**
- input

**Outputs**
- output\[any\]

**Description**
One input signal must be connected. Any number of input signals (each of the same size) may be connected.

**Limitations**
The signals connected to this model should all have the same size.

#### 11.3.2 Block Diagram Non-Linear

**DeadZone**

**Library**
Signal\Block Diagram Non-Linear

**Use**
**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model generates zero output when the input is within a specified region, called the dead zone. Otherwise the output equals the input plus or minus half the zone.
output = input + zone/2; (input < -zone/2)
output = 0; (-zone/2 <= input <= zone/2)
output = input - zone/2; (input > zone/2)

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>zone</td>
</tr>
</tbody>
</table>

**Limitations**

Only single signals (i.e. signals of size 1) can be connected to this model.

**Function-2DTable**

**Library**

Signal\Block Diagram Non-Linear

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This model uses a two-dimensional table with data points to calculate the output $z = f(x,y)$ as a function of the input $x$ and $y$. The output $z$ is calculated using linear interpolation between the table data points.
The first row denotes the $x$-values and the first column denotes the $y$-values.

The input data of the first column and first row needs to be monotonically increasing.

Discontinuities are allowed, by providing the same input point twice in first row or first column of the table.

Values outside of the table range, are computed by linear extrapolation of the last two points.

A table must be stored as an ASCII (text) file and should consist rows and columns of data. The first row consists of the $x$-values first column consist of the $y$-values. The row-column pairs are the corresponding $z$-values. Values must be separated by a space or a tab. No comment or other text may be part of the table-file. The filename of the input file can be specified using the complete path (e.g. c:\data\data.tbl ). When no path is given, the file is assumed to be in the experiment directory.

**Example**

Suppose we want to use the well known Matlab *peaks* function:

This function can be put in a matrix form as:
The first row and column denote the x-values and y-values and the other row-column pairs the corresponding peaks function values. This matrix can be entered in a text file:

The model 2DTableLookup.emx (Examples\Signal Processing) shows how to use this text file as a 2-D table.

**Interface**

**Inputs**

- **input1**: x-value
- **input2**: y-value

**Outputs**

- **output**: z-value

**Parameters**

- **filename**: The filename of the table file.
Function-Absolute

Library
Signal\Block Diagram Non-Linear

Use

Description
This model yields the absolute value of an input signal.

\[ outp = abs(inp); \]

Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

Function-Cosine

Library
Signal\Block Diagram Non-Linear

Use

Description
This model yields the cosine of an input signal.

\[ output = cos(input); \]

Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>
**Function-DB**

**Library**
Signal\Block Diagram Non-Linear

**Use**
**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This model returns an output signal in decibel (dB):

\[ output = 20\log_{10}(input); \]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Function-Log**

**Library**
Signal\Block Diagram Non-Linear

**Use**
**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This model returns the natural logarithm of the input.

\[ output = \log(input); \]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>
Function-Power

Library
Signal\Block Diagram Non-Linear

Use

Description
This model raises the values of an input signal to the power p.

\[
output = input^p;
\]

Interface

Inputs
input

Outputs
output

Parameters
p

Function-Sign

Library
Signal\Block Diagram Non-Linear

Use

Description
This model returns the sign of the input. A zero input results in a zero output.

\[
output = -1; (input < 0) \\
output = 0; (input = 0) \\
output = 1; (input > 0)
\]

Interface

Inputs
input

Outputs
output
**Function-Sine**

**Library**
Signal\Block Diagram Non-Linear

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model yields the sine of an input signal.

\[
output = \sin(input);
\]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Function-Square**

**Library**
Signal\Block Diagram Non-Linear

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model returns the square of the input signal.

\[
output = input^2;
\]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>
Function-SquareRoot

Library
Signal\Block Diagram Non-Linear

Use

Description
This model yields the square root of an input signal.

\[ outp = \sqrt{inp}; \]

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Function-SquareRootSign

Library
Signal\Block Diagram Non-Linear

Use

Description
This model yields the square root of an input signal with sign and multiplied by a parameter \( p \).

\[ output = \text{sign}(input) \times \sqrt{inp}/p; \]

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
</tr>
</tbody>
</table>
**Function-SquareSign**

**Library**  
Signal\Block Diagram Non-Linear

**Use**  
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**  
This model yields the square of an input signal with sign and multiplied by a parameter $p$.

$$output = p \times \text{sign}(input) \times input \times input;$$

**Interface**

**Inputs**  
<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**Outputs**  
<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**Parameters**  
<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
</tr>
</tbody>
</table>

---

**Function-Table**

**Library**  
Signal\Block Diagram Non-Linear

**Use**  
Domains: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**  
This model uses a one-dimensional table with data points to calculate the output $y = f(x)$ as a function of the input $x$. The output $y$ is calculated using linear interpolation between the table data points.

- The input data of the first column needs to be monotonically increasing.
- Discontinuities are allowed, by providing the same input point twice in the table.
- Values outside of the table range, are computed by linear extrapolation of the last two points.
A table must be stored either as an ASCII (text) file or as a matrix inside the equation model. In both cases the table should consist two columns of data. The first column consists of the x-values and the second column of the corresponding y-values.

**Reading data from a file**

If the table is read from a file, each line of the file may only contain one x- and one corresponding y-value. The two values must be separated by a space or a tab. Each new set of x- and y-values must start on a new line. No comment or other text may be part of the table-file. The filename of the input file can be specified using the complete path (e.g. C:\data\data.tbl). When no path is given, the file is assumed to be in the experiment directory.

**Interface**

**Inputs**

- **input**

**Outputs**

- **output**

**Parameters**

- **filename**: The filename of the table file.

**Reading data from a matrix**

If the table is read from a matrix in an equation model, each row may only contain one x- and one corresponding y-value. The two values must be separated by a coma and each column must be separated by a semi-colon.

**Note**

Table interpolation can also be used directly in an equation model by using the function `table`.
**Function-Tan**

**Library**
Signal\Block Diagram Non-Linear

**Use**

**Description**
This model yields the tangent of an input signal.

\[
output = \tan(input);
\]

Note that the tangent goes infinity for input signals that are a multiple of pi.

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Function-Truncation**

**Library**
Signal\Block Diagram Non-Linear

**Use**

**Description**
This model rounds the input towards zero (i.e. it removes the fraction of the input).

\[
output = \text{trunc}(input);
\]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**
SignalLimiter-Backlash

Library
Signal|Block Diagram Non-Linear

Use

Description
This model represents mechanical backlash between an input position and an output position.

\[
\begin{align*}
\text{output} &= 0; \text{ (input is within the dead zone)} \\
\text{output} &= \text{input} - \text{zone}/2; \text{ (input is increasing and out of the dead zone)} \\
\text{output} &= \text{input} + \text{zone}/2; \text{ (input is decreasing and out of the dead zone)}
\end{align*}
\]

\[
p_F = 0.5 \cdot k_2 \cdot \left( x - \sqrt{-x - \frac{s}{2}} \right) \left( ep \cdot s \right) + x + \sqrt{x - \frac{s}{2}} \left( ep \cdot s \right)^2 + k_1 \cdot x + d_{mv} \cdot p \cdot v
\]

Interface

Inputs
- input

Outputs
- output

Parameters
- zone: Size of the dead zone. 
  \( \text{zone} \geq 0 \)
- initial: Value of the output at time = 0. 
  \( \text{initial} \geq \text{input(time} = 0) - \text{zone}/2 \) 
  \( \text{initial} \leq \text{input(time} = 0) + \text{zone}/2 \)
**SignalLimiter-Hysteresis**

**Library**
Signal\Block Diagram Non-Linear

**Use**
**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
The output signal of this submodel switches between maximum and minimum, depending on the sign of the input signal, with hysteresis applied. When traversing between minimum and maximum (dead zone), the rate of change is defined by the parameter $k$.

![Hysteresis diagram](image_url)

**Interface**

**Inputs**
- input

**Outputs**
- output

**Parameters**
- minimum
- maximum
- hysteresis
- $k$

**Description**
- Minimum value of the output.
- Maximum value of the output.
- Magnitude of the hysteresis.
- Rate of change in the dead zone.
SignalLimiter-Limit

Library
Signal\Block Diagram Non-Linear

Use

Description
This model limits the input signal to minimum and maximum bounds.

\[
\begin{align*}
\text{output} &= \text{minimum}; (\text{input} < \text{minimum}) \\
\text{output} &= \text{input}; (\text{minimum} \leq \text{input} \leq \text{maximum}) \\
\text{output} &= \text{maximum} \ (\text{input} > \text{maximum})
\end{align*}
\]

Interface

Inputs
input

Outputs
output

Parameters
minimum Minimum value of the output.
maximum Maximum value of the output.
**SignalLimiter-JumpRateLimit**

**Library**
Signal\Block Diagram Non-Linear

**Use**
**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This model limits the input signal to a minimum and maximum jump and a minimum and maximum rate.

\[
\begin{align*}
\text{for } \text{minimum} < \text{input} < \text{maximum}: \\
\quad \text{output} &= \text{input} \\
\text{else} & \\
\quad \frac{d\text{output}}{dt} &= \frac{d\text{input}}{dt}; \quad (\text{minimumrate} < \frac{d\text{input}}{dt} < \text{maximumrate}) \\
\quad \frac{d\text{output}}{dt} &= \text{minimum}; \quad (\frac{d\text{input}}{dt} < \text{minimumrate}) \\
\quad \text{output} &= \text{maximum}; \quad (\frac{d\text{input}}{dt} > \text{maximumrate})
\end{align*}
\]

An example is shown below where a sinusoidal input signal is limited to a minimum jump of -0.2, a maximum jump of 0.2, a maximum rate of 0.4 and a minimum rate of -0.4.

![Jump and Rate Limiter](image)

**Interface**

**Inputs**
- **input**
  - **Description:** The inputs signal to be limited

**Outputs**
- **output**
  - **Description:** The limited output signal

**Parameters**
- **minimum**
- **maximum**
- **minimumrate**
- **maximumrate**
  - **Description:** Minimum jump of the output. Maximum jump of the output. Minimum rate of the output. Maximum rate of the output.
SignalLimiter-PWM

Library
Signal\Block Diagram Non-Linear

Use

Description
Pulse width modulation (PWM) is a powerful technique for controlling analog circuits with a processor's digital outputs. PWM is employed in a wide variety of applications, ranging from measurement and communications to power control and conversion. The output of a PWM block is a pulse train. The duty cycle, (the time that a pulse is on divided by the time the pulse is off) is proportional to the value of the input signal if the input is within the range $<-input_{amp}, +input_{amp}>$. For Bipolar PWM the output signalwitches between a positive and a negative value. For Unipolar PWM the output signalwitches between zero and positive or negative value.

An example is shown in the graph below. The parameter $input_{amp}$ is equal to 1 and the parameter $max output$ is equal to 5. The frequency of the PWM signal is 10 Hz.
Bipolar and Unipolar PWM conversion.

**Interface**

<table>
<thead>
<tr>
<th><strong>Inputs</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Outputs</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Parameters</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>The modulating frequency [Hz].</td>
</tr>
<tr>
<td>input_amp</td>
<td>Maximum value of the input signal.</td>
</tr>
<tr>
<td>output_amp</td>
<td>The output value will switch between output_amp, 0 and -output_amp.</td>
</tr>
</tbody>
</table>

**SignalLimiter-RateLimit**

**Library**
Signal\Block Diagram Non-Linear

**Use**

**Description**
This model limits the input signal to a minimum and maximum rate.

\[
d_{output}/dt = d_{input}/dt; \ (minimum < d_{input}/dt < maximum) \\
d_{output}/dt = minimum; \ (d_{input}/dt < minimum) \\
output = maximum \ (d_{input}/dt > maximum)
\]
En example is shown below where a sinusoidal input signal is limited to a maximum rate of 0.4 and a minimum rate of -0.8.

The rate limiter uses a first order filter to approximate the derivative of the input. Below the cut-off frequency $f_l$ the approximation is accurate and the model behaves as a rate limiter. Above the cut-off frequency $f_l$ the model output weakens to zero. For high values of the cut-off frequency $f_l$, the model will slow down simulation because it forces the integration method to take very small time-steps. A good trade-off for most models is a starting value of 100 [Hz].

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum</td>
<td>Minimum rate of the output.</td>
</tr>
<tr>
<td>maximum</td>
<td>Maximum rate of the output.</td>
</tr>
<tr>
<td>$f_l$</td>
<td>Cut-off frequency [Hz]</td>
</tr>
</tbody>
</table>

**SignalLimiter-Relay**

**Library**

Signal\Block Diagram Non-Linear

**Use**

**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.
Description
The output signal of this submodel switches between a max and a min parameter using the sign of the input signal.

\[
\begin{align*}
    output &= \text{minimum; } (input < 0) \\
    output &= \text{maximum; } (input \geq 0)
\end{align*}
\]

Interface

Inputs
input

Outputs
output

Parameters
minimum Minimum value of the output.
maximum Maximum value of the output.
SignalLimiter-RelayHysteresis

Library
Signal\Block Diagram Non-Linear

Use

Description
The output signal of this submodel switches between max and min parameters, depending on the sign of the input signal, with hysteresis and dead zone applied.

![Relay with Hysteresis](image)

Interface

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum</td>
</tr>
<tr>
<td>maximum</td>
</tr>
<tr>
<td>zone</td>
</tr>
<tr>
<td>hysteresis</td>
</tr>
</tbody>
</table>
**switch-Break**

**Library**
Signal\Block Diagram Non-Linear

**Use**
**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model switches between zero and the input signal, depending on the value of a condition input signal.

\[
\text{output} = 0; \quad (\text{condition} > 0) \\
\text{output} = \text{input}; \quad (\text{condition} \leq 0)
\]

**Interface**

**Inputs**
- input_high
- input_low
- condition: Switching condition

**Outputs**
- output

---

**Switch-Default**

**Library**
Signal\Block Diagram Non-Linear

**Use**
**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model switches between two input signals, depending on the value of a third input signal.

\[
\text{output} = \text{input}\_\text{high}; \quad (\text{condition} \geq 0) \\
\text{output} = \text{input}\_\text{low}; \quad (\text{condition} < 0)
\]

**Interface**

**Inputs**
- input_high
- input_low
### Switch-Make

**Library**
Signal/Block Diagram Non-Linear

**Use**

**Description**
This model switches between the input signal and zero, depending on the value of a condition input signal.

\[
\begin{align*}
\text{output} &= \text{input}; \ (\text{condition} > 0) \\
\text{output} &= 0; \ (\text{condition} \leq 0)
\end{align*}
\]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input_high</td>
<td></td>
</tr>
<tr>
<td>input_low</td>
<td></td>
</tr>
<tr>
<td>condition</td>
<td>Switching condition</td>
</tr>
</tbody>
</table>

**Outputs**
output

---

### Switch-Maximum

**Library**
Signal/Block Diagram Non-Linear

**Use**

**Description**
This model yields the maximum of two input signals.
Switch-Minimum

Library
Signal/Block Diagram Non-Linear

Use

Description
This model yields the minimum of two input signals.

\[
\begin{align*}
    \text{output} &= \text{input1}; \ (\text{input1} \leq \text{input2}) \\
    \text{output} &= \text{input2}; \ (\text{input1} > \text{input2})
\end{align*}
\]

Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1</td>
<td></td>
</tr>
<tr>
<td>input2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>
11.3.3 Control

Controlled Linear Systems

ControlledLinearSystem

Library
Signal\Control\Controlled Linear Systems

Use

Description
This is a masked model which opens the Controller Design Editor when edited. Using this editor the settings for a controlled linear system can be entered.

Depending on the choices made, various inputs and outputs are available. In the picture above, the most complex model is shown. Read more about it in the Controller Design Editor topic.

Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>Controller setpoint</td>
</tr>
<tr>
<td>d</td>
<td>Output Disturbance</td>
</tr>
<tr>
<td>n</td>
<td>Measurement Disturbance</td>
</tr>
<tr>
<td>di</td>
<td>Input Disturbance</td>
</tr>
<tr>
<td>uff</td>
<td>Feedforward Input</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>Plant output</td>
</tr>
<tr>
<td>uc</td>
<td>Feedforward Error Signal</td>
</tr>
</tbody>
</table>

Parameters
The parameters and initial values of this model are hidden for the user. Use the Controller Design Editor to edit this model (select the model and choose Go Down).

**ControlledSystem**

**Library**
Signal\Control\Controlled Linear Systems

**Implementations**
rz
rzff
rzffn
rzffnd
rzffnddi
rz
rznd
rznddi

**Use**

**Description - rz**
This model represents a controlled linear system described by graphically connected Linear systems:

![Diagram of a controlled linear system](image)

These Linear Systems (F,C,P and M) can be edited using the Linear Systems Editor or replaced by drag and drop (any desired model) giving maximum flexibility.

**Interface - rz**

**Inputs**

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>Controller setpoint</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Output</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>Plant output</td>
</tr>
</tbody>
</table>

**Parameters**

Depends on the implementation of the submodels.
### Description - rzff

This model represents a controlled linear system described by graphically connected Linear systems:

![Diagram of rzff model](image)

These Linear Systems (F,C,P and M) can be edited using the Linear Systems Editor or replaced by drag and drop (any desired model) giving maximum flexibility.

#### Interface - rzff

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>Controller setpoint</td>
</tr>
<tr>
<td>uff</td>
<td>Feedforward Input</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>Plant output</td>
</tr>
<tr>
<td>uc</td>
<td>Feedforward Error Signal</td>
</tr>
</tbody>
</table>

#### Parameters

Depends on the implementation of the submodels.

### Description - rzffn

This model represents a controlled linear system described by graphically connected Linear systems:

![Diagram of rzffn model](image)

These Linear Systems (F,C,P and M) can be edited using the Linear Systems Editor or replaced by drag and drop (any desired model) giving maximum flexibility.

#### Interface - rzffn

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td></td>
</tr>
<tr>
<td>uff</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td></td>
</tr>
<tr>
<td>uc</td>
<td></td>
</tr>
</tbody>
</table>
11. Library

| r    | Controller setpoint |
| n    | Measurement Disturbance |
| uff  | Feedforward Input |

Outputs

| Description |
| z           | Plant output       |
| uc          | Feedforward Error Signal |

Parameters

Depends on the implementation of the submodels.

Description - rzffnd

This model represents a controlled linear system described by graphically connected Linear systems:

These Linear Systems (F,C,P and M) can be edited using the Linear Systems Editor or replaced by drag and drop (any desired model) giving maximum flexibility.

Interface - rzffnd

Inputs

| Description |
| r           | Controller setpoint |
| d           | Output Disturbance  |
| n           | Measurement Disturbance |
| uff         | Feedforward Input   |

Outputs

| Description |
| z           | Plant output       |
| uc          | Feedforward Error Signal |

Parameters

Depends on the implementation of the submodels.

Description-rzffndddi

This model represents a controlled linear system described by graphically connected Linear systems:
These Linear Systems (F,C,P and M) can be edited using the Linear Systems Editor or replaced by drag and drop (any desired model) giving maximum flexibility.

**Interface-rzffnddi**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
</tr>
<tr>
<td>d</td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>di</td>
</tr>
<tr>
<td>uff</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
</tr>
<tr>
<td>uc</td>
</tr>
</tbody>
</table>

**Parameters**

Depends on the implementation of the submodels.

**Description - rzn**

This model represents a controlled linear system described by graphically connected Linear systems:

These Linear Systems (F,C,P and M) can be edited using the Linear Systems Editor or replaced by drag and drop (any desired model) giving maximum flexibility.

**Interface - rzn**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
</tr>
</tbody>
</table>
### n
- Measurement Disturbance

**Outputs**
- **Description**

**z**
- Plant output

**Parameters**
- Depends on the implementation of the submodels.

**Description - rznd**
This model represents a controlled linear system described by graphically connected Linear systems:

![Diagram](attachment:image.png)

These Linear Systems (F,C,P and M) can be edited using the Linear Systems Editor or replaced by drag and drop (any desired model) giving maximum flexibility.

**Interface - rznd**

**Inputs**
- **Description**
  - **r**
  - Controller setpoint

- **d**
  - Output Disturbance

- **n**
  - Measurement Disturbance

**Outputs**
- **Description**

**z**
- Plant output

**Parameters**
- Depends on the implementation of the submodels.

**Description - rznddi**
This model represents a controlled linear system described by graphically connected Linear systems:
These Linear Systems (F,C,P and M) can be edited using the Linear Systems Editor or replaced by drag and drop (any desired model) giving maximum flexibility.

**Interface - rznddi**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>Controller setpoint</td>
</tr>
<tr>
<td>d</td>
<td>Output Disturbance</td>
</tr>
<tr>
<td>n</td>
<td>Measurement Disturbance</td>
</tr>
<tr>
<td>di</td>
<td>Input Disturbance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>Plant output</td>
</tr>
</tbody>
</table>

**Parameters**

Depends on the implementation of the submodels.

---

**Neural Networks**

**BSplineNetwork**

**Library**

Signal\Control\Neural Networks

**Use**


**Description**

This is a masked model which opens the BSpline Editor when edited. Using this editor the settings for a B-Spline Network can be entered.

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>any</td>
<td>The user can defined any input.</td>
</tr>
</tbody>
</table>
error

The error signal: the difference between the desired output and the network output.

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>The network output</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>learning_rate</td>
<td>The learning rate</td>
</tr>
<tr>
<td>network_order</td>
<td>The order of the spline-interpolation.</td>
</tr>
<tr>
<td>online_learning</td>
<td>A boolean: Learn at each sample (True) or Learn after Leaving Spline (False).</td>
</tr>
<tr>
<td>regularization</td>
<td>Not yet supported.</td>
</tr>
<tr>
<td>regularization_width</td>
<td>Not yet supported.</td>
</tr>
<tr>
<td>load_weights</td>
<td>A boolean: Load weights before simulation.</td>
</tr>
<tr>
<td>save_weights</td>
<td>A boolean: Save weights after simulation.</td>
</tr>
</tbody>
</table>

**MLPNetwork**

**Library**

Signal\Control\Neural Networks

**Use**

Domains: Continuous, Discrete. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This is a masked model which opens the MLP Editor when edited. Using this editor the settings for a MLP Network can be entered.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>any</td>
<td>The user can defined any network input.</td>
</tr>
<tr>
<td>error</td>
<td>The error signal: the difference between the desired output and the network output.</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>any</td>
<td>The user can defined any network output.</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>nr_hidden</td>
<td>Number of hidden neurons.</td>
</tr>
<tr>
<td>learning_rate</td>
<td>The learning rate.</td>
</tr>
<tr>
<td>readWeights</td>
<td>A boolean: Load weights before simulation.</td>
</tr>
<tr>
<td>writeWeights</td>
<td>A boolean: Save weights after simulation.</td>
</tr>
</tbody>
</table>
PID Control

PIDControl

PID control stands for Proportional, Integral and Derivative control. PID controllers have been around since about 1940. Modern controllers perform the same functions as those, perhaps with a few embellishments and certainly more accurately, but the same functions nonetheless.

PID controllers are the best general purpose controllers to do the job. More sophisticated control algorithms will produce better performance when fitted to a specific process, but poorer performance results if the process changes. This sensitivity to process changes is called robustness, with more robust being less sensitive. The PID algorithm is an excellent trade-off between robustness and performance.

Although theory on PID-controllers is widespread and more or less uniform nowadays, in practice there are many algorithms and parameter settings. The 20-sim Control library, supports the most common algorithms.

Setpoint and other Variables

A standard control loop is shown in the figure below. A controller tries to steer a process in a way that minimizes the difference between a given setpoint and the output of that process. In other words, the controller tries to get the process output as close as possible to the given setpoint.

Setpoint

The setpoint (SP) is where the process output should match. It can be a static value (e.g. the desired temperature of a room) or a varying value (e.g. the desired position of a robot-tip).

The setpoint is where you would like the measurement to be. Error is defined as the difference between set-point and measurement.

Process

The process is the system that should be controlled. It is sometimes referred to as plant or system. The process should have has at least one impute to control its behavior and at least one output that is a measure of its behavior. Consider for example a gas heated house as process. The heater feed could be the process input and the measured room temperature the process output.
The process input is connected to the controller output or controller variable (CV). It is mostly the input for an actuator that can drive the process to a desired setpoint.

The process output is commonly known as process variable (PV), or measured variable (MV). Other names of the process output are system output and measurement.

**Error**

The error is defined as the setpoint minus the process output. It is a measure for how much the process deviates from the desired setpoint, and thus how much the controller should respond to get the process back to the desired setpoint.

**Setpoint Weighting**

For many controllers the controller input is equal to the error signal. Some controllers, however, use specialized inputs for their proportional, integral and derivative parts (setpoint weighting). They have two inputs, one for the setpoint and one for the measured variable and are therefore also described as 2-DOF controllers.

**Proportional Control**

**Gain**

When we talk about the proportional action of a controller, we generally refer to the proportional gain. The action means that the controller moves in proportion to the error between setpoint (SP) and process output (PV):

\[
\text{controller output} = K \times \text{error} = K \times (SP - PV)
\]

where the gain is denoted by the parameter K. Many terms have been used by different manufacturers to designate this action. It has been called proportional gain, gain, throttling band, sensitivity and proportional band.

**Proportional Band**

In practice, the controller output is limited, either by its own limitations or by the limitations of the corresponding actuator. Let \( u_{\text{max}} \) and \( u_{\text{min}} \) denote the minimum and maximum output of the controller. The proportional band of the controller is then defined as:

\[
P_B = \frac{u_{\text{max}} - u_{\text{min}}}{K} \times 100\%
\]

In the ideal case, a controller can have an unlimited output. The proportional band (PB) is then defined as:

\[
P_B = \frac{1}{K} \times 100\%
\]

This definition of proportional band is often used instead of the controller gain. The value is expressed in percent (%).
Direct Acting / Reverse Acting

Suppose a process with a controller output CV and a process output PV is in steady state and kept to a certain setpoint SP. For proportional control the following equations can be found:

\[
\begin{align*}
PV &= P(CO) \\
CV &= K*error = K*(SP - PV)
\end{align*}
\]

where \( P \) is the process function that yields a measured variable as a result of the controller output. If the controller output decreases as the measured variable increases the controller is said to be direct acting. If the controller output increases as the measured variable increases, then it is called reverse acting. In other words, the controller is direct acting if the gain \( K \) is positive and reverse acting if the gain \( K \) is negative.

This is not only valid for proportional control, but for all PID controllers in the 20-sim library. If you need a reverse acting controller, simply use a negative gain.

Offset

If you look at the equation for the proportional gain:

\[
CV = K*error = K*(SP - PV)
\]

you will notice that there has to be an error to produce a controller output. This means that with proportional control only, there will always be a small offset between the setpoint and the measured variable. To remove this offset, integral control has to be used.

Integral Control

With integral action, the controller output is proportional to the amount of time the error is present. Integral action eliminates offset that remains when proportional control is used.

controller output = \((1/Ti)*\text{int}(error)\)

where the parameter \( Ti \) is called the integral time. Integral action is also know as reset and the parameter \( Ti \) as reset time.

Integral action gives the controller a large gain at low frequencies that results in eliminating offset. Integrals give information concerning the past. That is why integrals are always late. Integrals provide stability but have a tendency to get stuck in the past. In most controllers the proportional and integral action are combined. The output of the combined proportional and integral action (in s-domain) is then:

\[
U = K \cdot \left(1 + \frac{1}{s \cdot Ti}\right) \cdot E
\]

with \( E \) equal to \( SP - PV \).
**Derivative Control**

With derivative action, the controller output is proportional to the rate of change of the measurement or error. Some manufacturers use the term rate or pre-act instead of derivative. Derivative, rate and pre-act are the same thing. The controller output is calculated by the rate of change of the error with time.

\[
\text{controller output} = Td \times \frac{d(error)}{dt} = Td \times \frac{d(SP - PV)}{dt}
\]

where the parameter \( Td \) is called **derivative time**. Derivative control is mathematically the opposite of integral action, but while we might have an integral-only controller, we would never have a derivative-only controller. The reason for this is that derivative control only knows the error is changing. It does not know what the setpoint actually is.

Derivative action has the potential to improve performance when sudden changes in measured variable occur, but is should be used with care. It is mostly a matter of using enough, not too much.

**Derivative Gain Limitation**

In most commercial processes sudden changes in process output may appear. In most cases a sudden change in the slope of such a process output cannot be avoided at all times. Using such a process output in controllers with pure derivative action, would lead to unwanted steps in the controller output. Moreover, high frequency noise in the measured signals may lead to unwanted large outputs of the controller.

To prevent this unwanted effect, the derivative action can be filtered by a first-order system with time constant \( Td/N \).

\[
s \cdot K \cdot Td \rightarrow \frac{s \cdot K \cdot Td}{1 + s \cdot \frac{Td}{N}}
\]

This approximation acts as a derivative for low-frequency signal components. The gain, however, is limited to \( K*N \). This means that high-frequency measurement noise is amplified at most by a factor \( KN \). This is why the parameter \( N \) is called the **derivative gain limitation**. Typical values of \( N \) are 8 to 20. Sometimes the reciprocal value of \( N \) is used, mostly with the name beta (\( \beta = 1/N \)).

**PID Controller Types**

In literature various PID controller laws and types have been described. In industry two types prevail: the parallel form and the series form.

**Parallel Form**

A PID controller in parallel form (also known as standard form, ISA form or non-interacting form), has the control equation:
Series Form
A PID controller in series form (also known as interacting form), has the control equation:

\[ U = K \cdot \left(1 + \frac{1}{s \cdot Ti} + s \cdot Td\right) \cdot E \]

The controller actions (P, I and D) act dependently as can be seen in the corresponding block diagram representation.

Note
P and PI controllers are the same in series and parallel form.

Setpoint Weighting
Standard PID controller equations operate on the error signal (Error Based):

- \( P \) – action: \( E_P = SP - PV \)
- \( I \) – action: \( E_I = SP - PV \)
- \( D \) – action: \( E_D = SP - PV \)

A more flexible structure is obtained by treating the setpoint (SP) and the process output (PV) separately (Setpoint Weighting):
The I-action always operates on the error to insure that the error between setpoint and process output will be minimized.

In most commercial controllers, the parameters b and c are chosen 1 or 0:

- $b = 1 \rightarrow$ proportional control using the error: $SP - PV$ (error feedback).
- $b = 0 \rightarrow$ only proportional control on the process output ($PV$).
- $c = 1 \rightarrow$ derivative control using the error: $SP - PV$ (error feedback).
- $c = 0 \rightarrow$ only derivative control on the process output ($PV$).

**Anti-Windup**

All actuators have physical limitations, a control valve cannot be more than fully open or fully closed, a motor has limited velocity, etc. This has severe consequences for control. Integral action in a PID controller is an unstable mode. This does not cause any difficulties when the loop is closed. The feedback loop will, however, be broken when the actuator saturates because the output of the saturating element is then not influenced by its input. The unstable mode in the controller may then drift to very large values. When the actuator desaturates it may then take a long time for the system to recover. It may also happen that the actuator bounces several time between high and low values before the system recovers.

**Integrator windup**

Integrator windup is illustrated in the figure below, which shows simulation of a system where the process dynamics is a saturation at a level of ±0.1 followed by a linear system with the transfer function:

$$G(s) = \frac{1}{s(s + 1)} \cdot x$$
Because of the saturation in the actuator, the control signal saturates immediately when the step is applied. The control signal then remains in saturation level and the feedback is broken. The integral part continues to increase because the error (SP - PV) is positive. The integral part starts to decrease when the process output (PV) has become larger than the setpoint (SP), but the process output remains saturated because of the large integral part. Slowly the process output decreases towards the setpoint.

The net effect is that there is a large overshoot. This phenomenon is called "integrator windup". A good insight in windup is found when looking at the proportional band.

**Proportional Band and Windup**

The values of the process output that correspond to the minimum and maximum output are denoted as ymax and ymin. The controller operates linearly only if the process output is in the range (ymax, ymin). The controller output saturates when the process output is outside this band. A good insight into the windup problem is obtained by investigating the range (ymax, ymin). All 20-sim controller models in parallel form with anti-windup scheme, have the extra variables PB_high and PB_low which are equal to ymax and ymin.

An illustration of the proportional band is given below. The same linear system is used with the same controller. As can be seen, the actuator is saturated from t = 0 until t = 14. At t = 14 the process output enters the range (PB_high, PB_low) and controller feedback is regained.
Anti-Windup

Integrator windup can be avoided, by making sure that the integral is kept to a proper value when the actuator saturates, so that the controller is ready to resume action, as soon as the control error changes. This anti-windup scheme is known as tracking or back calculation.

parallel form

As well known form of tracking is linear feedback anti windup. It is shown in the figure below (parallel form). The actuator is represented by a signal limiter. The difference between actuator input and output (TR) is fed back to the integrator through the gain $1/Ta$. As soon as the limiter saturates, this signal becomes non-zero and prevents the integrator from winding up. The tracking time constant $Ta$ can be used to tune the amount of anti windup.
The same scheme can also be used for controllers with a series form. A diagram is shown below.

**Tracking Time constant**
To prevent the integrator from saturating, the tracking time constant must be chosen small. Too small values, however decrease the controller performance. As a rule of thumb Åström suggested to choose the tracking time constant $T_d \leq T_a \leq T_i$. Some authors prefer a good controller performance and suggest to choose $T_a = T_i$.

**External Tracking**
As long as the actuator output is equal to the controller output, anti-windup scheme will not be activated and the controller is in normal operation (*control mode*). When the actuator saturates, the anti-windup scheme will be activated and prevent the controller output from wandering away. In effect the anti-windup scheme matches the controller output and actuator output. This is why the actuator output is also known as the tracking signal (TR).
When an external actuator signal is used (external tracking signal) is is important to compensate for the actuator gain. Otherwise the tracking signal is not equal to the controller output, during normal operation and the anti-windup scheme is activated.

**Actuator Model**

Anti-windup schemes are based on the difference between actuator input (controller output) and actuator output. These signals are not always available. Therefore an actuator model can be used inside the controller to yield this difference. In the library models, a signal limiter is used the actuator model:

- \( \text{output} = \text{minimum}; \ (\text{input} < \text{minimum}) \)
- \( \text{output} = \text{input}; \ (\text{minimum} \leq \text{input} \leq \text{maximum}) \)
- \( \text{output} = \text{maximum}; \ (\text{input} > \text{maximum}) \)
Initial Output

The output of PID controllers at time 0 depends on the given setpoint (SP), process output (PV) and control law. In general the process will not be at rest (PV <> 0) and the setpoint will not be equal to the process output (SP <> 0). This will result in an undesired step in the controller signal at startup. Even if the setpoint is equal to the process output (SP = PV) at startup, the use of setpoint weighting may result in a step in the control signal:

\[
P\text{-action: } E_p = b \cdot SP - PV \\
I\text{-action: } E_I = SP - PV \\
D\text{-action: } E_D = c \cdot SP - PV
\]

Let PV be a non-zero value and b or c equal to zero. The P or D -action will then lead to a step in the control signal.

To avoid such a step, the initial output of some PID-controllers can be set to any value. The slope of the the control output of these controllers at startup is equal to zero.

Initial output for with delays

Controllers with manual output at start-up, use the process output at t = 0, PV(0), to calculate an internal offset that compensates for the initial controller output. Care should be taken when delays are available between the process output and the controller input. Due to these, the measured process output at t = 0 in the controller ( PV(0)' ) may not be the same as the real process output at t = 0 ( PV(0) ). As a result, a wrong offset will be calculated and the initial output will not have the desired value. To avoid this, all initial values of delay elements between the process and controller should be chosen properly (e.g. equal to the initial process output)!

Commercial Controllers

According to b Åström the table below summarizes the properties of some commercial controllers.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Structure</th>
<th>Setpoint Weighting b</th>
<th>Setpoint Weighting c</th>
<th>Derivative Gain Limitation N</th>
<th>Sampling Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Allen Bradley PLC 5</td>
<td>P</td>
<td>1.0</td>
<td>1.0</td>
<td>None</td>
<td>Load dependent</td>
</tr>
<tr>
<td>2. Bailey Net 90</td>
<td>P</td>
<td>0.0 or 1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.25</td>
</tr>
<tr>
<td>3. Fisher Controls Provox</td>
<td>S</td>
<td>0.0</td>
<td>0.0</td>
<td>None</td>
<td>0.1, 0.25 or 1.0</td>
</tr>
<tr>
<td>4. Fisher Controls DPR</td>
<td>S</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>900,910</td>
<td>S</td>
<td>0.0</td>
<td>0.0 or 1.0</td>
<td>0.0</td>
<td>0.25</td>
</tr>
<tr>
<td>5. Fisher Porter Micro DCI</td>
<td>S</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.33, 0.5 or 1.0</td>
</tr>
<tr>
<td>6. Foxboro Model 761</td>
<td>S</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.25</td>
</tr>
<tr>
<td>7. Honeywell TDC</td>
<td>S</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.33, 0.5 or 1.0</td>
</tr>
<tr>
<td>8. Moore Products Type 352</td>
<td>S</td>
<td>0.0 or 1.0</td>
<td>1.0</td>
<td>3.3 – 10</td>
<td>0.2</td>
</tr>
<tr>
<td>9. Alfa Laval ECA40, ECA 400</td>
<td>S</td>
<td>1.0</td>
<td>0.0</td>
<td>17 or 20</td>
<td>0.036 – 1.56</td>
</tr>
</tbody>
</table>
Continuous

Naming Conventions

Two types of PID-controllers are available in this library. The first type of controllers use an error input and the second type of controllers use separate Setpoint (SP) and Measured Variable (MV) input.

Error Input

PID-Controllers with the error as a direct input signal, are all in series form. The name simply denotes the type of controller: P, PI, PD or PID. Two versions of each controller exists: continuous time and discrete time. They can be found in the subdirectories Continuous and Discrete.

Ports

All controllers have one input ports and one output port:

1. error: The error between setpoint and measured variable.
2. output: The controller output.

Parameters

Depending on the type of controller, the following parameters can be used:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 or 1.0</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>0.0 or 1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Literature


Expert information can also be found in the sci.eng.control newsgroup. An excellent frequently asked questions list can be found on the internet pages of Ron Graham (http://www.tcnj.edu/~rgraham/PID-tuning.html).
1. $kd$: The proportional gain of the controller.
2. $tauD$: The derivative time constant.
3. $beta$: The reciprocal derivative gain limitation.
4. $tauI$: The integral time constant.

**Controller Wizard**
A special form of controllers with error input is generated by the ControllerWizard.emx submodel. When you select this model and click **Go Down** the Filter Editor is opened, allowing you to specify controllers with frequency oriented parameters.

**Separate Input**
Controllers with separate inputs come in many forms. The naming denotes the type of controller and the options that are available. The type and options are also available in the model icons.

1. Two versions of each controller exists: continuous time and discrete time. They can be found in the subdirectories *Continuous* and *Discrete*. Continuous-time controllers have icons with blue text and discrete-time controllers have icons with green text.
2. The first characters denote the type of controller: $P$, $PD$, $PI$ or $PID$.
3. The character $p$ or $s$ denote the form: parallel ($p$) or series ($s$).
4. If setpoint weighting is used, the term $sp$ is added.
5. If an anti-windup scheme is incorporated, the term $aw$ is added.
6. If the output at startup can be set manually, the term $u0$ is added.
7. If an external tracking signal is used, the term $tr$ is added.

**Ports**
All controllers have two inputs ports and one output port:
1. *SP*: The setpoint
2. *MV*: The measured variable (also called process variable).
3. *output*: The controller output.

**Parameters**
Depending on the type of controllers, the following parameters can be used:
1. *K*: The proportional gain of the controller.
2. *Td*: The derivative time constant.
5. *b*: The setpoint weighting constant for the proportional part of the controller.
6. *c*: The setpoint weighting constant for the derivative part of the controller.
7. *Ta*: The tracking time constant of the anti-windup scheme.
8. *minimum*: The minimum controller output representing actuator saturation.
10. *output_initial*: The controller output at start-up.

