Launch Vehicle Multibody Dynamics Framework for Preliminary Design Studies

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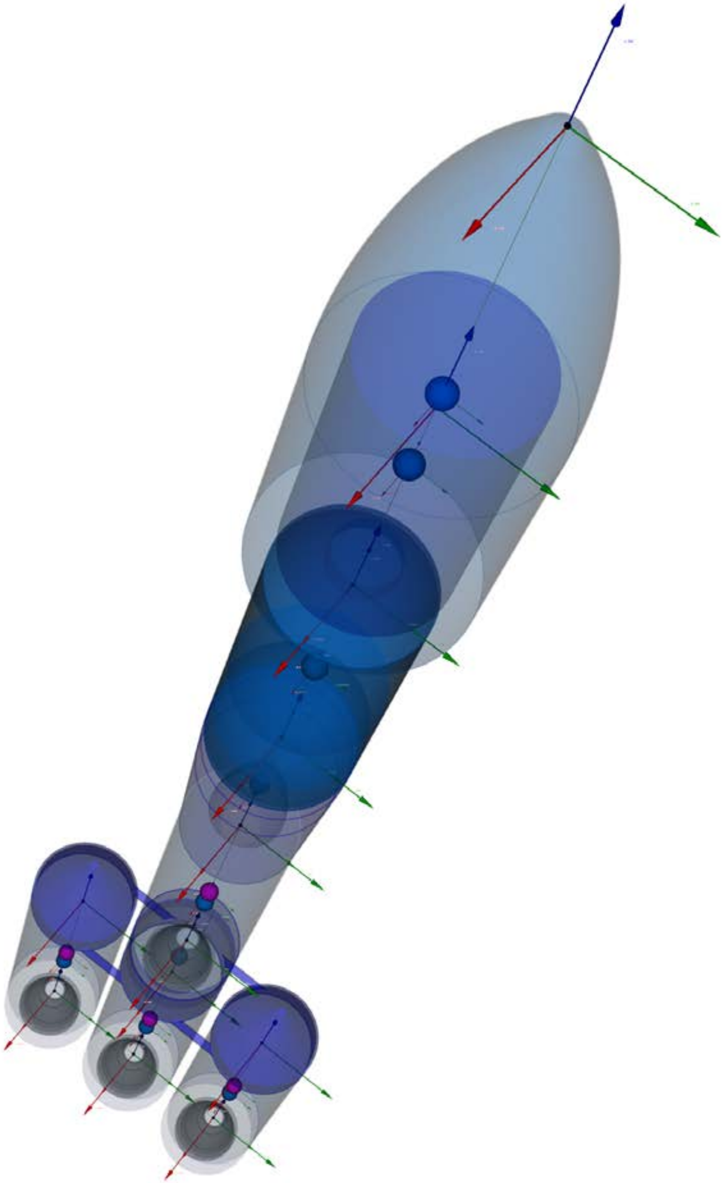
Introduction

1. **Launch vehicle dynamics modeling**
   - Highly interconnected disciplines
   - Experts perform design often independently

2. **Why is important?**
   - a multidisciplinary integrated model can reduce design efforts
   - Preliminary design requires iteration

3. **Dedicated developments**
   - NASA (POST2, TREETOPS, FRACTAL, etc.)
   - ESA (DCAP, Launcher MBS)
   - Commercial (ASTOS, STK, etc.)

