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Mathematical Modeling of Physical Systems


Planar Mechanics


- We shall now look at a first application of multi-bond graphs: *planar mechanics*.
- We shall notice that a mechanical model composed of multi-bond graphs grows quickly in size and becomes poorly readable.
- For this reason, it is important to wrap multi-bond graph models of mechanical components in a framework that is more suitable to a modular description of mechanical systems.

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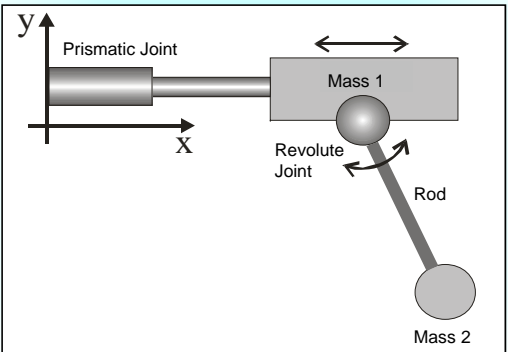
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A Crane Crab


- Let us start by modeling the following crane crab:




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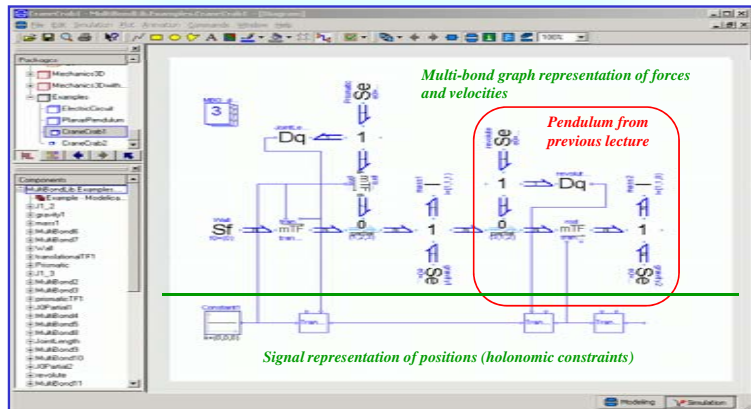


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A Crane Crab II



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A Crane Crab III

Diagram illustrating the mechanical structure of a crane crab, showing various components and joints:

- Wall
- Prismatic Joint
- Body
- Revolute Joint
- Translation
- Body

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A Crane Crab IV

Diagram illustrating the mechanical structure of a crane crab, showing various components and joints:

- Planar mechanics sub-library of the multi-bond graph library
- Standard Modelica multi-body systems library

- The standard Modelica multi-body systems library is a general-purpose 3D mechanics library. No separate support for planar mechanics is currently being offered.
- The multi-bond graph library contains separate sub-libraries for planar mechanics and 3D mechanics, as well as for modeling hard collisions between mechanical bodies and for modeling gravitational pools (celestial mechanics).

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Mechanical Connectors (Frames)

Diagram illustrating mechanical connectors and frames. A note states: "Although the connectors look the same, they are not compatible."

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Mechanical Connectors (Frames) II

Diagram illustrating mechanical connectors and frames. A note states: "Redundant connections needed because of the bond graph approach."

The component models of the standard multi-body systems library and the wrapped multi-bond graph library cannot be mixed.

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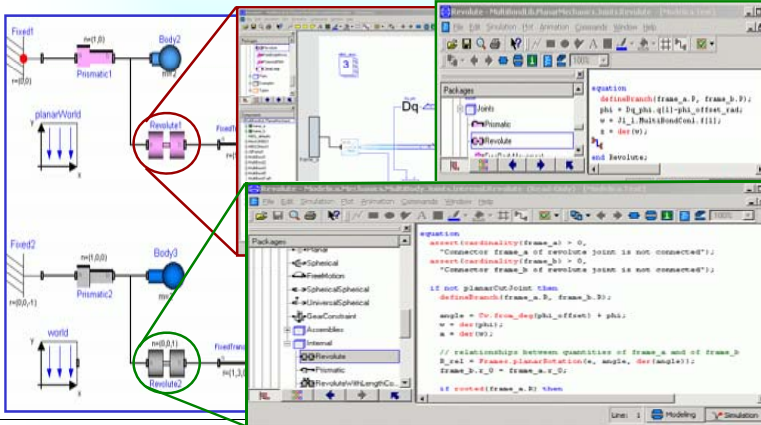


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Revolute Joints



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Revolute Joints II

- Using the multi-bond graph library, almost the entire model of the revolute joint has been coded graphically. There are only very few equations to be coded in the equation window. (There is still quite a bit of code there, because the object is being animated, and *Dymola* doesn't offer graphical support yet for coding animation models.)
- Using the multi-body library of the standard *Modelica* library, the entire revolute joint had to be coded by means of equations, leading to a fairly large equation model that is difficult to understand and even harder to maintain.