**Initial Values**
Although most controllers have one or more internal states, the initial values of these states do not need to be set manually. You use the default values (0) at the start of a simulation. To get a desired output of the controller at startup, the parameter *output_initial* should be used.

**Discrete Controllers**
The discrete controllers that are available in the library are directly derived from their continuous counterparts, using approximation by backward differences. These discrete models have identical behavior, as long as the sample time is not chosen too low. Discrete loops in 20-sim are automatically detected and assigned a default sample time. You can change the sample time in the Run Properties Editor (in the Properties menu select the Simulation command).

**Variables**
Some PID controllers (parallel form with anti-windup) have two internal variables that are of interest. *PB_high* and *PB_low*. These parameters are the upper and lower bound of the proportional band.
**Controller Use**

All controllers must can be used as shown in the figure below. The upper part shows a continuous time controller and the bottom part shows a discrete time controller.

**Error Input**

1. An error signal is generated with a plus minus element. Its serves as an input of the controller.

2. The controller output is connected with the process input.

As shown in the figure, analog to digital convertors and digital to analog convertors should be used, when connecting a discrete-time controller to a continuous-time process.

**Separate Input**

1. A setpoint signal is connected with the **SP** port of the controller.

2. The process output is connected with the **PV** port of the controller.

3. The controller output is connected with the process input.

As shown in the figure, analog to digital convertors and digital to analog convertors should be used, when connecting a discrete-time controller to a continuous-time process.
**ControllerWizard**

**Library**
Signal\Control\PID Control\Continuous

**Use**

**Description**
A special form of controllers with error input is generated by the ControllerWizard.emx submodel. When you select this model and click Go Down the Filter Editor is opened, allowing you to specify controllers with frequency oriented parameters.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
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<tbody>
<tr>
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</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>y</td>
</tr>
</tbody>
</table>

**Parameters**
Look in the Filter Editor helpfile to find a detailed description of the possible controller types and their parameters.

**Controller-P**

**Library**
Signal\Control\PID Control\Continuous

**Use**

**Description**
This is a P controller. The output of this controller (in s-domain) is:

\[ U = K \cdot E \]

with E equal to SP - PV.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>PV</td>
</tr>
</tbody>
</table>

Setpoint.
Process output.
Outputs
CV
Controller output: input for the process.

Parameters
K
Proportional gain.

Controller-PD_p

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PD controller in parallel form. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( 1 + \frac{s \cdot T_d}{1 + s \cdot N} \right) \cdot E \]

with E equal to SP - MV.

Interface

Inputs
SP
Setpoint.

MV
Measured variable or process output.

Outputs
output
Controller output: input for the process.

Parameters
K
Proportional gain.

Td
Derivative time constant (Td > 0).

N
Derivative gain limitation.

Initial Values
yes
Should be left default!
Controller-PD_s

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PD controller in series form. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( \frac{1 + s \cdot T_d}{1 + s \cdot \frac{T_d}{N}} \right) \cdot E \]

with E equal to SP - MV.

Interface

Inputs          Description
SP              Setpoint.
MV              Measured variable or process output.

Outputs
output          Controller output: input for the process.

Parameters
K               Proportional gain.
Td              Derivative time constant (Td > 0).
N               Derivative gain limitation.

Initial Values
yes             Should be left default!

Controller-PI

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PI controller. The output of this controller (in s-domain) is:
\[ U = K \cdot \left(1 + \frac{1}{s \cdot T_i}\right) \cdot E \]

with \( E \) equal to \( SP - MV \).

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SP</strong></td>
</tr>
<tr>
<td><strong>MV</strong></td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>output</strong></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>K</strong></td>
</tr>
<tr>
<td><strong>Ti</strong></td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>yes</strong></td>
</tr>
</tbody>
</table>

**Controller-PI_sp**

**Library**

Signal\Control\PID Control\Continuous

**Use**

**Domains**: Continuous, Discrete. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This is a PI controller with setpoint weighting. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( \left(b \cdot SP - MV\right) + \frac{1}{s \cdot T_i} \cdot (SP - MV) \right) \]

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SP</strong></td>
</tr>
<tr>
<td><strong>MV</strong></td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>output</strong></td>
</tr>
</tbody>
</table>
**Parameters**

- **K**  
  Proportional gain.
- **Ti**  
  Integral time constant \((Ti > 0)\).
- **b**  
  Proportional setpoint weighting parameter.

**Initial Values**

- **yes**  
  Should be left default!

---

**Controller-PI_sp_aw**

**Library**

- Signal\Control\PID Control\Continuous

**Use**

- **Domains**: Continuous, Discrete.  
  **Size**: 1-D.  
  **Kind**: Block Diagrams.

**Description**

This is a PI controller with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \cdot \left( b \cdot (SP - MV) + \frac{1}{s \cdot Ti} \cdot (SP - MV) \right)
\]

An anti-windup scheme has been added to this controller.

**Interface**

**Inputs**

- **SP**  
  Setpoint.
- **MV**  
  Measured variable or process output.

**Outputs**

- **output**  
  Controller output: input for the process.

**Parameters**

- **K**  
  Proportional gain.
- **Ti**  
  Integral time constant \((Ti > 0)\).
- **b**  
  Proportional setpoint weighting parameter.
- **Ta**  
  Tracking time constant.
- **minimum**  
  Minimum controller output.
- **maximum**  
  Maximum controller output.
Initial Values

yes Should be left default!

Interesting Variables

PB_high, PB_low Upper and lower bound of the proportional band.

Controller-PI_sp_aw_u0

Library

Signal\Control\PID Control\Continuous

Use


Description

This is a PI controller with setpoint weighting. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( b \cdot SP - MV \right) + \frac{1}{s \cdot Ti} \cdot (SP - MV) \]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up.

Interface

Inputs Description

SP Setpoint.

MV Measured variable or process output.

Outputs

output Controller output: input for the process.

Parameters

K Proportional gain.

Ti Integral time constant (Ti > 0).

b Proportional setpoint weighting parameter.

Ta Tracking time constant.

minimum Minimum controller output.

maximum Maximum controller output.

output_initial The controller output at start-up.

Initial Values

yes Should be left default!

Interesting Variables
Controller-PI_sp_aw_u0_tr

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PI controller with setpoint weighting. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( b \cdot (SP - MV) + \frac{1}{s \cdot Ti} \cdot (SP - MV) \right) \]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up. An external tracking signal must be supplied to activate the anti-windup scheme.

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
<tr>
<td>TR</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>Ta</td>
</tr>
<tr>
<td>output_initial</td>
</tr>
</tbody>
</table>

Initial Values

yes Should be left default!

Interesting Variables

PB_high, PB_low Upper and lower bound of the proportional band.
Controller-PID_p

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PID controller in parallel form. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( 1 + \frac{1}{s \cdot Ti} + \frac{s \cdot Td}{1 + s \cdot \frac{Td}{N}} \right) \cdot E \]

with E equal to SP - MV.

Interface

Inputs
<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
</tbody>
</table>

Outputs
<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Parameters
<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Td</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Ti</td>
</tr>
</tbody>
</table>

Initial Values
<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
</tr>
</tbody>
</table>
**Controller-PID_p_sp.**

**Library**
Signal\Control\PID Control\Continuous

**Use**
**Domains:** Continuous, Discrete. **Size:** 1-D. **Kind:** Block Diagrams.

**Description**
This is a PID controller in parallel form with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \cdot \left( (b \cdot SP - MV) + \frac{1}{s \cdot Ti} \cdot (SP - MV) + \frac{s \cdot Td}{1 + s \cdot \frac{Td}{N}} \cdot (c \cdot SP - MV) \right)
\]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>Setpoint.</td>
</tr>
<tr>
<td>MV</td>
<td>Measured variable or process output.</td>
</tr>
</tbody>
</table>

**Outputs**
output  Controller output: input for the process.

**Parameters**
K  Proportional gain.
Td  Derivative time constant (Td > 0).
N  Derivative gain limitation.
Ti  Integral time constant (Ti > 0).
b  Proportional setpoint weighting parameter.
c  Derivative setpoint weighting parameter.

**Initial Values**
yes  Should be left default!

**Interesting Variables**
PB_high, PB_low  Upper and lower bound of the proportional band.
**Controller-PID_p_sp_aw**

**Library**
Signal\Control\PID Control\Continuous

**Use**

**Description**
This is a PID controller in parallel form with setpoint weighting. The output of this controller (in s-domain) is:

\[ U = K \left( b \cdot SP - MV \right) + \frac{1}{s \cdot Ti} \cdot (SP - MV) + \frac{s \cdot Td}{1 + s \cdot \frac{Td}{N}} \cdot (c \cdot SP - MV) \]

An anti-windup scheme has been added to this controller.

**Interface**

**Inputs**
- **SP**: Setpoint.
- **MV**: Measured variable or process output.

**Outputs**
- **output**: Controller output: input for the process.

**Parameters**
- **K**: Proportional gain.
- **Td**: Derivative time constant (Td > 0).
- **N**: Derivative gain limitation.
- **Ti**: Integral time constant (Ti > 0).
- **b**: Proportional setpoint weighting parameter.
- **c**: Derivative setpoint weighting parameter.
- **Ta**: Tracking time constant.
- **minimum**: Minimum controller output.
- **maximum**: Maximum controller output.

**Initial Values**
- **yes**: Should be left default!

**Interesting Variables**
- **PB_high, PB_low**: Upper and lower bound of the proportional band.
Controller-PID_p_sp_aw_u0

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PID controller in parallel form with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \cdot \left( b \cdot SP - MV \right) + \frac{1}{s \cdot Ti} \cdot (SP - MV) + \frac{s \cdot Td}{1 + s \cdot \frac{Td}{N}} \cdot (c \cdot SP - MV)
\]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up.

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
</tbody>
</table>

Setpoint.
Measured variable or process output.

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Controller output: input for the process.

Parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Td</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>Ta</td>
</tr>
<tr>
<td>minimum</td>
</tr>
<tr>
<td>maximum</td>
</tr>
<tr>
<td>output_initial</td>
</tr>
</tbody>
</table>

Proportional gain.
Derivative time constant (Td > 0).
Derivative gain limitation.
Integral time constant (Ti > 0).
Proportional setpoint weighting parameter.
Derivative setpoint weighting parameter.
Tracking time constant.
Minimum controller output.
Maximum controller output.
The controller output at start-up.

Initial Values

yes

Should be left default!

Interesting Variables

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB_high, PB_low</td>
</tr>
</tbody>
</table>

Upper and lower bound of the proportional band.
Controller-PID_p_sp_aw_u0_tr

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PID controller in parallel form with setpoint weighting. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( b \cdot SP - MV \right) + \frac{1}{s \cdot Ti} \cdot (SP - MV) + \frac{s \cdot Td}{1 + s \cdot \frac{Td}{N}} \cdot (c \cdot SP - MV) \]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up. An external tracking signal must be supplied to activate the anti-windup scheme.

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setpoint.</td>
<td>SP</td>
</tr>
<tr>
<td>Measured variable or process output.</td>
<td>MV</td>
</tr>
<tr>
<td>Tracking signal.</td>
<td>TR</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller output: input for the process.</td>
<td>output</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain.</td>
<td>K</td>
</tr>
<tr>
<td>Derivative time constant (Td &gt; 0).</td>
<td>Td</td>
</tr>
<tr>
<td>Derivative gain limitation.</td>
<td>N</td>
</tr>
<tr>
<td>Integral time constant (Ti &gt; 0).</td>
<td>Ti</td>
</tr>
<tr>
<td>Proportional setpoint weighting parameter.</td>
<td>b</td>
</tr>
<tr>
<td>Derivative setpoint weighting parameter.</td>
<td>c</td>
</tr>
<tr>
<td>Tracking time constant.</td>
<td>Ta</td>
</tr>
<tr>
<td>The controller output at start-up.</td>
<td>output_initial</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
<th>Initial Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Should be left default!</td>
<td>yes</td>
</tr>
</tbody>
</table>

Interesting Variables

<table>
<thead>
<tr>
<th>Description</th>
<th>Interesting Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper and lower bound of the proportional band.</td>
<td>PB_high, PB_low</td>
</tr>
</tbody>
</table>
Controller–PID_s

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PID controller in series form. The output of this controller (in s-domain) is:

$$U = K \cdot \left(1 + \frac{1}{s \cdot T_d} \cdot \frac{1 + s \cdot T_i}{1 + s \cdot T_d} \cdot E\right)$$

with $E$ equal to $SP - MV$.

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
<th>SP</th>
<th>MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setpoint.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured variable or process output.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller output: input for the process.</td>
<td></td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>K</th>
<th>Td</th>
<th>N</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain.</td>
<td></td>
<td>Derivative time constant ($T_d &gt; 0$).</td>
<td>Derivative gain limitation.</td>
<td>Integral time constant ($T_i &gt; 0$).</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
<th>yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Should be left default!</td>
<td></td>
</tr>
</tbody>
</table>
Controller-PID_s_sp

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PID controller in series form with setpoint weighting. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( b + \frac{1}{s \cdot Ti} \right) \cdot \frac{1 + s \cdot c \cdot Td}{1 + s \cdot \frac{Td}{N}} \cdot SP - \left( 1 + \frac{1}{s \cdot Ti} \right) \frac{1 + s \cdot Td}{1 + s \cdot \frac{Td}{N}} \cdot MV \]

Interface

Inputs
- SP
- MV

Description
- Setpoint.
- Measured variable or process output.

Outputs
- output

Description
Controller output: input for the process.

Parameters
- K
- Td
- N
- Ti
- b
- c

Description
- Proportional gain.
- Derivative time constant (Td > 0).
- Derivative gain limitation.
- Integral time constant (Ti > 0).
- Proportional setpoint weighting parameter.
- Derivative setpoint weighting parameter.

Initial Values
- yes

Description
Should be left default!
Controller-PID_s_sp_aw

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PID controller in series form with setpoint weighting. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( b + \frac{1}{s \cdot Ti} \right) \cdot \frac{1 + s \cdot c \cdot Td}{1 + s} \cdot SP - \left( 1 + \frac{1}{s \cdot Ti} \right) \frac{1 + s \cdot Td}{N} \cdot MV \]

An anti-windup scheme has been added to this controller.

Interface

Inputs  
SP  
Setpoint.
MV  
Measured variable or process output.

Outputs  
output  
Controller output: input for the process.

Parameters
K  
Proportional gain.
Td  
Derivative time constant (Td > 0).
N  
Derivative gain limitation.
Ti  
Integral time constant (Ti > 0).
b  
Proportional setpoint weighting parameter.
c  
Derivative setpoint weighting parameter.
Ta  
Tracking time constant.
minimum  
Minimum controller output.
maximum  
Maximum controller output.

Initial Values
yes  
Should be left default!
Controller-PID_s_sp_aw_u0

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PID controller in series form with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \left[ \left( b + \frac{1}{s \cdot Ti} \right) \cdot \frac{1 + s \cdot c \cdot Td}{1 + s \cdot Td} \cdot SP - \left( \frac{1}{s \cdot Ti} \right) \cdot \frac{1 + s \cdot Td}{1 + s \cdot Td} \cdot MV \right]
\]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up.

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
</tbody>
</table>

Setpoint.
Measured variable or process output.

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Controller output: input for the process.

Parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Td</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>Ta</td>
</tr>
<tr>
<td>minimum</td>
</tr>
<tr>
<td>maximum</td>
</tr>
<tr>
<td>output_initial</td>
</tr>
</tbody>
</table>

Proportional gain.
Derivative time constant (Td > 0).
Derivative gain limitation.
Integral time constant (Ti > 0).
Proportional setpoint weighting parameter.
Derivative setpoint weighting parameter.
Tracking time constant.
Minimum controller output.
Maximum controller output.
The controller output at start-up.

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
</tr>
</tbody>
</table>

Should be left default!
Controller-PID_s_sp_aw_u0_tr

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PID controller in series form with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \left( b + \frac{1}{s \cdot Ti} \right) \frac{1+s \cdot c \cdot Td}{1+s \cdot Td} \cdot SP - \left( 1+ \frac{1}{s \cdot Ti} \right) \frac{1+s \cdot Td}{1+s \cdot Td} \cdot MV
\]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up. An external tracking signal must be supplied to activate the anti-windup scheme.

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
<tr>
<td>TR</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Td</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>Ta</td>
</tr>
<tr>
<td>output_initial</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
</tr>
</tbody>
</table>
P

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a P controller. The output of this controller is:

\[ output = kp \cdot error \]

with the input of the controller equal to the error and the output of the controller used as the plant input:

![Diagram of P controller](image)

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>error</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>kp</td>
</tr>
</tbody>
</table>

PD

Library
Signal\Control\PID Control\Continuous

Use

Description
This is a PD controller in series form. The transfer function of an ideal PD-controller is:
with the input of the controller equal to the error and the output of the controller used as the plant input:

\[
G(s) = \frac{kp (1 + s \cdot \tau_D)}{1 + s \cdot \beta \cdot \tau_D}
\]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>error</td>
<td>Input signal: plant-output minus set point.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>Output signal: input for the plant.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>kp</td>
<td>Proportional gain.</td>
</tr>
<tr>
<td>tauD</td>
<td>Derivative gain (tauD &lt;&gt; 0).</td>
</tr>
<tr>
<td>beta</td>
<td>Tameness constant (0 &lt; beta &lt;&lt; 1).</td>
</tr>
</tbody>
</table>

**Initial Values**

state_initial

output(0) = state_initial - kp*error(0)*/beta

**PI**

**Library**

Signal\Control\PID Control\Continuous

**Use**

**Domains**: Continuous, Discrete **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This is a PI controller. The transfer function of the controller is:

\[
G(s) = kp + \frac{kp}{s \cdot \tau_I}
\]

with the input of the controller equal to the error and the output of the controller used as the plant input:
Interface

**Inputs**

errors  
Input signal: plant-output minus set point.

**Outputs**

output  
Output signal: input for the plant.

**Parameters**

kp  
Proportional gain.

tauI  
Integral gain (tauI <> 0).

**Initial Values**

state(0)  
output(0) = state(0) - kp*error(0)

PID

**Library**

Signal\Control\PID Control\Continuous

**Use**

Domains: Continuous, Discrete  
Size: 1-D.  
Kind: Block Diagrams.

**Description**

This is a PID controller in series form. The transfer function is:

\[ G(s) = kp \cdot \left( 1 + \frac{1}{s \cdot tauI} \right) \left( \frac{1 + s \cdot tauD}{1 + s \cdot beta \cdot tauD} \right) \]

with the input of the controller equal to the error and the output of the controller used as the plant input:
Interface

**Inputs**
- error: Input signal: plant-output minus set point.

**Outputs**
- output: Output signal: input for the plant.

**Parameters**
- kp: Proportional gain.
- tauD: Derivative gain (tauD <> 0).
- tauI: Integral gain (tauD <> 0).
- beta: Tameness constant (0 < beta << 1).

**Initial Values**
- pdstate(0) = pdout(0) = pdstate(0) - kp*error(0)*/beta
- pistate(0) = output(0) = pistate(0) - pdout(0)

**Discrete**

**Naming Conventions**

Two types of PID-controllers are available in this library. The first type used an error input and the second type of controller use separate setpoint and Measured Variable input. Both types use the same internal description, so the use is just a question of flavor.

**Error Input**

PID-Controllers with the error as a direct input signal, are all in series form. The name simply denotes the type of controller: P, PI, PD or PID. Two versions of each controller exists: continuous time and discrete time. They can be found in the subdirectories Continuous and Discrete.

**Ports**

All controllers have one input ports and one output port:

1. error: The error between setpoint and measured variable.
2. output: The controller output.
Parameters
Depending on the type of controller, the following parameters can be used:
1. $kd$: The proportional gain of the controller.
2. $tauD$: The derivative time constant.
3. $beta$: The reciprocal derivative gain limitation.
4. $tauI$: The integral time constant.

Separate Input
Controllers with separate inputs come in many forms. The naming denotes the type of controller and the options that are available. The type and options are also available in the model icons.

1. Two versions of each controller exists: continuous time and discrete time. They can be found in the subdirectories `Continuous` and `Discrete`. Continuous-time controllers have icons with blue text and discrete-time controllers have icons with green text.
2. The first characters denote the type of controller: $P$, $PD$, $PI$ or $PID$.
3. The character p or s denote the form: parallel ($p$) or series ($s$).
4. If setpoint weighting is used, the term $sp$ is added.
5. If an anti-windup scheme is incorporated, the term $aw$ is added.
6. If the output at startup can be set manually, the term $u0$ is added.
7. If an external tracking signal is used, the term $tr$ is added.

Ports
All controllers have two inputs ports and one output port:
1. **SP**: The setpoint
2. **MV**: The measured variable (also called process variable).
3. **output**: The controller output.

**Parameters**

Depending on the type of controllers, the following parameters can be used:

1. **K**: The proportional gain of the controller.
2. **Td**: The derivative time constant.
3. **N**: The derivative gain limitation.
4. **Ti**: The integral time constant.
5. **b**: The setpoint weighting constant for the proportional part of the controller.
6. **c**: The setpoint weighting constant for the derivative part of the controller.
7. **Ta**: The tracking time constant of the anti-windup scheme.
8. **minimum**: The minimum controller output representing actuator saturation.
9. **maximum**: The maximum controller output representing actuator saturation.
10. **output_initial**: The controller output at start-up.

**Initial Values**

Although most controllers have one or more internal states, the initial values of these states do not need to be set manually. You use the default values (0) at the start of a simulation. To get a desired output of the controller at startup, the parameter **output_initial** should be used.

**Discrete Controllers**

The discrete controllers that are available in the library are directly derived from their continuous counterparts, using approximation by backward differences. These discrete models have identical behavior, as long as the sample time is not chosen too low. Discrete loops in 20-sim are automatically detected and assigned a default sampletime. You can change the sample time in the Run Properties Editor (in the **Simulator** from the **Properties** menu select the **Simulation** command).

**Variables**

Some PID controllers (parallel form with anti-windup) have two internal variables that are of interest, **PB_high** and **PB_low**. These parameters are the upper and lower bound of the proportional band.
Controller Use

All controllers must be used as shown in the figure below. The upper part shows a continuous time controller and the bottom part shows a discrete time controller.

**Error Input**

1. An error signal is generated with a plus minus element. Its serves as an input of the controller.
2. The controller output is connected with the process input.

As shown in the figure, analog to digital convertors and digital to analog convertors should be used, when connecting a discrete-time controller to a continuous-time process.

**Separate Input**

1. A setpoint signal is connected with the SP port of the controller.
2. The process output is connected with the PV port of the controller.

The controller output is connected with the process input.

As shown in the figure, analog to digital convertors and digital to analog convertors should be used, when connecting a discrete-time controller to a continuous-time process.
Controller-P

Library
Signal\Control\PID Control\Discrete

Use

Description
This is a P controller. The output of this controller (in s-domain) is:

\[ U = K \cdot E \]

with \( E \) equal to \( SP - PV \).

Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>Setpoint.</td>
</tr>
<tr>
<td>PV</td>
<td>Process output.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>Controller output: input for the process.</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Proportional gain.</td>
</tr>
</tbody>
</table>

Controller-PD_p

Library
Signal\Control\PID Control\Discrete

Use

Description
This is a PD controller in parallel form. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( 1 + \frac{s \cdot T_d}{1 + s \cdot N} \right) \cdot E \]

with \( E \) equal to \( SP - MV \).
**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setpoint.</td>
</tr>
<tr>
<td>Measured variable or process output.</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller output: input for the process.</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Td</td>
</tr>
<tr>
<td>N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain.</td>
</tr>
<tr>
<td>Derivative time constant (Td &gt; 0).</td>
</tr>
<tr>
<td>Derivative gain limitation.</td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Should be left default!</td>
</tr>
</tbody>
</table>

**Controller-PD_s**

**Library**

Signal\Control\PID Control\Discrete

**Use**


**Description**

This is a PD controller in series form. The output of this controller (in s-domain) is:

\[
U = K \cdot \left( \frac{1 + s \cdot \frac{Td}{N}}{1 + s \cdot \frac{Td}{N}} \right) \cdot E
\]

with E equal to SP - MV.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setpoint.</td>
</tr>
<tr>
<td>Measured variable or process output.</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller output: input for the process.</td>
</tr>
</tbody>
</table>

**Parameters**
K Proportional gain.
Td Derivative time constant (Td > 0).
N Derivative gain limitation.

**Initial Values**

yes Should be left default!

---

**Controller-PI**

**Library**

Signal\Control\PID Control\Discrete

**Use**

Domains: Continuous, Discrete. **Size:** 1-D. **Kind:** Block Diagrams.

**Description**

This is a PI controller. The output of this controller (in s-domain) is:

\[
U = K \cdot \left(1 + \frac{1}{s \cdot Ti}\right) \cdot E
\]

with \(E\) equal to SP - MV.

**Interface**

**Inputs**

- **SP** Setpoint.
- **MV** Measured variable or process output.

**Outputs**

- **output** Controller output: input for the process.

**Parameters**

- **K** Proportional gain.
- **Ti** Integral time constant (Ti > 0).

**Initial Values**

yes Should be left default!
Controller-PI_sp

Library
Signal\Control\PID Control\Discrete

Use

Description
This is a PI controller with setpoint weighting. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( b \cdot SP - MV \right) + \frac{1}{s \cdot Ti} \cdot (SP - MV) \]

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>b</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
</tr>
</tbody>
</table>

Controller-PI_sp_aw

Library
Signal\Control\PID Control\Discrete

Use

Description
This is a PI controller with setpoint weighting. The output of this controller (in s-domain) is:
An anti-windup scheme has been added to this controller.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>SP</th>
<th>MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setpoint.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured variable or process output.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller output: input for the process.</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>K</th>
<th>Ti</th>
<th>b</th>
<th>Ta</th>
<th>minimum</th>
<th>maximum</th>
</tr>
</thead>
</table>

**Initial Values**

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
</tr>
</tbody>
</table>

**Interesting Variables**

<table>
<thead>
<tr>
<th>Upper and lower bound of the proportional band.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB_high, PB_low</td>
</tr>
</tbody>
</table>

---

**Controller-PI_sp_aw_u0**

**Library**

Signal\Control\PID Control\Discrete

**Use**

**Domains**: Continuous, Discrete. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This is a PI controller with setpoint weighting. The output of this controller (in s-domain) is:

\[ U = K \cdot \left( (b \cdot SP - MV) + \frac{1}{s \cdot Ti} \cdot (SP - MV) \right) \]
An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up.

### Interface

**Inputs**

- **SP**: Setpoint.
- **MV**: Measured variable or process output.

**Outputs**

- **output**: Controller output: input for the process.

**Parameters**

- **K**: Proportional gain.
- **Ti**: Integral time constant ($Ti > 0$).
- **b**: Proportional setpoint weighting parameter.
- **Ta**: Tracking time constant.
- **minimum**: Minimum controller output.
- **maximum**: Maximum controller output.
- **output_initial**: The controller output at start-up.

**Initial Values**

- **yes**: Should be left default!

**Interesting Variables**

- **PB_high, PB_low**: Upper and lower bound of the proportional band.

### Controller-PI_sp_aw_u0_tr

**Library**

- [Signal\Control\PID Control\Discrete](#)

**Use**

- **Domains**: Continuous, Discrete. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This is a PI controller with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \cdot \left( b \cdot (SP - MV) + \frac{1}{s \cdot Ti} \cdot (SP - MV) \right)
\]
An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up. An external tracking signal must be supplied to activate the anti-windup scheme.

**Interface**

### Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
<tr>
<td>TR</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>Ta</td>
</tr>
<tr>
<td>output_initial</td>
</tr>
</tbody>
</table>

**Initial Values**

| yes |

**Interesting Variables**

| PB_high, PB_low |

\[
U = K \cdot \left( b \cdot SP - MV \right) + \frac{1}{s \cdot Ti} \cdot (SP - MV)
\]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up. An external tracking signal must be supplied to activate the anti-windup scheme.

**Controller-PID_p**

**Library**

Signal\Control\PID Control\Discrete

**Use**

Domains: Continuous, Discrete. **Size:** 1-D. **Kind:** Block Diagrams.

**Description**

This is a PID controller in parallel form. The output of this controller (in s-domain) is:
$U = K \cdot \left( 1 + \frac{1}{s \cdot Ti} + \frac{s \cdot Td}{1 + s \cdot \frac{Td}{N}} \right) \cdot E$

with $E$ equal to $SP - MV$.

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>Setpoint.</td>
</tr>
<tr>
<td>MV</td>
<td>Measured variable or process output.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>Controller output: input for the process.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>Proportional gain.</td>
</tr>
<tr>
<td>$Td$</td>
<td>Derivative time constant ($Td &gt; 0$).</td>
</tr>
<tr>
<td>$N$</td>
<td>Derivative gain limitation.</td>
</tr>
<tr>
<td>$Ti$</td>
<td>Integral time constant ($Ti &gt; 0$).</td>
</tr>
</tbody>
</table>

**Initial Values**

| yes | Should be left default! |

**Controller-PID_p_sp.**

**Library**

Signal\Control\PID Control\Discrete

**Use**


**Description**

This is a PID controller in parallel form with setpoint weighting. The output of this controller (in s-domain) is:
$$U = K \left( b \cdot \text{SP} - \text{MV} \right) + \frac{1}{s \cdot T_i} \cdot \left( \text{SP} - \text{MV} \right) + \frac{s \cdot T_d}{1 + s \cdot \frac{T_d}{N}} \cdot (c \cdot \text{SP} - \text{MV})$$

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>SP</th>
<th>MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setpoint.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured variable or process output.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller output: input for the process.</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>K</th>
<th>Td</th>
<th>N</th>
<th>Ti</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Derivative time constant (Td &gt; 0).</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Derivative gain limitation.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integral time constant (Ti &gt; 0).</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proportional setpoint weighting parameter.</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Derivative setpoint weighting parameter.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
<th>yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Should be left default!</td>
<td></td>
</tr>
</tbody>
</table>

**Interesting Variables**

<table>
<thead>
<tr>
<th>Description</th>
<th>PB_high, PB_low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper and lower bound of the proportional band.</td>
<td></td>
</tr>
</tbody>
</table>

**Controller-PID_p_sp_aw**

**Library**

Signal\Control\PID Control\Discrete

**Use**

**Domains:** Continuous, Discrete. **Size:** 1-D. **Kind:** Block Diagrams.

**Description**

This is a PID controller in parallel form with setpoint weighting. The output of this controller (in s-domain) is:
An anti-windup scheme has been added to this controller.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>SP</th>
<th>MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setpoint.</td>
<td>Measured variable or process output.</td>
<td></td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller output: input for the process.</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>K</th>
<th>Td</th>
<th>N</th>
<th>Ti</th>
<th>b</th>
<th>c</th>
<th>Ta</th>
<th>minimum</th>
<th>maximum</th>
</tr>
</thead>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
<th>yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Should be left default!</td>
<td></td>
</tr>
</tbody>
</table>

**Interesting Variables**

<table>
<thead>
<tr>
<th>Description</th>
<th>PB_high, PB_low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper and lower bound of the proportional band.</td>
<td></td>
</tr>
</tbody>
</table>

**Controller-PID\_p\_sp\_aw\_u0**

**Library**

Signal\Control\PID Control\Discrete

**Use**

**Domains:** Continuous, Discrete. **Size:** 1-D. **Kind:** Block Diagrams.

**Description**

This is a PID controller in parallel form with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \left\{ \left( b \cdot SP - MV \right) + \frac{1}{s \cdot Ti} \left( SP - MV \right) + \frac{s \cdot Td}{1 + s \cdot \frac{Td}{N}} \left( c \cdot SP - MV \right) \right\}
\]
An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up.

### Interface

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>Setpoint.</td>
</tr>
<tr>
<td>MV</td>
<td>Measured variable or process output.</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
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<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>Controller output: input for the process.</td>
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</tbody>
</table>

**Parameters**

<table>
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<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Proportional gain.</td>
</tr>
<tr>
<td>Td</td>
<td>Derivative time constant (Td &gt; 0).</td>
</tr>
<tr>
<td>N</td>
<td>Derivative gain limitation.</td>
</tr>
<tr>
<td>Ti</td>
<td>Integral time constant (Ti &gt; 0).</td>
</tr>
<tr>
<td>b</td>
<td>Proportional setpoint weighting parameter.</td>
</tr>
<tr>
<td>c</td>
<td>Derivative setpoint weighting parameter.</td>
</tr>
<tr>
<td>Ta</td>
<td>Tracking time constant.</td>
</tr>
<tr>
<td>minimum</td>
<td>Minimum controller output.</td>
</tr>
<tr>
<td>maximum</td>
<td>Maximum controller output.</td>
</tr>
<tr>
<td>output_initial</td>
<td>The controller output at start-up.</td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Initial Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>Should be left default!</td>
</tr>
</tbody>
</table>

**Interesting Variables**

| PB_high, PB_low | Upper and lower bound of the proportional band. |

---

**Controller-PID_p_sp_aw_u0_tr**

**Library**

Signal\Control\PID Control\Discrete

**Use**

**Domains:** Continuous, Discrete. **Size:** 1-D. **Kind:** Block Diagrams.
Description

This is a PID controller in parallel form with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \cdot \left( (b \cdot SP - MV) + \frac{1}{s \cdot Ti} \cdot (SP - MV) + \frac{s \cdot Td}{1 + s \cdot \frac{Td}{N}} \cdot (c \cdot SP - MV) \right)
\]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up. An external tracking signal must be supplied to activate the anti-windup scheme.

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
<tr>
<td>TR</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Td</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>Ta</td>
</tr>
<tr>
<td>output_initial</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
</tr>
</tbody>
</table>

Interesting Variables

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB_high, PB_low</td>
</tr>
</tbody>
</table>
**Controller-PID_s**

**Library**
Signal\Control\PID Control\Discrete

**Use**

**Description**
This is a PID controller in series form. The output of this controller (in s-domain) is:

\[ U = K \left( 1 + \frac{1}{s \cdot Ti} \right) \left( \frac{1 + s \cdot Td}{1 + s \cdot N} \right) \cdot E \]

with E equal to SP - MV.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Td</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Ti</td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
</tr>
</tbody>
</table>

**Controller-PID_s_sp**

**Library**
Signal\Control\PID Control\Discrete

**Use**

**Description**
This is a PID controller in series form with setpoint weighting. The output of this controller (in s-domain) is:
Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SP</strong></td>
<td>Setpoint.</td>
</tr>
<tr>
<td><strong>MV</strong></td>
<td>Measured variable or process output.</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>output</strong></td>
<td>Controller output: input for the process.</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>K</strong></td>
<td>Proportional gain.</td>
</tr>
<tr>
<td><strong>Td</strong></td>
<td>Derivative time constant ($Td &gt; 0$).</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>Derivative gain limitation.</td>
</tr>
<tr>
<td><strong>Ti</strong></td>
<td>Integral time constant ($Ti &gt; 0$).</td>
</tr>
<tr>
<td><strong>b</strong></td>
<td>Proportional setpoint weighting parameter.</td>
</tr>
<tr>
<td><strong>c</strong></td>
<td>Derivative setpoint weighting parameter.</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>yes</strong></td>
<td>Should be left default!</td>
</tr>
</tbody>
</table>

Controller-PID_s_sp_aw

Library

Signal\Control\PID Control\Discrete

Use

**Domains**: Continuous, Discrete. **Size**: 1-D. **Kind**: Block Diagrams.

Description

This is a PID controller in series form with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \cdot \left( b + \frac{1}{s \cdot T_i} \right) \cdot \frac{1 + s \cdot c \cdot T_d}{1 + s \cdot \frac{T_d}{N} \cdot SP} - \left( 1 + \frac{1}{s \cdot T_i} \right) \cdot \frac{1 + s \cdot T_d}{1 + s \cdot \frac{T_d}{N} \cdot MV} \]

An anti-windup scheme has been added to this controller.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
</tr>
<tr>
<td>MV</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
</tr>
<tr>
<td>Td</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>Ta</td>
</tr>
<tr>
<td>minimum</td>
</tr>
<tr>
<td>maximum</td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
</tr>
</tbody>
</table>

**Controller-PID_s_sp_aw_u0**

**Library**

Signal\Control\PID Control\Discrete

**Use**

**Domains**: Continuous, Discrete. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This is a PID controller in series form with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \cdot \left( \frac{b}{s} + \frac{1}{s \cdot Ti} \right) \cdot \frac{1 + s \cdot N}{1 + s \cdot Ti} \cdot \frac{1 + s \cdot Td}{Td} \cdot SP - \left( \frac{1}{s \cdot Ti} + \frac{1 + s \cdot Td}{Td} \right) \cdot MV
\]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up.
### Interface

#### Inputs

- **SP**
  - Description: Setpoint.

- **MV**
  - Description: Measured variable or process output.

#### Outputs

- **output**
  - Description: Controller output: input for the process.

#### Parameters

- **K**
  - Description: Proportional gain.

- **Td**
  - Description: Derivative time constant \( (Td > 0) \).

- **N**
  - Description: Derivative gain limitation.

- **Ti**
  - Description: Integral time constant \( (Ti > 0) \).

- **b**
  - Description: Proportional setpoint weighting parameter.

- **c**
  - Description: Derivative setpoint weighting parameter.

- **Ta**
  - Description: Tracking time constant.

- **minimum**
  - Description: Minimum controller output.

- **maximum**
  - Description: Maximum controller output.

- **output_initial**
  - Description: The controller output at start-up.

#### Initial Values

- **yes**
  - Description: Should be left default!

### Controller-PID_s_sp_aw_u0_tr

#### Library

- **Signal\Control\PID Control\Discrete**

#### Use

- **Domains**: Continuous, Discrete. **Size**: 1-D. **Kind**: Block Diagrams.