4. **Objective**
   - Introduce the first building blocks towards a multidisciplinary launch vehicle model integrated in one single tool



Outline

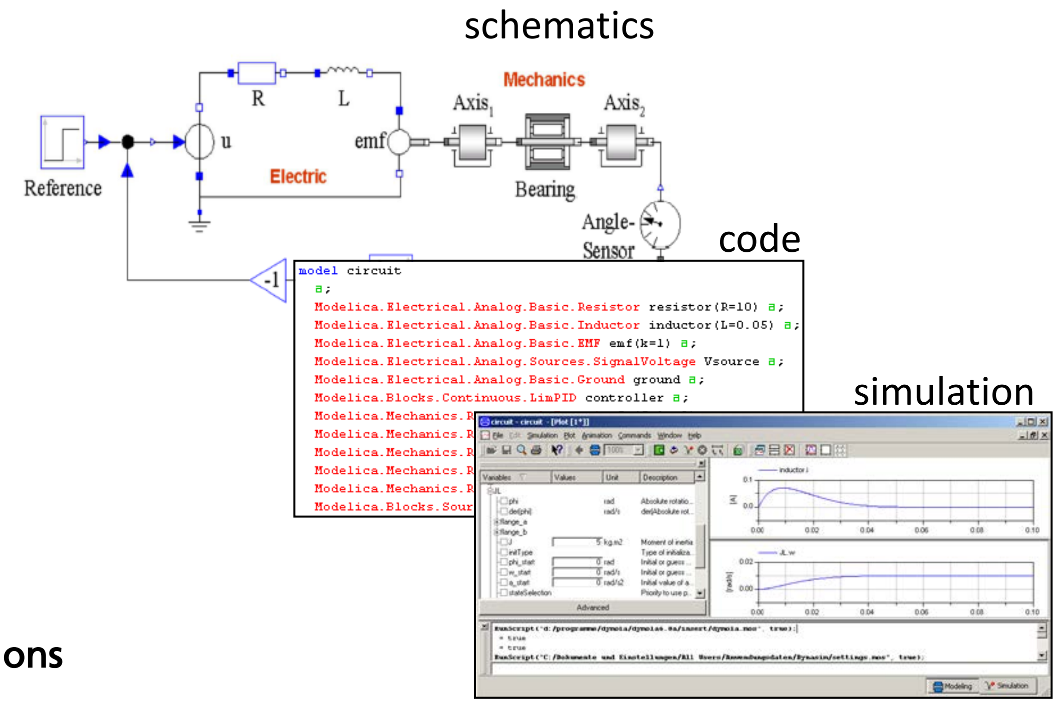
1. **Modeling Methodology**
2. **Modeling Framework**
3. **Multibody Dynamics Model**
4. **Application Example**
5. **Summary and Outlook**

Modeling Methodology

Modelica: a language for modeling of complex physical systems

1. **Applications**
   - Automotive
   - Aeronautics
   - Robotics
   - Power plants, etc.

2. **Domains**
   - Mechanical
   - Electrical/Electronic
   - Hydraulic
   - Thermal
   - Control, etc.



Models are described by
differential, algebraic, and **discrete equations**

Image credits and all infos at http://www.modelica.org

Modeling Methodology

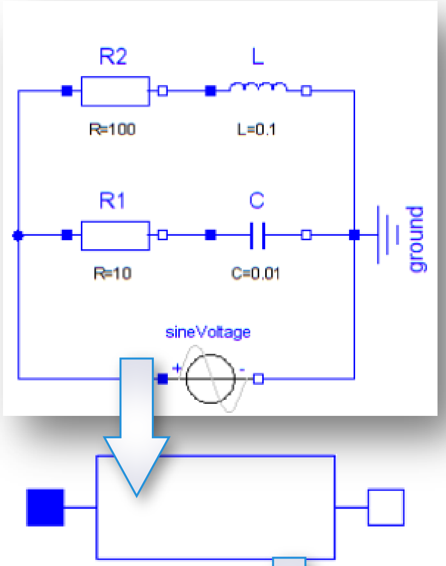
Main features of Modelica

1. **Declarative**
   - Declarations are given through equations
   - Acausal modeling
   - First principles

2. **Multi-domain**
   - Different domains can be combined
   - Interaction with ports, or connectors
   - Physical meaning

3. **Object-oriented**
   - Facilitates structuring
   - Reusability of components