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Rationale for Multi-bond Graphs

- It is important to keep the distance between the lowermost graphical layer and the equation layer small, such that as few equations as possible need to be maintained in alphanumerical form.
- Bond graphs and multi-bond graphs provide the most primitive graphical interface that is still fully object-oriented.* Hence, when using bond graphs, the distance between the lowermost graphical layer (the bond graph layer) and the equation layer is minimized.

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Rationale for Multi-bond Graphs II

- However, this does not imply that bond graphs offer an optimal user interface. For mechanical systems, this is certainly not the case.
- Wrapping bond graphs* enables the modeler to map *any* graphical object-oriented modeling paradigm onto a lower-level bond graph layer that simplifies the maintenance of the resulting application libraries.

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Animation

- In **Dymola**, mechanical models can be **automatically animated**. The end user of the models doesn't need to be concerned about this facet of modeling.
- However, individual bonds cannot be animated. The animation must take place at a higher conceptual level, namely that of multi-body system components, such as masses and joints.
- For this reason, a wrapping of multi-bond graphs is **necessary** if the resulting models are to be animated.

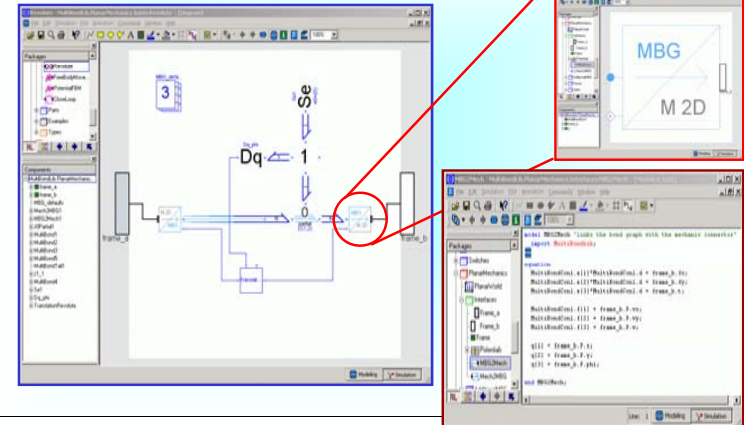
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The Wrapper Models



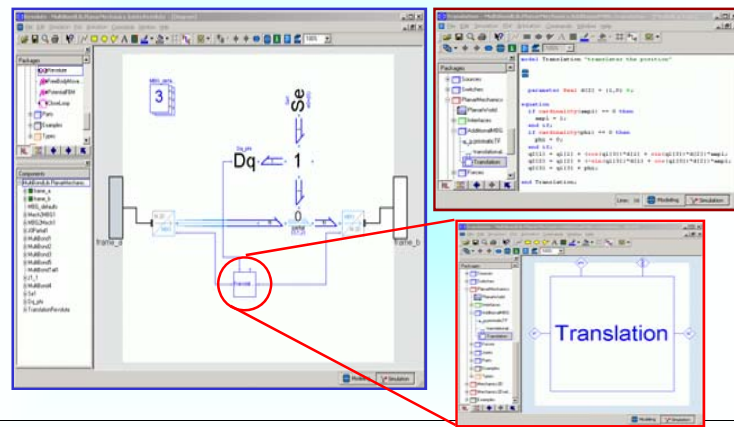
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The Position Translation Model



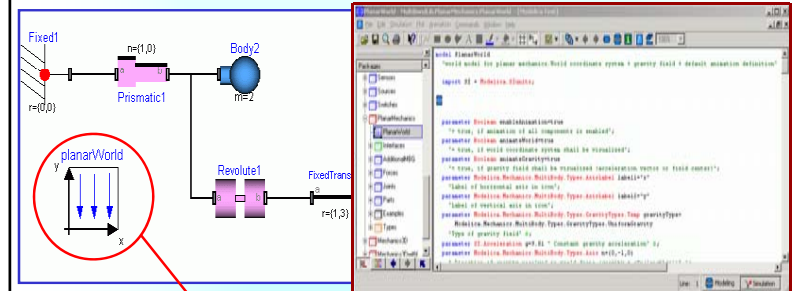
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The Planar World Model



Every planar mechanical model must invoke the "planarWorld" model.

The primary purpose of the world model is to set up the animation.

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Crane Crab Simulation Results

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2D Simulation of 1D Models

- It is of course always possible to make use of the planar library also for the simulation of 1D models.
- Let us investigate, what the overhead of such an approach would be.
- To this end, we shall simulate the sliding mass model now using the planar mechanics library.