#### Description

This is a PID controller in series form with setpoint weighting. The output of this controller (in s-domain) is:

\[
U = K \cdot \left( b + \frac{1}{s \cdot Ti} \right) \cdot \frac{1 + s \cdot c \cdot Td}{1 + s \cdot Td} \cdot SP - \left( 1 + \frac{1}{s \cdot Ti} \right) \cdot \frac{1 + s \cdot Td}{1 + s \cdot Td} \cdot MV
\]

An anti-windup scheme has been added to this controller as well as an offset for manual output at start-up. An external tracking signal must be supplied to activate the anti-windup scheme.
Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
<th>SP</th>
<th>MV</th>
<th>TR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setpoint.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured variable or process output.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracking signal.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller output: input for the process.</td>
<td></td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>K</th>
<th>Td</th>
<th>N</th>
<th>Ti</th>
<th>b</th>
<th>c</th>
<th>Ta</th>
<th>output_initial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain.</td>
<td></td>
<td>Derivative time constant (Td &gt; 0).</td>
<td></td>
<td></td>
<td>Derivative gain limitation.</td>
<td>Integral time constant (Ti &gt; 0).</td>
<td>Proportional setpoint weighting parameter.</td>
<td>Derivative setpoint weighting parameter.</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
<th>yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Should be left default!</td>
<td></td>
</tr>
</tbody>
</table>

P

Library

Signal\Control\PID Control\Discrete

Use


Description

This is a P controller. The output of this controller is:

\[ \text{output} = K_p \cdot \text{error} \]

with the input of the controller equal to the error and the output of the controller used as the plant input:
### Interface

#### Inputs

<table>
<thead>
<tr>
<th>Description</th>
<th>Error Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input signal: plant-output minus set point.</td>
<td>error</td>
</tr>
</tbody>
</table>

#### Outputs

<table>
<thead>
<tr>
<th>Description</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output signal: input for the plant.</td>
<td>output</td>
</tr>
</tbody>
</table>

#### Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>kp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain.</td>
<td></td>
</tr>
</tbody>
</table>

### PD

#### Library

Signal\Control\PID Control\Discrete

#### Use

**Domains**: Continuous, Discrete **Size**: 1-D. **Kind**: Block Diagrams.

#### Description

This is a PD controller in series form. The transfer function of an ideal PD-controller is:

\[
G(s) = \frac{kp (1 + s \cdot \tau_D)}{1 + s \cdot 
\beta \cdot \tau_D}
\]

with the input of the controller equal to the error and the output of the controller used as the plant input:

![Control System Diagram](image)

Interface

#### Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error Input</td>
</tr>
</tbody>
</table>

| Input signal: plant-output minus set point. | error |

<table>
<thead>
<tr>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output signal: input for the plant.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>kp</td>
</tr>
</tbody>
</table>

| Proportional gain. | |

20-sim 5.1 Reference Manual
**11. Library**

11.2120-sim 5.1 Reference Manual

---

**Inputs**

**error**
Input signal: plant-output minus set point.

**Outputs**

**output**
Output signal: input for the plant.

**Parameters**

**kp**
Proportional gain.

**tauD**
Derivative gain (tauD <> 0).

**beta**
Tameness constant (0 < beta << 1).

**Initial Values**

**state_initial**
output(0) = state_initial - kp*error(0)*/beta

---

**PI**

**Library**
Signal\Control\PID Control\Discrete

**Use**
Domains: Continuous, Discrete **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
This is a PI controller. The transfer function of the controller is:

\[
G(s) = kp + \frac{kp}{s \cdot \tau_D}
\]

with the input of the controller equal to the error and the output of the controller used as the plant input:

![Block Diagram](image)

---

**Interface**

**Inputs**

**error**
Input signal: plant-output minus set point.

**Outputs**

**output**
Output signal: input for the plant.

---

20-sim 5.1 Reference Manual
kp  \hspace{1cm} \text{Proportional gain.}

tauI \hspace{1cm} \text{Integral gain (tauI <> 0).}

**Initial Values**

state(0) \hspace{1cm} \text{output(0) = state(0) - kp*error(0)}

**PID**

**Library**

Signal\Control\PID Control\Discrete

**Use**


**Description**

This is a PID controller in series form. The transfer function is:

\[
G(s) = kp \cdot \left( \frac{1}{1 + \frac{1}{s \cdot \text{tauI}}} \right) \left( \frac{1 + s \cdot \text{tauD}}{1 + s \cdot \beta \cdot \text{tauD}} \right)
\]

with the input of the controller equal to the error and the output of the controller used as the plant input:

**Interface**

**Inputs**

error  \hspace{1cm} \text{Description}

\text{Input signal: plant-output minus set point.}

**Outputs**

output  \hspace{1cm} \text{Output signal: input for the plant.}

**Parameters**

kp  \hspace{1cm} \text{Proportional gain.}

tauD \hspace{1cm} \text{Derivative gain (tauD <> 0).}

tauI \hspace{1cm} \text{Integral gain (tauD <> 0).}

beta \hspace{1cm} \text{Tameness constant (0 < beta << 1).}

**Initial Values**

pdstate(0)  \hspace{1cm} \text{pdout(0) = pdstate(0) - kp*error(0)/beta}
11.3.4 Cost Functions

Continuous

CostFunction

Library
Signal\Cost Functions\Continuous

Implementations
IE
ISE
IAE
ISTE
ITAE
ITSE
IAEWAI
ISEWSI
ITAEWAI

Use

Description - IE
This submodel yields the following cost function:

\[ output = \int(e); \]

Description - ISE
This submodel yields the following cost function:

\[ output = \int(e^2); \]

Description
This submodel yields the following cost function:

\[ output = \int(abs(e)); \]

Description - ISTE
This submodel yields the following cost function:

\[ output = \int(time^2*e^2); \]

Description - ITAE
This submodel yields the following cost function:
\[ \text{output} = \text{int}(\text{time} \cdot \text{abs}(e)); \]

**Description - ITSE**
This submodel yields the following cost function:

\[ \text{output} = \text{int}(\text{time} \cdot e^2); \]

\[ \text{Description - IAEWAI} \]
This submodel yields the following cost function:

\[ \text{output} = \text{int}(|e| + \lambda \text{abs}(\text{input})); \]

**Description - ISEWSI**
This submodel yields the following cost function:

\[ \text{output} = \text{int}(e^2 + \lambda \text{input}^2); \]

**Description**
This submodel yields the following cost function:

\[ \text{output} = \text{int}(\text{time} \cdot \text{abs}(e) + \lambda \text{abs}(\text{input})); \]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>Input signal</td>
</tr>
<tr>
<td>input</td>
<td>Input signal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>\lambda</td>
<td>Weighting factor.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output_initial</td>
<td>The initial value of the output.</td>
</tr>
</tbody>
</table>

**Discrete**

**CostFunction**

**Library**
Signal\Cost Functions\Discrete

**Implementations**
IE
ISE
IAE
Use

Description - IE
This submodel yields the following cost function:

\[ output = \text{sum}(e); \]

Description - ISE
This submodel yields the following cost function:

\[ output = \text{sum}(e^2); \]

Description - IAE
This submodel yields the following cost function:

\[ output = \text{sum}(\text{abs}(e)); \]

Description - ISTE
This submodel yields the following cost function:

\[ output = \text{sum}(\text{time}^2 \times e^2); \]

Description - ITAE
This submodel yields the following cost function:

\[ output = \text{sum}(\text{time} \times \text{abs}(e)); \]

Description - ITSE
This submodel yields the following cost function:

\[ output = \text{sum}(\text{time} \times e^2); \]

Description - IAEWAI
This submodel yields the following cost function:

\[ output = \text{sum}(\text{abs}(e) + \lambda \text{abs}(\text{input})); \]

Description - ISEWSI
This submodel yields the following cost function:

\[ output = \text{sum}(e^2 + \lambda \text{input}^2); \]
\[ output = \text{sum}(time*\text{abs}(e) + lambda*\text{abs}(input)); \]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>Input signal</td>
</tr>
<tr>
<td>input</td>
<td>Input signal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lambda</td>
<td>Weighting factor.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output_initial</td>
<td>The initial value of the output.</td>
</tr>
</tbody>
</table>

### 11.3.5 Discrete

**AD**

**Library**

Signal\Discrete

**Use**

Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**

This model incorporates the basic functions of an analog to digital convertor: sample and hold, output window (i.e. restriction of the output between a minimum and maximum value) and quantization. The quantization is specified in bits. For example 8 bits quantization means the output has \(2^8 - 1 = 255\) possible values between the given minimum and maximum.

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum</td>
<td>Minimum output value.</td>
</tr>
<tr>
<td>maximum</td>
<td>Maximum output value</td>
</tr>
<tr>
<td>bits</td>
<td>Quantization levels (bits).</td>
</tr>
<tr>
<td>initial</td>
<td>Initial output</td>
</tr>
</tbody>
</table>
Limitations

- The input of this model is a continuous signal. The output of this model is a discrete signal. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sampletime. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).
- The initial output is bounded by the window given by the minimum and maximum and rounded by the number of bits used.

Clock-Discrete

**Library**
Signal\Discrete

**Use**

**Description**
This models generates a logical discrete clock signal, i.e. a signal that changes from true (1) to false (0) and vice-versa, each sample time.

**Interface**

**Outputs**
output

**Parameters**
initial

**Description**
Initial value of the output.
Limitations
The output of this model is a discrete signal. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sample time. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).

DA-Delay

Library
Signal\Discrete

Use

Description
This model incorporates the basic functions of a digital to analog convertor: zero order hold, output window (i.e. restriction of the output between a minimum and maximum value) and quantization. The quantisation is specified in bits. For example 8 bits quantisation means the output has $2^{8} - 1 = 255$ possible values between the given minimum and maximum.

The standard models of the discrete library assume that there is no time needed to perform the calculations the a discrete loop. In general these calculations do take time. To take this into account, the output of this model is delayed in time. This time delay can be set by the user and should correspond to the time needed to perform all calculations of the discrete loop in a real system.

Interface

Inputs
input

Outputs
output

Parameters
minimum
maximum
bits
t_calc

Description
Minimum output value.
Maximum output value
Quantisation levels (bits).
Time needed to perform all calculations of the discrete loop.

Limitations
The input of this model is a discrete signal. The output of this model is a continuous signal. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sample time. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).
**DA**

**Library**
Signal\Discrete

**Use**
**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This model incorporates the basic functions of a digital to analog convertor: zero order hold, output window (i.e. restriction of the output between a minimum and maximum value) and quantization. The quantization is specified in bits. For example 8 bits quantization means the output has $2^8 - 1 = 255$ possible values between the given minimum and maximum.

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum</td>
<td>Minimum output value.</td>
</tr>
<tr>
<td>maximum</td>
<td>Maximum output value</td>
</tr>
<tr>
<td>bits</td>
<td>Quantization levels (bits).</td>
</tr>
</tbody>
</table>

**Limitations**
The input of this model is a discrete signal. The output of this model is a continuous signal. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sampletime. You can set this sample time to any desired value in the Simulator (choose Properties > Run and then the Discrete System tab.)

**Delay-n**

**Library**
Signal\Discrete

**Use**
**Domains:** Discrete. **Size:** 1-D. **Kind:** Block Diagrams.

**Description**
This is the z-delay function with n samples delay.
output(k) = input(k - n*T)
with k = n * T , n = 1,2,3,...

The sample time T can be set in the Simulator (choose Properties, Simulation and Discrete System).

Interface

Inputs
input

Outputs
output

Initial Values
output_initial
The initial value of the block.

Parameters
n
The number of sample delays (n = 1,2,3,..).

Limitations

• The parameter n can not be changed during simulation. If it is increased, re-processing of the model is necessary.

• The input and output of this model are discrete signals. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sample time. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).

Delay

Library
Signal\Discrete

Use

Description
This is the the z-delay function with one sample interval delay.

output(k) = input(k - T)
with k = n * T , n = 0,1,2,3,...

The sample time T can be set in the Simulator (choose Properties, Simulation and Discrete System).
Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

Outputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

Initial Values

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output_initial</td>
</tr>
<tr>
<td>The initial value of the block.</td>
</tr>
</tbody>
</table>

Limitations

The input and output of this model are discrete signals. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sampletime. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).

DiscreteDifferential

Library

Signal\Discrete

Use


Description

This model represents the discrete equivalent of the continuous differentiation:

\[
\begin{align*}
output(0) &= initial; \\
output(1) &= (u(1) - initial)/\text{sampletime}; \\
output (k) &= (u(k) - u(k-1))/\text{sampletime}; \\
&\text{where } k = n * T, n = 2,3,4,...
\end{align*}
\]

The sampletime T can be set in the Simulator (choose Properties, Simulation and Discrete System). The discrete transfer function of this model is:

\[
H(z) = \frac{(z - 1)}{( z * \text{sampletime})}
\]

which is the equivalent (using the backward difference transformation) of the continuous time transferential:

\[
H(s) = s
\]

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>
Outputs
output

Parameters
initial Initial value of the output.

Limitations
The input and output of this model are discrete signals. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sampletime. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).

DiscreteIntegral

Library
Signal\Discrete

Use

Description
This model represents the discrete equivalent of the continuous integration:

\[
output(k) = initial; \ (k = 0) \\
inp(k-T)*T + inp(k-2T)*T + inp(k-3T)*T \\
+ ... + inp(0)*T + initial; \ (k = n * T , n = 1,2,3,...)
\]

The sampletime T can be set in the Simulator (choose Properties, Simulation and Discrete System). The discrete transfer function of this model is:

\[
H(z) = \text{sampletime} / ( z - 1)
\]

which is the equivalent (using the forward difference transformation) of the continuous time transfer function:

\[
H(s) = 1/s
\]

Interface

Inputs Description
input

Outputs
output

Parameters
### Hold

<table>
<thead>
<tr>
<th><strong>Library</strong></th>
<th>Signal\Discrete</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Use</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Domains</strong></td>
<td>Discrete, Continuous. <strong>Size</strong>: 1-D. <strong>Allowed in</strong>: Block Diagrams.</td>
</tr>
<tr>
<td><strong>Description</strong></td>
<td>This model forms the interconnection between a discrete and continuous system: zero order hold.</td>
</tr>
<tr>
<td><strong>Interface</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td>Description</td>
</tr>
<tr>
<td>input</td>
<td>discrete signal</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>continuous signal</td>
</tr>
</tbody>
</table>

### Limitations

The input of this model is a discrete signal. The output of this model is a continuous signal. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sample time. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).
Description
When you select this model and click *Go Down* a special editor opens (Linear System Editor), allowing you to enter a linear system in State Space form, as a Transfer Function or by adding poles and zeros:

Note
This is a discrete linear system, using the transformation. The transformation is based on a sampletime (here 0.1 s). You can change the sampletime by going to a continuous-time linear system (click the $\mathcal{Z}$ button) and back (click again the $\mathcal{Z}$ button).

Interface

Inputs
input

Outputs
output

Initial Values
The model has internal states that are not accessible.

Parameters
Library
Signal\Discrete
Use
Description
This model can be used to represent quantization of an input signal. It rounds the input as shown in the graph below. The quantization interval is specified by the least significant bit (lsb). The maximum output error is half a least significant bit.

Note
Compare this model with the model Quantisize-Truncate which represents quantization by truncation. Truncation results in a maximum error of a least significant bit.

Interface

**Inputs**
- **input**

**Outputs**
- **output**

**Parameters**
- **lsb** Least significant bit.
Quantize-Truncate

Library
Signal\Discrete

Use

Description
This model can be used to represent quantization of an input signal. It truncates the input as shown in the graph below. The quantization interval is specified by the least significant bit (lsb). The maximum output error is a least significant bit.

Note
Compare this model with the model Quantisize-Round which represents quantization by rounding. Rounding results in a maximum error of half a least significant bit.

Interface

Inputs
input

Outputs
output

Parameters
lsb Least significant bit.
### Sample

**Library**
Signal\Discrete

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model samples and holds the input every $T$ [s].

$$output = input; \ (t = k)$$

where $k = n*T$, with $n = 0,1,2,3, ...$

The sampletime $T$ can be set in the Simulator (choose Properties, Run and Discrete System).

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Limitations**
The input of this model is a continuous signal. The output of this model is a discrete signal. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sampletime. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).

### SampleTime

**Library**
Signal\Discrete

**Use**
Domains: Discrete. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model outputs the current sampletime [s].

$$output = sampletime; \ (t = k)$$

The sampletime $T$ can be set in the Simulator (choose Properties, Run and Discrete System).
Interface

Inputs
- 

Outputs
output 

Description
sampletime \{s\}

Sigma

Library
Signal\Discrete

Use

Description
This model represents a discrete summation operator:

\[
\begin{align*}
\text{output}(k) &= \text{initial}; \\
\text{with } k &= 0 \\
\text{outp}(k) &= \text{inp}(k-T) + \text{inp}(k-2T) + \text{inp}(k-3T) + \ldots + \text{inp}(0) + \text{initial} \\
\text{with } k &= n \times T, \, n = 1,2,3,\ldots
\end{align*}
\]

The sampletime \(T\) can be set in the Simulator (choose Properties, Simulation and Discrete System).

Interface

Inputs
input

Outputs
output

Parameters
initial 

Description
Initial value of the output.

Limitations
The input and output of this model are discrete signals. 20-sim will automatically detect the existence of discrete models. Each chain of discrete models will be assigned a specific sampletime. You can set this sample time to any desired value in the Simulator (choose Properties, Simulation and Discrete System).
11.3.6 Events

Event

Library
Signal\Events

Implementations
CrossingBoth
CrossingDown
CrossingUp

Use

Description - CrossingBoth
This is the block implementation of the event function. The output signal is a boolean which goes from false (0) to true (1) when the input signal crosses zero (offset = 0):

\[
output = \text{event}(input - \text{offset});
\]

If desired, you can change the parameter offset to trigger the event on a non-zero input value.

The output of the event block for a sinusoidal input (parameter offset = 0).

Interface - CrossingBoth

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
output event signal (boolean)

**Parameters**

offset output is true (event) when the input signal crosses this value (default = 0)

**Description - CrossingDown**

This is the block implementation of the eventdown function. The output signal is a boolean which goes from false (0) to true (1) when the input signal crosses zero with a negative slope (offset = 0):

\[
output = \text{eventdown} (input - offset);
\]

If desired, you can change the parameter `offset` to trigger the event on a non-zero input value.

![EventCrossingDown](image)

*The output of the event block for a sinusoidal input (parameter offset = 0).*

**Interface - CrossingDown**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>event signal (boolean)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>offset</td>
<td>output is true (event) when the input signal crosses this value (default = 0).</td>
</tr>
</tbody>
</table>
**Description - CrossingUp**

This is the block implementation of the eventup function. The output signal is a boolean which goes from false (0) to true (1) when the input signal crosses zero with a positive slope (offset = 0):

\[ output = \text{eventup} \left( \text{input} - \text{offset} \right); \]

If desired, you can change the parameter `offset` to trigger the event on a non-zero input value.

![The output of the event block for a sinusoidal input (parameter offset = 0).](image)

**Interface - CrossingUp**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>event signal (boolean)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>offset</td>
<td>output is true (event) when the input signal crosses this value (default = 0).</td>
</tr>
</tbody>
</table>
**FrequencyEvent**

**Library**
Signal\Events

**Use**
**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This is the block implementation of the frequencyevent function. The output signal is a boolean which is true (1) every time when $p$ [s] have passed. The function starts after an offset of $o$ [s]. The offset parameter is optional.

\[
output = \text{frequencyevent}(p,o);
\]

![FrequencyEvent](image)

*The output of the frequencyevent block with a period of 1 s and an offset of 2 s.*

**Interface**

**Outputs**
- output: event signal (boolean)

**Parameters**
- period: period in [s]
- offset: offset in [s]
**TimeEvent**

**Library**
Signal\Events

**Use**
**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This is the block implementation of the timeevent function. The output signal is a boolean which is true (1) at a specific time given by the parameter `triggerTime`:

\[
output = \text{timeevent}(\text{triggerTime});
\]

![Graph](image_url)

*The output of the timeevent block with a triggerTime of 5 s.*

**Interface**

**Outputs**
output  
**Description**  
event signal (boolean)

**Parameters**
triggerTime  
**Description**  
time in [s] when the output is true.
11.3.7 Filters

Library
Signal\Block Diagram

Use

Description
When you select this model and click Go Down a special editor opens (Filter Editor), allowing you to choose a filter:

![Filter Editor](image)

Interface

Inputs
- input

Outputs
- output

Initial Values
- The model has internal states that are not accessible.

Parameters
- Parameters are entered by the Filter Editor.
**LowPassFilter-BW2**

**Library**
Signal\Filters

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
This is a second order Butterworth filter. The bandwidth is given in Hz. The phase and magnitude plot (bandwidth = 1 Hz) are shown in the figure below.

![Linear System : Bode Plot (Magnitude)](image1)

![Linear System : Bode Plot (Phase)](image2)

**Interface**

**Outputs**
input, output

**Parameters**

**Initial Values**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW</td>
<td>Bandwidth (Hz)</td>
</tr>
<tr>
<td>y_initial</td>
<td>Output value of the filter at t = 0 s.</td>
</tr>
</tbody>
</table>
**LowPassFilter-BW4**

**Library**
Signal\Filters

**Use**
Domains: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
This is a fourth order Butterworth filter. The bandwidth is given in Hz. The phase and magnitude plot (bandwidth = 1 Hz) are shown in the figure below.

![Magnitude and Phase Plots](image)

**Interface**

**Outputs**
- input, output

**Parameters**
**LowPassFilter-FO**

**Library**
Signal\Filters

**Use**
Domains: Continuous. **Size:** 1-D. **Kind:** Block Diagrams.

**Description**
This is a first order filter. with transfer function:

\[
Y(s) = \frac{1}{s} \cdot \frac{U(s)}{2 \cdot \pi \cdot BW + 1}
\]

The bandwidth is given in Hz. The phase and magnitude plot (bandwidth = 1 Hz) are shown in the figure below.
11. Library

**Interface**

**Outputs**
- input, output

**Parameters**
- **BW**
  - Bandwidth (Hz)

**Initial Values**
- **state_initial**
  - Output value of the filter at t = 0 s.
LowPassFilter-SO

Library
Signal\Filters

Use

Description
This is a second order filter, with transfer function:

\[ Y(s) = \frac{(2 \cdot \pi \cdot BW)^2}{s^2 + 2 \cdot \pi \cdot BW \cdot \frac{s}{Q} + (2 \cdot \pi \cdot BW)^2} \cdot U(s) \]

The bandwidth is given in Hz. The phase and magnitude plot (bandwidth = 1 Hz) are shown in the figure below.

Interface

Outputs
input, output

Description

Parameters
11. Library

<table>
<thead>
<tr>
<th>BW</th>
<th>Bandwidth (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>Quality ()</td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>state1_initial</th>
<th>Output rate of the filter at t = 0 s.</th>
</tr>
</thead>
<tbody>
<tr>
<td>state2_initial</td>
<td>Output value of the filter at t = 0 s.</td>
</tr>
</tbody>
</table>

11.3.8 Import Export

**Matlab**

**DoFromMatlab**

**Library**

Signal\Import Export\Matlab

**Use**

Domains: Continuous, Discrete. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**

This submodel sends a command to the Matlab workspace during simulation, and gets the output signal from the Matlab workspace.

**Interface**

**Outputs**

| output | The variable from the Matlab workspace. |

**Parameters**

| command | Command string in Matlab format |
name: Name of the variable inside the Matlab workspace.

Tip
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes " in the command string instead.

DoMatlab-Final

Library
Signal\Import Export\Matlab

Use

Description
This submodel sends a command to the Matlab workspace at the end of the simulation.

Interface

Parameters

command
Command string in Matlab format

Tip
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes " in the command string instead.

DoMatlab-Initial

Library
Signal\Import Export\Matlab

Use

Description
This submodel sends a command to the Matlab workspace at the start of the simulation.

Interface

Inputs

Outputs
### DoMatlab

**Library**
Signal\Import Export\Matlab

**Use**

**Description**
This submodel sends a command to the Matlab workspace during simulation.

**Interface**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>command</td>
<td>Command string in Matlab format</td>
</tr>
</tbody>
</table>

**Tip**
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes " in the command string instead.

### FromMatlab

**Library**
Signal\Import Export\Matlab

**Use**

**Description**
This submodel gets an output from the Matlab workspace during simulation.

**Interface**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>name</td>
<td>Name of the variable inside the Matlab workspace</td>
</tr>
</tbody>
</table>
Tip
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the
command string for Matlab, use 2 single quotes " in the command string instead.

TodoFromMatlab

Library
Signal\Import Export\Matlab

Use

Description
This submodel sends the input signal to the Matlab workspace, sends the command to
the workspace, and gets the output variable back. This is done during the 20-sim
simulation.

Interface

Inputs

Description
input
The variable for the Matlab workspace.

Outputs

output
The variable from the Matlab workspace.

Parameters

command
Command string in Matlab format
nameInput
Name of the input variable in the Matlab workspace.
nameOutput
Name of the output variable in the Matlab workspace.

Tip
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the
command string for Matlab, use 2 single quotes " in the command string instead.
**ToDoMatlab**

**Library**
Signal\Import Export\Matlab

**Use**

**Domains:** Continuous, Discrete. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This submodel sends the input signal and a command to the Matlab workspace during simulation.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**Outputs**

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>command</td>
</tr>
<tr>
<td>name</td>
</tr>
</tbody>
</table>

**Tip**
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes " in the command string instead.

---

**ToMatlab-Plot**

**Library**
Signal\Import Export\Matlab

**Use**

**Domains:** Continuous, Discrete. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This submodel sends the input signal to the Matlab workspace, stores the input inside the Matlab workspace into a matrix, and plots the result in a graph. Each row of the matrix corresponds with a major simulation step, so the input is limited to a scalar or vector. Note: the name is set during the processing phase only.

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**Parameters**
name Name of the variable inside the Matlab workspace

Tip
20-sim uses a single quote ’ for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes " in the command string instead.

ToMatlab-Store

Library
Signal\Import Export\Matlab

Use

Description
This submodel sends the input signal to the Matlab workspace and stores the input inside the Matlab workspace into a matrix. Each row of the matrix corresponds with a major simulation step, so the input is limited to a scalar or vector. Note: the name is set during the processing phase only.

Interface

Inputs Description
input The variable to send to the Matlab workspace.

Outputs

Parameters
name Name of the variable inside the Matlab workspace

Tip
20-sim uses a single quote ’ for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes " in the command string instead.
**ToMatlab-Timed**

**Library**
Signal\Import Export\Matlab

**Use**
Domains: Continuous, Discrete. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This submodel sends the time and input signal to the Matlab workspace. The input is limited to a scalar or vector. Note: the name is set during the processing phase only.

**Interface**

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>The variable to send to the Matlab workspace.</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>name</td>
<td>Name of the variable inside the Matlab workspace</td>
</tr>
</tbody>
</table>

**Tip**
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes '" in the command string instead.

---

**ToMatlab-TimedPlot**

**Library**
Signal\Import Export\Matlab

**Use**
Domains: Continuous, Discrete. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This submodel sends the time and input signal to the Matlab workspace, stores the time and input inside the Matlab workspace into a matrix, and plots the result in a graph. Each row of the matrix corresponds with a major simulation step, so the input is limited to a scalar or column vector. Note: the name is set during the processing phase only.

**Interface**

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>The variable to send to the Matlab workspace.</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>name</td>
<td>Name of the variable inside the Matlab workspace</td>
</tr>
</tbody>
</table>
Tip
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes " in the command string instead.

ToMatlab-TimedStore

Library
Signal\Import Export\Matlab
Use
Description
This submodel sends the time and input signal to the Matlab workspace and stores the time and input inside the Matlab workspace into a matrix. Each row of the matrix corresponds with a major simulation step, so the input is limited to a scalar or column vector. Note: the name is set during the processing phase only

Interface

Inputs

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of the variable inside the Matlab workspace</td>
</tr>
</tbody>
</table>

Tip
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes " in the command string instead.

ToMatlab

Library
Signal\Import Export\Matlab
Use
Description
This submodel sends a variable to the Matlab workspace during simulation.
11. Library

Interface

Inputs  Description
input  The variable to send to the Matlab workspace.

Parameters
name  Name of the variable inside the Matlab workspace

Tip
20-sim uses a single quote ' for strings. If you wish to include a single quote inside the command string for Matlab, use 2 single quotes " in the command string instead.

11.3.9 Logical

Boolean

And

Library
Signal\Logical\Boolean

Use

Implementations
This submodel has 8 implementations varying from a 2-input AND to a 9-input AND.

- inputs_2
- inputs_3
- inputs_4
- inputs_5
- inputs_6
- inputs_7
- inputs_8
- inputs_9

Description
The output signal of this model is according the truth table below:

<table>
<thead>
<tr>
<th>input1</th>
<th>input2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>false</td>
</tr>
</tbody>
</table>
The output signal for the other AND implementations follows a similar pattern. The output signal is only true when all input signals are equal to true.

### Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>boolean</td>
<td>First AND input</td>
<td>false/true</td>
</tr>
<tr>
<td>input2</td>
<td>boolean</td>
<td>Second AND input</td>
<td>false/true</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>Result of the AND operation</td>
<td>false/true</td>
</tr>
</tbody>
</table>

### Restrictions

This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

### Clock

#### Library

Signal\Logical\Boolean

#### Use

**Domains**: Discrete, Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

#### Implementations

This model has a continuous-time and a discrete-time implementation.

- Continuous
- Discrete

#### Description

This model generates a logical continuous clock signal, i.e. a signal that changes from true (1) to false (0) and back, each period $T$ with $T = (1/frequency)$.
If the discrete implementation is chosen, the frequency must be smaller than half of the sample frequency, otherwise not a good clock signal will result. To have the top part of the clock signal equally long to the down part, choose the frequency equal to the sample frequency divided by $2^n$, with $n$ an integer equal or larger than one.

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Unit</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong>s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>initial</td>
<td>boolean</td>
<td>initial output</td>
<td></td>
<td>false/true</td>
</tr>
<tr>
<td>frequency</td>
<td>real</td>
<td>clock frequency</td>
<td>Hz</td>
<td>$&gt; 0.0$ Hz</td>
</tr>
</tbody>
</table>

| **Outputs** | | | | |
| output | boolean | Clock output | | false/true |

**Restrictions**

Make sure that the simulation uses step sizes which are small enough to calculate the clock signal going up and going down: step size $\ll$ clock period.

**CMOS_CD4020**

**Library**

Signal\Logical\Boolean

**Use**

Description
Binary counter modeled after the CMOS 4020 chip. The 4020 is a 14-stage binary ripple counter with a clock input (CP), an overriding asynchronous master reset input (MR) and 12 buffered parallel outputs (Q0, and Q3 to Q13). The counter advances on the true-to-false transition of CP. A HIGH on MR clears all counter stages and forces all outputs to false, independent of the state of CP.

Interface
<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP</td>
<td>boolean</td>
<td>clock input (HIGH-to-LOW, edge-triggered)</td>
<td>false/true</td>
</tr>
<tr>
<td>MR</td>
<td>boolean</td>
<td>master reset input (active HIGH)</td>
<td>false/true</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q0 ... Q13</td>
<td>boolean</td>
<td>counter outputs</td>
<td>false/true</td>
</tr>
</tbody>
</table>

Restrictions
This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

CompareGE

Library
Signal\Logical\Boolean

Use

Description
This model compares two input real signals and outputs the result as a boolean output according to the following table:

<table>
<thead>
<tr>
<th>inputs</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1 &gt;= input 2</td>
<td>true</td>
</tr>
<tr>
<td>input1 &lt; input 2</td>
<td>false</td>
</tr>
</tbody>
</table>

Interface
<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>real</td>
<td>First input</td>
<td>real</td>
</tr>
<tr>
<td>input2</td>
<td>real</td>
<td>Second input</td>
<td>real</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>Result of the input1 &gt;= input2</td>
<td>false/true</td>
</tr>
</tbody>
</table>
**CompareGT**

**Library**
Signal\Logical\Boolean

**Use**

**Description**
This model compares two input real signals and outputs the result as a boolean output according to the following table:

<table>
<thead>
<tr>
<th>inputs</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1 &gt; input 2</td>
<td>true</td>
</tr>
<tr>
<td>input1 &lt;= input 2</td>
<td>false</td>
</tr>
</tbody>
</table>

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td>real</td>
<td>First input</td>
<td>real</td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>Result of the input1 &gt; input2</td>
<td>false/true</td>
</tr>
</tbody>
</table>

**CompareLE**

**Library**
Signal\Logical\Boolean

**Use**

**Description**
This model compares two input real signals and outputs the result as a boolean output according to the following table:

<table>
<thead>
<tr>
<th>inputs</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1 &lt;= input 2</td>
<td>true</td>
</tr>
<tr>
<td>input1 &gt; input 2</td>
<td>false</td>
</tr>
</tbody>
</table>

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td>real</td>
<td>First input</td>
<td>real</td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>Result of the input1 &lt;= input2</td>
<td>false/true</td>
</tr>
</tbody>
</table>

20-sim 5.1 Reference Manual
CompareLT

Library
Signal\Logical\Boolean

Use

Description
This model compares two input real signals and outputs the result as a boolean output according to the following table:

<table>
<thead>
<tr>
<th>inputs</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1 &lt; input2</td>
<td>true</td>
</tr>
<tr>
<td>input1 &gt;= input2</td>
<td>false</td>
</tr>
</tbody>
</table>

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>real</td>
<td>First input</td>
<td>real</td>
</tr>
<tr>
<td>input2</td>
<td>real</td>
<td>Second input</td>
<td>real</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>Result of the input1 &lt; input2</td>
<td>false/true</td>
</tr>
</tbody>
</table>

False

Library
Signal\Logical\Boolean

Use

Description
The output signal of this model is equal to false

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>False</td>
<td>false</td>
</tr>
</tbody>
</table>
FTriggerTypeFlipFlop

**Library**
Signal\Logical\Boolean

**Use**
**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Implementations**
This model has a continuous-time and a discrete-time implementation.
- Continuous
- Discrete

**Description**
Initially the output is equal to the parameter `initial`. Otherwise the output signal is changed each time the control input changes from true to false (falling edge of the control input):

\[
\text{output} = \text{not oldoutput}; \ (\text{oldcontrol} = \text{true and control} = \text{false}) \\
\text{output} = \text{oldoutput}; \ (\text{otherwise})
\]

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>control</td>
<td>boolean</td>
<td>control input</td>
<td>false/true</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>output</td>
<td>false/true</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td></td>
<td>initial output</td>
<td>false/true</td>
</tr>
</tbody>
</table>

**Restrictions**
This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

**Invertor**

**Library**
Signal\Logical\Boolean

**Use**
**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
The output signal of this model is according the truth table below:

<table>
<thead>
<tr>
<th>input</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>
**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input</td>
<td>boolean</td>
<td>Invertor input</td>
<td>false/true</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>inverse of the input</td>
<td>false/true</td>
</tr>
</tbody>
</table>

**Restrictions**

This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

**Nand**

**Library**

Signal\Logical\Boolean

**Use**

**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Implementations**

This has 8 implementations varying from a 2-input NAND to a 9-input NAND.

- inputs_2
- inputs_3
- inputs_4
- inputs_5
- inputs_6
- inputs_7
- inputs_8
- inputs_9

**Description**

The output signal of this model is according the truth table below:

<table>
<thead>
<tr>
<th>input1</th>
<th>input2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>

The output signal for the other NAND implementations follows a similar pattern. The output signal is only false when all input signals are equal to true.

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
</table>

20-sim 5.1 Reference Manual
### Inputs

<table>
<thead>
<tr>
<th>Input</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1</td>
<td>boolean</td>
<td>First NAND input</td>
<td>false/true</td>
</tr>
<tr>
<td>input2</td>
<td>boolean</td>
<td>Second NAND input</td>
<td>false/true</td>
</tr>
</tbody>
</table>

### Outputs

<table>
<thead>
<tr>
<th>Output</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>boolean</td>
<td>Result of the NAND operation</td>
<td>false/true</td>
</tr>
</tbody>
</table>

### Restrictions

This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

### Nor

**Library**
Signal\Logical\Boolean

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Implementations**
This block has 8 implementations varying from a 2-input NOR to a 9-input NOR.
- inputs_2
- inputs_3
- inputs_4
- inputs_5
- inputs_6
- inputs_7
- inputs_8
- inputs_9

**Description**
The output signal of this submodel for the two-input NOR is according the truth table below:

<table>
<thead>
<tr>
<th>input1</th>
<th>input2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>

The output signal for the other NOR implementations follows a similar pattern. The output signal is only true when all input signals are equal to false.

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1</td>
<td>boolean</td>
<td>First NOR input</td>
<td>false/true</td>
</tr>
<tr>
<td>input2</td>
<td>boolean</td>
<td>Second NOR input</td>
<td>false/true</td>
</tr>
</tbody>
</table>
11. Library

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>boolean</td>
<td>Result of the NOR operation</td>
<td>false/true</td>
</tr>
</tbody>
</table>

**Restrictions**
This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

**Or**

**Library**
Signal\Logical\Boolean

**Use**

**Implementations**
This block has 8 implementations varying from a 2-input OR to a 9-input OR.
- inputs_2
- inputs_3
- inputs_4
- inputs_5
- inputs_6
- inputs_7
- inputs_8
- inputs_9

**Description**
The output signal of this submodel for the two-input OR is according the truth table below:

<table>
<thead>
<tr>
<th>input1</th>
<th>input2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>true</td>
</tr>
</tbody>
</table>

The output signal for the other OR implementations follows a similar pattern. The output signal is only false when all input signals are equal to false.

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>boolean</td>
<td>First OR input</td>
<td>false/true</td>
</tr>
<tr>
<td>input2</td>
<td>boolean</td>
<td>Second OR input</td>
<td>false/true</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>Result of the OR operation</td>
<td>false/true</td>
</tr>
</tbody>
</table>
**Restrictions**

This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

**ResetSetFlipFlop**

**Library**

Signal\Logical\Boolean

**Use**

Domains: Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Implementations**

This model has a continuous-time and a discrete-time implementation.

- Continuous
- Discrete

**Description**

The initial output of this model is equal to the parameter `initial`. Otherwise the output signal is according the truth table below:

<table>
<thead>
<tr>
<th>set</th>
<th>reset</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>previous output</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>

The truth table shows an R-dominated latch, meaning that if both set and reset are true, the reset input dominates.

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>set</td>
<td>boolean</td>
<td>set input</td>
<td>false/true</td>
</tr>
<tr>
<td>reset</td>
<td>boolean</td>
<td>reset input</td>
<td>false/true</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>output</td>
<td>false/true</td>
</tr>
<tr>
<td>Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>initial</td>
<td>boolean</td>
<td>initial output</td>
<td>false/true</td>
</tr>
</tbody>
</table>

**Restrictions**

This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.
RTriggerTypeFlipFlop

Library
Signal\Logical\Boolean

Use

Implementations
This model has a continuous-time and a discrete-time implementation.
- Continuous
- Discrete

Description
Initially the output is equal to the parameter initial. Otherwise the output signal is changed each time the control input changes from false to true (rising edge of the control input):

\[
\begin{align*}
\text{output} &= \text{not oldoutput;} \quad (\text{oldcontrol} = \text{false and control} = \text{true}) \\
\text{output} &= \text{oldoutput;} \quad \text{(otherwise)}
\end{align*}
\]

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>control</td>
<td>boolean</td>
<td>control input</td>
<td>false/true</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>output</td>
<td>false/true</td>
</tr>
<tr>
<td>Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>initial</td>
<td>boolean</td>
<td>initial output</td>
<td>false/true</td>
</tr>
</tbody>
</table>

Restrictions
This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

SetResetFlipFlop

Library
Signal\Logical\Boolean

Use

Implementations
This model has a continuous-time and a discrete-time implementation.
- Continuous
- Discrete
Description
The initial output of this model is equal to the parameter initial. Otherwise the output signal is according the truth table below:

<table>
<thead>
<tr>
<th>set</th>
<th>reset</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>previous output</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true set condition</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>false reset condition</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>true set condition</td>
</tr>
</tbody>
</table>

The truth table shows an S-dominated latch, meaning that if both set and reset are true, the set input dominates.

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>set</td>
<td>boolean</td>
<td>set input</td>
<td>false/true</td>
</tr>
<tr>
<td>reset</td>
<td>boolean</td>
<td>reset input</td>
<td>false/true</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>output</td>
<td>false/true</td>
</tr>
<tr>
<td>Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>initial</td>
<td>boolean</td>
<td>initial output</td>
<td>false/true</td>
</tr>
</tbody>
</table>

Restrictions
This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

True

Library
Signal\Logical\Boolean

Use

Description
The output signal of this model is equal to true

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>True</td>
<td>true</td>
</tr>
</tbody>
</table>
Xor

Library
Signal\Logical\Boolean

Use

Implementations
This block has 8 implementations varying from a 2-input XOR to a 9-input XOR.
- inputs_2
- inputs_3
- inputs_4
- inputs_5
- inputs_6
- inputs_7
- inputs_8
- inputs_9

Description
The output signal of this submodel for the two-input XOR is according the truth table below:

<table>
<thead>
<tr>
<th>input1</th>
<th>input2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>

The output signal for the other XOR implementations follows a similar pattern. The output signal is only true when there are an odd number of true inputs.

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>boolean</td>
<td>First XOR input</td>
<td>false/true</td>
</tr>
<tr>
<td>input2</td>
<td>boolean</td>
<td>Second XOR input</td>
<td>false/true</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>Result of the XOR operation</td>
<td>false/true</td>
</tr>
</tbody>
</table>

Restrictions
This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.
Real

And

Library
Signal\Logical\Real

Use

Implementations
This has 8 implementations varying from a 2-input AND to a 9-input AND.

- inputs_2
- inputs_3
- inputs_4
- inputs_5
- inputs_6
- inputs_7
- inputs_8
- inputs_9

Description
The output signal of this model is according the truth table below:

<table>
<thead>
<tr>
<th>input1</th>
<th>input2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>true</td>
</tr>
</tbody>
</table>

with

<table>
<thead>
<tr>
<th></th>
<th>false</th>
<th>true</th>
</tr>
</thead>
<tbody>
<tr>
<td>inputs</td>
<td>&lt;= 0.5</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>output</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

The output signal for the other AND implementations follows a similar pattern. The output signal is only true when all input signals are equal to true.