4. **Architectural**
   - Hierarchical system architecture capabilities
   - Visual component programming




```
model Resistor
  extends OnePort;
  parameter Real R;
equation
  v = R*i;
end Resistor;
```

Modeling Framework

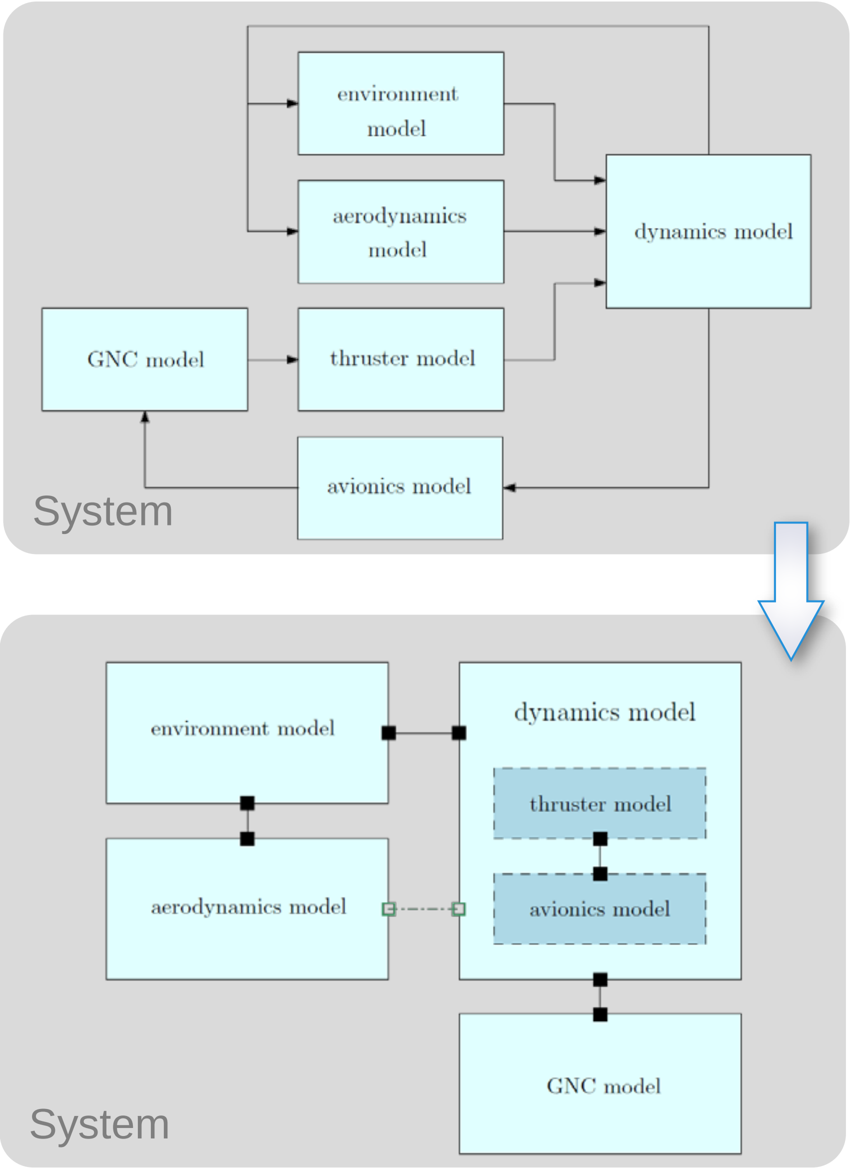
1. **Dynamical Systems Representation**
2. **Integrated Launcher Modeling**
3. **DLR Modelica Space Systems Library**