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2D Simulation of 1D Models II

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Mathematical Modeling of Physical Systems

Translation Logs

Translation of `model_1d_2d.mh`
DAE having 695 scalar unknowns and 695 scalar equations

STATISTICS

Original Model

- Number of components: 105
- Variables: 705
- Constants: 0
- Parameters: 13 (93 scalars)
- Unknowns: 647 (655 scalars)
- Differentiated variables: 6 scalars
- Equations: 403
- Nonlinear: 250

Translated Model

- Constants: 105 scalars
- Free parameters: 40 scalars
- Parameter depending: 19 scalars
- Inputs: 0
- Outputs: 0
- Continuous time states: 6 scalars
- Time-varying variables: 36 scalars
- Algebra variables: 644 scalars
- Assumed default time resolution: 1
- LogDefaultInitialConditions: gives more information
- Number of mixed real-discrete systems of equations: 0
- Sizes of linear systems of equations: 1
- Sizes after manipulation of the linear systems: 1
- Sizes of nonlinear systems of equations: 1
- Sizes after manipulation of the nonlinear systems: 1
- Number of numerical Jacobians: 0

Finished
// experiment StopTime=10
Finished

Wrapped 1D mechanical bond graph model

Translation of `model_1d_2d.mh`
DAE having 3705 scalar unknowns and 3705 scalar equations

STATISTICS

Original Model

- Number of components: 268
- Variables: 2470
- Constants: 0
- Parameters: 423 (715 scalars)
- Unknowns: 1047 (3705 scalars)
- Differentiated variables: 18 scalars
- Equations: 1436
- Nonlinear: 984

Translated Model

- Constants: 1722 scalars
- Free parameters: 53 scalars
- Parameter depending: 577 scalars
- Inputs: 0
- Outputs: 0
- Continuous time states: 6 scalars
- Time-varying variables: 101 scalars
- Algebra variables: 2042 scalars
- Number of mixed real-discrete systems of equations: 0
- Sizes of linear systems of equations: 10, 10, 10, 10
- Sizes after manipulation of the linear systems: 10, 2, 0
- Sizes of nonlinear systems of equations: 1
- Sizes after manipulation of the nonlinear systems: 1
- Number of numerical Jacobians: 0


Finished
// experiment StopTime=10
Finished

Wrapped 2D mechanical bond graph model

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Simulation Logs

Messages - Dynasim

Syntax Error | Translation | Dialog Error | Simulation

Log-file of program : /dynasim
(generated: Thu Dec 12 10:45:32 2006)

```

dynasim started
... "dcm.tcn" loading (dynasim input file)
... "slidingMasses.wat" creating (simulation result file)

Integration started at T = 0 using integration method DASSL
(DAS multi-step solver (dassl/dasslrt of Petstod modified by Dynasim))
Integration terminated successfully at T = 10

CPU-time for integration : 0.02 seconds
CPU-time for one GRID interval : 0.02 milli-seconds
Number of result points : 501
Number of GRID points : 501
Number of (successful) steps : 76
Number of P-evaluations : 237
Number of Jacobian-evaluations : 16
Number of (model) time events : 0
Number of (D) time events : 0
Number of state events : 0
Number of step events : 0
Minimum integration stepsize : 2e-005
Maximum integration stepsize : 0.253
Maximum integration order : 5
Calling terminal section
... "dcm.tcn" creating (final states)

```

Messages - Dynasim

Syntax Error | Translation | Dialog Error | Simulation

Log-file of program : /dynasim
(generated: Thu Dec 14 11:59:27 2006)

```


dynasim started
... "dcm.tcn" loading (dynasim input file)
... "maps_10_2DMech.wat" creating (simulation result file)

Integration started at T = 0 using integration method DASSL
(DAS multi-step solver (dassl/dasslrt of Petstod modified by Dynasim))
Integration terminated successfully at T = 10

CPU-time for integration : 0.02 seconds
CPU-time for one GRID interval : 0.04 milli-seconds
Number of result points : 501
Number of GRID points : 501
Number of (successful) steps : 76
Number of P-evaluations : 239
Number of Jacobian-evaluations : 16
Number of (model) time events : 0
Number of (D) time events : 0
Number of state events : 0
Number of step events : 0
Minimum integration stepsize : 2e-005
Maximum integration stepsize : 0.253
Maximum integration order : 5
Calling terminal section
... "dcm.tcn" creating (final states)

```

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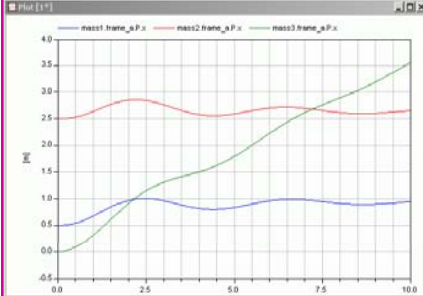
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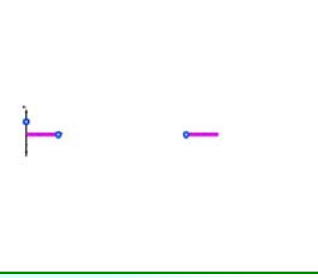
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Simulation Results


Plot [1]

mass1.here_a.P.s. mass2.here_a.P.s. mass3.here_a.P.s.





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- Zimmer, D. and F.E. Cellier (2006), ["The Modelica Multi-bond Graph Library"](#), *Proc. 5th Intl. Modelica Conference*, Vienna, Austria, Vol.2, pp. 559-568.

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