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>real</td>
<td>First AND input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>input2</td>
<td>real</td>
<td>Second AND input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td>Result of the AND operation</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>
Restrictions
This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.

Clock

Library
Signal\Logical\Real

Use

Implementations
This model has a continuous-time and a discrete-time implementation.
- Continuous
- Discrete

Description
This models generates a logical continuous clock signal, i.e. a signal that changes from true (1) to false (0) and back, each period T with T = (1/frequency)

![Clock signal diagram](image)

If the discrete implementation is chosen, the frequency must be smaller than half of the sample frequency, otherwise not a good clock signal will result. To have the top part of the clock signal equally long to the down part, choose the frequency equal to the sample frequency divided by 2^n, with n an integer equal or larger than one.

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
</tr>
</thead>
</table>
### Parameters

<table>
<thead>
<tr>
<th></th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>real</td>
<td>initial output</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>frequency</td>
<td>real</td>
<td>clock frequency {Hz}</td>
<td>&gt; 0.0 Hz</td>
</tr>
</tbody>
</table>

### Outputs

<table>
<thead>
<tr>
<th></th>
<th>Data type</th>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>real</td>
<td>Clock output</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>

### Restrictions

Make sure that the simulation uses step sizes which are small enough to calculate the clock signal going up and going down: step size << clock period.

---

**CMOS_CD4020**

### Library

Signal\Logical\Real

### Use

**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

### Description

Binary counter modeled after the CMOS 4020 chip. The 4020 is a 14-stage binary ripple counter with a clock input (CP), an overriding asynchronous master reset input (MR) and 12 buffered parallel outputs (Q0, and Q3 to Q13). The counter advances on the 1-to-0 transition of CP. A HIGH on MR clears all counter stages and forces all outputs to 0, independent of the state of CP.

### Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP</td>
<td>real</td>
<td>clock input (HIGH-to-LOW, edge-triggered)</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>MR</td>
<td>real</td>
<td>master reset input (active HIGH)</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q0 ... Q13</td>
<td>real</td>
<td>parallel outputs</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>

### Restrictions

This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.

---

**CompareGE**

### Library

Signal\Logical\Real

### Use

**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

### Description

This model compares two input real signals and outputs the result as 0 or 1 according to the following table:
CompareGT

Library
Signal\Logical\Real

Use

Description
This model compares two input real signals and outputs the result as 0 or 1 according to the following table:

<table>
<thead>
<tr>
<th>inputs</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1 &gt;= input2</td>
<td>1</td>
</tr>
<tr>
<td>input1 &lt; input2</td>
<td>0</td>
</tr>
</tbody>
</table>

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>real</td>
<td>First input</td>
<td>real</td>
</tr>
<tr>
<td>input2</td>
<td>real</td>
<td>Second input</td>
<td>real</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td>Result of the input1 &gt;= input2</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>

CompareLE

Library
Signal\Logical\Real

Use

Description
This model compares two input real signals and outputs the result as 0 or 1 according to the following table:

<table>
<thead>
<tr>
<th>inputs</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1 &gt; input 2</td>
<td>1</td>
</tr>
<tr>
<td>input1 &lt;= input2</td>
<td>0</td>
</tr>
</tbody>
</table>

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>real</td>
<td>First input</td>
<td>real</td>
</tr>
<tr>
<td>input2</td>
<td>real</td>
<td>Second input</td>
<td>real</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td>Result of the input1 &gt; input2</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>
### CompareLT

**Library**
Signal\Logical\Real

**Use**
Domains: Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This model compares two input real signals and outputs the result as 0 or 1 according to the following table:

<table>
<thead>
<tr>
<th>inputs</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1 &lt; input2</td>
<td>1</td>
</tr>
<tr>
<td>input1 &gt;= input2</td>
<td>0</td>
</tr>
</tbody>
</table>

### Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>input1</td>
<td>real</td>
<td>First input</td>
<td>real</td>
</tr>
<tr>
<td>input2</td>
<td>real</td>
<td>Second input</td>
<td>real</td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td>Result of the input1 &lt;= input2</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>

---

### DTypeFlipFlop

**Library**
Signal\Logical\Real

**Use**
Domains: Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Implementations**
This model has a continuous-time and a discrete-time implementation.
- Continuous
- Discrete
**Description**

The initial output of this model is equal to the initial value $oldoutput\_initial$. Otherwise the output signal is equal to the input signal each time the control input changes from false to true:

$$output = input; \ (oldcontrol = false \ and \ control = true)$$
$$output = oldoutput; \ (otherwise)$$

with

<table>
<thead>
<tr>
<th>false</th>
<th>true</th>
</tr>
</thead>
<tbody>
<tr>
<td>inputs</td>
<td>&lt;= 0.5 &gt; 0.5</td>
</tr>
<tr>
<td>output</td>
<td>0.0    1.0</td>
</tr>
</tbody>
</table>

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input</td>
<td>real</td>
<td>input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>control</td>
<td>real</td>
<td>control input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td>output</td>
<td>0 or 1</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>oldcontrol_initial</td>
<td>real</td>
<td>Initial value of the control signal.</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>oldoutput_initial</td>
<td>real</td>
<td>Initial value of the output</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
</tbody>
</table>

**Restrictions**

This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.

**False**

**Library**

Signal\Logical\Real

**Use**


**Description**

The output signal of this model is equal to 0

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td>False</td>
<td>0</td>
</tr>
</tbody>
</table>
FTriggerTypeFlipFlop

Library
Signal\Logical\Real

Use

Implementations
This model has a continuous-time and a discrete-time implementation.
- Continuous
- Discrete

Description
Initially the output is equal to the parameter initial. Otherwise the output signal is changed each time the control input changes from true to false (falling edge of the control input):

\[
\text{output} = \begin{cases} 
\text{not oldoutput} & (\text{oldcontrol} = \text{true and control} = \text{false}) \\
\text{oldoutput} & (\text{otherwise}) 
\end{cases}
\]

with

<table>
<thead>
<tr>
<th>inputs</th>
<th>false</th>
<th>true</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;= 0.5</td>
<td></td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>output</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>control</td>
<td>real</td>
<td>control input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td>output</td>
<td>1 or 0</td>
</tr>
<tr>
<td>Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>initial</td>
<td>real</td>
<td>initial output</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
</tbody>
</table>

Restrictions
This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.

Invertor

Library
Signal\Logical\Real

Use

Description
The output signal of this model is according the truth table below:
### Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>boolean</td>
<td>Invertor input</td>
<td>( \leq 0.5 / &gt; 0.5 )</td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>inverse of the input</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>

### Restrictions

This block operates with boolean inputs. Real of integer inputs can also be used but will lead to a warning during processing. Be careful with using real or integer inputs: A value of 0.0 is converted to false, any other value is converted to true.

### Nand

**Library**

Signal\Logical\Real

**Use**


**Implementations**

This has 8 implementations varying from a 2-input NAND to a 9-input NAND.

- inputs_2
- inputs_3
- inputs_4
- inputs_5
- inputs_6
- inputs_7
- inputs_8
- inputs_9

**Description**

The output signal of this model is according the truth table below:

<table>
<thead>
<tr>
<th>input1</th>
<th>input2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>

with
The output signal for the other NAND implementations follows a similar pattern. The output signal is only false when all input signals are equal to true.

### Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>real</td>
<td>First AND input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>input2</td>
<td>real</td>
<td>Second AND input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td>Result of the NAND operation</td>
<td>1 or 0</td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Restrictions

This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.

### Nor

#### Library

Signal\Logical\Real

#### Use

Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

#### Implementations

This has 8 implementations varying from a 2-input NOR to a 9-input NOR.

- inputs_2
- inputs_3
- inputs_4
- inputs_5
- inputs_6
- inputs_7
- inputs_8
- inputs_9

#### Description

The output signal of this submodel for the two-input NOR is according the truth table below:

<table>
<thead>
<tr>
<th>input1</th>
<th>input2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>
The output signal for the other NOR implementations follows a similar pattern. The output signal is only true when all input signals are equal to false.

### Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>real</td>
<td>First AND input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>input2</td>
<td>real</td>
<td>Second AND input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td>Result of the NOR operation</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>

### Restrictions

This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.

### Or

**Library**

Signal\Logical\Real

**Use**

**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Implementations**

This has 8 implementations varying from a 2-input AND to a 9-input AND.

- inputs_2
- inputs_3
- inputs_4
- inputs_5
- inputs_6
- inputs_7
- inputs_8
- inputs_9

**Description**

The output signal of this submodel for the two-input OR is according the truth table below:

<table>
<thead>
<tr>
<th>input1</th>
<th>input2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
</tbody>
</table>
with

<table>
<thead>
<tr>
<th></th>
<th>false</th>
<th>true</th>
</tr>
</thead>
<tbody>
<tr>
<td>inputs</td>
<td>&lt;= 0.5</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>output</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

The output signal for the other OR implementations follows a similar pattern. The output signal is only 0 when all input signals are equal to 0.

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>input1</td>
<td>real</td>
<td>First OR input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>input2</td>
<td>real</td>
<td>Second OR input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>output</td>
<td>real</td>
<td>Result of the OR operation</td>
<td>1 or 0</td>
</tr>
</tbody>
</table>

**Restrictions**

This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.

**ResetSetFlipFlop**

**Library**

Signal\Logical\Real

**Use**


**Implementations**

This model has a continuous-time and a discrete-time implementation.

- Continuous
- Discrete

**Description**

The initial output of this model is equal to the parameter initial. Otherwise the output signal is according the truth table below:

<table>
<thead>
<tr>
<th>set</th>
<th>reset</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>previous output</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>
The truth table shows an R-dominated latch, meaning that if both set and reset are true, the reset input dominates.

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td>boolean</td>
<td>set input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td></td>
<td>boolean</td>
<td>reset input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>Outputs</td>
<td>boolean</td>
<td>output</td>
<td>1 or 0</td>
</tr>
<tr>
<td>Parameters</td>
<td>boolean</td>
<td>initial output</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
</tbody>
</table>

**Restrictions**

This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.

**RTriggerTypeFlipFlop**

**Library**

Signal\Logical\Real

**Use**


**Implementations**

This model has a continuous-time and a discrete-time implementation.

- Continuous
- Discrete

**Description**

Initially the output is equal to the parameter initial. Otherwise the output signal is changed each time the control input changes from false to true (rising edge of the control input):

\[
\text{output} = \text{not oldoutput}; \ (\text{oldcontrol} = \text{false and control} = \text{true}) \\
\text{output} = \text{oldoutput}; \ (\text{otherwise})
\]

with

<table>
<thead>
<tr>
<th></th>
<th>false</th>
<th>true</th>
</tr>
</thead>
<tbody>
<tr>
<td>inputs</td>
<td>&lt;= 0.5</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>output</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>


### SetResetFlipFlop

#### Library

Signal\Logical\Real

#### Use

**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

#### Implementations

This model has a continuous-time and a discrete-time implementation.

- Continuous
- Discrete

#### Description

The initial output of this model is equal to the parameter *initial*. Otherwise the output signal is according the truth table below:

<table>
<thead>
<tr>
<th>set</th>
<th>reset</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>previous output</td>
</tr>
<tr>
<td>true</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>false</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>true</td>
</tr>
</tbody>
</table>

with

<table>
<thead>
<tr>
<th></th>
<th>false</th>
<th>true</th>
</tr>
</thead>
<tbody>
<tr>
<td>inputs</td>
<td>&lt;= 0.5</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>output</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

The truth table shows an S-dominated latch, meaning that if both set and reset are true, the set input dominates.

#### Interface

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>control</td>
<td>boolean</td>
<td>control input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>output</td>
<td>boolean</td>
<td>output</td>
<td>1 or 0</td>
</tr>
<tr>
<td>initial</td>
<td>boolean</td>
<td>initial output</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
</tbody>
</table>

#### Restrictions

This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.
### Inputs

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>set</td>
<td>boolean</td>
<td>set input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
<tr>
<td>reset</td>
<td>boolean</td>
<td>reset input</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
</tbody>
</table>

### Outputs

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>boolean</td>
<td>output</td>
<td>0 or 1</td>
</tr>
</tbody>
</table>

### Parameters

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>boolean</td>
<td>initial output</td>
<td>&lt;= 0.5 / &gt; 0.5</td>
</tr>
</tbody>
</table>

### Restrictions

This block operates with real inputs. Boolean inputs can also be used but will lead to a warning during processing.

### TriggerTypeFlipFlop

This model has been renamed to RTriggerTypeFlipFlop. Please use the RTriggerTypeFlipFlop, because the TriggerTypeFlipFlop will be removed from future versions of 20-sim.

### True

**Library**
Signal\Logical\Real

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
The output signal of this model is equal to 1.0 (true)

**Interface**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Data type</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outputs</td>
<td>real</td>
<td>1.0</td>
<td>fixed output</td>
</tr>
</tbody>
</table>

### Xor

**Library**
Signal\Logical\Real

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
The output signal of this model is according the truth table below:

<table>
<thead>
<tr>
<th>input2</th>
<th>false</th>
<th>true</th>
</tr>
</thead>
</table>
## Signal Processing

### AmplitudeSensor

**Library**
Signal\Signal Processing

**Use**
**Domains:** Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description**
This model measures the amplitude of harmonic signals, i.e. periodic signals, that go through zero twice every period. For half a period (between the passes through zero) the input signal is monitored. The largest value is stored and given as the absolute output signal, the next half period. That is why this sensor always has an output delay of half a period.
### Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>Initial output value</td>
</tr>
</tbody>
</table>

### AssertSignal

**Library**

Signal\Signal Processing

**Use**

Domains: Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.
Introduction
The AssertSignal model can be used to test if model gives the correct outcome (test) during a simulation, by comparing it with a known signal (valid). If the difference is smaller than a preset tolerance, the output boolean signal testResult is true. If the difference is larger than the tolerance, the boolean signal testResult becomes false and stays false until the end of the simulation run. In combination with the Scenario Manager you can use this for test automation.

Description - Default
This model compares a test input signal with a valid input signal. If both signals are the same within a given tolerance, the testResult is true:

\[
\text{if } \text{abs(valid - test)} < \text{tolerance} \\
\text{testresult} = \text{true} \\
\text{timeAtFailure} = -1 \\
\text{else} \\
\text{testresult} = \text{true} \\
\text{timeAtFailure} = \text{first time when condition failed}
\]

Description - Boolean
This model compares a test input signal with a valid input signal. If both signals are the same, the testresult is true:

\[
\text{if } \text{valid} = \text{test} \\
\text{testresult} = \text{true} \\
\text{timeAtFailure} = -1 \\
\text{else} \\
\text{testresult} = \text{true} \\
\text{timeAtFailure} = \text{first time when condition failed}
\]

Interface

Inputs

test
valid

Outputs

testResult boolean
timeAtFailure time at which

Parameters

tolerance > 0
Maximum

Library
Signal\Signal Processing

Use

Description
This submodel yields the maximum value of an input signal.

Interface

Inputs | Description
-------|------------
input   | Input signal

Outputs | Description
-------|------------
output  | Maximum value of the input signal

Mean

Library
Signal\Signal Processing

Use

Description
This submodel yields the mean of an input signal using the integral function:

\[ output = \frac{\text{int}(input)}{\text{time}} \]

Interface

Inputs | Description
-------|------------
input   | Input signal

Outputs | Description
-------|------------
output  | Mean value of the input signal
**Minimum**

**Library**
Signal\Signal Processing

**Use**

**Domains**: Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This submodel yields the minimum value of an input signal.

**Interface**

<table>
<thead>
<tr>
<th><strong>Inputs</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>Input signal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Outputs</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>Minimum value of the input signal</td>
</tr>
</tbody>
</table>

**MovingAverage**

**Library**
Signal\Signal Processing

**Use**

**Domains**: Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This submodel yields the average of an input signal over a window $T_0$ (s) using an integral function:

$$\text{output} = \frac{\text{int}(\text{input},0)}{T_0}$$

**Interface**

<table>
<thead>
<tr>
<th><strong>Inputs</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>Input signal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Outputs</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Parameters</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>Time window</td>
</tr>
</tbody>
</table>
PhaseSensor

Library
Signal\Signal Processing

Use

Description
This model measures the phase of a harmonic signals (i.e. periodic signals, that go through zero twice every period) with respect to another harmonic signal. Two inputs are used:

- Reference
- Input

The PhaseSensor block measures the zero crossings of both the input and the reference, to assess the phase difference between both. The phase output is the phase of the input signal with respect to the reference signal. The measurement will not work if the input sines have a non-zero mean.

![Graph](image)

Interface

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>the signal of which the phase is measured</td>
</tr>
</tbody>
</table>
Library

Signal\Signal Processing

Use

Description
This submodel yields the root mean square of an input signal using an integral function:

\[ output = \sqrt{ \int \text{input}^2 / \text{time} } \]

Interface

Inputs
input
Description
Input signal

Outputs
output

StandardDeviation

Library
Signal\Signal Processing

Use

Description
This submodel yields the standard deviation of an input signal using an integral function:

\[ output = \sqrt{ \int \left( \text{input} - \text{mean} \right)^2 / \text{time} } \]

where mean is the mean of the input
Interface

Inputs
input

Description
Input signal

Outputs
output

Standard deviation of the input signal

Variance

Library
Signal\Signal Processing

Use

Description
This submodel yields the variance of an input signal using an integral function:

\[ output = \int \frac{(input - mean)^2}{time} \]

where mean is the mean of the input

Interface

Inputs
input

Description
Input signal

Outputs
output

Variance of the input signal

11.3.11 Sources

Constant

Library
Signal\Sources

Use

Description
The output of this model is equal to the parameter C.
\[ output = C; \]

**Interface**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

| C       | The output is equal to C. |

**DataFromFile**

**Library**

Signals\Sources

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**

This is a masked model which opens the Data Input Wizard when edited. You can use this wizard to open a data file.
### Items

- **Filename**: Enter the filename of the datafile or use the *Browse* button.
- **Name in 20-sim**: The 20-sim name that corresponds with the column data. You can enter any desired name.
- **Variable / Output**: The data may be a variable (useful for plotting in the simulator) or an output of the model (use as an input for other models).
- **More / Less**: If you open the options below with the *More* button.
- **Time**: The column that stores the time data and the units in which the time data is stored (seconds, milliseconds,...)
- **Offset First Data Point**: If the file data is a recording that starts at for example 11.1 s, the simulation will not show any output until the time has passed 11.1 s. You can force the simulation to start at 0 s by selecting the *Offset First Data Point* option.

### Interface

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>outputs</td>
<td>user defined outputs</td>
</tr>
</tbody>
</table>
File format
20-sim supports data files in Comma Separated Values format (.csv). The first line is used as a header describing the column name. Without a proper header line, you have to define the 20-sim variable names for each column yourself. The first column should always contain the time values. The other columns should contain the corresponding data values (see also data).

Example CSV file format with header:

"time","x","y"
0.0, 1, 2
0.1, 5, 10
0.2, 6, 11

Compatibility
This model has been extended in 20-sim 4.8 and is not backward compatible with previous versions of 20-sim! It means that once you have opened the Data Input Wizard the model can only be run in 20-sim 4.8 or higher.

Joystick

Library
Signal\Sources

Use

Description
This model uses the joystick.dll function to get a joystick input.

Tips
- Use attempting real-time simulation when using joystick input to prevent the simulation from being calculated to quickly.

Interface

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>outputs</td>
<td>Various outputs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>Various scaling parameters</td>
</tr>
</tbody>
</table>
### Keyboard

**Library**
Signal\Sources

**Use**

**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model uses the keyboard.dll function to get a keyboard input. The keyboard input is an integer number and displayed by the output signal `keycode`. The default model has four additional output signals with a default value of zero and a value of 1 when the keyboard arrows are pressed.

**Tips**
- Inspect the contents of the model and change it to read other keyboard inputs.
- Open the Example model `Examples/2D mechanics/ScaraRobotKeyboard` to see a demonstration of the keyboard input.
- Use attempting real-time simulation when using keyboard inputs to prevent the simulation from being calculated to quickly.

**Interface**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>left</td>
<td>left keyboard arrow pressed</td>
</tr>
<tr>
<td>right</td>
<td>right keyboard arrow pressed</td>
</tr>
<tr>
<td>up</td>
<td>up keyboard arrow pressed</td>
</tr>
<tr>
<td>down</td>
<td>down keyboard arrow pressed</td>
</tr>
<tr>
<td>keycode</td>
<td>number of the keyboard input</td>
</tr>
</tbody>
</table>

**Parameters**

- **Scale**
  - Various scaling parameters

---

### MotionProfile

**Library**
Signal\Sources

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Description**
This is a masked model which opens the Motion Profile Editopr when edited.

**Interface**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
</table>

---
Parameters
stroke amplitude of the profile
start_time start time of the profile
stop_time time when the maximum is reached
return_time start time of the return motion
end_time finish time of the return motion
period period of the profile

Tip
For advanced options with motion profiles you can use the Motion Profile Wizard block.

MotionProfile-Wizard

Library
Signals\Sources
Use
Description
This is a masked model which opens the Motion Profile Wizard when edited. Depending on the selections entered, various motion profiles can be generated.

Interface

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>position</td>
</tr>
<tr>
<td>v</td>
<td>velocity</td>
</tr>
<tr>
<td>a</td>
<td>acceleration</td>
</tr>
</tbody>
</table>

Parameters
stroke amplitude of the profile
start_time start time of the profile
stop_time time when the maximum is reached
return_time start time of the return motion
end_time finish time of the return motion
period period of the profile
One

Library
Signal\Sources
Use
Description
The output of this model is equal to one.

\[
\text{output} = 1.0;
\]

Interface

Outputs | Description
--- | ---
output | 

Pi

Library
Signal\Sources
Use
Description
The output of this model is equal to pi.

\[
\text{output} = \pi;
\]

Interface

Outputs | Description
--- | ---
output | 

SignalGenerator-Cycloid

Library
Signal\Sources
Use
Description
This model generates a cycloidal step signal:
\[ t\Delta = 2\pi \frac{(time - start\_time)}{(stop\_time - start\_time)} \]

\[
\text{output} = 0; \ (t\Delta < 0) \\
\text{output} = \text{amplitude} \frac{(t\Delta - \sin(t\Delta))}{2\pi}; \ (0 \leq t\Delta \leq 2\pi) \\
\text{output} = \text{amplitude}; \ (t\Delta > 2\pi)
\]

**Interface**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

- **start\_time**: The start time of the step.
- **stop\_time**: The stop time of the step.
- **amplitude**: The amplitude of the step.

---

**SignalGenerator-FileInput**

**Library**
Signal\Source

**Use**

**Domains**: Continuous. **Size**: 1-D. **Kind**: Block Diagrams.

**Note**
This model is obsolete. Use the DataFromFile block instead to read data file.

**Description**
This model generates an output by linear interpolation of data read from file. The data on file is stored in columns. The first column contains the time values \(t\) and the second column contains the corresponding output values \(y\).

- The time data of the first column needs to be monotonically increasing.
- Discontinuities are allowed, by providing the same time point twice in the table.
- Values outside of the range, are computed by linear extrapolation of the last two points.
file:

0  0.5
0.5 -1
2.5 -1
3.5  0
4.5  1
5.5  1.75
7   2.5
8   2.5

Example of an input file.

The input file must be an ASCII (text) file and should consist at least two columns of data. The first column (number 0) should always contain the time values. The other columns (number 1, 2, 3, etc.) should contain the corresponding data values. The parameter `column` is used to specify which column is used for as output data.

The various values must be separated by a comma, a space or a tab. Each new set of time and data values must start on a new line. No comment or other text may be part of the file. The filename of the input file can be specified using the complete path (e.g. c:\data\data.tbl ). When no path is given, the file is assumed to be in the experiment directory.

**Interface**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>filename</td>
<td>Filename of the input file.</td>
</tr>
<tr>
<td>column</td>
<td>column number.</td>
</tr>
</tbody>
</table>

**Example**

Example data.tbl file with header and 1 column with data:

"time","y"
0.0, 0.5
0.5, -1
2.5, -1
3.6, 9
SignalGenerator-Gaussian Noise

Library
Signal\Sources

Implementations
frequency_limited_FOH
frequency_limited_ZOH
unlimited

Use

Description - frequency_limited_FOH
This model generates a gaussian noise signal with gaussian distribution and variance 1 and random seed s. The noise is multiplied by the parameter amplitude.

\[ output = \text{amplitude} \times \text{gauss}(1,seed); \]

The noise signal is limited to a maximum frequency, which can be adjusted (parameter). Values in-between two noise samples are interpolated (first order hold).

Interface - frequency_limited_FOH

Outputs
output

Parameters
seed random seed
amplitude output scaling factor: does not influence the distribution
frequency frequency band of the noise

Description - frequency_limited_ZOH
This model generates a gaussian noise signal with gaussian distribution and variance 1 and random seed s. The noise is multiplied by the parameter amplitude.

\[ output = \text{amplitude} \times \text{gauss}(1,seed); \]

The noise signal is limited to a maximum frequency, which can be adjusted (parameter). Values in-between two noise samples are interpolated (first order hold).

Interface - frequency_limited_ZOH

Outputs
output

Parameters
seed random seed
amplitude  output scaling factor: does not influence the distribution
frequency  frequency band of the noise

**Description - unlimited**
This model generates a gaussian noise signal with gaussian distribution and variance 1 and random seed s. The noise is multiplied by the parameter amplitude.

\[ output = amplitude \times \text{gauss}(1, \text{seed}); \]

The noise signal has no frequency limitation.

**Note**
It is advised only to use this implementation with fixed step integration methods such as Euler and Runge Kutta 2/4. If you run this implementation with a variable step integration method, simulations may get very slow!

**Interface - unlimited**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>seed</th>
<th>random seed</th>
</tr>
</thead>
<tbody>
<tr>
<td>amplitude</td>
<td>output scaling factor: does not influence the distribution</td>
</tr>
</tbody>
</table>

**Limitations**
seed must be a number in the region \(<0,65000>\).

**Random Seed**

20-sim generates a sequence of random numbers for each simulation differently depending upon the value of the random seed parameter. The random noise function and gaussian noise function are affected by this. The default value of the random seed is 0. The maximum value is 65000.

**Default value (0)**
When the random seed value is 0 (default value), 20-sim generates a new sequence of random numbers for each simulation and for each new random function. E.g. when two random functions with default random seed value (0) are used in one model, they will generate different sequences of random numbers during a simulation.

**Other values (>0)**
When the random seed value is chosen larger than zero, 20-sim generates the same sequence of random numbers for each simulation. Moreover 20-sim will generate the same sequence of random numbers for each random function that uses the same random seed parameter (>0). E.g. when two random functions with random seed value 50, are used in one model, they will generate the same sequence of random numbers during a simulation.
SignalGenerator-Pulse

Library
Signal\Sources

Use

Description
This models yields a pulse signal:

\[
\begin{align*}
\text{output} &= 0; \ (\text{time} < \text{start\_time}) \\
\text{output} &= \text{amplitude}; \ (\text{start\_time} \leq \text{time} \leq \text{stop\_time}) \\
\text{output} &= 0; \ (\text{time} \geq \text{stop\_time})
\end{align*}
\]

Interface

Outputs
output

Parameters
start_time  The start time of the pulse.
stop_time  The stop time of the pulse.
amplitude  The amplitude of the step.

SignalGenerator-Ramp

Library
Signal\Sources

Use

Description
This models yields a ramp signal:

\[
\begin{align*}
\text{output} &= 0; \ (\text{time} < \text{start\_time}) \\
\text{output} &= \text{slope} \times \text{ramp(start\_time)}; \ (\text{time} \geq \text{start\_time})
\end{align*}
\]

Interface

Outputs
output
Parameters

start_time  The start time of the ramp.
slope  The slope of the ramp.

SignalGenerator-Random

Library
Signal\Sources

Implementations
frequency_limited_FOH
frequency_limited_ZOH
unlimited

Use

Description - frequency_limited_FOH
This model generates a random (noise) signal with values between \(-amplitude\) and \(+amplitude\) and random seed s. The

\[
output = \text{ran}(ampl, seed);
\]

The noise signal is limited to a maximum frequency, which can be adjusted (parameter). Values in-between two noise samples are interpolated (first order hold).

Interface - frequency_limited_FOH

Outputs  Description
output

Parameters

seed  random seed
amplitude  \(-amplitude <= output <= +amplitude\)
frequency  frequency band of the noise

Description - frequency_limited_ZOH
This model generates a random (noise) signal with values between \(-amplitude\) and \(+amplitude\) and random seed s.

\[
output = \text{ran}(ampl, seed);
\]

The noise signal is limited to a maximum frequency, which can be adjusted (parameter). Values in-between two noise samples are interpolated (first order hold).
Interface - frequency_limited_ZOH

Outputs
output

Parameters
seed         random seed
amplitude    -amplitude <= output <= +amplitude
frequency    frequency band of the noise

Description - unlimited
This model generates a random (noise) signal with values between -amplitude and +amplitude and random seed s.

\[ output = \text{ran}(\text{ampl}, \text{seed}); \]

The noise signal has no frequency limitation.

Note
It is advised only to use this implementation with fixed step integration methods such as Euler and Runge Kutta 2/4. If you run this implementation with a variable step integration method, simulations may get very slow!

Interface - unlimited

Outputs
output

Parameters
seed         random seed
amplitude    -amplitude <= output <= +amplitude

Limitations
seed must be a number in the region <0,65000>.

SignalGenerator-Step

Library
Signal\Sources

Use

Description
This models yields a step signal:
output = 0; (time < start time)
output = amplitude; (time >= start_time)

Interface

Outputs
output

Parameters
start_time  The start time of the step.
amplitude   The amplitude of the step.

SignalGenerator-StepTime

Library
Signal\Sources

Use

Description
This model generates an output signal equal to the simulator time step.

Interface

Outputs
output  Simulated time.

Signalgenerator-Sweep

Library
Signal\Sources

Implementations
Default
Logarithmic
ZeroMean

Use

Description - Default
The output of this model is a linear sine sweep. The signal starts with angular frequency "omega_start" and ends at an angular frequency "omega_stop".
In the picture below the three available sweep functions are shown. The curve on top shows the linear sine sweep. The middle curve shows the logarithmic sine sweep and the bottom curve shows the linear sine sweep with zero mean.

**Interface - Default**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

- start_time: The start time of the sweep.
- stop_time: The stop time of the sweep.
- amplitude: The amplitude of the sweep.
- omega_start: The start frequency of the sweep.
- omega_stop: The stop frequency of the sweep.

**Description - Logarithmic**

The output of this model is a logarithmic sine sweep. Compared to the linear sine sweep the lower frequencies are stretched out and the higher frequencies are squeezed. The signal starts with angular frequency "omega_start" and ends at an angular frequency "omega_stop".

In the picture below the three available sweep functions are shown. The curve on top shows the linear sine sweep. The middle curve shows the logarithmic sine sweep and the bottom curve shows the linear sine sweep with zero mean. The middle curve clearly uses more time for the lower frequencies and less time for the higher frequencies.
Interface - Logarithmic

Outputs

Description

output

Parameters

The start time of the sweep.

The stop time of the sweep.

The amplitude of the sweep.

The start frequency of the sweep.

The stop frequency of the sweep.

Description - ZeroMean

The output of this model is a linear sine sweep with compensation in the first period to get a zero mean output. A zero mean is important when the signal is integrated twice. To prevent drift the mean should be zero. Double integrals can occur in physical systems. For example when a force sweep is applied to a mechanical system and the position is measured, the mean force should be precisely zero to prevent the system from drifting away. The signal starts with angular frequency "omega_start" and ends at an angular frequency "omega_stop".

In the picture below the three available sweep functions are shown. The curve on top shows the linear sine sweep. The middle curve shows the logarithmic sine sweep and the bottom curve shows the linear sine sweep with zero mean. The bottom curve differs slightly from the top curve in the first period.
Interface - ZeroMean

Outputs
output

Parameters
start_time  The start time of the sweep.
stop_time   The stop time of the sweep.
amplitude   The amplitude of the sweep.
omega_start The start frequency of the sweep.
omega_stop  The stop frequency of the sweep.

SignalGenerator-Time

Library
Signal\Sources

Use

Description
This model generates an output signal equal to the (simulated) time.
output = time;

**Interface**

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**SignalMonitor**

**Library**

Signal\Block Diagram , Signal\Sources

**Use**

Domains: Continuous, Discrete. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**

This model shows the value of its input in the Simulator. When you open the Simulator (select Properties and Plot) the input of this model is automatically selected as plotvariable. As label for this variable the local name of the SignalMonitor model is chosen. It is therefore advised to give each SignalMonitor model a useful name (select the model, click the right mouse button and select Attributes from the right mouse menu).

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**WaveGenerator-Cosine**

**Library**

Signal\Sources

**Use**

Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**

This model generates a cosine wave.

\[
output = amplitude * \cos(omega * time);
\]

**Interface**

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
</table>
output

**Parameters**
- **amplitude**: The amplitude of the wave.
- **omega**: The angular frequency of the wave.

---

**WaveGenerator-PhasedSine**

**Library**
Signal\Sources

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model generates a sine wave with phase shift.

\[
output = amplitude \times \sin(omega \times time + phase);
\]

**Interface**

**Outputs**
- **output**

**Parameters**
- **amplitude**: The amplitude of the wave.
- **omega**: The angular frequency of the wave.
- **phase**: The phase shift of the wave.

---

**WaveGenerator-Saw**

**Library**
Signal\Source

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model generates a saw wave.
output = upward ramp; (each cycle)

**Interface**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>amplitude</td>
<td>The amplitude of the wave.</td>
</tr>
<tr>
<td>omega</td>
<td>The angular frequency of the wave.</td>
</tr>
</tbody>
</table>

**WaveGenerator-Sine**

**Library**
Signal\Sources

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model generates a sine wave.

\[
output = amplitude \cdot \sin(\omega \cdot time);
\]

**Interface**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>amplitude</td>
<td>The amplitude of the wave.</td>
</tr>
<tr>
<td>omega</td>
<td>The angular frequency of the wave.</td>
</tr>
</tbody>
</table>

**WaveGenerator-Square**

**Library**
Signal\Sources

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model generates a block wave:
output = amplitude; (first wave halve)
output = 0; (second wave halve)

**Interface**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters**

| amplitude | The amplitude of the wave. |
| omega     | The angular frequency of the wave. |

**WaveGenerator-SquareExp**

**Library**

Signal\Sources

**Use**

**Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**

This model generates a non-ideal block wave. The steepness of the edges are defined by the rise time. The rise time is defined as 63% of the amplitude being reached.

![Exponential Block](image)

The output can be described as an exponential function:
\[
\text{output} = \text{amplitude} \times (1 - \exp(\text{time}/\text{rise\_time})); \text{ (first wave halve)} \\
\text{output} = \text{amplitude} \times \exp(\text{time}/\text{rise\_time}); \text{ (second wave halve)}
\]

### Interface

**Outputs**
- output

**Parameters**
- amplitude: The amplitude of the wave.
- omega: The angular frequency of the wave.
- rise\_time: Rise time

---

### WaveGenerator-Triangle

**Library**
- Signal\Sources

**Use**
- **Domains**: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
- This model generates a triangular wave.

\[
\text{output} = \text{upward ramp}; \text{ (first wave halve)} \\
\text{output} = \text{downward ramp}; \text{ (second wave halve)}
\]

### Interface

**Outputs**
- output

**Parameters**
- amplitude: The amplitude of the wave.
- omega: The angular frequency of the wave.
### Zero

**Library**
Signal\Sources

**Use**

**Description**
The output of this model is equal to zero.

\[
\text{output} = 0.0;
\]

**Interface**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

### 11.3.12 Stochastic

#### Mean

**Library**
Signal\Signal Processing

**Use**

**Description**
This submodel yields the mean of an input signal using the integral function:

\[
\text{output} = \frac{\text{int(input)}}{\text{time}}
\]

**Interface**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>Input signal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>Mean value of the input signal</td>
</tr>
</tbody>
</table>
SignalGenerator-Gaussian Noise

Library
Signal\Sources

Implementations
frequency_limited_FOH
frequency_limited_ZOH
unlimited

Use

Description - frequency_limited_FOH
This model generates a gaussian noise signal with gaussian distribution and variance 1 and random seed s. The noise is multiplied by the parameter amplitude.

\[ output = \text{amplitude} \times \text{gauss}(1, seed); \]

The noise signal is limited to a maximum frequency, which can be adjusted (parameter). Values in-between two noise samples are interpolated (first order hold).

Interface - frequency_limited_FOH

Outputs
output

Parameters
seed random seed
amplitude output scaling factor: does not influence the distribution
frequency frequency band of the noise

Description - frequency_limited_ZOH
This model generates a gaussian noise signal with gaussian distribution and variance 1 and random seed s. The noise is multiplied by the parameter amplitude.

\[ output = \text{amplitude} \times \text{gauss}(1, seed); \]

The noise signal is limited to a maximum frequency, which can be adjusted (parameter). Values in-between two noise samples are interpolated (first order hold).

Interface - frequency_limited_ZOH

Outputs
output

Parameters
seed random seed
amplitude  output scaling factor: does not influence the distribution  
frequency  frequency band of the noise

**Description - unlimited**

This model generates a gaussian noise signal with gaussian distribution and variance 1 and random seed s. The noise is multiplied by the parameter amplitude.

\[ output = \text{amplitude} \ast \text{gauss}(1, \text{seed}); \]

The noise signal has no frequency limitation.

**Note**

It is advised only to use this implementation with fixed step integration methods such as Euler and Runge Kutta 2/4. If you run this implementation with a variable step integration method, simulations may get very slow!

**Interface - unlimited**

**Outputs**

- output

**Parameters**

- seed  random seed
- amplitude  output scaling factor: does not influence the distribution

**Limitations**

seed must be a number in the region <0,65000>.

**Signalgenerator-Random**

**Library**

Signal\Sources

**Implementations**

- frequency_limited_FOH
- frequency_limited_ZOH
- unlimited

**Use**

**Domains:** Discrete, Continuous. **Size:** 1-D. **Allowed in:** Block Diagrams.

**Description - frequency_limited_FOH**

This model generates a random (noise) signal with values between -amplitude and +amplitude and random seed s. The

\[ output = \text{ran}(@\text{ampl,seed}); \]
The noise signal is limited to a maximum frequency, which can be adjusted (parameter). Values in-between two noise samples are interpolated (first order hold).

**Interface - frequency_limited_FOH**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>seed</td>
<td>random seed</td>
</tr>
<tr>
<td>amplitude</td>
<td>-amplitude &lt;= output &lt;= +amplitude</td>
</tr>
<tr>
<td>frequency</td>
<td>frequency band of the noise</td>
</tr>
</tbody>
</table>

**Description - frequency_limited_ZOH**

This model generates a random (noise) signal with values between -amplitude and +amplitude and random seed s.

\[ output = \text{ran}(ampl,seed); \]

The noise signal is limited to a maximum frequency, which can be adjusted (parameter). Values in-between two noise samples are interpolated (first order hold).

**Interface - frequency_limited_ZOH**

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>seed</td>
<td>random seed</td>
</tr>
<tr>
<td>amplitude</td>
<td>-amplitude &lt;= output &lt;= +amplitude</td>
</tr>
<tr>
<td>frequency</td>
<td>frequency band of the noise</td>
</tr>
</tbody>
</table>

**Description - unlimited**

This model generates a random (noise) signal with values between -amplitude and +amplitude and random seed s.

\[ output = \text{ran}(ampl,seed); \]

The noise signal has no frequency limitation.