Modeling Framework

Dynamical Systems Representation

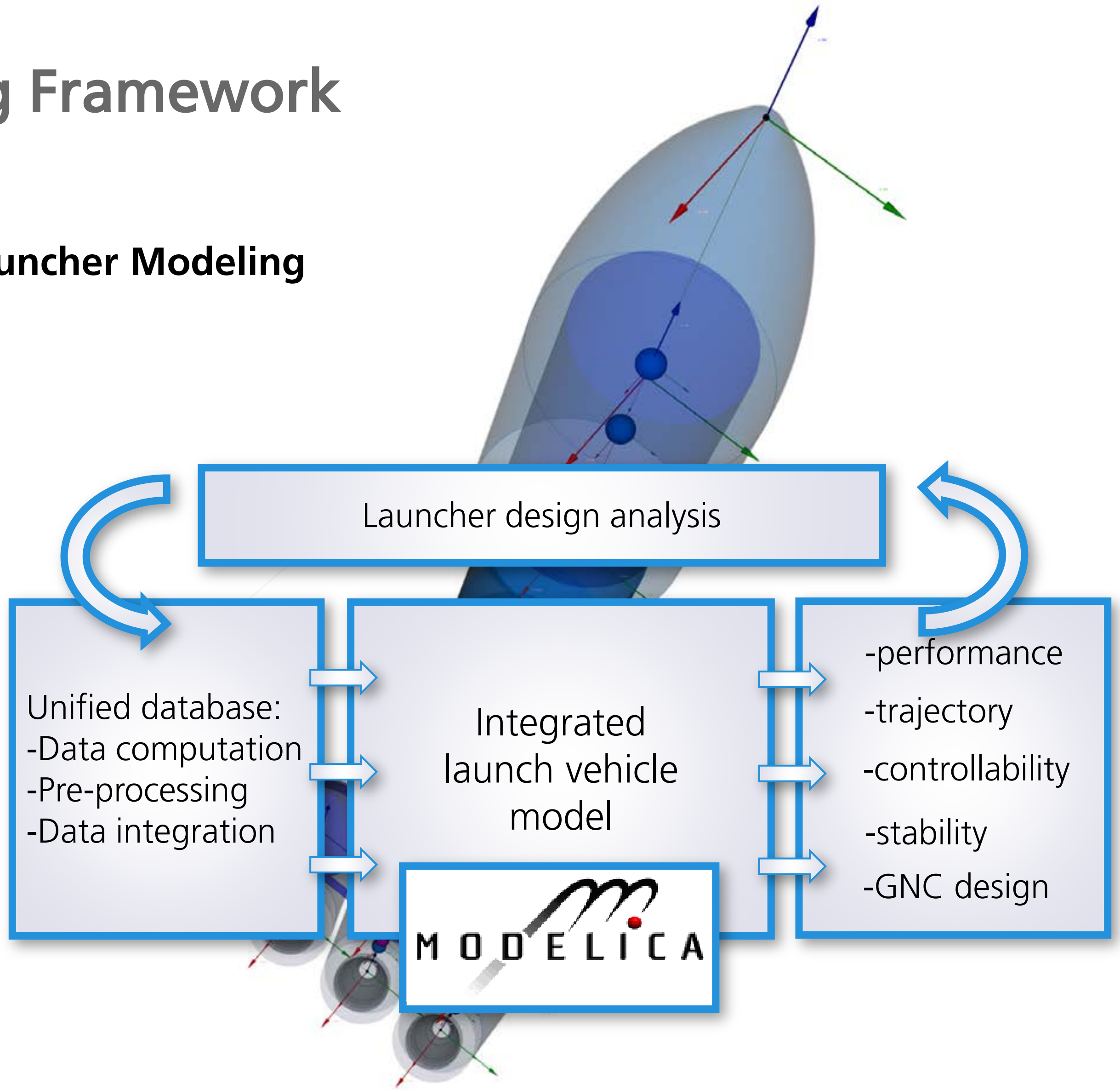
1. **Classical input-output representation**
   - Systems are considered as signal processors
   - Fixed causality: inputs and outputs

2. **Acausal approach, or 'energy exchange' representation**
   - Systems are considered as energy exchangers
   - Acausal connectors:
     flow and potential quantities
   - Systems satisfy energy conservation
   - Similar to Bond-Graphs, Port-Hamiltonian systems, etc.