**Note**

It is advised only to use this implementation with fixed step integration methods such as Euler and Runge Kutta 2/4. If you run this implementation with a variable step integration method, simulations may get very slow!
**Interface - unlimited**

**Outputs**
output

**Description**

**Parameters**
seed  random seed
amplitude  -amplitude <= output <= +amplitude

**Limitations**
seed must be a number in the region <0,65000>.

---

**SignalGenerator-RandomInteger**

**Library**
Signal\Stochastic

**Use**
Domains: Discrete, Continuous. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**
This model generates uniformly distributed random integers in the range \([0, m-1]\), where \(m\) is an integer. All output random variables are independent and identically distributed. With the parameter random seed you can choose to make the distribution variable or fixed for each simulation run.

![Random Integer](image)

RandomInteger output with a frequency of 1 Hz and \(m = 5\).

The output signal is limited to a maximum frequency, which can be adjusted (parameter). Values in-between two samples are interpolated (first order hold).
11. Library

**Interface**

**Outputs**
output

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>seed</td>
<td>random seed</td>
</tr>
<tr>
<td>m</td>
<td>the output range [0, m-1]</td>
</tr>
<tr>
<td>frequency</td>
<td>frequency band of the output</td>
</tr>
</tbody>
</table>

**Limitations**

seed must be a number in the region <0,65000>.

**SignalGenerator-VariableBlock**

**Library**
Signal\Stochastic

**Use**


**Description**

This model generates a block signal that alternates between 0 and 1. The mean time interval of a section is given by the parameter meanTimeInterval. The distribution of the time interval is uniform between [0, 2*meanTimeInterval]. With the parameter random seed you can choose to make the distribution variable or fixed for each simulation run.
VariableBlock output with a mean time interval of 1 s.

**Interface**

**Outputs**

output

**Parameters**

meanTimeInterval

mean time \( s \) before the output signal changes

seed

**Limitations**

seed must be a number in the region \( <0,65000> \).

**SignalGenerator-VariablePulse**

**Library**

Signal\Signal\Stochastic

**Use**

Description
This model generates a pulse train with a pulse value of 1. The pulse width is given by the parameter \textit{pulseLength}. The mean time interval between two pulses is given by the parameter \textit{meanTimeInterval}. The distribution of the time interval is uniform between [0, 2*\textit{meanTimeInterval}]. With the parameter \textit{random seed} you can choose to make the distribution variable or fixed for each simulation run.

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    width=\textwidth,
    height=\textwidth/2,
    axis lines=left,
    xlabel={time [s]},
    ylabel={Variable Pulse},
    xmin=0, xmax=10,
    ymin=0, ymax=1.5,
    xtick={0,2,4,6,8,10},
    ytick={0,0.5,1,1.5},
    xticklabels={},
    yticklabels={0,0.5,1,1.5},
    grid=both,
    grid style={line width=0.1pt, draw=gray!10, dashed},
    xlabel style={at={(0.5,1.0)}, anchor=north},
    ylabel style={at={(0,0.5)}, anchor=south east},
    legend style={at={(0.05,0.2)}, anchor=north west},
]
\addplot[red, only marks, mark size=2pt, mark options={solid}] table {
    0 0
    2 1
    4 1
    6 1
    8 1
    10 0
};
\node[align=center] at (axis cs:0.5,0.5) {mean time interval};
\node[align=center] at (axis cs:4,1.2) {pulse length};
\end{axis}
\end{tikzpicture}
\end{center}

VariablePulse output with a pulse length of 0.3 s and a mean time interval of 1 s.

Interface

\begin{description}
\item[Outputs]
  \begin{description}
  \item[output] \\
  \end{description}
\item[Parameters]
  \begin{description}
  \item[meanTimeInterval] mean time \{s\} before the output signal changes
  \item[pulseLength] length of the pulse \{s\}
  \item[seed] random seed
  \end{description}
\item[Limitations]
  \begin{description}
  \item[seed] must be a number in the region <0,65000>.
  \end{description}
\end{description}
**StandardDeviation**

**Library**
Signal\Signal Processing

**Use**

**Description**
This submodel yields the standard deviation of an input signal using an integral function:

$$output = \sqrt{\int \frac{(input - mean)^2}{time}}$$

where mean is the mean of the input

**Interface**

**Inputs**
- **input**: Input signal

**Outputs**
- **output**: Standard deviation of the input signal

**Variance**

**Library**
Signal\Signal Processing

**Use**

**Description**
This submodel yields the variance of an input signal using an integral function:

$$output = \int \frac{(input - mean)^2}{time}$$

where mean is the mean of the input

**Interface**

**Inputs**
- **input**: Input signal

**Outputs**
- **output**: Variance of the input signal
11.3.13 Transfer Functions

Using Transfer Functions

The Transfer Functions library contains a number of predefined transfer functions and a general transfer function model that opens the Linear System Editor.

Without Dead Time

<table>
<thead>
<tr>
<th>name</th>
<th>formula</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LinearSystem</td>
<td>-</td>
<td>Any Linear System without time delay</td>
</tr>
<tr>
<td>FO</td>
<td>$Y(s) = \frac{k}{\tau s + 1} \cdot U(s)$</td>
<td>First Order</td>
</tr>
<tr>
<td>FOL</td>
<td>$Y(s) = \frac{k(s\tau_L + 1)}{s\tau + 1} \cdot U(s)$</td>
<td>First Order with Lead Time</td>
</tr>
<tr>
<td>FOLA</td>
<td>$Y(s) = \frac{k(s\tau + 1)}{s\tau_L + 1} \cdot U(s)$</td>
<td>First Order with Lag</td>
</tr>
<tr>
<td>SOI</td>
<td>$Y(s) = \frac{k}{s(\tau s + 1)} \cdot U(s)$</td>
<td>Second Order with Integrator</td>
</tr>
<tr>
<td>SOO</td>
<td>$Y(s) = \frac{k}{(\tau_1 s + 1)(\tau_2 s + 1)} \cdot U(s)$</td>
<td>Second Order Overdamped</td>
</tr>
<tr>
<td>SOOL</td>
<td>$Y(s) = \frac{k(\tau_2 s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1)} \cdot U(s)$</td>
<td>Second Order Overdamped with Lead Time</td>
</tr>
<tr>
<td>SOU</td>
<td>$Y(s) = \frac{k}{\tau^2 s^2 + 2\zeta\tau s + 1} \cdot U(s)$</td>
<td>Second Order Underdamped</td>
</tr>
<tr>
<td>SOUO</td>
<td>$Y(s) = \frac{\omega^2 k}{s^2 + 2\zeta\omega s + \omega^2} \cdot U(s)$</td>
<td>Second Order Underdamped, Omega description</td>
</tr>
</tbody>
</table>

With Dead Time

<table>
<thead>
<tr>
<th>name</th>
<th>formula</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZOD</td>
<td>$Y(s) = ke^{-\theta s} \cdot U(s)$</td>
<td>Zero Order plus Dead Time</td>
</tr>
</tbody>
</table>
11. Library

FOD
\[ Y(s) = \frac{ke^{-\theta s}}{\tau s + 1} U(s) \]
First Order plus Dead Time

SOID
\[ Y(s) = \frac{ke^{-\theta s}}{s(\tau s + 1)} U(s) \]
Second Order with Integrator plus Dead Time

SOOD
\[ Y(s) = \frac{ke^{-\theta s}}{(\tau_1 s + 1)(\tau_2 s + 1)} U(s) \]
Second Order Overdamped plus Dead Time

SOOLD
\[ Y(s) = \frac{k(\tau s + 1)e^{-\theta s}}{(\tau_1 s + 1)(\tau_2 s + 1)} U(s) \]
Second Order Overdamped with Lead Time plus Dead Time

SOUD
\[ Y(s) = \frac{ke^{-\theta s}}{\tau^2 s^2 + 2\zeta \tau s + 1} U(s) \]
Underdamped plus Dead Time

SOUDO
\[ Y(s) = \frac{\omega^2 ke^{-\theta s}}{s^2 + 2\zeta \omega s + \omega^2} U(s) \]
Underdamped plus Dead Time, Omega description

Linear System

Library
Signal\TransferFunctions

Use

Description
When you select this model and click Go Down a special editor opens (Linear System Editor), allowing you to enter a linear system in State Space form, as a Transfer Function or by adding poles and zeros:
Interface

Inputs

Description

Initial Values

The model has internal states that are not accessible.

Parameters

Parameters are entered by the Linear System Editor.
TransferFunction

Library
Signal\Transfer Functions

Implementations
FO
FOL
FOLA
SOI
SOO
SOU
SOUO
SOOL

Use

Description - FO
This model describes a first order process determined by k and tau. The transfer function of this process is:

\[ Y(s) = \frac{k}{\tau s + 1} \cdot U(s) \]

Interface - FO

Inputs
input

Outputs
output

Initial Values
state_initial
The initial value of the output.

Parameters
k
Proportional gain [\].

tau
Process time constant [s].

Description - FOL
This model describes a first order process with lead time determined by the parameters k, tau and tauL. The transfer function of this process is:
$$Y(s) = \frac{k(st + 1)}{st + 1}U(s)$$

**Interface - FOL**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>state_initial</td>
<td>Internal state.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>Proportional gain [].</td>
</tr>
<tr>
<td>tau</td>
<td>Process time constant [s].</td>
</tr>
<tr>
<td>tauL</td>
<td>Lead time constant [s].</td>
</tr>
</tbody>
</table>

**Description - FOL A**

This model describes a first order process with lag determined by the parameters $k$, $\tau$ and $\tau_L$. The transfer function of this process is:

$$Y(s) = \frac{k(st + 1)}{st + 1}U(s)$$

**Interface - FOL A**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>state_initial</td>
<td>Internal state.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>Proportional gain [].</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Process time constant [s].</td>
</tr>
<tr>
<td>$\tau_L$</td>
<td>Lag time constant [s].</td>
</tr>
</tbody>
</table>
**Description - SOI**
This model describes a second order process with integrator determined by the parameters $k$ and $\tau$. The transfer function of this process is:

$$Y(s) = \frac{k}{s(\tau s + 1)} \cdot U(s)$$

**Interface - SOI**

**Inputs**
- **Description**
- input

**Outputs**
- **Description**
- output

**Initial Values**
- state1_initial: Internal state.
- state2_initial: The initial value of the output.

**Parameters**
- $k$: Proportional gain [ ].
- $\tau$: Process time constant [s].

**Description - SOO**
This model describes an overdamped second order process determined by the parameters $k$, $\tau_1$ and $\tau_2$. The transfer function of this process is:

$$Y(s) = \frac{k}{(\tau_1 s + 1)(\tau_2 s + 1)} \cdot U(s)$$

**Interface - SOO**

**Inputs**
- **Description**
- input

**Outputs**
- **Description**
- output

**Initial Values**
- state1_initial: Internal state.
- state2_initial: The initial value of the output.

**Parameters**
Proportional gain \([\text{[]}]\).

First process time constant \([\text{s}]\).

Second process time constant \([\text{s}]\).

**Description - SOU**

This model describes an underdamped second order process, determined by the parameters \(k\), \(\tau\) and \(\zeta\). The transfer function of this process is:

\[
Y(s) = \frac{k}{\tau^2 s^2 + 2\zeta\tau s + 1} \cdot U(s)
\]

**Interface - SOU**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>state1_initial</td>
</tr>
<tr>
<td>state2_initial</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k)</td>
</tr>
<tr>
<td>(\tau)</td>
</tr>
<tr>
<td>(\zeta)</td>
</tr>
</tbody>
</table>

**Description - SOUO**

This model describes an underdamped second order process, determined by the parameters \(k\), \(\omega\) and \(\zeta\). The transfer function of this process is:

\[
Y(s) = \frac{\omega^2 k}{s^2 + 2\zeta\omega s + \omega^2} \cdot U(s)
\]

**Interface - SOUO**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**Outputs**
Initial Values
state1_initial  Internal state.
state2_initial  The initial value of the output after the dead time has passed.

Parameters
k  Proportional gain [].
omega  Natural frequency [rad/s].
zeta  Damping factor [].

Description - SOOL
This model describes an overdamped second order process with lead time determined by the parameters k, tau1, tau2 and tauL. The transfer function of this process is:

\[ Y(s) = \frac{k(\tau_L s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1)} \cdot U(s) \]

Interface - SOOL

Inputs  Description
input  

Outputs  output  

Initial Values
state1_initial  Internal state.
state2_initial  The initial value of the output.

Parameters
k  Proportional gain [].
tau1  First process time constant [s].
tau2  Second process time constant [s].
tauL  Lead time constant [s].
TransferFunctionWithDeadTime

Library
Signal\Transfer Functions

Implementations
ZOD
FOD
SOID
SOOD
SOUD
SOOLD
SOUDO

Use

Description - ZOD
This model describes a first zero process plus dead time determined by \( k \) and \( \theta \). The transfer function of this process is:

\[ Y(s) = ke^{-\theta s} \cdot U(s) \]

Interface - ZOD

Inputs
input

Outputs
output

Parameters
\( k \) Proportional gain [ ].
\( \theta \) Dead time [ s ].

Description - FOD
This model describes a first order process plus dead time determined by \( k \) \( \tau \) and \( \theta \). The transfer function of this process is:

\[ Y(s) = \frac{ke^{-\theta s}}{\tau s + 1} \cdot U(s) \]
Interface - FOD

Inputs
input

Outputs
output

Initial Values
state_initial
The initial value of the output after the dead time has passed.

Parameters
k
Proportional gain [].
tau
Process time constant [s].
theta
Dead time [s].

Description - SOID
This model describes a second order process with integrator plus dead time determined by the parameters k and tau. The transfer function of this process is:

\[ Y(s) = \frac{k}{s(\tau s + 1)} \cdot U(s) \]

Interface - SOID

Inputs
input

Outputs
output

Initial Values
state1_initial
Internal state.
state2_initial
The initial value of the output after the dead time has passed.

Parameters
k
Proportional gain [].
tau
Process time constant [s].
theta
Dead Time [s].
Description - SOOD
This model describes an overdamped second order process plus dead time determined by the parameters k, tau1 and tau2. The transfer function of this process is:

\[ Y(s) = \frac{ke^{-\theta s}}{(\tau_1 s + 1)(\tau_2 s + 1)} \cdot U(s) \]

Interface - SOOD

Inputs
- Description
  - input

Outputs
- output

Initial Values
- state1_initial: Internal state.
- state2_initial: The initial value of the output after the dead time has passed.

Parameters
- k: Proportional gain [\].
- tau1: First process time constant [s].
- tau2: Second process time constant [s].
- theta: Dead Time [s].

Description - SOUD
This model describes an underdamped second order process plus Dead Time, determined by the parameters k, tau and zeta. The transfer function of this process is:

\[ Y(s) = \frac{ke^{-\theta s}}{\tau^2 s^2 + 2\zeta\tau s + 1} \cdot U(s) \]

Interface - SOUD

Inputs
- Description
  - input

Outputs
- output

Initial Values
11. Library

state1_initial  Internal state.
state2_initial  The initial value of the output after the dead time has passed.

Parameters
k  Proportional gain [\].
tau  Natural period of oscillation [s].
zeta  Damping factor [].
theta  Dead Time [s].

Description - SOOLD
This model describes an overdamped second order process with lead time plus dead time determined by the parameters k, tau1, tau2 and tauL. The transfer function of this process is:

\[ Y(s) = \frac{k(\tau_1 s + 1)e^{-\theta s}}{\tau_1 s + 1)(\tau_2 s + 1)}U(s) \]

Interface - SOOLD

Inputs
input

Outputs
output

Initial Values
state1_initial  Internal state.
state2_initial  The initial value of the output after the dead time has passed.

Parameters
k  Proportional gain [\].
tau1  First process time constant [s].
tau2  Second process time constant [s].
tauL  Lead time constant [s].
theta  Dead Time [s].

Description - SOUDO
This model describes an underdamped second order process plus Dead Time, determined by the parameters k, omega and zeta. The transfer function of this process is:
\[ Y(s) = \frac{\omega^2 ke^{-\theta s}}{s^2 + 2\zeta \omega s + \omega^2}.U(s) \]

**Interface - SOUDO**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
</tbody>
</table>

**Outputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
</tr>
</tbody>
</table>

**Initial Values**

<table>
<thead>
<tr>
<th>description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>state1_initial</td>
<td>Internal state.</td>
</tr>
<tr>
<td>state2_initial</td>
<td>The initial value of the output after the dead time has passed.</td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>Proportional gain [].</td>
</tr>
<tr>
<td>omega</td>
<td>Natural frequency [rad/s].</td>
</tr>
<tr>
<td>zeta</td>
<td>Damping factor []</td>
</tr>
<tr>
<td>theta</td>
<td>Dead Time [s].</td>
</tr>
</tbody>
</table>

### 11.3.14 Various

**Library**

Library\: Signal\: Various

**Use**

Domains: Continuous, Discrete. **Size**: 1-D. **Allowed in**: Block Diagrams.

**Description**

This model generates a sound whenever the input is true. The sound must be stored on a .wav-file. At every simulation point where the input is true, the sound is restarted. This may result in the sound not to be hear because of every restart. Therefore it is best to make the input only true at one simulation point. This is demonstrated in the Examples library by the model: Examples\: Tips and Tricks\: PlaySound

**Interface**

**Inputs**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

---

20-sim 5.1 Reference Manual 1237
input

**Parameters**

- **Boolean**: If true, a sound is played
- **String**: File name of the .wav-file (including the path)
12 Modeling Tutorial

12.1 Friction

12.1.1 Introduction

In all machines incorporating parts with relative motion, friction is present. Friction is a natural resistance to relative motion between two contacting bodies. At particular locations in machines, friction is an undesirable property. Friction can lead to bad performance of for example a servo system. At other locations, friction plays an important role and is desirable, as is the case for example in actions as walking and grasping and in a brake system. In most systems, friction has a negative influence on the performance of the system. Under certain conditions, friction in a system can result in effects like a steady state error, tracking errors, especially nearby velocity reversals (reversal bump effect: getting stuck when moving through zero velocity), limit cycles (hunting) and/or stick-slip.

To overcome these negative effects, insight in friction phenomena, and proper models of these phenomena are useful. This chapter will give attention to these aspects of friction and describe the friction models that are available in the 20-sim library.

12.1.2 Normal Force

Assume a mass is dragged over a surface and experiences friction.

![Diagram of friction forces](image)

A tension force $F_t$ has to be applied to overcome the amount of friction force $F_f$. The friction force will depend on the applied normal force as:

$$F_t = F_n \ast f(x,v,\ldots);$$

where $f$ is the friction function which depends on the displacement $x$, velocity $v$ etc.

In most cases a normal force is available (disk breaks, surface friction, clutches etc.). Therefore all models in the 20-sim friction library are described with a normal force input. For those models that do not experience a normal force (bearings), a unity normal force $F_n = 1 \text{ [N]}$ is applied.
12.1.3 Friction Phenomena

There are different phenomena of friction. The following friction phenomena are described in the friction models in 20-sim:

- **static friction**: the torque or force necessary to initiate motion from rest (the so-called break-away force); it is often larger than the Coulomb friction,
- **Coulomb friction (kinetic friction, dynamic friction)**: the friction component that is only dependent on the direction of velocity, not of the magnitude of the velocity,
- **viscous friction**: the friction component that is proportional to velocity and goes to zero at zero velocity,
- **Striebeck friction (Striebeck effect)**: the friction phenomenon that arises from the use of fluid lubrication and gives rise to decreasing friction with increasing velocity at low velocity,
- **pre-sliding displacement (Dahl effect)**: the spring-like behavior of friction that causes a displacement linear dependent on the applied force if this applied force is less than the break-away force,
- **varying break-away force (rising static friction)**: the dependence of the break-away force on the rate of increase of the applied force,
- **frictional lag**: the delay in the change of the friction force as a function of a change in the velocity.

Beside the friction phenomena mentioned above, some other effects with respect to friction are reported in the literature. These effects are not incorporated into the 20-sim library of friction models:

- **Time-dependent friction**: From experiments it is known that friction changes with time. These changes of friction with time are due to such things as loss of lubricant, deformation of the surface material, change in temperature due to generated heat and/or accumulation of wear debris.
- **Position-dependent friction**: A dependence of the friction on the position of a system is another effect that is experimentally observed and is well known by a lot of researchers. This position-dependency is caused by spatial inhomogeneities in the transmission of the system due to contact geometry and/or loading which varies as a function of position. As the load varies, the normal force between the sliding surfaces varies, causing a varying friction (friction is linear dependent on the normal force). By preloading the transmission elements and roller bearings this dependency of friction on the load can be decreased.
- **Direction-dependent friction**: A lot of researchers have found the friction to be dependent on the direction of the motion of a system. Different Coulomb and viscous friction levels in the left and right directions of a single, linear motion have been observed experimentally on many occasions. Theoretically, this may be due to anisotropies in material or geometry.
12.1.4 Wet and Dry Friction

**Wet Friction**

Most machines are lubricated in order to decrease the effects of friction. But in most cases, this is not sufficient and significant friction effects remain.

There are four regimes of lubrication in a system with grease or oil in which the phenomena act that are mentioned in the previous section: static friction, boundary lubrication, partial fluid lubrication and full lubrication. Each of these four regimes contribute to the dynamics of the system. In the figure below, these four regimes are given in the plot of the friction force as a function of the sliding velocity, sometimes referred to as the *Stribeck curve*.

A description of the four regimes is:

**Regime 1: Static friction and pre-sliding displacement**

Although in this regime of static friction there is no sliding, because of the fact that contacts between two surfaces are compliant, there are small motions when a force is applied. The contact between two surfaces can be seen as an elastic contact. The displacement is an approximately linear function of the applied force (a spring-like behavior), up to a critical force at which breakaway occurs and sliding begins. The transition from the elastic contact with pre-sliding displacement in static friction to sliding is not abrupt: first sliding starts at the boundary of a contact and then it propagates toward the center.

**Regime 2: Boundary lubrication**

In this regime the sliding velocity is very low and is not adequate to build a fluid film of the lubricant between the sliding surfaces. The boundary layer of the surfaces serves to provide lubrication. In most cases, the friction in this boundary lubrication regime is higher than in case of fluid lubrication, as is the situation in regimes three and four.

**Regime 3: Partial fluid lubrication**

Lubricant is brought into the load-bearing region between the sliding surfaces through motion. Some lubricant is expelled by pressure arising from the load, but as a result of the viscosity not all of the lubricant will escape and thus a thin film of lubricant is formed between the sliding surfaces. Not at all places of the contact of the surfaces this film will exist; at some places there is still solid-to-solid contact: there is partial fluid lubrication. As the velocity becomes larger, more lubricant will be brought between the surfaces and less solid-to-solid contacts will exist. This explains the descending friction force when the velocity increases, called the Stribeck effect.
There is a time lag between a change in the velocity or load conditions and the change in friction to a new steady state level: the phenomenon of frictional lag takes place. This effect is a consequence of the state in the frictional contact that does not come to its new equilibrium instantly: it takes time for the lubricant to be brought or removed between the load bearing region of the sliding surfaces.

**Regime 4: Full fluid lubrication**

In this regime the solid-to-solid contacts are all eliminated. The wear is reduced by orders of magnitude. The viscosity of the lubricant is determinative for the friction force and the friction phenomenon now at work is the well-behaved viscous friction, besides the Coulomb friction.

*The four dynamic regimes of friction in the plot of friction force as a function of sliding velocity.*

**Dry Friction**

Dry friction is friction between two bodies in absence of contaminations of the contact surfaces. This is an ideal situation which is not possible to achieve in real systems, due to the fact that chemical reactions will occur at the surfaces. Therefore dry friction will show some of the effects described above. Some special effects due to the use of lubricants, such as the Stribeck effect and sometimes viscous friction will not be significant in dry friction.
12.1.5 Static and Dynamic Phenomena

The friction phenomena can be grouped in static and dynamic phenomena:

- **static friction phenomena:**
  - static friction
  - Coulomb friction (dynamic friction)
  - viscous friction
  - Striebeck friction (Striebeck effect)
- **dynamic friction phenomena:**
  - pre-sliding displacement (Dahl effect)
  - rising static friction (varying break-away force)
  - frictional lag

Static friction models only have a static dependency on velocity. Even when the applied force is very small, the result is a non-zero velocity. This means a significant displacement is found after some time. Therefore static friction models should only be used in systems where the applied forces are large (\(>>\) static friction), or change sign often.

Dynamic friction models incorporate a spring like behavior for small forces. I.e. no significant displacement is found when the applied force is smaller that the static friction.

**Coulomb friction**

Static friction phenomena only have a static dependency on velocity. The first static friction model was the classic model of friction of Leonardo Da Vinci: friction force is proportional to load, opposes the direction of motion and is independent of contact area. Coulomb (1785) further developed this model and the friction phenomena described by the model became known as **Coulomb friction**. The model is given in the figure below.

```
Friction force

Siding velocity

The Coulomb friction model.
```

The friction force can be described as:
\[ F_f = F_n \times \mu_c \times \text{sign}(v); \]

with \( \mu_c \) the Coulomb friction coefficient. The Coulomb friction model is, because of its simplicity, often used. In many textbooks it is also referred to as dynamic friction and \( \mu_s \) described as the dynamic friction coefficient.

**Static Friction**

Morin (1833) introduced the idea of static friction: friction force opposes the direction of motion when the sliding velocity is zero.

The static friction force is equal to the tensile forces until a maximum or minimum is reached:

\[ F_{f_{\text{max}}} = F_n \times \mu_s; \]
\[ F_{f_{\text{min}}} = -F_n \times \mu_s; \]

with \( \mu_s \) the static friction coefficient.

**Viscous friction**

Reynolds (1866) developed expressions for the friction force caused by the viscosity of lubricants. The term viscous friction is used for this friction phenomenon.

The friction force can be described as:
\( F_f = F_n \cdot \mu_v \cdot v; \)

with \( \mu_v \) the **viscous friction coefficient**.

**Coulomb plus Viscous friction**

This viscous friction combined with the Coulomb friction gave the model given in the figure below.

![The Coulomb plus viscous friction model.](image)

**Static plus Coulomb plus Viscous friction**

When static friction is added, a friction model appears that is commonly used in engineering: the **Static plus Coulomb plus Viscous friction model**. This model is depicted in the figure below.

![The static, Coulomb plus viscous friction model.](image)

**Static plus Coulomb plus Viscous plus Stribeck friction**

Stribeck (1902) observed that for low velocities, the friction force is decreasing continuously with increasing velocities and not in a discontinuous matter as described above. This phenomenon of a decreasing friction at low, increasing velocities is called the Stribeck friction or effect. The model including **Static, Coulomb, Viscous and Stribeck friction** is given below.
The static, Coulomb, viscous plus Stribeck friction model.

The Stribeck effect is described by the parameter \( v_{st} \) which is the characteristic Stribeck velocity. It denotes the sliding velocity where only a 37% of the static friction is active. In other words, small values of \( v_{st} \) give a fast decreasing Stribeck effect and large values of \( v_{st} \) give a slow decreasing Stribeck effect.

Continuous Functions

All these friction models above show a discontinuity at zero velocity. At zero velocity the friction force as a function of only velocity is not specified. What for example should the friction force be at zero velocity in the Coulomb friction model? The discontinuous behavior of this model near zero velocity is sometimes approximated with a continuous function, for example:

\[
F = \tanh(slope \cdot v);
\]

and the inverse

\[
v = \arctanh(F)/slope;
\]

with \( slope \) a very large constant. The use of continuous functions results in straightforward models that are easy to simulate for large forces and velocities. For small forces and velocities, the \( slope \) parameter has to be chosen sufficiently high, to avoid creep (the model starts to move, even when the applied force is smaller than the static or Coulomb friction force). This results in stiff models, which are hard to simulate.

LuGre friction model

The LuGre model is inspired by the bristle interpretation of friction (surfaces are very irregular at the microscopic level and two surfaces make contact at a number of asperities, which can be thought of as elastic bristles), in combination with lubricant effects.
Friction is modeled as the average deflection force of elastic springs. When a tangential force is applied the bristles will deflect. If the deflection is sufficiently large, the bristles start to slip. The average deflection at steady state slip is determined by the velocity, so that for low velocities the steady state deflection, and therefore the friction force, decreases with increasing velocity. This corresponds to more lubricant being forced into the interface, and pushing the surfaces apart, as the velocity increases. This produces the Strubeck effect. The model also includes rate dependent friction phenomena such as varying break-away force and frictional lag. The model behaves like a well damped spring with a stiffness at zero speed for small motions.

12.1.6 Comparison of Friction Models

In order to get insight in the friction phenomena, a friction model should incorporate as much friction phenomena and behave as much as real friction. In the table below an overview of the different models of the 20-sim library with respect to the friction phenomena is given.

<table>
<thead>
<tr>
<th></th>
<th>Coulomb model</th>
<th>Coulomb, viscous model</th>
<th>static, Coulomb, viscous model</th>
<th>static, Coulomb, viscous, Strubeck model</th>
<th>LuGre model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>static friction phenomena</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coulomb</td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>viscous</td>
<td></td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>static</td>
<td></td>
<td></td>
<td>V</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>Strubeck</td>
<td></td>
<td></td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td><strong>dynamic friction phenomena</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pre-sliding displacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>varying break-away force</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>frictional lag</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
</tbody>
</table>

From this overview it can be seen that all friction phenomena are incorporated in the LuGre model. From the literature, it is known that the behavior of the LuGre model is much alike real friction.
For most engineering applications, a static friction model, for example a static, Coulomb, viscous friction model, is sufficient. If all friction effects should be modeled, the LuGre friction model seems best suited.

12.1.7 Literature


12.2 Bond Graphs

12.2.1 Dynamic Systems

An important aspect in mechatronic systems is the dynamic behavior, i.e. the behavior of the system as function of time. Especially in systems that display swift changes or systems that should behave accurately, the dynamic behavior is important. It is therefore useful to predict the dynamic behavior of a system. Modeling and simulation is useful for making such predictions.

There are various methods of modeling and simulating dynamic systems. A well known one is the Lumped Parameter Method.

With the Lumped Parameter Method, the dynamic behavior of a system is concentrated in discrete points. The interaction of these points gives us insight in the behavior of the real system. The more discrete points are used the more accurate the model will be.

There are various ways to represent lumped parameter models. Well known representations are iconic diagrams, differential equations, block diagrams and bond graphs.

Let's consider the suspension of a car. A lumped parameter model starts with the identification of the various lumps (or parts or components) of this system. We start with the car body. It is supposed to be a rigid body and therefore this part is represented with the icon of a mass. The suspension of the car is represented by a spring damper combination. The wheel is considered to have a significant mass and to be elastic. This component is therefore represented by a mass and spring icon. Finally the road is modeled by path generator function. The resulting ideal physical model (IPM) is shown below.

![Iconic diagram of a car suspension.](image)
12.2.2 Bond Graphs

Bond graphs are a network-like description of physical systems in terms of ideal physical processes. With the bond graph method we split up the system characteristics into an (imaginary) set of separate elements. Each element describes an idealized physical process. To facilitate drawing of bond graphs, the common elements are denoted by special symbols.

Look again at the car suspension example. In the picture below at the right a bond graph is shown that has been entered in 20-sim. All elements of the ideal physical model have corresponding elements in the bond graph. The connections between the elements in the bond graph, which are known as bonds, represent ideal energy transfer between the elements, i.e. no energy is stored, generated or dissipated. Bonds are drawn with harpoons (the half arrows).

![Car suspension model and bond graph](image)

The car suspension model (middle) and corresponding bond graph model (right).

For the mechanical domain, ideal velocity sources are in bond graphs denoted by the symbol $S_f$. Dampers are denoted by an $R$, springs by a $C$ and masses by a $I$. With a $1$ a structural connection of elements is denoted and with a $0$ a velocity difference is denoted.

A bond graph describes a physical system as a number of physical concepts (the elements) connected by energy flows (the bonds).

12.2.3 Effort and Flow

A bond between two elements transfers power from one element to the other. This flow of energy can be described in many ways. For bond graphs a uniform approach is chosen:

The flow of energy between two elements (and thus a bond) is always characterized by two variables, of which the product is power. According to the bond graph notation, these variables are called effort ($e$) and flow ($f$).
The effort and flow variables make up a combination that is typical for a physical domain. The product of effort and flow is always power. We call such a pair of variables power conjugated variables. For example voltage and current are used for electrical networks and force and velocity are used for mechanical (translation) systems. The table below shows the variables for the domains that are currently supported in 20-sim.

<table>
<thead>
<tr>
<th>Domain</th>
<th>effort (e)</th>
<th>flow (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>power</td>
<td>effort e</td>
<td>flow f</td>
</tr>
<tr>
<td>mechanical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(translation)</td>
<td>force $F$ [N]</td>
<td>velocity $v$ [m/s]</td>
</tr>
<tr>
<td>mechanical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(rotation)</td>
<td>torque $T$ [Nm]</td>
<td>angular velocity $omega$ [rad/s]</td>
</tr>
<tr>
<td>pneumatic</td>
<td>pressure $p$ [Pa]</td>
<td>volume flow $phi$ [m$^3$/s]</td>
</tr>
<tr>
<td>thermal</td>
<td>temperature $T$ [K]</td>
<td>entropy flow $dS$ [J/Ks]</td>
</tr>
<tr>
<td>electric</td>
<td>voltage $u$ [V]</td>
<td>current $i$ [A]</td>
</tr>
<tr>
<td>hydraulic</td>
<td>pressure $p$ [Pa]</td>
<td>volume flow $phi$ [m$^3$/s]</td>
</tr>
<tr>
<td>magnetic</td>
<td>current $i$ [A]</td>
<td>voltage $u$ [V]</td>
</tr>
<tr>
<td>pseudothermal</td>
<td>temperature $T$ [K]</td>
<td>heat flow $dQ$ [W]</td>
</tr>
</tbody>
</table>

The effort and flow variables for several domains.

To most general domain is power. Bonds of this domain can connected to elements of all domains. For the thermal domain there is one pair of effort and flow, $T$ and $dS$, that multiplies to power. The pair $T$ and $dQ$ however, is more often used but does not multiply to power. Therefore the domain with these variables is called pseudothermal.

**Note**
- There is a direct relation between the across and through variables of an iconic diagram an the effort and flow variables of a bond graph:

<table>
<thead>
<tr>
<th>Domain</th>
<th>Non-mechanical domains</th>
<th>Mechanical Domains</th>
</tr>
</thead>
<tbody>
<tr>
<td>across variable</td>
<td>effort</td>
<td>flow</td>
</tr>
<tr>
<td>through variable</td>
<td>flow</td>
<td>effort</td>
</tr>
</tbody>
</table>

The relation between across and through variables and effort and flow variables.
20-sim propagates domains. If a bond of the general power domain is coupled with an element of the electrical domain, it automatically becomes an electrical bond. The other end of the bond can then only be connected to another element of the electrical domain.

If you want to use a bond of a domain that is not supported or has variables other than across and through, use the general power domain. The across and through variables can then be used as an alias for your own variables.

### 12.2.4 Bonds

The power of a bond is positive when both effort and flow have a positive value or both effort and flow have a negative value (power = effort × flow).

To denote the orientation, i.e. the direction of positive power, we use the harpoon at the end of a bond. An element with an inward bond connected, consumes power when the product of effort and flow is positive.

![A bond as power connection.](image)

When two elements are connected by a bond, one element will always determine the effort, while the opposite element will always determine the flow. The element that determines the effort, gets an enforced flow from the other element.

We can therefore also see a bond as a bilateral signal connection (effort-signal and flow-signal), of which the directions are opposite to each other.

With *direction* we mean the direction of the flow of information, just like in a block diagram. In a block diagram the effort and flow variables, which together form the flow of power, are not shown as a couple. This breaks up the symmetry between the physical system and the the structure of the model.

![A bond as a bilateral signal flow.](image)

The interpretation of a bond as a bilateral signal flow, does not fix the individual direction of the effort and the flow. It only means the direction of the effort and flow are opposite. For the derivation of a simulation model out of a bond graph however, the individual directions are of importance.
To indicate the individual direction of the effort and flow, we use a small stroke (causal stroke) perpendicular to the bond. This stroke indicates the direction of the effort. The direction of the flow is opposite.

The choice of the direction of signals, also known as causality, depends on the element that is connected to the bond.

### 12.2.5 Standard Elements

To facilitate drawing of bond graphs, the common elements are denoted by special mnemonic symbols. The elements can be divided in several classes:

- **Junctions**: (0 junction, 1 junction) elements that couple energy between various other elements.
- **Buffers**: (C,I) elements that store energy.
- **Dissipators**: (R) elements that dissipate energy.
- **Sources**: (Se,Sf) elements that generate energy.
- **Modulated Sources**: (MSe, MSf) elements that generate energy (driven by signals).
- **Transformers and Gyrators**: (TF, GY) elements that convert energy (ideally).
- **Modulated Transformers and Gyrators**: (MTF, MGY) elements that convert energy (driven by signals).
- **Other elements**: other elements and user defined elements.

### 12.2.6 Orientation

The orientation of a bond, i.e. the direction of the half arrow, denotes the direction of positive power. An element with an incoming bond consumes power when the product of effort and flow is positive. For R, C and I-elements an incoming bond is the standard orientation. For sources the standard orientation is outgoing, because a source supplies power to the rest of the system. For the TF and GY-element the standard orientation is one incoming bond and one outgoing bond, since this reflects the natural flow of power. For the other bonds in a model, as much as possible an orientation from source to load is applied.

### 12.2.7 Bonds and Signals

Bond Graph models are useful when describing systems with powerflow. In mechatronic systems these systems are usually coupled to systems that handle (powerless) signals. These systems are more conveniently described by block diagrams. Bond graphs can be combined with block diagrams. The coupling can be performed by special submodels.

**Sensors**

In general a sensor measures the flow, the effort, the integral of the flow or the integral of the effort. Sensors can be found in the 20-sim bond graph library.
In 20-sim 1 junctions have a signal output which is equal to the flow. From a 1 junction a signal can be drawn which can be used as input for a block diagram. In a similar way an effort signal can be drawn from a 0 junction.

**Junctions**

**Modulated Elements**

The result of a block diagram can be converted into power by means of a generator. In a bond graph model, this can be done by connecting a signal to modulated source elements. These elements convert input signals into efforts or flows. Other elements that use a signal input are modulated transformers and modulated gyrators.

**Example**

An example model where a bond graph and a block diagram are coupled is shown in the picture below. As can be seen an effort signal is measured at the 0 junction. In the block diagram part it is processed and fed back into the bond graph at the modulated effort source.
12.2.8   Simplification of Bond Graph Models

When a bond graph model has been created by converting all elements of the iconic diagram into bond graph elements and connecting the elements, simplifications can be performed. This can be easily done by applying the following set of rules (the bonds that have no half arrow, are allowed in both orientations).

1. Eliminate loose junctions.

2. Eliminate junctions.

3. Melt equal junctions.

4. Eliminate sources with a zero output.

5. Eliminate junction in combination with a sign change on the source element.
6. Eliminate a double difference (two 0-junctions coupled with two 1-junctions)

![Diagram of bond graph before and after simplification]

Note
Simplification rules 1, 2, 3 and 6 can be performed automatically in 20-sim using the Simplify Model command.

12.2.9 Causality

Causal analysis is the determination of the direction of the efforts and flows in a bond graph model. The result is a causal bond graph which can be considered as a compact block diagram. From causal bond graph we can directly derive an equivalent block diagram. In 20-sim causality is assigned automatically. To create a causal bond graph 20-sim will perform the following steps.

1. Apply causality for all elements with fixed causality (Se,Sf,Mse,MSf,user defined models), i.e. assign a causal stroke to all bonds connected to elements with fixed causality.

2. Apply, as much as possible, causality for elements that have a constraint causality (0 junction, 1 junction, TF,GY,MTF,MTY,user defined models).

3. Apply causality for an arbitrary element with preferred causality (C,I,user defined models). If possible, let this be the preferred causality. Now iterate step 2 and 3 as far as possible.

4. Apply causality for an arbitrary element with indifferent causality (R,user defined models). If this causality is not fixed, choose a causality arbitrarily. Now iterate step 2, 3 and 4 as far as possible.

In many cases, the bond graph model is causal after step 2. However, sometimes as causal conflict occurs. This means the model is not correct arithmetically. Often this points out an ill-defined model. Redefinition of the ideal physical model will solve the problem. Sometimes the model is only causal after step 4. This means the model contains an algebraic loop. Models with algebraic loops are generally hard to simulate.
Example
Causal assignment will be illustrated by an example. We will manually create a causal bond graph out of the following model:

\[
\begin{align*}
&\text{Se: } u_{in} \quad 1 \quad \text{GY} \quad 1 \\
&\begin{array}{c}
\text{R: } R_e \\
\text{I: } L \\
\text{I: } J \\
\text{R: } R_d
\end{array}
\end{align*}
\]

1. Apply fixed causality:

\[
\begin{align*}
&\text{Se: } u_{in} \quad 1 \quad \text{GY} \quad 1 \\
&\begin{array}{c}
\text{R: } R_e \\
\text{I: } L \\
\text{I: } J \\
\text{R: } R_d
\end{array}
\end{align*}
\]

2. Apply constraint causality. This step is not yet applicable.

3. Apply preferred causality. We can choose between the two I-elements. Let's select the left one and assign causality in its preferred form:

\[
\begin{align*}
&\text{Se: } u_{in} \quad 1 \quad \text{GY} \quad 1 \\
&\begin{array}{c}
\text{R: } R_e \\
\text{I: } L \\
\text{I: } J \\
\text{R: } R_d
\end{array}
\end{align*}
\]

4. Apply constraint causality. The 1 junction on the left has one bond with effort-out causality (seen from the 1 junction). The other bonds connected must therefore have effort-in causality (seen from the 1 junction). In a same way we can now assign causality for the GY-element:

\[
\begin{align*}
&\text{Se: } u_{in} \quad 1 \quad \text{GY} \quad 1 \\
&\begin{array}{c}
\text{R: } R_e \\
\text{I: } L \\
\text{I: } J \\
\text{R: } R_d
\end{array}
\end{align*}
\]

5. Apply preferred causality. Only the right I-element is left. We can assign causality in its preferred form:
6. Apply constraint causality. The 1 junction on the right has one bond with effort-out causality (seen from the 1 junction). The other bonds connected must therefore have effort-in causality. Therefore we can assign causality for the R-element:

6. Apply constraint causality. The 1 junction on the right has one bond with effort-out causality (seen from the 1 junction). The other bonds connected must therefore have effort-in causality. Therefore we can assign causality for the R-element:

12.2.10 Creating a Bond Graph model

There are various methods described in literature to convert an ideal physical model into a bond graph. The simplest method is a direct conversion of the parts of the ideal physical model into bond graph elements. It is based on the fact that for every physical domain, junctions have a special interpretation. This allows us to make tables of ideal physical model parts and their direct representation as bond graph elements. The drawback of the method is that it is not generally applicable: for physical domains that are not described here, the user is referred to other methods.

1. Create an ideal physical model.
2. Replace each part of the ideal physical model with corresponding bond graph elements. Standard replacements are shown in the tables of this tutorial.
3. Select the bond graph elements in the 20-sim library and drag and drop them to the 20-sim editor.
4. Connect the elements according to the ideal physical model.
5. Simplify the bond graph according to the given rules.
6. Compile the bond graph model and run a simulation.
12.2.11 From Iconic Diagram to Bond Graph

There are various methods described in literature to convert a iconic diagrams into bond graph models. The simplest method is a direct conversion of iconic diagrams into bond graph elements. It is based on the fact that for every physical domain, junctions have a special interpretation. This allows us to make tables of iconic diagrams and their direct representation as bond graph elements. The drawback of the method is that it is not generally applicable: for physical domains that are not described here, the user is referred to other methods.

- Mechanical Domain
- Electrical Domain

12.2.12 Iconic Diagrams to Bond Graphs (Electrical Domain)

In the electrical domain, terminals and knots can be replaced by 0 junctions. With this knowledge and the description of various icons a table can be created that shows icons of electrical elements and their equivalent bond graph elements. The method of creating a bond graph model is:

1. Create an iconic diagram of the electrical system.
2. Reference points or grounds are split up as much as possible.
3. Replace every element of the diagram by its bond graph equivalent using the conversion table.
4. Replace every knot that has been left by a 0 junction.
5. Connect all elements and junctions with bonds according to the layout of the electrical system.
6. Simplify the resulting bond graph model, using the given set of simplification rules.

Example

The method will be illustrated by an example. We will convert an electrical circuit into a bond graph model.

1. Create an iconic diagram

2. Split up reference points.
3. Replace elements by bond graph equivalents. Note that we have arranged the orientation of the bonds (the direction of the half arrow) as much as possible in the direction of the power flow from the source to the load elements.

4. Replace every knot that has been left by a 0 junction. In this model no knots have been left. Step 4 is therefore not applicable.

5. Connect all elements and junctions with bonds, according to the layout of the electrical system. A comparison between the iconic diagram and the bond graph model clearly shows the symmetry between both representations. It is obvious that any change or addition in the iconic diagram, can be easily implemented in the bond graph model.

7. Simplify the resulting bond graph model. First we eliminate the Sources (Se elements) with zero output.
8. Eliminate loose junctions.


The simplified model does not show a direct symmetry with the iconic diagram. It does give a clear insight in the flows of power from the voltage source to the other elements.

12.2.13 Iconic Diagrams to Bond Graphs (Mechanical Domain)

In the mechanical domain, both translational and rotational, terminals and knots can be replaced by 1 junctions. With this knowledge and the description of various icons a table can be created that shows icons of mechanical elements and their equivalent bond graph elements. The method of creating a bond graph model is:

1. Create an iconic diagram of the mechanical system.
2. Reference points or grounds are split up as much as possible.
3. Replace every element of the diagram by its bond graph equivalent using the conversion table.
4. Replace every knot that has been left by a 1 junction.
5. Connect all elements and junctions with bonds, according to the layout of the mechanical system.
6. Simplify the resulting bond graph model, using the given set of simplification rules.
Example

The method will be illustrated by an example. We will convert an mechanical structure (translational) into a bond graph model.

1. Create an iconic diagram

![Diagram of a mechanical structure](image)

2. Split up reference points. In this diagram this is not possible.

3. Replace elements by bond graph equivalents. Note that we have arranged the orientation of the bonds (the direction of the harpoon) as much as possible in the direction of the power flow from the source to the load elements.

![Bond graph diagram](image)

4. Replace every knot that has been left by a 1 junction.
5. Connect all elements and junctions with bonds, according to the layout of the mechanical system. A comparison between the iconic diagram and the bond graph model clearly shows the symmetry between both representations. It is obvious that any change or addition in the iconic diagram, can be easily implemented in the bond graph model.

6. Simplify the resulting bond graph model. First we eliminate the Sources (Se elements) with zero output.

7. Eliminate loose junctions.
8. Eliminate junctions.

The simplified model does not show a direct symmetry with the iconic diagram. It does give a clear insight in the flows of power from the force source to the other elements.

12.2.14 From Bond Graph to Block Diagram

With a causal bond graph model, equivalent block diagram models can easily be derived. To create a block diagram, the following steps have to be performed.

- Change bonds by equivalent bilateral signals.

- Replace elements by corresponding block diagram symbols. Use the correct effort and flow description which can be found in the element tables. As an example both descriptions for the R-element are given.
Replace the junctions by signal summation points and signal splitters. If correct, the bonds have already be replaced by effort and flow signals. Out of these signals and the junction description you can derive the effort and flow equations for the junction. As an example the conversion for a 1 junction is shown.

**Example**

As an example in the figure below a causal bond graph model is shown.

![Bond Graph Model](image)

Using the given set of rules and the element descriptions an equivalent block diagram models is found, which is shown below.

![Block Diagram Model](image)

The resulting block diagram model can be simplified by combining blocks and elimination of loops. Out of the block diagram, easily a set of dynamic equations can be deduced.
12. Modeling Tutorial

12.2.15 From Bond Graph to Equations

With a causal bond graph model, equivalent dynamic equations can easily be derived. To create the dynamic equations, the following steps have to be performed.

- Denote for every bond its effort and flow pair. You can use names that are obvious or methodically use numbers. Some examples are shown at the right.

- Replace elements by corresponding dynamic equations. Use the correct effort and flow description which can be found in the element tables. As an example descriptions for the R-element are given.

- Replace the junctions by the correct equations. For 0 junctions the efforts are equal. All flows of the bonds pointing towards the 0 junction should be added and all flows of the bonds pointing from the 0 junction should be subtracted. For 1 junctions the flows are equal. All efforts of the bonds pointing towards the 0 junction should be added and all efforts of the bonds pointing from the 0 junction should be subtracted. Some examples are shown at the right.

- Rearrange the equations by removing redundant variables.

**Example**

As an example in the figure below a causal bond graph model is shown. We will derive the set of dynamic equations out of this model.
1. Denote all efforts and flows. This is shown below:

\[
\begin{align*}
\text{Se: } u_{in} & \quad \text{L: } \text{i in = constant, i in = free} \\
\text{R: } u_r & \quad \text{L: } i_r \\
\text{I: } i_l & \quad \text{L: } (1/L) \int u_l \\
\text{1 junction} & \quad i_{in} = i_r = i_l = i_m \\
\text{GY} & \quad u_m = k_m \omega_m \\
& \quad T_m = k_m i_m \\
\text{I} & \quad T_j = (1/J) \int \omega_j \\
\text{R} & \quad T_r = d \omega_r \\
\text{1 junction} & \quad \omega_m = \omega_j = \omega_r \\
& \quad T_m - T_j - T_r = 0
\end{align*}
\]

2. Write the dynamic equations of the elements and junctions:

<table>
<thead>
<tr>
<th>elements</th>
<th>equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>( u_{in} = \text{constant}, i_{in} = \text{free} )</td>
</tr>
<tr>
<td>R</td>
<td>( u_r = \text{Re} i_r )</td>
</tr>
<tr>
<td>I</td>
<td>( i_l = (1/L) \int u_l )</td>
</tr>
<tr>
<td>1 junction</td>
<td>( i_{in} = i_r = i_l = i_m )</td>
</tr>
<tr>
<td>GY</td>
<td>( u_m = k_m \omega_m )</td>
</tr>
<tr>
<td></td>
<td>( T_m = k_m i_m )</td>
</tr>
<tr>
<td>I</td>
<td>( T_j = (1/J) \int \omega_j )</td>
</tr>
<tr>
<td>R</td>
<td>( T_r = d \omega_r )</td>
</tr>
<tr>
<td>1 junction</td>
<td>( \omega_m = \omega_j = \omega_r )</td>
</tr>
<tr>
<td></td>
<td>( T_m - T_j - T_r = 0 )</td>
</tr>
</tbody>
</table>

3. Reduce the amount of equations. We replace the equalities of the 1 junctions: \( i_{in} = i_r = i_l = i_m = i \) and \( \omega_m = \omega_j = \omega_r = \omega \).

<table>
<thead>
<tr>
<th>elements</th>
<th>equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>( u_{in} = \text{constant} )</td>
</tr>
<tr>
<td>R</td>
<td>( u_r = \text{Re} i )</td>
</tr>
</tbody>
</table>
12. Modeling Tutorial

\[ i = \frac{1}{L} \int u_l \]

1 junction
\[ u_{in} - u_r - u_l - u_m = 0 \]

GY
\[ u_m = k_m \omega \]
\[ T_m = k_m i \]

I
\[ T_j = \frac{1}{J} \int \omega \]

R
\[ T_r = d \omega \]

1 junction
\[ T_m - T_l - T_r = 0 \]

The resulting dynamic equations can be used for simulation. 20-sim can automatically extract the dynamic equations out of a bond graph model. The equations can be shown using the Show Equations command or used in the Simulator for simulation.

### 12.2.16 Ports

A port is a location where an element can exchange information (in case of a signal port) or power (in case of a power port) with its environment. So, it is the model port that defines the connection with the element. A port is an important concept, as it allows you to describe the properties of the bonds that can be connected to the element, i.e., its direction, size, domain, etc. Ports can be defined in 20-sim using the Interface Editor.
Port Variables

All ports of a submodel are shown in the Interface tab. In the figure below a standard C-element is shown with one power port \( p \). Each bond graph port has an effort and a flow variable. In 20-sim these variables are be denoted with the extensions \( .e \) and \( .f \) and are also known as power-port variables. You can see an example in the figure below where equations are defined using the variables \( p.e \) and \( p.f \).
Port Properties

Ports can be added and defined in the 20-sim Interface Editor. The Interface Editor of the C-element is shown below.

Bond graph ports have several properties:

- **Name**: The name of the port.
- **Type**: Next to bond graph ports, 20-sim also knows iconic diagram ports and signal ports
• **Orientation**: The orientation of a connected bond (indicated by the half arrow).
  - *fixed in orientation*: The bond will point towards the element.
  - *fixed out orientation*: The bond will point from the element to another element.
• **Rows/Columns**: The standard size of a port and corresponding bond is 1 but you can also define ports with larger sizes.
• **Domain**: The domain of the port.
• **Causality**: The preferred causality of the port variable (effort and flow). You have to defined here what should be the input variable (effort or flow) and what should be the output variable (effort or flow).

### 12.2.17 Creating your own Elements

In 20-sim you can easily create your own bond graph elements. The process of creation consists of three parts:

1. For any bond connected to your submodel an internal port has to be defined. For each port you have to specify some data:
   - The physical domain.
   - The size.
   - The orientation.
   - The causality.
2. Create the icon for the component. This can be done with a specialized drawing editor.
3. Create the element description. This can be done by (differential) equations or by a bond graph.

### 12.2.18 Bond Graph Literature

A vast number of publications and books on bond graph modeling have been issued. Here is only referred to some well known books. A comprehensive collection of bond graph literature can be found on the Internet pages of prof. F. Cellier (http://www.ece.arizona.edu/~cellier/bg.html) and the mirror site at the Glasgow University (http://www.eng.gla.ac.uk/bg/).

Alan J. Blundell (1982)
Bond Graphs for Modelling Engineering Systems

Peter C. Breedveld, Geneviève Dauphin-Tanguy (1992)
Bond Graphs for Engineers

François Edouard Cellier (1991)
12. Modeling Tutorial

Continuous System Modeling

Dean C. Karnopp, Ronald C. Rosenberg (1968)
Analysis and Simulation of Multiport Systems - The Bond Graph Approach to Physical Systems Dynamics
M.I.T. Press.

Dean C. Karnopp, Ronald C. Rosenberg (1974)
System Dynamics: A Unified Approach

Dean C. Karnopp, Donald L. Margolis, Ronald C. Rosenberg (1990)
System Dynamics: A Unified Approach - 2nd Edition

Lennart Ljung, Torkel Glad (1994)
Modeling of Dynamic Systems
Prentice Hall, Englewood Cliffs, N.J.

Henry M. Paynter (1961)
Analysis and Design of Engineering Systems

Ronald C. Rosenberg, Dean C. Karnopp (1983)
Introduction to Physical System Dynamics

Nobuhide Suda (1988)
System Dynamics
Koronasha, Tokyo. (in Japanese)

Jean U. Thoma (1982)
Grundlagen und Anwendungen der Bonddiagramme
Girardet Taschenbuch GT20, Essen, Germany.

Jean U. Thoma (1989)
Simulation by bond graphs - Introduction to a Graphical Method
Springer-Verlag, New York.
12.2.19 Standard Elements

0 and 1 junctions

Junctions couple one or more elements of a model in a power continuous mode: no energy is stored or dissipated. Examples are a series junction or parallel junction in an electrical network, a fixed connection between two mechanical parts etc. Two types of junctions exist: 0 junctions and 1 junctions.

0 junction

\[ e_1 = e_2 = e_3 \]
\[ f_1 - f_2 - f_3 = 0 \]

The 0 junction represents a coupling where all efforts of the connected bonds are equal. As a consequence of the property of power continuity the sum of the flows must be equal to zero. The orientation of the bonds determines the sign of the flow summation: all flows of the bonds pointing towards the 0 junction should be added and all flows of the bonds pointing from the 0 junction should be subtracted. This summation corresponds to the Kirchhoff current law for electrical networks. The equality of the efforts, limits the causality. Only one bond may have an "effort-in" causality (the stroke pointed towards the 0 junction). All other bonds must have (seen from the 0 junction) an "effort-out" causality (stroke pointing from the 0 junction). In other words: the 1 junction has a constraint causality.
1 junction

\[ e_1 \quad 1 \quad e_2 \quad e_3 \]

\[ f_1 = f_2 = f_3 \]

\[ e_1 - e_2 - e_3 = 0 \]

The 1 junction is the dual form of the 0 junction (effort and flow are opposite). The 1 junction represents coupling where all flows of the connected bonds are equal. As a consequence of the property of power continuity the sum of the efforts must be equal to zero. The orientation of the bonds determines the sign of the flow summation: all efforts of the bonds pointing towards the 1 junction should be added and all efforts of the bonds pointing from the 1 junction should be subtracted. This summation corresponds to the Kirchhoff voltage law for electrical networks. The equality of the flows, limits the causality. Only one bond may have an "effort-out" causality (the stroke pointing from the 1 junction). All other bonds must have (seen from the 1 junction) an "effort-in" causality (stroke pointing to the 1 junction). In other words: the 1 junction has a constrained causality.

0 junction

Suppose we have the following 0 junction with one bond (1) pointing towards the junction and two bonds (2 and 3) pointing from the junction.

\[ e_1 \quad 0 \quad e_2 \quad e_3 \]

\[ f_1 = f_2 = f_3 \]

\[ f_1 - f_2 - f_3 = 0 \]

1. For a 0 junction the efforts are always equal! This means:
   \[ e_1 = e_2 = e_3 \]

2. The junction is power continuous. For the figure above this means:
   \[ e_1 \times f_1 = e_2 \times f_2 + e_2 \times f_2 \]

3. Combining 1 and 2 yields:
   \[ f_1 - f_2 - f_3 = 0 \]
The last equation can also be derived with a rule of thumb: All flows of the bonds pointing *towards* the 0 junction should be added and all flows of the bonds pointing *from* the 0 junction should be subtracted.

The first equation, limits the causality. Only one bond may have an *effort-in* causality (the stroke pointed towards the 0 junction). All other bonds must have (seen from the 0 junction) an *effort-out* causality (strokes pointing from the 0 junction). For the example junction this means three possible causal forms can exist:

1. For a 1 junction the flows are always equal! This means:
   
   \[ f_1 = f_2 = f_3 \]

2. The junction is power continuous. For the figure above this means:
   
   \[ e_1 f_1 = e_2 f_2 + e_3 f_2 \]

3. Combining 1 and 2 yields:
   
   \[ e_1 - e_2 - e_3 = 0 \]

The last equation can also be derived with the rule of thumb: All effort of the bonds pointing *towards* a 1 junction should be added and all efforts of the bonds pointing *from* the 1 junction should be subtracted.
The first equation, limits the causality. Only one bond may have an *flow-in* causality (the stroke pointed from the 1 junction). All other bonds must have (seen from the 1 junction) a *flow-out* causality (strokes pointed towards the 1 junction). For the example junction this means three possible causal forms can exist:

\[
\begin{align*}
&f_2 = f_3 = f_1, \\
e_1 = e_2 + e_3
\end{align*}
\]

### Buffers

Buffers are bond graph elements that can store energy. There are two types of buffers: *C-elements* and *I-elements*. The table below shows the effort and flow descriptions that belong to these elements. The parameters “C” and “I” are the *buffer constants*, which determine a linear buffer behavior. Examples of C-elements are a mechanical spring and an electrical capacitor. Examples of an I-element are a mechanical inertia and an electrical inductance.

<table>
<thead>
<tr>
<th>C-element</th>
<th>Bond Graph Element</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effort-in causality</td>
<td><img src="image" alt="C-element" /></td>
<td>( f = C \cdot \frac{de}{dt} )</td>
</tr>
<tr>
<td>Effort-out causality</td>
<td><img src="image" alt="C-element" /></td>
<td>( e = \int f )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I-element</th>
<th>Bond Graph Element</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effort-in causality</td>
<td><img src="image" alt="I-element" /></td>
<td>( f = \frac{1}{I} \cdot \int e )</td>
</tr>
<tr>
<td>Effort-out causality</td>
<td><img src="image" alt="I-element" /></td>
<td>( e = I \cdot \frac{df}{dt} )</td>
</tr>
</tbody>
</table>

Buffer elements do not fix the direction of the effort and flow. Both effort-in as well as effort-out causality is allowed. With simulation however, we prefer to avoid differentiation. In other words, with the C-element the effort-out causality is *preferred* and with the I-element the effort-in causality is *preferred*.
**Resistance**

A resistance, $R$, dissipates free energy. This energy of any arbitrary domain is transported *irreversibly* to the thermal domain. This means the power towards a resistance is always positive. In the table below the effort and flow description of the resistance is shown. Examples of a resistance are a mechanical damper and an electrical resistor.

<table>
<thead>
<tr>
<th>$R$-element</th>
<th>bond graph element</th>
<th>equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>effort-in causality</td>
<td>$\begin{array}{c} e \ f \end{array} \rightarrow R$</td>
<td>$f = (1/R) e$</td>
</tr>
<tr>
<td>effort-out causality</td>
<td>$\begin{array}{c} e \ f \end{array} \leftarrow R$</td>
<td>$e = R f$</td>
</tr>
</tbody>
</table>

The direction of effort and flow is not restricted for a resistance and there is no preferred form for the equation. In other words: the $R$-element has an *indifferent causality*.

**Sources**

Sources represent the interaction of a systems with its environment. There are two types of source elements: effort sources ($Se$) and flow sources ($Sf$).

In the table below the effort and flow description of the source elements is shown. Examples of a flow source are an electrical current source and a hydraulic pump that generates a constant flow of liquid. Examples of an effort source are an electrical voltage source and a constant mechanical force.

<table>
<thead>
<tr>
<th>element</th>
<th>bond graph element</th>
<th>equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>effort source</td>
<td>$\begin{array}{c} e \ f \end{array} \Rightarrow Se$</td>
<td>$e = c$, $f =$ free</td>
</tr>
<tr>
<td>flow source</td>
<td>$\begin{array}{c} e \ f \end{array} \Rightarrow Sf$</td>
<td>$f = c$, $e =$ free</td>
</tr>
</tbody>
</table>

The direction of effort and flow for sources are restricted. In other words: the $Se$-element (effort-out) and $Sf$-element (effort-in) have a *fixed causality*. 
Modulated Sources

Next to the standard effort and flow sources, that generate a constant effort and flow, bond graph modeling also allows the use of so called modulated sources. In these sources the resulting effort or flow are equal to a (fluctuating) value provided by an input signal. Two types of modulated sources are known: the modulated effort source $\text{MSe}$ and the modulated flow source $\text{MSf}$. In the table below the effort and flow description of the source elements is shown.

<table>
<thead>
<tr>
<th>element</th>
<th>bond graph element</th>
<th>equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>modulated effort source</td>
<td>$\text{MSe}$</td>
<td>$e = u, f = \text{free}$</td>
</tr>
<tr>
<td>modulated flow source</td>
<td>$\text{MSf}$</td>
<td>$f = u, e = \text{free}$</td>
</tr>
</tbody>
</table>

The direction of effort and flow for sources are restricted. In other words: the MSe-element (effort-out) and MSf-element (effort-in) have a fixed causality.

Transformers and Gyrators

Transformers and gyrators are bond graph elements that can convert energy ideally, as well in one physical domain as well as between one physical domain and another. A transformer is denoted by the mnemonic code $\text{TF}$ and a gyrator by the code $\text{GY}$. In the table below the effort and flow equations are shown. The parameters $r$ and $n$ are the transformation ratio and gyration ratio. An example of a transformer is a mechanical gear. An example of a gyrator is a DC-motor.

<table>
<thead>
<tr>
<th>TF-element</th>
<th>bond graph element</th>
<th>equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>effort-in causality</td>
<td>$\text{TF}$</td>
<td>$f_1 = (1/n) f_2$  $e_2 = (1/n) e_1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$f_2 = n f_2$   $e_1 = n e_2$</td>
</tr>
<tr>
<td>effort-out causality</td>
<td>$\text{TF}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GY-element</th>
<th>bond graph element</th>
<th>equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>effort-in causality</td>
<td>$\text{GY}$</td>
<td>$f_1 = (1/r) e_2$  $f_2 = (1/r) e_1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e_1 = r f_2$    $e_2 = r f_1$</td>
</tr>
</tbody>
</table>
The directions of the flow and effort are partly fixed for a transformer. Like the 1 junction and the 0 junction, the causality is constraint. For a transformer, an effort-in causality on the incoming bond results in an effort-out causality on the outgoing bond and vice-versa. For a gyrator, an effort-in causality on the incoming bond results in an effort-in causality on the outgoing bond and vice-versa.

Modulated Transformers and Gyrators

Next to transformers and gyrators with a fixed transformation ratio and gyration ratio, in bond graphs also modulated transformers (MTF) and modulated gyrators (MGY) are supported. In these models the transformation ratio of gyration ratio are equal to a (fluctuating) value provided by an input signal. In the table below the effort and flow equations are shown.

<table>
<thead>
<tr>
<th>MTF-element</th>
<th>bond graph element</th>
<th>equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>effort-in causality</td>
<td><img src="image" alt="MTF" /></td>
<td>$f_1 = \frac{1}{u} f_2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e_2 = \frac{1}{u} e_1$</td>
</tr>
<tr>
<td>effort-out causality</td>
<td><img src="image" alt="MTF" /></td>
<td>$f_2 = u f_2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e_1 = u e_2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MGY-element</th>
<th>bond graph element</th>
<th>equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>effort-in causality</td>
<td><img src="image" alt="MGY" /></td>
<td>$f_1 = \frac{1}{u} e_2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$f_2 = \frac{1}{u} e_1$</td>
</tr>
<tr>
<td>effort-in causality</td>
<td><img src="image" alt="MGY" /></td>
<td>$e_1 = u f_2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e_2 = u f_1$</td>
</tr>
</tbody>
</table>

The directions of the flow and effort are partly fixed for a modulated transformer. Like the 1 junction and the 0 junction, the causality is constraint. For a transformer, an effort-in causality on the incoming bond results in an effort-out causality on the outgoing bond and vice-versa. For a gyrator, an effort-in causality on the incoming bond results in an effort-in causality on the outgoing bond and vice-versa.
An important aspect in mechatronic systems is the dynamic behavior, i.e. the behavior of the system as function of time. Especially in systems that display swift changes or systems that should behave accurately, the dynamic behavior is important. It is therefore useful to predict the dynamic behavior of a system. Modeling and simulation is useful for making such predictions.

There are various methods of modeling and simulating dynamic systems. A well known one is the Lumped Parameter Method.

With the Lumped Parameter Method, the dynamic behavior of a system is concentrated in discrete points. The interaction of these points gives us insight in the behavior of the real system. The more discrete points are used the more accurate the model will be.

There are various ways to represent lumped parameter models. Well known representations are iconic diagrams, differential equations, block diagrams and bond graphs.

Let's consider the suspension of a car. A lumped parameter model starts with the identification of the various lumps (or parts or components) of this system. We start with the car body. It is supposed to be a rigid body and therefore this part is represented with the icon of a mass. The suspension of the car is represented by a spring damper combination. The wheel is considered to have a significant mass and to be elastic. This component is therefore represented by a mass and spring icon. Finally the road is modeled by path generator function. The resulting ideal physical model (IPM) is shown below.

Iconic diagram of a car suspension.

If we can represent the various parts of an ideal physical model by predefined models or components modeling is easy. In 20-sim a large library of components is available allowing you to create a model just by selecting the proper components and connect them according to the ideal physical model. To make modeling even more easy, the components are displayed in the editor by icons which look like the corresponding parts.
of the ideal physical model. In 20-sim these kind of models are called iconic diagrams (sometimes other simulation tools refer to this kind of modeling as component based modeling). 20-sim can automatically compute simulation code out of an iconic diagram and start a simulation.

Look again at the car suspension example. In the picture below at the right an iconic diagram is shown that has been entered in 20-sim. As you can see, the iconic diagram similar to the ideal physical model. Each component of the iconic diagram represents a physical process. For example the mass component represents the law of motion \( F = m \cdot a \) and the spring represents the linear spring equation \( F = k \cdot x \). The connections between the components in the iconic diagram represent ideal energy transfer between those components, i.e. no energy is stored, generated or dissipated.

An iconic diagram describes a physical system as a number of physical concepts (the components) connected by energy flows (the connections).

### 12.3.3 Across and through

A connection between two components transfers energy from one component to the other. This flow of energy can be described in many ways. In 20-sim a uniform approach is chosen:

The flow of energy between two components of an iconic diagram can be characterized by two variables, of which the product is power. These variables are called *across* \((a)\) and *through* \((t)\).

The across and though variables make up a combination that is typical for a physical domain. For example voltage and current are used for electrical networks and force and velocity are used for mechanical (translation) systems. The table below shows the variables for the domains that are currently supported in 20-sim.

<table>
<thead>
<tr>
<th>Domain</th>
<th>across ((a))</th>
<th>through ((t))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Current</td>
<td>Force</td>
</tr>
<tr>
<td>Current</td>
<td>Voltage</td>
<td>Velocity</td>
</tr>
<tr>
<td>Force</td>
<td>Velocity</td>
<td>Torque</td>
</tr>
</tbody>
</table>

A iconic diagram model of a car suspension.
12. Modeling Tutorial

<table>
<thead>
<tr>
<th>Domain</th>
<th>Non-mechanical domains</th>
<th>Mechanical Domains</th>
</tr>
</thead>
<tbody>
<tr>
<td>across variable</td>
<td>effort</td>
<td>flow</td>
</tr>
<tr>
<td>through variable</td>
<td>flow</td>
<td>effort</td>
</tr>
</tbody>
</table>

The across and through variables for several domains.

The most general domain is power. Connections of this domain can be used for all domains. For the thermal domain there is one pair of across and through, T and dS, that multiplies to power. The pair T and dQ however is more often used but does not multiply to power. Therefore the domain with these variables is called pseudothermal.

There is a direct relation between the across and through variables of an iconic diagram and the effort and flow variables of a bond graph:

The relation between across and through variables and effort and flow variables.

Note

- 20-sim propagates domains. If a connection of the general power domain is tied to a component of the electrical domain, it automatically becomes an electrical connection. The other end of the connection can then only be tied to another component of the electrical domain. In this way it is prevented to connect components of different physical domains.
- If you want to use a connection of a domain that is not supported or has variables other than across and through, use the general power domain. The across and through variables can then be used as an alias of your own variables.
12.3.4 Connections

When two components in an Iconic Diagram are connected, one component will always compute the across variable, while the opposite component will always determine the through variable.

We can therefore also interpret a connection as a bilateral signal connection (across-signal and through-signal), of which the directions are opposite to each other.

With "direction" we mean the computational direction, just like signals in a block diagram. In a block diagram the across and through variables, which together form the flow of power, are not shown as a couple. This breaks up the symmetry between the physical system and the structure of the model.

The interpretation of a connection as a bilateral signal flow, does not fix the individual direction of the across variable and the through variable. It only means the direction of the across variable and through variable are opposite.

The specific computational direction of across and and through variables is called causality. In 20-sim an advanced algorithm detects the possible causalities of each submodel and tries to combine these in such a way, that optimal simulation code will be generated. The result can be inspected using the Causality Info command from the View menu. The result of this command is shown in the example below. The computational direction of forces and velocities is clearly shown for all the connections.

![Diagram showing connections and causality](image)
12.3.5 **Orientation (Across)**

When simulating, you have to know how across and through variables are oriented to make a correct interpretation of what is happening. 20-sim can show the orientation when you select the Orientation Info option of the View menu.

**Across variables in the Top Level**

Across variables in the top level of a model are always defined with respect to a single global reference. In the picture below an electrical iconic diagram is shown with three voltages (u₁ = 5 V, u₂ = 3 V and u₃ = 1 V). This means these voltages are all defined with respect to the same reference, e.g., the ground u = 0 V.

![Electric diagram](image)

All variables values of a connection can be easily inspected during simulation by placing the mouse pointer on top of that connection as shown below. The connection between the mass and the spring (see picture below) shows an across value v = 0.84 m/s. This means the point where the mass and spring are connected has a global velocity of v = 0.84 m/s.

![Connection values](image)

In the figure below the connection between the capacitor and the resistor shows a negative voltage of u = -2e-5 V.

![Connection values](image)

**Across variables in Submodels**

In submodels you have to inspect how across variables are defined. For example an ideal electrical resistor (see figure below) uses separate high and low terminals. The internal equations are:

\[ p.u = p\_high.u - p\_low.u; \]
\[ p\_high.i = p\_low.i = p.i; \]
\[ p.u = R \ast p.i; \]
where p.high and p_low are the ports to the connections at both sides of the resistor. p_high.u and p_low.u are voltages defined with respect to the global reference, but p.u is the voltage difference between the high and low port and therefore not defined with respect to the global reference.

The definition of across variables depends on the definition of number of terminals of a port, which is shown in the Type Editor. To inspect the ports, put the mouse pointer on top of the Type section and select **edit type** from the right mouse menu.

**Note**

- The geometrical layout of the iconic diagram does not have a meaning. If a resistor is drawn upside down, its current is still defined with respect to the resistor (flowing towards or from). If a mass is drawn upside down, its force is still defined with respect to that mass (pulling or pushing).
- To show or hide the orientation of an Iconic Diagram select or deselect the Orientation Info option of the View menu.

### 12.3.6 Orientation (Through)

When simulating, you have to know how across and through variables are oriented to make a correct interpretation of what is happening. 20-sim can show the orientation when you select the Orientation Info option of the View menu.

**Through variables in connections**

Through variables in connections are always defined with respect to the components they are connected with. 20-sim automatically assigns an orientation for these through variables. This orientation can be made visible by selecting the Orientation Info command of the View Menu.
**Non-mechanical**

Through variables that are not of the mechanical domain are always shown with an arrow in the connection. The arrow indicates the direction of the positive flow. The figure below shows a negative current: \( i = -2e^{-5} \text{ A} \). This means the current flows in the opposite direction of the arrow.

![Non-mechanical Diagram](image)

**Mechanical**

Through variables of the mechanical domain are always shown with two arrows. The arrows indicate the direction of the positive force. The figure below shows a positive force: \( F = 0.45 \text{ N} \). This means the spring pushes with a force of \( F = 0.45 \text{ [N]} \) upon the mass and the mass pushes with a force of \( F = 0.45 \text{ N} \) upon the spring (note: a negative force would mean pulling instead of pushing).

![Mechanical Diagram](image)

This interpretation of forces in 20-sim is only valid when a positive velocity defined from the left to the right, and from the bottom to the top!

**Through Variables in Submodels**

In submodels, you have to use the Type Editor to find out how through variables are defined. For example an ideal mass (see next figure) uses the option any number of terminals for its port (inspect the port in the Type Editor). The port equations are:

\[
\begin{align*}
    p.v &= p1.v = p2.v;
\end{align*}
\]

The internal equations are:

\[
\begin{align*}
    p.v &= (1/m)\times\text{int}(p.F) \\
    x &= \text{int}(p.v);
\end{align*}
\]

where \( p1 \) and \( p2 \) are the ports to the connections at both sides of the mass. \( p1.v \) and \( p2.v \) are velocities defined with respect to the global reference. However, \( p.F \) (see also in the figure below) is the sum of the forces applied on both sides.
The definition of through variables depends on the definition of number of terminals of a port, which is shown in the Type Editor. To inspect the ports, put the mouse pointer on top of the Interface tab and select Edit from the right mouse menu.

**Note**

- The geometrical layout of the iconic diagram does not have a meaning. If a resistor is drawn upside down, its current is still defined with respect to the resistor (flowing towards or from). If a mass is drawn upside down, its force is still defined with respect to that mass (pulling or pushing).
- To show or hide the orientation of an Iconic Diagram select or deselect the Orientation Info option of the View menu.

### 12.3.7 Global Reference

20-sim iconic diagram models do not contain geometrical information. It is not important how a model is drawn, but how the elements are connected. To make a correct interpretation of the simulation results, the definition of references has to be known.

**Across**

Across variables in the top level of a model are always defined with respect to a single global reference. For all domains this global reference is equal to 0. The interpretation of this reference is up to the user. For example a zero pressure could be the absolute vacuum or the air pressure at ground level. For most physical domains, unless specified otherwise, a standard interpretation is used. This is shown in the table below.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Across (a)</th>
<th>Global Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>power</td>
<td>across a</td>
<td>zero</td>
</tr>
</tbody>
</table>
Through variables in connections are always defined with respect to the components they are connected with.

Non-Mechanical

Through variables that are not of the mechanical domain are always shown with an arrow indicating the direction of the positive flow.

Mechanical

Through variables of the mechanical domain are always shown with two arrows indicating the direction of the positive force. Since mechanical variables are often geometrically interpreted, these arrows assume a positive velocity from the left to the right and from the bottom to the top.

See for example the system shown above. Look at the connection between the spring and the fixed world. Most users will correctly interpret a positive force as one that "makes the mass slow down". The same model is shown below. To prevent an incorrect interpretation such as a positive force "makes the mass accelerate", the arrows are pointing inwards.

This interpretation is only valid when you assume that a positive velocity is from the left to the right and from the bottom to the top!
12.3.8 Causality

The connection between two components describes the flow of power from one to the other. This power flow is always described by across and through variables. For example an electrical connection can be described by the variables voltage $u$ and current $i$ ($u*i =$ power). Each Iconic Diagram component creates a causal relation between these variables. E.g. an electric resistor can be described by the equation:

$$u = i*R;$$

where $R$ is the resistance. Here the voltage is a function of the current. In 20-sim we say the component has a voltage out causality. This causality is not fixed. We can easily invert the equation:

$$i = u/R;$$

Now the component has a current out causality. Which of the two equations will be used for the simulation depends on the other components.

In 20-sim an advanced algorithm detects the possible causalities of each model and tries to combine these in such a way, that optimal simulation code will be generated. You can help this algorithm by manually setting the causality of ports.

12.3.9 Ports

A port is a location where a component can exchange information (in case of a signal port) or power (in case of a power port) with its environment. So, it is the port that defines the connection with a component. A port is an important concept, as it allows you to describe the properties of the connection that can be made to the component, i.e., its direction, size, domain, etc. Ports can be defined in 20-sim using the Type Editor.
Port Variables

All ports of a submodel are shown in the Type window of the 20-sim Editor. In the figure below an electrical Resistor is shown with one power port \( p \). Each port has an across and through variable. In 20-sim these variables are denoted with the extensions \(.a\) and \(.t\). You can also use the names that are specific for a certain domain. For the electrical domain the extensions \(.u\) and \(.i\) are used. You can see an example in the figure below (Implementation section) where equations are defined using the variables \( p.u \) and \( p.i \).
Port Properties

Ports can be added and defined in the 20-sim Type Editor. You can open the Interface Editor in the Interface tab (right mouse menu). The Interface Editor of the Resistor is shown below.
Port Properties

Iconic Diagram Ports have several properties:

- **Name**: The name of the port.
- **Type**: Next to Iconic diagram ports, 20-sim also knows bond graph ports and signal ports.
- **Size**: The standard size of a port and corresponding connection is 1 but you can also define ports with larger sizes.
- **Orientation**: The orientation of a port defines how the though variable is connected.
  - **Input**: A positive through variable will act upon a component in the positive direction (mechanical domain) or flows into the component (non-mechanical domain).
  - **Output**: A positive through variable will act upon a component in the negative direction (mechanical domain) or flows from the component (non-mechanical domain).

Note: The port orientation and the orientation of the corresponding connection can be made visible in 20-sim by arrows.