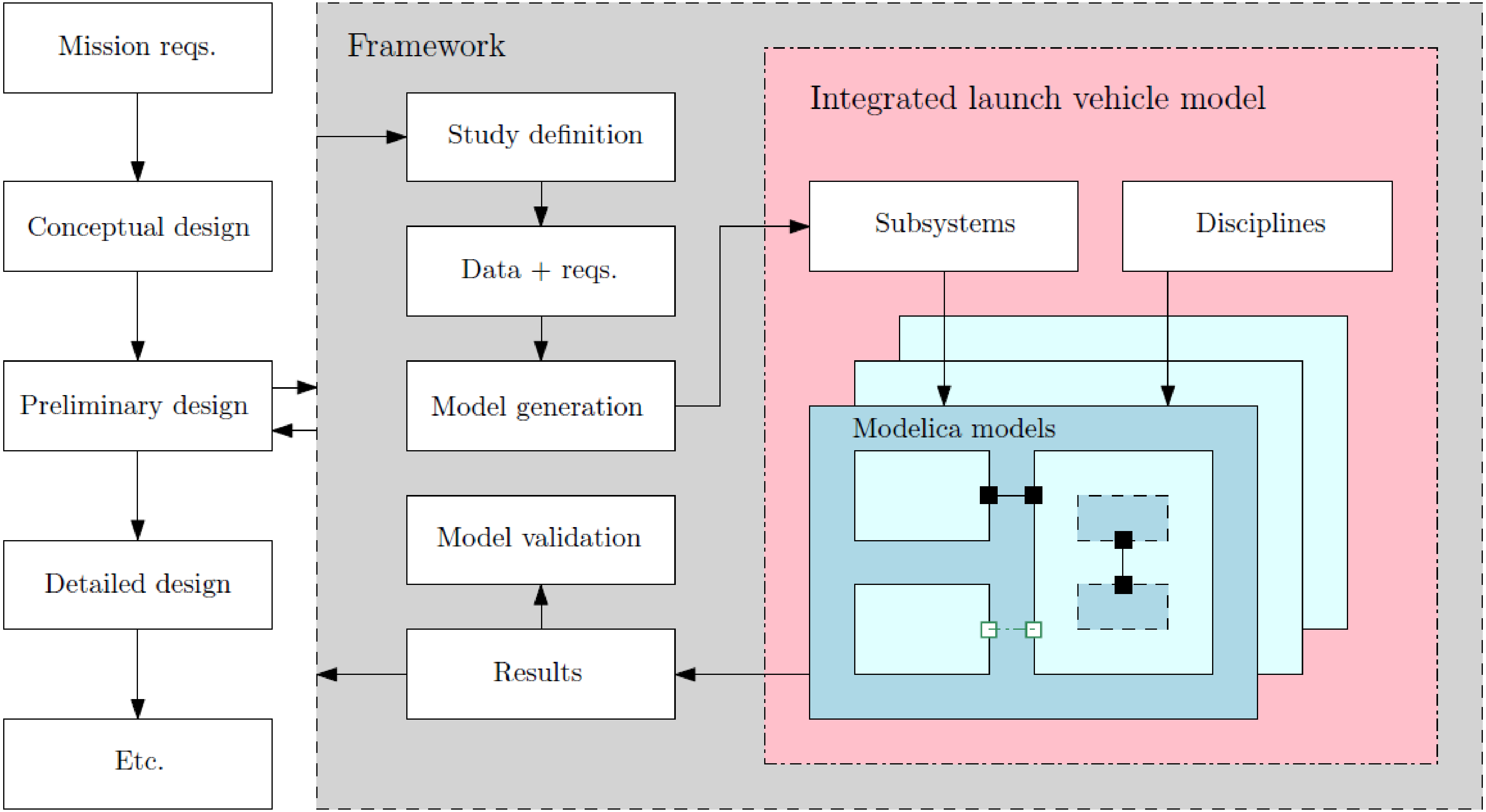


Modeling Framework

Integrated Launcher Modeling

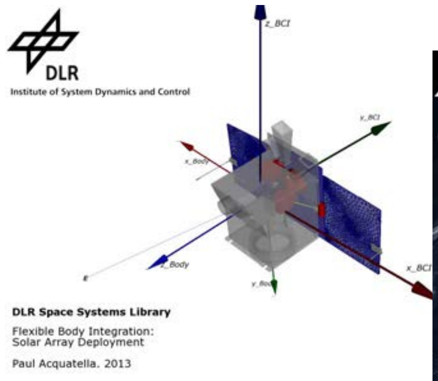


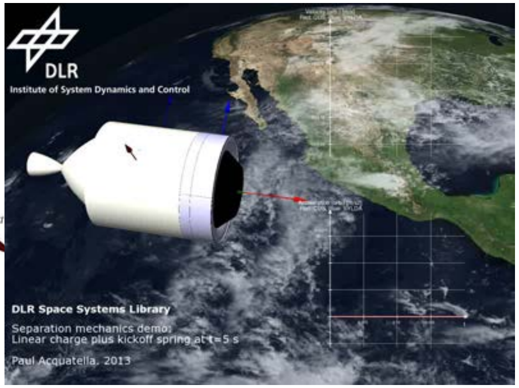
Modeling Framework



Modeling Framework

DLR Modelica Space Systems Library



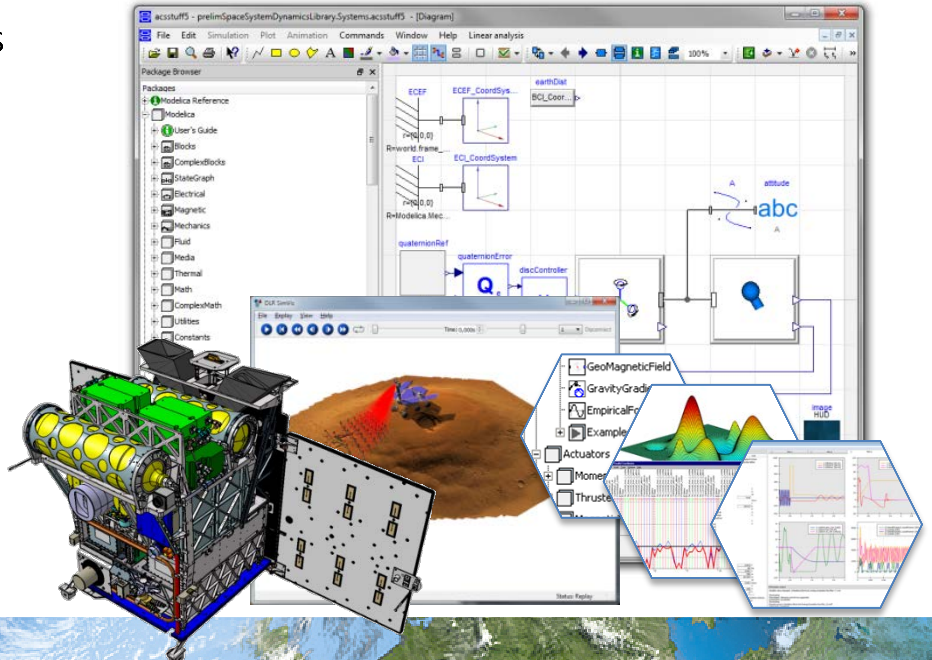


1. **World Component**
   - Defines ECI & ECEF coordinate systems
   - Manages time and date (Julian & Calendar)
   - Calculates moon and sun position

2. **Advanced space simulation environment**
   - State-of-the-art space environment models
   - EGM96 gravity model
   - NRLMSISE-00 atmospheric density model