- **Domain**: The physical domain of the port.
- **Causality**: The causality of the port variable (across and through). You have to define here what should be the input variable (across or through) and what should be the output variable (across or through).
By default, an iconic diagram port is a port where power can be exchanged between a component and its environment in terms of an across variable and a through variable. Such a port is represented by one terminal. However, there are two special cases where it is desirable to define an iconic diagram port that has more than one terminal. These are the Separate High / Low Terminals port and the Any Number of Terminals port. These options are only for advanced users!

- **Separate High / Low Terminals**: Select the port to have two terminals. Only for experienced users!
- **Any Number of Terminals**: Select the port to have any number of terminals. Only for experienced users!

### 12.3.10 Ports with more than one Terminal

By default, an iconic diagram port is a port where power can be exchanged between a component and its environment in terms of an across variable and a through variable. Such a port is represented by one terminal (connection point). However, there are two special cases where it is desirable to define an iconic diagram port that has more than one terminal.

#### Separate High / Low Terminals

Consider, as an example, an mechanical spring. The power that flows into such a component is uniquely determined by the velocity difference between the two terminals of the component and the common force that acts upon both ends. Because of this one could say that there is one port, whose power is determined by one across value (the velocity difference) and one through value (the common force), but is represented by two terminals. To support this, 20-sim allows you to define a special type of iconic diagram port by indicating that is has Separate High / Low Terminals. The two terminals of the connection are named high and low. If the port is named p, the formal equations are:

**fixed in orientation**

\[
\begin{align*}
  p.t &= p1.t = p2.t \\
  p.a &= p\_high.a - p\_low.a 
\end{align*}
\]

**fixed out orientation**

\[
\begin{align*}
  p.t &= p1.t = p2.t \\
  p.a &= - p\_high.a + p\_low.a 
\end{align*}
\]

In 20-sim these equations are automatically derived.

#### Any Number of Terminals

Consider, as an example, a mass. A characteristic of this component is that you can connect many springs and dampers to it. Implicitly, one expects that the net force (i.e., the summation of the forces applied by the connected components) will be applied to the mass, and that it will have a single velocity. To support this, 20-sim allows you to define a special type of iconic diagram port by indicating the kind to be Any Number of Terminals. The terminals of the connection are named 1, 2, 3 etc.. If the port is named p, the formal equations are:
\[ p.a = p1.a = p2.a = p3.a = \ldots \]
\[ p.t = \text{sign}(p1) \times p1.t + \text{sign}(p2) \times p2.t + \text{sign}(p3) \times p3.t + \ldots \]
sign = 1 when \( p1 \) has a fixed in orientation etc.
sign = -1 when \( p2 \) has a fixed out orientation etc.

In 20-sim these equations are automatically derived.

### 12.3.11 Creating Iconic Diagrams

When you understand the concepts of across and through, including orientation, constructing an iconic diagram is easy:

1. Create an ideal physical model.
2. Select the components that represent the various parts of the ideal physical model and drag and drop them to the 20-sim editor. Iconic Diagram components can be found in the model library. Some standard components are shown in the tables of this tutorial.
3. Connect the components according to the ideal physical model.
4. Compile the model and run a simulation. For a good interpretation of the plots, you must know that across variables are always defined with respect to a global reference and through variables are always defined with respect to the components.

### 12.3.12 Creating your own Components

In 20-sim you can easily create your own components. The process of creation consists of three parts:

1. For any connection an internal port has to be defined. For each port you have to specify some data:
   - The physical domain.
   - The size.
   - The orientation.
   - The causality.
2. Create the icon for the component. This can be done with a specialized drawing editor.
3. Create the component description. This can be done by (differential) equations or by an iconic diagram.
Index

- - -
  - 237, 257
  - * -
    * 182, 235
  - . -
    ./ 238
    .^ 238
    .cse 485
    .csv 485
    .emxz 31, 32
    .fmu 593
  - / -
    / 239
  - [ -
    [ 275
  - ] -
    ] 275
  - ^ -
    ^ 240
  - + -
    + 182, 236, 257
  - < -
    < 254
    <= 254
    <> 255
  - = -
    == 255
  - > -
    > 256
    >= 256
  - 0 -
    0 633, 1273
    0 junction 1274
    0-junction 633, 634
  - 1 -
    1 622, 623, 1273, 1275

1-3-5-7-9 Polynomial 456, 468
1D 878
1-junction 622, 623

- 2 -

  20sim 2, 7, 8, 11, 12, 24, 237
  20-sim 2, 7, 8, 11, 12, 22, 23, 24, 237, 573, 574, 584, 585, 586, 589
  20-sim Coordinates 595
  20-sim Dynamic DLL 521
  20-sim Filter Editor 415
  20-sim Inspector 604
  20-sim library 21
  20-sim Model 302
  20-sim Scenery 302
  20-sim scenery file 604
  20-sim submodel for Arduino/AVR 521
    255 349
  2D 878
  2-D 876
  2D Library 876
  2D motion 876
  2D Springs 897
  2D-Animation 344
  2D-modelling 913
  2D-point-X 917
  2DSmallRotation library 876
  2Dtable 1033

- 3 -

  3 degrees of freedom 913
  32-bit machine code 65
  3-4-5 Polynomial 456, 468
  3D Animation 108
  3D Animation Plot 324
  3D Animation Properties 326
  3D Body 911
  3D Library 911
  3D mechanics 2
  3D Mechanics Editor 286
  3D Points 911
  3D Representation 293

20-sim 5.1 Reference Manual 1295
Index

3D-body 917
3D-files 342
3D-mass 911

- A -
A 689
ABCD matrix 408
abort 267
Abs 162
Absolute 133, 134, 235, 1036
absolute error 100
absolute tolerance 413
absolute value 162
AC motor 793, 799
AC synchronous motor 502
acceleration 464, 894, 960
AccelerationActuator 792, 924
AccelerationActuator-Relative 792, 924
AccelerationSensor-Absolute 864, 972
AccelerationSensor-Relative 865, 973
accumulator 786
accuracy 100
acmotor 799
ACMotor-TorqueLoop 793
Across 87, 1281
Actions 436
Activation 8
activation function 377
Activation Function Type 379
Active 114
activity 634
Actuated Joints 308
actuator 808, 809, 810, 811, 812, 914, 918, 928, 933, 934, 935
Actuator Model 1069
Actuator Properties dialog 318
Actuators 897
AD 1126
Adams-Bashford 133
Add 1030
Add New 49
Add Plot Window 449
Add to Favorites 110
Add to Input Probes 110
Add to Output Probes 110
Add/Delete 114, 532
Addition 236
Additional Outputs 302
Additional Toolboxes 285
Adjoint 205, 207
Advanced Scripts 581
After the run 521
algebraic 110, 163
algebraic loop in 65
algebraic loop out 65
Algebraic loops 40, 70, 132, 278
algebraic solver 132
algebraic variables 40
Algebraic variables solved 40
Alias 90
alias variable 65
Alias Variables 110
All Runs 108
Allow model updates 40
Allow Symbol Prefixes 91
Always Look up Vector 344
Ambient color 348
Ambient Light 347
amplifier 672
Amplitude 371, 429
amplitudesensor 1186
Analog 1129
Analog filter 415
Analog to Digital Convertor 1126
analysis 96
Analyze Causality 45
and 252, 1158, 1172
angle 831
angular acceleration 831
angular velocity (constant) 810, 811
angular velocity (variable) 811, 812
Index

angular velocity = 0 826, 942
Animation Properties 326
annotations 151
ANSI-C Code 521
ANSI-C Function 521
antisym 208
Anti-Windup 1069
Any Number of Terminals 85, 1293
API 574
Apply Regularization 385
Apply to: 103
arccos 224
arccosh 225
Archive 30
arcsin 223
arcsinh 226
arctan 226
arctanh 227
arduino 2
Array 276
Array Division 238
array multiplication 237
Array Power 238
Artificial intelligence 375, 380
As Constraint Joint 308
As Global Parameter 304
Assert Test 449
AssertSignal 1187
atan2 228
Attempting Real-Time simulation 126
Attenuate 1006
Attenuation 355
Attributes 326
Author 40
Auto Causality 40
Auto Indent 22
Auto Recovery Filename 28, 43
Automatic Tests 1187
Average 1189, 1216
Averaging Integration 1021
Avi 332
Axes 103
- B -
B 349
back plane 344
Background 103
Background Color 334
Background Image 334
Backgrounds 62
Backlash 813, 935, 1044
BackPropogation Networks 375
Backward Difference transformation 415
Backward Differentiation Formula 134
Backward Euler 132
Band 400
Band Pass 400
Band Stop 400
Bandwith 1145, 1146
Base 10 Logarithm 171
basic libraries 689
Basic Script 580
basis function 380
BDF 134
bearing 814, 826
BeltPulley 839, 978
Bessel 400
bilateral signal 1283
bilinear transformation 415
binary 159
binary operators 241, 242, 243, 244, 245, 246, 247, 248, 249, 250
Bipolar Sigmoid 379
Bipolar Sigmoid Activation Function Scale 379
bitand 241
bitclear 242
bitcmp 243
bitget 244
bitinv 245
bitmap 352
bitor 246
bitset 247
bitshift 248
bitshiftright 249
bitxor 250
Block Diagram 1264
Block Diagrams 1126
blue 349
Bode Plots 371, 429
body points 911
Body Properties Dialog 304
body without rotational inertia 916
Bond Graph Literature 1271
Bond Graph Models 1255
Bond Graph Models,Simplification 1255
Bond Graph,Equations 1266
Bond Graph,Iconic Diagram 1259
Bond Graphs 24, 1250, 1258, 1259, 1261
Bond Graphs,Iconic Diagrams 1259, 1261
Bonds 1252, 1253
Boolean 154, 157, 158
boolean and 252, 1158
boolean CMOS_CD4020 1160
boolean CompareGE 1161
boolean CompareGT 1162
boolean CompareLE 1162
boolean CompareLT 1163
boolean false 1163
boolean F-type Trigger Flip Flop 1164
boolean invertor 1164
boolean nand 1165
boolean nor 1166
Boolean Not 257
boolean or 253, 1167
Boolean ResetSet Flip Flop 1168
boolean R-type Trigger Flip Flop 1169
boolean SetReset Flip Flop 1169
boolean true 1170
boolean xor 1170
Brackets 145
Break 814
Breakpoint Editor 114
Breakpoints 113, 114
Bridge 676
Broydon Fletcher Goldfarb Shanno 544
Brush DC Motors 497
Brushless DC Motors 500
Brute Force 108
Brute force simulation 40
Bryant angles 304, 349
B-spline 380
B-spline Network 380
bsplinenetwork 1062
Buffers 1276
Building Hydraulic Models 691
built-in 285
Built-in Compiler 100
Bulk modulus 689
Butterworth 400, 1145, 1146
BW 1145, 1146
by 263

C 521, 610, 611
C++ class for 20-sim submodel 521
C-2 648
C-3 636
cam 839, 979
Cam Motion Profiles 456
Cam Wizard 452, 456
Camera 344
Camera Settings 296
CamProfile.dll 839, 979
cams 452, 839, 979
Capacitor 664
Capacitor.emx 664
carriage 897
Index

Case 266
cast 161
casting 161
Catch up with lost time 126
Category 442
Causal analysis 45
causal conflict 45
Causal Form 66, 279
causal order 66, 279
Causal Strokes 45, 1283
Causality 66, 84, 272, 273, 279, 1256, 1289
Causality Info 25
CCCS 681
C-code Folders 28, 43
C-Code for 20-sim submodel 521
C-Code Generation 28, 43, 521
Cd 689
ceil 163
C-elements 1276
center of stiffness 900
centi 91
CentrifugalPump 721
changing mass 960
Chebychev 400
check 300
Check Complete Model 39
Check Energetic Behavior 45
Check for Model Updates 61
Check Model 302
checkvalve 738
checkvalve-states 762
Chinese 20
Choose Colors 25
Choosing a Motor 517
Chrome 352
Circle 344
circle elements 336, 339, 340, 355
Clear 108
Clear After Every Run 532
Clock 1173
Clock Signal 1159
Clock-Continuous 1159
clock-discrete 1127
clockinterrupt 129
closed chain mechanism 297
Closed Forms 355
closed loop system 410
Clutch 820
cmaBender 661, 925
cMAStretcher 662, 926
CMOS_CD4020 1160, 1174
code 22, 138, 139
code block 139
Code Blocks 71, 282
code generation 2
Cogging 511
collect 218
Collision 939
Collision-Relative 937
colon 275
Color 90, 349
Color Syntax Highlighting 22
Color Themes 103
Colors 25, 103
Column 53
Columns 208, 275, 1289
Combining of divisions 36
Combining of multiplications 36
Combining splitters 36
comment 144
Comments 144
Commercial Controllers 1074
Company 40
Compare CSV 449
CompareGE 1161, 1174
CompareGT 1162, 1175
CompareLE 1162, 1175
CompareLT 1163, 1176
Comparison of Friction Models 1247
compensator 360, 399
Compiling 32, 65
Compiling Models 65
complete set of equations 74, 284
Component Properties 286
Components 1294
computational direction 1283
Cone 340
Confirmation on Delete 28, 43
connecting of joints 300
Connecting Sensors 315
Connecting Submodels 33
connection 698, 832, 963
connection mode 33, 35
Connections 35, 47, 1283
Constant 348, 1193
constant current 686
Constant Values 146
constant voltage 688
Constants 17, 23, 98, 146, 148
constraint 84, 163
constraint equal 84
Constraint Joint 297
constraint not equal 84
Constraint Settings 308
constraint variables 40
Constraint variables solved 40
constraints on motion 884
Continue 114
Continuous Descent 544
continuous pulse 456, 468
Continuous-Discrete Tranformations 415
Continuous-Time 51
Continuous-Time and Discrete-Time Models 55, 92, 93
contra-rotating shafts 845
ControlledLinearSystem 1056
ControlledSystem 1057
Controller 395, 396, 397, 398, 399, 1096, 1098, 1119, 1120, 1121, 1122
Controller Design Editor 360
controller output 1064
controller variable 1064
Controller-P 1079, 1103
Controller-PD_p 1080, 1103
Controller-PD_s 1081, 1104
Controller-PI 1081, 1105
Controller-PI_sp 1082, 1106
Controller-PI_sp_aw 1083, 1106
Controller-PI_sp_aw_u0 1084, 1107
controller-PI_sp_aw_u0_tr 1085, 1108
Controller-PID_p 1086, 1109
Controller-PID_p_sp 1087, 1110
Controller-PID_p_sp_aw 1088, 1111
Controller-PID_p_sp_aw_u0 1089, 1112
controller-pid_p_sp_aw_u0_tr 1090, 1113
Controller-PID_s 1091, 1115
Controller-PID_s_sp 1092, 1115
Controller-PID_s_sp_aw 1093, 1116
Controller-PID_s_sp_aw_u0 1094, 1117
controller-pid_s_sp_aw_u0_tr 1095, 1118
controllerwizard 1079
convection 994
Convert 1259
converting from real to boolean 161
Copy 110
Copy from States 532
Copy Initials 98
Copy Parameters 98
Copy Specified 110
Copy States 108, 119
correct order of execution 71, 282
cos 229, 232
cosh 229
cosine 1036
cosine wave 1211
cost function 572
counterbalancevalve 764
counter-moving ports 983
Index

counting 275
coupling 858
CPS 434
crankrod 842, 981
Create Datafile 532
Created 40
Creating 1258, 1294
Creating Components 1294
Creating Elements 1271
Creating, Bond Graphs 1258
Creating, Iconic Diagrams 1294
cross 208
CrossingBoth 1139
CrossingDown 1139
CrossingUp 1139
crossover yerk 456, 468
Cube 337, 595
Cubic 456, 468
cumulative power spectral density 434
current 686
current controlled current source 681
Current time 408
CurrentSensor.emx 665
CurrentSource 686
CurrentSource.emx 686
CurrentSource-CCCS 681
CurrentSource-CCCS.emx 681
Curve 101
curve fitting 549
custom libraries 27
CV 1064
cyclic 456, 468
Cyclic Motions 456, 468
Cycloid 1199
Cycloidal 456, 468
Cylinder 339, 352, 699
CylinderChamberA 700
cylinderchamberb 701
cylinderdouble 704
cylindersingle 708
cylinderSingleSpringReturn 706
CylinderSpringReturn 703
- D -
D Controller 396
DA 1129
da-delay 1128
Damper 825, 900, 941, 966
Dashed Bonds 40
data 183
Data Files 478
Data Input Wizard 1194
Data Types 157
Datafile 1041, 1200
DataFromFile 1194
Davidson Fletcher Powel 544
DB 1037
DC Motors 518
DCmotor 663, 800
DC-motor 663, 800
DCmotor.emx 663, 800
Ddt 164
De 612
deactivate license 11
deactivation 11
DeadZone 1032
deal voltage source 687
debug mode 121
Debugger 113
debugging 96
deci 91
decimal 159
declarations 23
Decrypt Models 58
Decryption 58
Default Lights and Cameras 344
Default Line Thickness 28, 43
Default Shared Y-Axis 28, 43
default value 98
default values 149
degree of freedom 913
<table>
<thead>
<tr>
<th>Term</th>
<th>Page Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>degrees of freedom</td>
<td>876, 880</td>
</tr>
<tr>
<td>deinstallation</td>
<td>11</td>
</tr>
<tr>
<td>Delay</td>
<td>1007, 1130</td>
</tr>
<tr>
<td>delay-n</td>
<td>1129</td>
</tr>
<tr>
<td>Delay-Pade</td>
<td>1006</td>
</tr>
<tr>
<td>Delay-Step</td>
<td>1007</td>
</tr>
<tr>
<td>Delay-Time</td>
<td>1007</td>
</tr>
<tr>
<td>delay-variabletime</td>
<td>1008</td>
</tr>
<tr>
<td>delete</td>
<td>35</td>
</tr>
<tr>
<td>demonstration</td>
<td>7</td>
</tr>
<tr>
<td>Demux</td>
<td>1009, 1010, 1011</td>
</tr>
<tr>
<td>denominator</td>
<td>364, 420</td>
</tr>
<tr>
<td>Department</td>
<td>40</td>
</tr>
<tr>
<td>Dependent</td>
<td>110</td>
</tr>
<tr>
<td>dependent rate</td>
<td>65, 68, 281</td>
</tr>
<tr>
<td>dependent state</td>
<td>65, 68, 281</td>
</tr>
<tr>
<td>Dependent states</td>
<td>40</td>
</tr>
<tr>
<td>Dependent/Algebraic</td>
<td>110</td>
</tr>
<tr>
<td>Derivative</td>
<td>164</td>
</tr>
<tr>
<td>Derivative action</td>
<td>1067</td>
</tr>
<tr>
<td>Derivative Gain Limitation</td>
<td>1014, 1067</td>
</tr>
<tr>
<td>Derivative time</td>
<td>1067</td>
</tr>
<tr>
<td>description</td>
<td>90, 98</td>
</tr>
<tr>
<td>Desired Area of Operation</td>
<td>517</td>
</tr>
<tr>
<td>det</td>
<td>209</td>
</tr>
<tr>
<td>Determinant</td>
<td>209</td>
</tr>
<tr>
<td>Df</td>
<td>613</td>
</tr>
<tr>
<td>diag</td>
<td>209</td>
</tr>
<tr>
<td>Diesel</td>
<td>710</td>
</tr>
<tr>
<td>difference equations</td>
<td>362, 418</td>
</tr>
<tr>
<td>Differential</td>
<td>844, 1131</td>
</tr>
<tr>
<td>differential equations</td>
<td>362, 418</td>
</tr>
<tr>
<td>differential form</td>
<td>68, 281</td>
</tr>
<tr>
<td>DifferentialGear</td>
<td>843</td>
</tr>
<tr>
<td>DifferentialPressure</td>
<td>735</td>
</tr>
<tr>
<td>Differentiate</td>
<td>1013</td>
</tr>
<tr>
<td>Differentiate-</td>
<td>1012</td>
</tr>
<tr>
<td>Differentiate-Calculus</td>
<td>1012</td>
</tr>
<tr>
<td>Differentiate-Default</td>
<td>1015</td>
</tr>
<tr>
<td>Differentiate-FO</td>
<td>1013</td>
</tr>
<tr>
<td>Differentiate-SVF</td>
<td>1014</td>
</tr>
<tr>
<td>Differentiation</td>
<td>1014, 1015</td>
</tr>
<tr>
<td>Differentiator</td>
<td>396</td>
</tr>
<tr>
<td>Diffuse color</td>
<td>348</td>
</tr>
<tr>
<td>Digital</td>
<td>1129</td>
</tr>
<tr>
<td>digital filter</td>
<td>415</td>
</tr>
<tr>
<td>Digital linear controllers</td>
<td>394</td>
</tr>
<tr>
<td>Digital linear filters</td>
<td>394</td>
</tr>
<tr>
<td>Digital to Analog Convertor</td>
<td>1129</td>
</tr>
<tr>
<td>Diode</td>
<td>666, 676</td>
</tr>
<tr>
<td>Diode Bridge</td>
<td>676</td>
</tr>
<tr>
<td>Diode-Ideal</td>
<td>666</td>
</tr>
<tr>
<td>direct</td>
<td>219</td>
</tr>
<tr>
<td>Direct acting</td>
<td>1065</td>
</tr>
<tr>
<td>direct search</td>
<td>544</td>
</tr>
<tr>
<td>Direction (using order of Connection Points)</td>
<td>308</td>
</tr>
<tr>
<td>Directional Light</td>
<td>348</td>
</tr>
<tr>
<td>Disable plot</td>
<td>101</td>
</tr>
<tr>
<td>discharge coefficient</td>
<td>689</td>
</tr>
<tr>
<td>Discrete</td>
<td>415</td>
</tr>
<tr>
<td>Discrete Differential</td>
<td>1131</td>
</tr>
<tr>
<td>Discrete Integral</td>
<td>1132</td>
</tr>
<tr>
<td>Discrete Sample time</td>
<td>362, 418</td>
</tr>
<tr>
<td>Discrete System</td>
<td>128, 175</td>
</tr>
<tr>
<td>Discrete Time Interval</td>
<td>128</td>
</tr>
<tr>
<td>DiscreteDifferential</td>
<td>1131</td>
</tr>
<tr>
<td>DiscreteIntegral</td>
<td>1132</td>
</tr>
<tr>
<td>Discrete-Time</td>
<td>51</td>
</tr>
<tr>
<td>Discrete-Time Models</td>
<td>51</td>
</tr>
<tr>
<td>discrete-time system</td>
<td>415</td>
</tr>
<tr>
<td>disk space</td>
<td>4</td>
</tr>
<tr>
<td>DisplacementMotor</td>
<td>712</td>
</tr>
<tr>
<td>displacementmotor-leakage</td>
<td>714</td>
</tr>
<tr>
<td>displacementpump</td>
<td>717</td>
</tr>
<tr>
<td>displacementpump-leakage</td>
<td>724</td>
</tr>
<tr>
<td>dissipative element</td>
<td>619, 627</td>
</tr>
<tr>
<td>Dissolve</td>
<td>2, 36</td>
</tr>
<tr>
<td>Distribute curves</td>
<td>40</td>
</tr>
<tr>
<td>disturbances</td>
<td>360</td>
</tr>
<tr>
<td>Term</td>
<td>Page(s)</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Div</td>
<td>239, 240</td>
</tr>
<tr>
<td>Divide</td>
<td>1025</td>
</tr>
<tr>
<td>Division</td>
<td>239</td>
</tr>
<tr>
<td>DLL</td>
<td>185, 186</td>
</tr>
<tr>
<td>dlldynamic</td>
<td>193</td>
</tr>
<tr>
<td>dly</td>
<td>165</td>
</tr>
<tr>
<td>Do</td>
<td>263, 264</td>
</tr>
<tr>
<td>Documentation</td>
<td>583</td>
</tr>
<tr>
<td>Documentation Editor</td>
<td>59</td>
</tr>
<tr>
<td>DoFromMatlab</td>
<td>1150</td>
</tr>
<tr>
<td>Domain</td>
<td>87</td>
</tr>
<tr>
<td>domain changes</td>
<td>630</td>
</tr>
<tr>
<td>Domain name</td>
<td>90</td>
</tr>
<tr>
<td>Domains</td>
<td>86, 87, 90</td>
</tr>
<tr>
<td>Domains,Quantities and Units Editor</td>
<td>86</td>
</tr>
<tr>
<td>DoMatlab</td>
<td>269, 1152</td>
</tr>
<tr>
<td>DoMatlab-Final</td>
<td>1151</td>
</tr>
<tr>
<td>DoMatlab-Initial</td>
<td>1151</td>
</tr>
<tr>
<td>double acting cylinder</td>
<td>704</td>
</tr>
<tr>
<td>Double Click Function</td>
<td>28, 43</td>
</tr>
<tr>
<td>DoubleSwitch-Level</td>
<td>667</td>
</tr>
<tr>
<td>drag and drop</td>
<td>27, 33, 35, 300</td>
</tr>
<tr>
<td>Drag and Drop .fmu</td>
<td>607</td>
</tr>
<tr>
<td>Drawing Rules</td>
<td>880</td>
</tr>
<tr>
<td>DTypeFlipFlop</td>
<td>1176</td>
</tr>
<tr>
<td>DTypeFlipFlop-Discrete</td>
<td>1176</td>
</tr>
<tr>
<td>Duplication</td>
<td>357</td>
</tr>
<tr>
<td>During the run</td>
<td>521</td>
</tr>
<tr>
<td>Dutch</td>
<td>20</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>511</td>
</tr>
<tr>
<td>DXF-files</td>
<td>342</td>
</tr>
<tr>
<td>Dynamic Backgrounds</td>
<td>62</td>
</tr>
<tr>
<td>Dynamic DLL's</td>
<td>194</td>
</tr>
<tr>
<td>Dynamic Error Budgeting</td>
<td>434</td>
</tr>
<tr>
<td>Dynamic Model</td>
<td>484</td>
</tr>
<tr>
<td>Dynamic Systems</td>
<td>1249, 1280</td>
</tr>
<tr>
<td>dynamic variables</td>
<td>110</td>
</tr>
<tr>
<td><strong>E</strong></td>
<td></td>
</tr>
<tr>
<td>Eddy Current</td>
<td>511</td>
</tr>
<tr>
<td>Edit Condition</td>
<td>114</td>
</tr>
<tr>
<td>Edit Implementation</td>
<td>49</td>
</tr>
<tr>
<td>Edit Modes</td>
<td>294</td>
</tr>
<tr>
<td>Edit window</td>
<td>290</td>
</tr>
<tr>
<td>Editing Domains</td>
<td>90</td>
</tr>
<tr>
<td>editor</td>
<td>2, 21, 22</td>
</tr>
<tr>
<td>Effort</td>
<td>87, 1250</td>
</tr>
<tr>
<td>effort detector</td>
<td>612</td>
</tr>
<tr>
<td>effort in</td>
<td>272</td>
</tr>
<tr>
<td>effort source</td>
<td>620, 628</td>
</tr>
<tr>
<td>Effortioncausality</td>
<td>272</td>
</tr>
<tr>
<td>EffortSensor</td>
<td>613, 1253</td>
</tr>
<tr>
<td>Eigen Frequencies</td>
<td>369, 427</td>
</tr>
<tr>
<td>Electric</td>
<td>87, 661</td>
</tr>
<tr>
<td>Electric Switch</td>
<td>667, 677</td>
</tr>
<tr>
<td>electrical inductance</td>
<td>671</td>
</tr>
<tr>
<td>Elements</td>
<td>275, 1271</td>
</tr>
<tr>
<td>Eliminating double differences</td>
<td>36</td>
</tr>
<tr>
<td>Eliminating junctions</td>
<td>36</td>
</tr>
<tr>
<td>Eliminating nodes</td>
<td>36</td>
</tr>
<tr>
<td>Else</td>
<td>259, 261, 262</td>
</tr>
<tr>
<td>Elsif</td>
<td>261</td>
</tr>
<tr>
<td>Enable plot</td>
<td>101</td>
</tr>
<tr>
<td>Enable XMLRPC Interface</td>
<td>28, 43</td>
</tr>
<tr>
<td>Encoder</td>
<td>867</td>
</tr>
<tr>
<td>Encrypt Models</td>
<td>57</td>
</tr>
<tr>
<td>encrypted</td>
<td>30</td>
</tr>
<tr>
<td>Encryption</td>
<td>57</td>
</tr>
<tr>
<td>end</td>
<td>37, 258, 259, 261, 262, 263, 264</td>
</tr>
<tr>
<td>End Angle</td>
<td>452</td>
</tr>
<tr>
<td>end plane</td>
<td>334</td>
</tr>
<tr>
<td>end position</td>
<td>336</td>
</tr>
<tr>
<td>End Time</td>
<td>464</td>
</tr>
<tr>
<td>end_time</td>
<td>456, 468</td>
</tr>
<tr>
<td>Endless</td>
<td>100, 126</td>
</tr>
<tr>
<td>Energy</td>
<td>45, 614</td>
</tr>
<tr>
<td>energyfunction</td>
<td>165</td>
</tr>
<tr>
<td>EnergySensor.emx</td>
<td>614</td>
</tr>
<tr>
<td>English</td>
<td>20</td>
</tr>
<tr>
<td>Enter equations in 3D Mechanics Editor</td>
<td>323</td>
</tr>
<tr>
<td>Enter expressions in 3D Mechanics Editor</td>
<td>323</td>
</tr>
</tbody>
</table>
Index

Equal 84, 181, 254, 255, 256
equation 22
equation editor 21, 22, 23
equation model 22
Equation Sections 139
Equations 74, 138, 139, 284, 1266
Equations interpreted as code 40
Equations, Bond Graph 1266
Error 1064
error message 39
Errors 39, 40, 113
Euler 132
Euler Parameters 304, 349
event 144, 179, 180, 1139
Event delta 100
eventdown 179
Events 144
eventup 179
Every 28, 43
Examples 27
Execution 71, 282
Execution Order 138
Exp 166
exp10 167
exp2 167
Expand Vectors/Matrices 98, 110
Expand Vectors/Matrices: 110
Explode 35
Exponential 166
Exponential Base 10 167
Exponential Base 2 167
Exponential Window 1017
export 55, 59, 92
Export 3D Animation to Unity 600
Export to Matlab 12, 55
Export to Simulink 55
Exporting Simulations 121
Expression 321
Expressions 323
Expressions Editor 323
External Tracking 1069
externals 92
eye 210
- F -
F3 26
fading colors 109
false 154, 1163, 1177
Fast Fourier Transform 404
fast mode 121
fast simulation 121
Faulhaber 2006 492
favorites 110
femto 91
fft 407
FFT Analysis 404
FFT plot 404
FFT settings 404
FFT Window 407
File Data 183, 204
File Input 1041, 1200
FileInput 183
Filename 1194
Files of Type 30
Filter 394, 400, 404, 1015, 1067, 1144, 1145, 1146
Filter Editor 394, 1015
Filtering 415
Final Equations 139
finalequations 138, 139
Find 26, 109
Find again 26
Find box 26
Find tab 21, 26
Finish 100
finishtime 154, 202
first 220
First Order Filter 401, 403
Fixation of bodies 884
Fixed 47
Fixed Causality 66, 279
fixed in orientation 1289
fixed out 84
fixed out orientation 1289
fixed position 47, 76
fixed sample time 118
Fixed Sampletime 129
fixed time step 118
fixed world 826, 891, 914, 942
FixedWorld 826, 942
Flash 332
Flat 351, 352
Flexible Components 897
Flip Flop 1164, 1178
FlipFlop 1176, 1185
Flipping 911
Floating License 7, 8, 11
floating mechanism 304
floor 168
Flow 87, 1250
flow conductance 689
flow detector 613
flow in 273
flow source 621, 629
flowcontrolvalve 740
flowcontrolvalve-states 765
Flowincausality 273
FlowSensor 614, 736, 1253
FlowSource 718
flowsource-leakage 726
Fluid Properties 710
FluidProperties 710
FMI 2, 55, 92, 94
FMI Import 93
FMU 2, 55, 92, 94
FMU 1.0 export 521
FMU 2.0 export 521
FMU export 92, 94
FMU Import 92, 93
Fonts 28, 43, 103
For 263

For To Do 263
Force 914, 915, 927
force (constant) 927
force (variable) 928
ForceActuator 928
ForceActuator-Relative 928
Force-Relative 927
forces 896
ForceSensor-Relative 974
Fork 982
Form 66, 279
Forward Euler transformation 415
Fourier Analysis 404
fourthreewaydirectionalvalve 741
fourthreewaydirectionalvalve-states 767
FourThreeWayProportionalValve 743
FourThreeWayProportionalValve-States 769
frame 349
frame hierarchy 335
frame rate 332
Frames 344
frames per second 334
free 7
freeze 891, 914
frequency 128, 404, 433
frequency range 404
Frequency Response 411
Frequency Sweep 1207
frequencyevent 180, 1142
Friction 619, 627, 826, 942
friction literature 1248
Friction Phenomena 1240
FrictionRelative 947
FrictionSimple 952
FrictionSimple-Relative 956
From Matlab 98
FromMatlab 270, 1152
front plane 344
F-type Trigger Flip Flop 1164, 1178
Full Screen 124, 324
Functions  23, 162
- G -
  G  349, 689
  Gain  395, 422, 1016, 1065
  Gain Margin  371, 429
  Gain-Phase  433
  Gasoline  710
  Gauss  221, 1202, 1217
  Gaussian Noise  221, 1202, 1203, 1217
  Gear  845
  gear box  845
  gear ratio  845, 856
  gearbox  856
  General Modified Sine with Constant Velocity 456, 468
  General Properties  28, 43, 334, 351
  Generate 20-sim Model  302
  Generate Code  449
  Generate CSV  449
  Generate Global Parameters  299
  Generating Unity Animation  606
  Generic Filter  400
  Geneva Mechanism  456, 468
  German  20
  Getting started  15
  Ghost Modes  294
  giga  91
  Global  78, 79, 155
  Global Maximum  109
  Global Minimum  109
  Global parameters  78, 98, 155
  global parameters multiple assignment
  Global Reference  1287
  Global Relations Editor  80
  global variables  78, 110, 155
  globals  78
  Globals tab  80
  Go Down  18, 37
  Go Up  18, 37
  Gouroud  351
  gradient fill  28, 43
  gradient search  544
  Graph Animation  358
  graphical editor  21, 24
  gravity  960
  green  349
  green input and output lines  51
  Grid  103
  Ground  670, 994
  Ground.emx  670
  GY  615
  GY-2  650, 652
  GY-3  637
  GY-element  1278
  Gyrator  615, 619, 629
  Gyrators  1278
- H -
  halt  267
  hamming  407
  hann  407
  Has Damping  308
  Has Minimum  308
  Has Spring  308
  Head Sensor  737
  heatcapacity  995
  heatflow  1000
  heatflowsensor  1004
  hecto  91
  Help  1
  Help Page  40
  hex  159
  hexadecimal  159
  Hidden  98, 110, 146, 149, 152, 157, 326
  Hidden layer  377
  Hidden layers  375
  Hidden Parameters  98
  hidden variable  65
  Hidden Variables  110
  Hide 3D Objects  326
  Hide curve  101

20-sim 5.1 Reference Manual  1306
Index

Index:

- Hide plot 101
- Hierarchical Models 18
- hierarchy 18, 37, 335
- high 85
- High / Low Terminals 85, 1293
- High frequency noise 1067
- High pass 400, 401
- High Pass First Order Filter 401
- High Pass Second Order Filter 401
- high-frequency measurement noise 1067
- High-frequency roll-off filter 399
- Hinge X-rotation 308
- Hinge Y-rotation 308
- Hinge Z-rotation 308
- Histogram 560
- H-matrix (4x4) 315
- Hold 175, 1133
- Home 37
- homogeneous 210
- hose 695
- how to speed up simulations 121
- How to use the Parameters 482
- html document 59
- HTTP 28, 43
- Hydraulic 87
- hydraulic accumulator 786
- hydraulic pipe 695
- Hydraulic Powersensor 737
- HydraulicInertia 694
- Hysteresis 511, 1045, 1052
- Hz 128, 1145, 1146

- I -
  - i 616, 617
  - I Controller 396
  - I-2 651
  - I-3 638
  - IC-2 618
  - Icon 18
  - Icon Editor 21, 75
  - Icon Size 28, 43

- Icon tab 21
- Iconic Diagram 1259
- iconic diagram models 24
- Iconic Diagram Ports 1289
- Iconic Diagram,Bond Graph 1259
- Iconic Diagrams 27, 661, 1259, 1261, 1280
- Iconic Diagrams,Bond Graphs 1259, 1261
- ideal capacitor 664
- ideal current source 686, 687
- ideal cylinder 699
- ideal DC-motor 663, 800
- ideal electrical inductance 671
- ideal electrical resistor 676
- ideal mass 960
- ideal physical model 1249, 1280
- ideal voltage source 688
- Identified with 128
- I-elements 1276
- If 258, 259, 261, 262
- If Then 258
- If Then Else 259, 262
- If Then Elsif 261
- Image 334
- images 25
- imaginary 433
- impacts 964
- Implementation 18, 449
- Implementations 49
- Implode 35
- Import 92, 98, 114
- Import 20-sim Scenery file 600
- Import Data 433
- Import Gain-Phase 433
- Import Real-Imag 433
- Importing Simulations 122
- impulse 221
- included toolboxes 7
- indentation 335
- independent rate 65
- independent state 65
indexer 839, 979
indexers 839, 979
indifferent 84
Indifferent Causality 66, 279
Inductor 671
Inductor.emx 671
Inertia 831
Initial 133, 134
Initial Equations 139
initial output 1074
Initial Values 17, 98
Initial Values Quick Tour 17
Initial Values Reset 121
Initial Weights Fill Scale 379
initial yerk 456, 468
initial equations 138, 139
Initialize variables 40
Initialize Variables on Nan 113
Initials to Zero 98
inner 210
Input Equations 65
Input from File 204, 1200
Input is not used 40
input noise 434
input probes 110
input signal 83
Input/Output 595
insert a submodel 33
Inspect Models 18
installation 8, 575, 584
Installing 20-sim 8
Installing Unity Toolbox 593
instructions 65
int 169
Integer 157, 159
Integral 169, 1132
Integral Form 68, 281
integral time 1066
Integrate 1018, 1022
Integrate Data 404
Integrate-ExpWindow 1017
Integrate-FO 1018
integrate-folimited 1019
Integrate-Limited 1020
Integrate-RectWindow 1021
Integrate-Reset 1021
Integration Error 133, 134
Integration Methods 100, 126
integrationmethod 202
Integrator 396
interacting form 1067
Interesting 110, 152, 157
interesting variable 65
interface 22, 82
Interface Editor 21, 82
Interface tab 21
intermediate points 33
Intermittent 456, 468
Interpreter Code 65
Interval 1021
introduction 476, 573
introduction to friction 1239
inverse 211, 1023
inverseH 211
inverting equations 66, 279
Invertor 1164, 1178
IPM 1249, 1280
ipython 584
ISA form 1067
ISO VG 100 710
ISO VG 150 710
ISO VG 22 710
ISO VG 32 710
ISO VG 46 710
ISO VG 68 710
iterate 144
- J -
Jacobian Matrix 315
jerk 452
Join Parameter Variation 532
Joint Constraint Settings 299
Joint Constraint Settings dialog 299
Joystick 1196
Jump 26, 1047
Jump and Rate Limiter 1047
Junction 1275
Junctions 1273

- K -
Kerosene 710
Keyboard 63, 124, 1197
keyboard keys 330
Keyboard Shortcuts Editor 63
Keyboard shortcuts simulator 124
keys 330
Keywords 40, 142, 146
kilo 91
kind 110

- L -
Label 103
Lag Filter 402
laminar flow 689, 730, 733
LaminarResistance 730
language 20, 22
Language Reference 136, 138, 139, 146, 157, 162, 234, 258
Laplace variable 364, 420
Larger Than 256
Last Run 108
layers 375
Lead Filter 402
leakage 407
Learn after Leaving Spline 380, 385
Learn at each Sample 380, 385
learning rate 379, 380, 385
left-hand frames 344
left-handed 351
Less Than 254
Lever 983, 991
lever ratio 983
Libraries 28, 43
library 2, 21, 27, 40, 304
Library Folders 28, 43
library names 28, 43
library paths 28, 43
Library tab 21, 292
License 8, 11
License Activation 8
license Key 8
License Unity Toolbox 592
Lightwave Object files 342
Likes 84
Likes Causality 66, 279
limint 169
Limit 169, 1046
limitations 7
Limited Integration 169, 1020
limited stiffness 911
Limits 508
Line 336, 695
Line Climber 544
Linear 348
Linear Actuators 897
linear differential equations 362, 418
linear feedback anti windup 1069
Linear Motors 504
Linear Slides 897
Linear System 410, 1023, 1226
Linear System Editor 415, 1023, 1226
linear time- invariant models 415
Linearization Explained 410
Linearization moment 40
Linearization Tolerances 413
Linearization Type 40
Linearize at 408
Linearize Model 408
linearized symbolically 876
LinearSystem 1133
linsolve 212
Literature 1075
Load Scene 332
Load Weights at Start of Simulation 379, 385
Localhost 28, 43
Locate License File 11
locks 330
Log 170, 1037
Log Variables 449
log10 171
log2 171
Logarithm Base 10 171
Logarithm Base 2 171
Logging 450
Logical Nand 1179
Logical-Invertor 1178
Logical-Nor 1180
Logical-Or 1181
Loop 3D Animation 40
Loop Flushing Valve 746
Loops 70, 278
low 85
Low Pass 400, 403, 1145, 1146
Low Pass First Order Filter 403
Low Pass Second Order Filter 403
Low Terminals 85, 1293
LowPassFilter-BW2Hz 1145
lowpassfilter-bw4 1146
LowPassFilter-BW4Hz.emx 1146
lowpassfilter-fo 1147
lowpassfilter-so 1149
Lumped Parameter Method 1249, 1280
hydraulic line 695
- M -
Machine Code 65
Magnetic 87
Main Model 18, 40
main reference frame 335
major 154
major step 72
Manager 40
Manipulate 330
Manual output 1074
mask 53, 415
Masked Models 53
Mass 960
Material 355
matlab 2, 12, 55, 110, 268, 269, 270, 408, 521, 532, 573, 578
matlab simulink connection 12
Matlab-Code folders 28, 43
Matlab-Code Generation 28, 43
matplotlib 584
Matrices 53, 110, 274, 275
Matrix 237, 275, 276
Matrix Declaration 274
Matrix is assigned a scalar 40
Matrix Notation 275
Matrix Operators 276
Matrix Use 276
max 151, 213
maximum 133, 134, 1054, 1189
Maximum allowed lost time 126
maximum continuous torque 511
Maximum Efficiency 516
maximum phase current 500
maximum phase to phase voltage 500
Maximum Power 516
Maximum Step Size 134
Maximum Value 110
Maxon 486
Maxon motors 486
Maxwell reciprocity 618
Mean 1189, 1216
mean time interval 1221
measured variable 1064
measurement 360, 1064
Mechanical 87, 791
mechanism 839, 979
mechanisms 452, 839, 979
mega 91
Melt equal junctions 36
Menu Scripting 575
Mesh 351
Message Log 96
Message window 293
m-file 55
MGY 619, 1279
MGY-2 652
MGY-3 639
MGY-element 1279
micro 91
Migrating from Older Versions 288
milli 91
min 151, 213
Minimize/Maximize 538
Minimum 1055, 1190
Minimum / Maximum 532, 538
Minimum Value 110
minor steps 72
Minus 1030
Mixed models 51
MLP Network 377
mlpnetwork 1063
Mod 240
Modal 962
ModalSummer 963
Model exchange 92
Model Help 40
Model Hierarchy 21, 37, 98
Model Hierarchy: 110
Model Layout 137
model libraries 27
model library 24
model name 62
Model Properties 40
Model Settings 40, 295
Model tab 21, 291
Model Template Folders 28, 43
modeling 610
models 18, 610
Modified Sine 456, 468
Modified Sine with Constant Velocity 456, 468
modified sine with constant velocity 456, 468
Modified Trapezoidal 456, 468
Modulated dissipative element 619
Modulated effort source 620
Modulated Elements 1253
Modulated flow source 621
Modulated gyrator 619
Modulated Gyrators 1279
Modulated Sources 1278
Modulated transformer 621
Modulated Transformers 1279
ModulatedCurrentSource 687
ModulatedCurrentSource.emx 687
modulatedflowsource 719
modulatedflowsource-leakage 727
modulatedheatflow 1001
modulatedpressuresource 719
ModulatedTemperatureSource 1001
ModulatedVoltageSource 687
ModulatedVoltageSource.emx 687
Module 442
Modulus Operator 240
Momentum Constant 379
Monitor 1031, 1211
Monte Carlo analysis 108, 560
More 332, 1194
motion 300, 452, 468
Motion Profile 452, 1197
Motion profile parameters 468
Motion Profile Wizard 464, 467, 1197
MotionProfile-Wizard.emx 1198
Move curve 101
Move plot 101
Moving 330
Moving Objects 330
MovingAverage 1190
MR 619
MR-2 653
MR-3 641
MSC% 456, 468
MSC50 456, 468
MSe 620
MSe-2 654
MSe-3 642
MSe-element 1278
MSf 621
MSf-2 655
MSf-3 642
MSf-element 1278
msum 213
MTF 621, 1279
MTF-2 655
MTF-3 643
MTF-element 1279
mul 182
multiplydivide 35
Multi Layer Perceptron 377
multi-bond 53
multi-connection 53
Multi-Dimensional Models 53
Multi-Dimensional Ports 53
Multi-Line Tabbing 22
multiple port restrictions 84
Multiple Run 108, 571
Multiple Run results 108, 532
Multiple Run Wizard 531
multiple-run 108
multiplication 89, 235, 237
multiplication factor 91
Multiplication/Offset 103
Multiplications 91
Multiply 1006, 1025
MultiplyDivide 182, 1025
multiplyH 214
multi-signal 53
Mux 1026, 1027, 1028
Naming Conventions 62, 1099
Nand 1165, 1179
nano 91
Natural Logarithm 170
Negate 1029
net energy 45
net power 45
net power flow 45
network 375, 380
Network is Discrete 385
Network Name 379, 385
Neural Networks 375, 380
neuron 377
neurons 375, 380
New 3D Animation Plot 116
new in 20-sim 2
New Simulation Plot 115
Newlines 145
Newton Raphson 544
next 176
Next Camera 344
Next Local Maximum 109
Next Local Minimum 109
Nichols 373, 431
Nichols Chart 373, 415, 431
No Emphasising Threshold 28, 43
Node 698, 832, 963
Node.emx 672
Noise 221, 222, 1202, 1205, 1217, 1218
Nominal Operating Point 511
Non-actuated 308
non-interacting form 1067
Nor 1166, 1180
norm 214
Normal Force 1239
Normal stop 267
norminf 215
Not 257
Not Equal 84, 255
Notch Filter 403, 404
NTC     1003
Number     85, 1293
Number Hidden Neurons     379
number of frames per second     334
Number of Splines     385
numerator     364, 420
numerical linearization     413
Numerical Output     532
Numerical Values     109
numpy     584
Nyquist     374, 430
Nyquist Diagram     374, 430
Nyquist Plot     415

- O -
Object Attributes     326
Object Tree     326
objects     326, 330
octave     2, 573, 575
octaveforge     575
offset     352, 1066
Offset First Data Point     1194
OK     532
OK to Continue     449
Omega (3x1)     315
Omega and Velocity (3x1)     315
Omega-X     315
Omega-Y     315
Omega-Z     315
one     1199
One Junction     623, 631, 1273, 1275
One Step     108
One Step Simulation     108, 113
One_in     84
One_out     84
OneJunction     622
oneup     156
Only Frames     332
OpAmp     672
OpAmp.emx     672
Open     30
open chain mechanism     297
open end     892
open loop system     410
Open Model     30
Operating Point     119, 408
operating system     4
operational amplifier     672
Operators     23, 234
optimization     538, 544
Optimization Method     538
Optimization Methods     544
Optimization Results     538
optimization run     108
Optimize Divisions     40
Optimize Duplicate Expression     40
Optimize Equation Structure     40
Optimize Static Expressions     40
Optimizing Equation Structure     65
Or     253, 1167, 1181
orange outlines     37
order     385, 456, 468
Order of Execution     71, 282
Order of Execution     71, 282
Orientation     84, 85, 315, 349, 1253, 1284, 1285, 1289
Orientation Info     25, 1284
orifice     731
orifice area     689
Origin     352
OrthoGraphic     344
oscillating     456, 468
oscillating signal generators     456, 468
Other Motors     519
output     1078, 1102
Output After Each     100, 126
output delay     362, 418
Output Equations     65
Output Filename     302
Output is not used     40
Output position     308
output probes 110
Output Sigma 434
output signal 83
Output tab 21
Override the General Spring Damper Values 299
overshoot 370, 428

- P -
P 1079, 1096, 1119
P Controller 395, 1096, 1119
p_vapour 689
Pack 30, 31, 55
Packed Files 31
Pade Time Delay 1006
Pair-wise transfer function 404
Parallel 348
Parallel Form 1067
Parameter is not used 40
parameter name 62
parameter sweep 108, 532
Parameter Sweeps 532
parameters 17, 98, 149, 479
Parameters Quick Tour 17
parameters ranges 151
Parameters/Initial Values Editor 98
Parametric modeling 321
Parametric Modeling 323
Parasitic 789
ParasiticVolume 789
Parenthesis 145
Partial Cubic 456, 468
Partial Trapezoidal 456, 468
Pass Band 400
PD 1096, 1120
PD Controller 396, 1096, 1120
peaks 404
penumbra 348
Permanent Magnet Motorsunction 496
Perpendicular Search 544
Perspective 344
PgDown 37
Por Up 37
phase 371, 429, 433
Phase Margin 371, 429
phase to phase inductance 505
phase to phase resistance 505
Phased Sine Wave.emx 1212
phasesensor 1191
Phong 351
physical domain 87
Physical Domains 87
physical model 1249, 1280
physical systems 610
pi 1081, 1097, 1121, 1199
PI Controller 397, 1097, 1121
pico 91
pictures 25
PID 1098, 1122
PID Compensator 399
PID Control 1064
PID Controller 397, 398, 399, 1098, 1122
PID-1 Controller 397
PID-2 Controller 398
piezo actuator 661, 662, 925, 926
PilotOperatedCheckValve 748
PilotOperatedCheckValve-States 773
pipe 695
planar motion 876
Plane Distance 344
PlanetaryGear 847
plant 360, 1064
Play button 436
PlaySound 1237
Plot 96, 101
Plot Properties Editor 103
Plot Title 103
Plot Window 2, 101
plug-in 593
Plus 1030
PlusMinus 35, 182, 1030
Pneumatic 87
point mass  882
point model  886
Polack Ribiere  544
Pole Zero  372, 432
Pole Zero Diagram  372, 432
pole zero notation  366, 424
Poles  366, 415, 424, 1023
Poles and Zeros (including root locus)  415
Polynomial  456, 468
Polynomials  364, 420
Port is not used  40
port name  83
Port Names  25, 140
Port Properties  1268, 1289
Port Relations tab  84
Port Variables  87, 1289
Ports  82, 85, 1268, 1289, 1293
port-size  53
position  304, 315, 348, 464, 595, 893, 921, 960
Position (3x1)  315
Position Sensor  893, 921
Position/Orientation  315
PositionActuator  804, 930
PositionActuator-Relative  801, 929
PositionSensor-Absolute  870, 975
PositionSensor-Relative  871, 975
Position-X  315
Position-Y  315
Position-Z  315
positive direction  880
Possible loss of data  40
Potentiometer  675, 872
Power  45, 87, 240, 896, 1038
power flow  45
Power Interaction Port  308
Power ports  140
power sensor  625
power spectral density  404, 434
powerflow  896
power-port variables  138, 140
PowerSensor  737, 873
PowerSplitter  626
powerport  87
pre-act  1067
Predefined Constants  148
Predefined Variables  154
preferred  84
Preferred Causality  45, 66, 279
Preferred out  84
Prefilter  360, 404
prefix  91
Prefix Minus Sign  257
Prefix Plus Sign  257
prefixes  89
Prepare Scripting Folder  578
Pressing Mode  33
pressure  689
Pressure Compensator  750, 775
pressurereducingvalve  752
pressurereducingvalve-states  778
pressurereliefvalve  753
pressurereliefvalve-states  779
pressuresensor  738
pressuresource  720
previous  177
Previous Local Maximum  109
Previous Local Minimum  109
Previous Runs  108
privacy  5
process  39, 1064
process output  1064
Process tab  21
process variable  1064
Processed Files  32
processing  32, 40
processor  4
professional  7
profile  456, 464, 468
Profiles  332, 456, 468
Index

Programming Language  521
Project  40
Projection  344
Properties  292, 326, 1289
Property Page  28, 43
Proportional Band  1065
proportional gain  1065
PSD  434
Psensor  626, 1253
Pseudo Domain  90
Pseudo Pneumatic  87
PseudoHydraulic  87
PseudoThermal  87
PseudoThermalH  87
PTC  1003
Pulse  456, 468, 1204
purchase  285
PV  1064
pwm  1048
python  573, 584, 585, 586, 589
Python 3.4  8
Python Scripting Help  588

- Q -
Qsensor  627, 1253
quadratic  348, 407
quanties  98
Quantisize-Round  1135
Quantisize-Truncate  1136
quantities  86, 89, 90
Quantities and Units Editor  86
Quantities Mismatch  40
QuantitiesAndUnits.ini  86
Quantity  91, 110, 146, 149, 152
Quantity name  90

- R -
R  349, 627
R-2  656
R-3  644
RackPinionGear  849, 984
radiation  996
Radius  341
Raising Power  1038
Ramp  221, 456, 468, 1204
ran  222
Random  154, 222, 1205, 1218
random form  66, 279
random integers  1220
random noise  222, 1203
random numbers  1203
Random Seed  222, 1203
range  275
ranges  149, 151, 275
Rate  68, 281, 1049, 1067
Rate Limiter  1047, 1049
Rates  110
ratio  615, 619
raw Pseudo bonds  40
Ray Tracing  332
Read Datafile  108
readonly  151
real  157, 160, 433
real and  1172
Real Clock  1173
real CMOS_CD4020  1174
real CompareGE  1174
real CompareGT  1175
real CompareLE  1175
real CompareLT  1176
real false  1177
real F-type Trigger Flip Flop  1178
Real Invertor  1178
real ResetSet Flip Flop  1182
real R-type Trigger Flip Flop  1183
real SetReset Flip Flop  1184
Real Time 3D Animation  108
Real Time Toolbox  520
Real-Imag  433
realtime  154
Realtime Simulation  100
Real-Time simulation  126
Index

Rectangular Window 1021
Rectifier 676
red 349
Reduction Tolerance 415
Redundant Equations 40
Reference Body is Floating option 304
Reference Frame 335, 349
Registration/Update License 11
Regularization 385
Relative 133, 134
relative error 100
relative tolerance 413
Relay 1050
RelayHysteresis 1052
Remove redundant equations 65
Rename Implementation 49
render 351
Rendering 351
Repeat 265
Repeat Until 265
replace models 35
Replace parameters 40
Replay 108
Representation 293
Request License 11
requirements 4
resample 118
Reserved Words 142
reset 1066
Reset Initial Values 121
Reset Initials 121
Reset Model 450
reset time 1066
ResetSet Flip Flop 1168, 1182
Resettable Integration 172, 1021
resint 172
Resistance 1277
Resistor 619, 627, 676, 1002
Resistor.emx 676
resolution 404
resonance frequencies 404
resonant frequencies 404
resonant peaks 404
Restore Default 28, 43
Return Angle 452
Return Time 464
return_time 456, 468
reverse acting 1065
rewrite equations 68, 281
rewriting equations 66, 279
rho 689
right hand frames 344
ripple 400, 497
rise time 370, 428
Root Locus Gain 422
root locus plot 372, 432
Root Mean Square 1192
Rotation 87, 595
Rotation (3x3) 315
Rotation Axis 308
rotation speed 873
rotational inertia 831, 882
rotational spring 832
round 172
Rounding 1135
Row 53
Rows 215, 275, 1289
Rows/Columns 1268, 1289
RS232 28, 43
R-type Trigger Flip Flop 1169, 1183
Run 96, 108
Run Number 109
Run Properties Editor 100
Run Simulation 449
run tasks 573
Runge Kutta 2 133
Runge Kutta 4 133
Runge Kutta Dormand Prince 8 134
Runge-Kutta-Fehlberg 133
Running a 1-D B-Spline Network 386
Running a Simulation 15, 108
running in real-time 608
running the Unity Animation 608
Runtime 139

- S -
s 128, 415
SAE 10W-30 710
SAE 10W-40 710
SAE 15W-40 710
SAE 75W-140 710
Safe Operating Area 511
Sample 176, 177, 1126, 1137
Sample and Hold 1133
sample frequency 51, 128
sample rate 51
sample time 118, 415
Sampletime 154, 177, 1126, 1133, 1137
Sampling 177
Save 30
Save As 30
Save Encrypted 30
Save Scene 332
Save Weights at End of Simulation 385
Save Weights at Start of Simulation 379
Saw Wave 1212
Scale 595
Scaling 103, 349
Scenario 436, 442
Scenario Manager 436, 442, 1187
Scenario Manager - File Storage 451
Scenario Manager Reset Model 450
Scenario Manager Logging 450
Scenery Filename 302
Scenes 332
scipy 584
scope 26, 78, 79, 80
Screen 124
Scripting 573, 574, 578, 584, 585, 586, 587, 588

Scripting Interface 28, 43
Scripting Menu 575
Scripting_API 574
Scrolling 37
Se 628
Se-2 657
Se-3 645
Sea Water 710
search 26
Search box 26
Second Order Filter 401, 403
see 344
Se-element 1277
Segment 340
segments 338, 339, 340, 341
Select 326
Selecting Objects 328
selection box 328
selection mode 35
Selection Properties 292
sensitivity 556, 1065
Sensitivity analysis 556
Sensor 893, 894, 921
Sensor Types 315
Sensors 315, 892, 911
Separate High / Low Terminals 85, 1293
sequential 139
Serial 28, 43
Series Form 1067
servomotor 803, 931
Set As Reference Body 304
Set Parameter 449
Set Values 532
setpoint 1064, 1075, 1078, 1102
Setpoint Weighting 1068
SetReset Flip Flop 1169, 1184
Setting Causality 45
settings 40, 202
settling time 370, 428
setoolsetting 2, 202
<table>
<thead>
<tr>
<th>Term</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sf</td>
<td>629</td>
</tr>
<tr>
<td>Sf-2</td>
<td>658</td>
</tr>
<tr>
<td>Sf-3</td>
<td>645</td>
</tr>
<tr>
<td>Sf-element</td>
<td>1277</td>
</tr>
<tr>
<td>S-function</td>
<td>55</td>
</tr>
<tr>
<td>S-functions</td>
<td>521</td>
</tr>
<tr>
<td>SGY</td>
<td>629</td>
</tr>
<tr>
<td>SGY-2</td>
<td>658</td>
</tr>
<tr>
<td>SGY-3</td>
<td>646</td>
</tr>
<tr>
<td>shape</td>
<td>456, 468</td>
</tr>
<tr>
<td>shared</td>
<td>92</td>
</tr>
<tr>
<td>shock absorber</td>
<td>964</td>
</tr>
<tr>
<td>shortcuts</td>
<td>63, 124</td>
</tr>
<tr>
<td>Show 3D Objects</td>
<td>326</td>
</tr>
<tr>
<td>Show Curve</td>
<td>101</td>
</tr>
<tr>
<td>Show Equations</td>
<td>74, 284</td>
</tr>
<tr>
<td>Show Grid</td>
<td>40</td>
</tr>
<tr>
<td>Show Hidden</td>
<td>98</td>
</tr>
<tr>
<td>Show Name</td>
<td>25</td>
</tr>
<tr>
<td>Show Names For New Submodel</td>
<td>28, 43</td>
</tr>
<tr>
<td>Show plot</td>
<td>101</td>
</tr>
<tr>
<td>Show results after processing</td>
<td>40</td>
</tr>
<tr>
<td>Show Terminals</td>
<td>25, 47</td>
</tr>
<tr>
<td>Show Variables:</td>
<td>110</td>
</tr>
<tr>
<td>Shuttle Valve</td>
<td>755, 781</td>
</tr>
<tr>
<td>SI Symbol</td>
<td>90</td>
</tr>
<tr>
<td>sidops</td>
<td>136, 237</td>
</tr>
<tr>
<td>SIDOPS+</td>
<td>136</td>
</tr>
<tr>
<td>Sigma</td>
<td>1138</td>
</tr>
<tr>
<td>Sigmoid</td>
<td>377</td>
</tr>
<tr>
<td>Sign</td>
<td>173, 1038, 1041</td>
</tr>
<tr>
<td>Signal</td>
<td>27</td>
</tr>
<tr>
<td>Signal Ports</td>
<td>140</td>
</tr>
<tr>
<td>SignalGenerator-Cycloid</td>
<td>1199</td>
</tr>
<tr>
<td>SignalGenerator-FileInput</td>
<td>1200</td>
</tr>
<tr>
<td>SignalGenerator-GaussianNoise</td>
<td>1202, 1215</td>
</tr>
<tr>
<td>SignalGenerator-Pulse</td>
<td>1204</td>
</tr>
<tr>
<td>SignalGenerator-Ramp</td>
<td>1204</td>
</tr>
<tr>
<td>SignalGenerator-Random</td>
<td>1205, 1218</td>
</tr>
<tr>
<td>SignalGenerator-RandomInteger</td>
<td>1220</td>
</tr>
<tr>
<td>SignGenerator-Step</td>
<td>1206</td>
</tr>
<tr>
<td>SignGenerator-StepTime</td>
<td>1207</td>
</tr>
<tr>
<td>SignalGenerator-Sweep</td>
<td>1207</td>
</tr>
<tr>
<td>SignalGenerator-Time</td>
<td>1210</td>
</tr>
<tr>
<td>SignalGenerator-VariableBlock</td>
<td>1221</td>
</tr>
<tr>
<td>SignalMonitor</td>
<td>1031, 1211</td>
</tr>
<tr>
<td>Signals</td>
<td>1253</td>
</tr>
<tr>
<td>Silent stop</td>
<td>267</td>
</tr>
<tr>
<td>Simple Transformer</td>
<td>630</td>
</tr>
<tr>
<td>Simplification</td>
<td>36, 1255</td>
</tr>
<tr>
<td>Simplification,Bond Graph Models</td>
<td>1255</td>
</tr>
<tr>
<td>simulation</td>
<td>96</td>
</tr>
<tr>
<td>Simulation Code</td>
<td>65</td>
</tr>
<tr>
<td>Simulation Quick Tour</td>
<td>15</td>
</tr>
<tr>
<td>simulator</td>
<td>2, 96</td>
</tr>
<tr>
<td>Simulator Setting</td>
<td>449</td>
</tr>
<tr>
<td>Simulink</td>
<td>12, 55, 521</td>
</tr>
<tr>
<td>Simulink S-function</td>
<td>521</td>
</tr>
<tr>
<td>sin</td>
<td>230, 232</td>
</tr>
<tr>
<td>sincos</td>
<td>232</td>
</tr>
<tr>
<td>Sine</td>
<td>456, 468, 1039</td>
</tr>
<tr>
<td>Sine Sweep</td>
<td>1207</td>
</tr>
<tr>
<td>Sine Wave</td>
<td>1212, 1213</td>
</tr>
<tr>
<td>single</td>
<td>7</td>
</tr>
<tr>
<td>single acting cylinder</td>
<td>700, 703, 706, 708</td>
</tr>
<tr>
<td>single license</td>
<td>8</td>
</tr>
<tr>
<td>Single-Step Simulation</td>
<td>108, 113</td>
</tr>
<tr>
<td>sinh</td>
<td>231</td>
</tr>
<tr>
<td>SISO</td>
<td>364, 415, 420</td>
</tr>
<tr>
<td>size</td>
<td>53, 332</td>
</tr>
<tr>
<td>skew</td>
<td>216</td>
</tr>
<tr>
<td>Skip</td>
<td>114</td>
</tr>
<tr>
<td>Skydrol 500B-4</td>
<td>710</td>
</tr>
<tr>
<td>SkyHookDamper</td>
<td>966</td>
</tr>
<tr>
<td>Slides</td>
<td>897</td>
</tr>
<tr>
<td>slow simulation</td>
<td>121</td>
</tr>
<tr>
<td>Small Rotations</td>
<td>876, 879</td>
</tr>
<tr>
<td>Smart Contraint Solving</td>
<td>135</td>
</tr>
<tr>
<td>Smooth Line</td>
<td>33</td>
</tr>
</tbody>
</table>
Snap to Grid 40
Solo 326
Solve algebraic variables 40
Solving Differential Equations 68, 281
sound 1237
source 620, 621, 628, 629
Sources 1277
SP 1064, 1078, 1102
space bar 35
Specular color 348
Speed Factor 100
speed up simulator 121
Sphere 338, 352
spindle 852, 987
Spiral 341
spline function 380
Splitter 1031
Spot Angle 348
Spot Exponent 348
Spot Light 348
Spring 832, 967
Spring Damper 297
Spring Damper Joint 297
SpringDamper 833, 968
spring-damper 833
Springs 897
sqr 173
sqrt 174
square 173, 343, 1039
Square Brackets 145, 274
Square Root 174
Square Root with Sign 1040
Square Sign 1041
Square Wave 1213
squareroot 1040
stall torque 506
Stand-alone ANSI-C 521
Stand-alone C-code 521
standalone FMU 94
standard 7
standard deviation 434, 1192, 1224
standard deviations 434
Standard Elements 1253
standard form 1067
StandardCameras_Orthographic.scn 344
Star and Delta Networks 505
Start 100
Start Angle 452
Start of simulation 408
start plane 334
start position 336
Start Simulation 449
Start Time 464
start_time 456, 468
starttime 154, 202
state 68, 281
State and Time Events 144
state events 100, 144
State Space 1023
State Space Models 362, 415, 418
State Variable Filter 1014
Statements 23, 258
States 110
States/Rates 110
state-space description 408
Static and Dynamic Phenomena 1243
Static Backgrounds 62
steady state 119
Steady State Gain 422
steady state value 370, 428
Steepest Descent 544
steepness 506
Step 223, 370, 428, 1206
Step Response 370, 415, 428
Step Size 100, 132, 133, 134
Step-by-Step 114
StepMotor 806
Steps 532
stepsize 154, 202
STF 630
<table>
<thead>
<tr>
<th>Word</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>STF-2</td>
<td>659</td>
</tr>
<tr>
<td>STF-3</td>
<td>647</td>
</tr>
<tr>
<td>stiffness</td>
<td>900, 911</td>
</tr>
<tr>
<td>stiffness and damping</td>
<td>299</td>
</tr>
<tr>
<td>STL-files</td>
<td>342</td>
</tr>
<tr>
<td>Stop</td>
<td>108, 126</td>
</tr>
<tr>
<td>Stop Angle</td>
<td>452</td>
</tr>
<tr>
<td>Stop band</td>
<td>400</td>
</tr>
<tr>
<td>Stop Simulation</td>
<td>449</td>
</tr>
<tr>
<td>Stop Time</td>
<td>464</td>
</tr>
<tr>
<td>stop_time</td>
<td>456, 468</td>
</tr>
<tr>
<td>Stopsimulation</td>
<td>267</td>
</tr>
<tr>
<td>Storage element</td>
<td>610, 616</td>
</tr>
<tr>
<td>Straight Lines</td>
<td>33</td>
</tr>
<tr>
<td>String</td>
<td>157, 160</td>
</tr>
<tr>
<td>Strip charted</td>
<td>116</td>
</tr>
<tr>
<td>Stroke</td>
<td>452, 456, 464, 468</td>
</tr>
<tr>
<td>strokes</td>
<td>45</td>
</tr>
<tr>
<td>structural connection</td>
<td>832, 963</td>
</tr>
<tr>
<td>Submodel</td>
<td>33, 40, 1271</td>
</tr>
<tr>
<td>Submodel Colors</td>
<td>28, 43</td>
</tr>
<tr>
<td>Submodel Name to be used in 20-sim</td>
<td></td>
</tr>
<tr>
<td>Submodels</td>
<td>18</td>
</tr>
<tr>
<td>Subtract</td>
<td>1030</td>
</tr>
<tr>
<td>Subtract DC-component</td>
<td>404</td>
</tr>
<tr>
<td>Subtraction</td>
<td>237</td>
</tr>
<tr>
<td>sum</td>
<td>182</td>
</tr>
<tr>
<td>swapbytes</td>
<td>251</td>
</tr>
<tr>
<td>swapping the connection points</td>
<td>308</td>
</tr>
<tr>
<td>Sweep</td>
<td>532, 1207</td>
</tr>
<tr>
<td>Switch</td>
<td>266, 667, 677, 1053, 1054</td>
</tr>
<tr>
<td>Switch Case</td>
<td>266</td>
</tr>
<tr>
<td>Switch-Break</td>
<td>1053</td>
</tr>
<tr>
<td>Switch-Default</td>
<td>1053</td>
</tr>
<tr>
<td>switching</td>
<td>631</td>
</tr>
<tr>
<td>Switch-Level</td>
<td>677</td>
</tr>
<tr>
<td>Switch-Make</td>
<td>1054</td>
</tr>
<tr>
<td>Switch-Maximum</td>
<td>1054</td>
</tr>
<tr>
<td>Switch-Minimum</td>
<td>1055</td>
</tr>
<tr>
<td>sym</td>
<td>216</td>
</tr>
<tr>
<td>Symbol</td>
<td>91</td>
</tr>
<tr>
<td>Symbol Prefixes</td>
<td>91</td>
</tr>
<tr>
<td>Symbolic Linear Systems</td>
<td>417</td>
</tr>
<tr>
<td>Symbolic Linearization</td>
<td>413</td>
</tr>
<tr>
<td>Symplectic gyrator</td>
<td>629</td>
</tr>
<tr>
<td>sympy</td>
<td>584</td>
</tr>
<tr>
<td>Syntax Highlighting Threshold</td>
<td>28, 43</td>
</tr>
<tr>
<td>system</td>
<td>1064</td>
</tr>
<tr>
<td>System Gain</td>
<td>422</td>
</tr>
<tr>
<td>system output</td>
<td>1064</td>
</tr>
<tr>
<td>- T -</td>
<td></td>
</tr>
<tr>
<td>Table</td>
<td>204, 1041</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>59</td>
</tr>
<tr>
<td>Tabular Function</td>
<td>1041</td>
</tr>
<tr>
<td>Tachometer</td>
<td>873</td>
</tr>
<tr>
<td>tan</td>
<td>233, 1043</td>
</tr>
<tr>
<td>tanh</td>
<td>233</td>
</tr>
<tr>
<td>Tank</td>
<td>788, 790</td>
</tr>
<tr>
<td>Tank with resistance</td>
<td>788</td>
</tr>
<tr>
<td>TankNoRes</td>
<td>790</td>
</tr>
<tr>
<td>Tapping Mode</td>
<td>33</td>
</tr>
<tr>
<td>targets</td>
<td>522, 524</td>
</tr>
<tr>
<td>Targets.ini</td>
<td>522, 524</td>
</tr>
<tr>
<td>taskbar</td>
<td>21, 23, 25</td>
</tr>
<tr>
<td>TCP</td>
<td>28, 43</td>
</tr>
<tr>
<td>tdelay</td>
<td>174</td>
</tr>
<tr>
<td>Tecnotion</td>
<td>491</td>
</tr>
<tr>
<td>Tecnotion motors</td>
<td>491</td>
</tr>
<tr>
<td>temperaturesensor</td>
<td>1005</td>
</tr>
<tr>
<td>temperaturesource</td>
<td>1003</td>
</tr>
<tr>
<td>tera</td>
<td>91</td>
</tr>
<tr>
<td>Terminal</td>
<td>85</td>
</tr>
<tr>
<td>terminal inductance</td>
<td>505</td>
</tr>
<tr>
<td>Terminal Properties</td>
<td>47</td>
</tr>
<tr>
<td>terminal resistance</td>
<td>505</td>
</tr>
<tr>
<td>Terminals</td>
<td>25, 33, 47, 76, 85, 1293</td>
</tr>
<tr>
<td>Test Automation</td>
<td>1187</td>
</tr>
<tr>
<td>Texture</td>
<td>352</td>
</tr>
<tr>
<td>Texture Offset</td>
<td>352</td>
</tr>
<tr>
<td>texture wrap</td>
<td>352</td>
</tr>
</tbody>
</table>
Index

TF     632
TF-2    660
TF-3.emx   647
TF-element 1278
Then     258, 259, 261, 262
Thermal  87, 993
Thermal Duty Cycle 511
Thermal Model 520
ThermalConductance 998
ThermalResistor 999
thermistor 1003
ThreeDBody 911
ThreeDFixedWorld 914
ThreeDForceActuator 915
ThreeDForceActuator-Relative 914
ThreeDMass 916
ThreeDPoint-X 917
ThreeDPositionSensor-Y 921
threedspringdamper 922
ThreeDZeroForce 923
throttling band 1065
Through 87, 1281
Tick Style 103
tilde 216
Tile Horizontal 116
Tile Vertical 116
Time     154, 1194, 1210
Time Delay 174, 1007
Time Domain Toolbox 531
Time Events 144
Time window 1021
timeevent 180, 1143
timer 129
Timing   100
timingbelt 853, 989
Title     40
To        263
To Matlab 98, 110
ToDoMatlab 1153, 1154
Toggle Full Screen 124
tokens 522, 527
Tolerance 415, 538
Tolerances 40, 408
ToMatlab 268, 1157
ToMatlab-Plot 1154
ToMatlab-Store 1155
ToMatlab-Timed 1156
ToMatlab-TimedPlot 1156
ToMatlab-TimedStore 1157
tool wrapper 55
toolbox 2, 7
Toolboxes 285
Toolwrapper 92
Tool-wrapper 94
Torque 808, 896
torque (constant) 808
torque (variable) 809, 810
torque constant 506
torque f 496
Torque.emx 808
TorqueActuator 810
TorqueActuator-Relative 809
Torque-Relative 808
TorqueSensor-Relative 874
Torus 340
trace 217
tracking time constant 1069
train 375, 380
Training 380
Training a 1-D B-Spline Network 390
Training Simulators 125
transducer 873
Transfer Function 404, 1023
Transfer Functions 364, 415, 420, 1225
TransferFunction 1228
TransferFunctionWithDeadTime 1233
Transform Dependents states 40
transformation 415, 879
transformer 621, 630, 632
Transformer.emx 679
Transformers 1278
Translation 20, 87
Translation Axis 308
translational spring 967
Transmission 856, 991
Transmission-Universal 992
Transparency 352, 355
transpose 218
Trapezoidal 456, 468
Triangle Wave 1215
Trigger-type Flipflop 1185
TriggerTypeFlipFlop 1185
troubleshooting 12
typecast 2
type conversion 40
Type conversion found 40
Type Editor 1268, 1284, 1289
type of motion 464
typecasting 161
Types 98, 146, 149, 152
- U -
umbra 348
unattended installation 12
Unbalance 836
Undo Buffer Memory Size 28, 43
Uniform distribution 1202, 1217
uninstalling 11
Unipolar Sigmoid 379
Unit 98, 110, 146, 149, 152
Unit Conversion when SI disabled 40
Unit Conversion when SI enabled 40
Unit Delay 165, 177
Unit is unknown 40
Unit missing for variable when SI disabled 40
Unit name 91
Unit Symbol 90
units 86, 89, 90, 91, 98
Units Editor 86
unity 2
Unity Animation 606
Unity Application 593
Unity Cube 595
Unity Import Scenery 604
Unity Simulation 593
Unity Toolbox 591
UnityCoordinates 595
Universal Joint coupling 858
Universal Notch Filter 404
Unlit 351
Unlit Flat 351
Unpack 30, 31, 55
Until 265
Unwrap Phase 371, 429
Index

update another model  40
Update Icons  49
Update Interfaces  49
Update Submodel  449
Updates  61
updating plot  40
use  477
Use as Result  532
Use BDF Integration Scheme  134
Use Built-in Compiler  100
Use Newton Solver  134
- V -
Value  98, 110
Values  98, 146, 149, 532
vapour pressure  689
Variable  110
Variable Chooser  110
Variable is never given a value  40
Variable is not used  40
Variable is set but not used  40
Variable Multiple set  40
Variable Name  62, 90, 103
Variable Pulse  1222
variable sampletime  129
variable voltage  687
variabledisplacementmotor  713
variabledisplacementmotor-leakage  716
variabledisplacementpump  720
variabledisplacementpump-leakage  728
variablelaminarresistance  733
variableorifice  733
Variables  17, 110, 152, 154
Variables Pane  22
Variables Quick Tour  17
Variables:  110
variance  1193, 1202, 1217, 1224
Variation Analysis  566
VCVS  683
Vector  275, 276, 347
Vectors  53, 110, 274, 275, 352
Velocity  315, 464, 811, 894, 933
Velocity (3x1)  315
velocity (constant)  810, 811, 933
velocity (variable)  811, 812, 934, 935
VelocityActuator  812, 935
VelocityActuator-Relative  811, 934
VelocityActuator-Relative.emx  811
Velocity-Relative  810, 933
VelocitySensor-Absolute  875, 977
VelocitySensor-Relative  876, 977
Velocity-X  315
Velocity-Y  315
Velocity-Z  315
Version  7, 40
version number  40
View  25
View menu  25
View Modes  294
viewer  7
Vode Adams  134
voltage  687, 688
voltage constant  506
voltage controlled voltage source  683
VoltageSensorCurrentSensor.emx  681
VoltageSource.emx  688
VoltageSource-VCVS  683
VoltageSource-VCVS.emx  683
Volume  789, 790
Volume-Constant  790
VW13  710
- W -
Warning  39, 268
warnings  39, 40, 113, 161
Water  710
wav file  1237
WaveGenerator-Cosine  1211
WaveGenerator-PhasedSine  1212
WaveGenerator-Saw  1212
WaveGenerator-Sine  1213
WaveGenerator-Square  1213
Index

Wavegenerator-SquareExp 1214
WaveGenerator-Triangle 1215
weight 380
Welcome 1
Wet and Dry Friction 1241
While 264
While Do 264
White Space 143
whitespace 143
Window 1017, 1021
Windows Media Video 332
WireFrame 334, 351
Working Point 408
WormGear 860
wrap 352
Writing Comments 144
Writing DLL's 186
Writing Dynamic DLL's 194
Writing your own Scripts 583

- X -
XMLRPC 28, 43
XML-RPC 574
Xor 253, 1171, 1185
X-rotation 308
X-translation 308
X-value 109
X-Y-X Euler 304

- Y -
Y-Axis 352
yellow 328
yerk 456, 464, 468
YouTube 332
Y-rotation 308
Y-translation 308
Y-value 109

- Z -
z 415
Z-1 1130
Z-Axis 352
Zero Junction 631, 1273
Zero Order Hold 175, 1133
ZeroForce 971
zerojunction 633, 634
Zeros 366, 415, 424, 1023
Zeros and Poles 415
ZeroTorque 838
zip-file 31
Zoom 37
Z-rotation 308
Z-translation 308
Z-X-Z-Euler 349
20-sim is a modeling and simulation program that runs under Microsoft Windows. With 20-sim you can simulate the behavior of dynamic systems, such as electrical, mechanical and hydraulic systems or any combination of these.

20-sim fully supports graphical modeling, allowing to design and analyze dynamic systems in an intuitive and user friendly way, without compromising power. 20-sim supports the use of components. This allows you to enter models as in an engineering sketch: by choosing components from the library and connecting them, your engineering scheme is actually rebuilt, without entering a single line of math!