3. **Built upon advanced Modelica libraries**
   - Multibody Standard Library
   - DLR Visualization Library
   - DLR Optimization Library
   - DLR Flexible Bodies Library

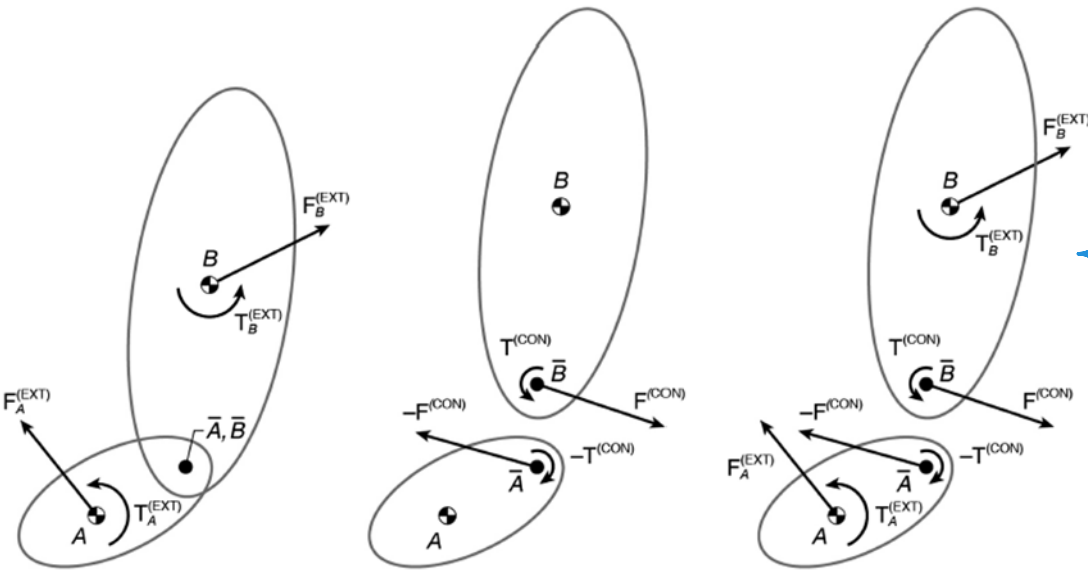
4. **Advanced control laws**
   - Experience from robot and flight control
   - Model inversion



Multibody Dynamics Model

Automatic joint loads computation

based on Constraint Force Equation (CFE) methodology (proposed by NASA Langley)



a) External forces and moments b) Internal forces and moments c) Resultant forces and moments

$$m_A\,\ddot{\mathbf{r}}_A = \mathbf{f}_A^{ext} + \mathbf{f}_A^{con},$$

$$\mathbf{I}_A\,\dot{\boldsymbol{\omega}}_A + \boldsymbol{\omega}_A \times \mathbf{I}_A\,\boldsymbol{\omega}_A = \boldsymbol{\tau}_A^{ext} + \rho_A \mathbf{f}_A^{con} + \boldsymbol{\tau}_A^{con}$$

$$\mathbf{f}_A^{con} + \mathbf{f}_B^{con} = \mathbf{0}$$

$$\boldsymbol{\tau}_A^{(con)} + \boldsymbol{\tau}_B^{(con)} + (\mathbf{r}_{\bar{B}} - \mathbf{r}_{\bar{A}}) \times \mathbf{f}_B^{con} = \mathbf{0}$$

$$(\mathbf{r}_{\bar{A}} - \mathbf{r}_{\bar{B}}) \cdot \mathbf{e}_A = 0$$

$$\mathbf{e}_A \cdot \mathbf{e}_B = 0$$

$$\Rightarrow \quad \ddot{\mathbf{g}} = \mathbf{0}$$

done automatically by **Modelica**

Ref: Tartabini et al.
Modeling Multibody Stage Separation Dynamics Using Constraint Force Equation Methodology
Journal of Spacecraft and Rockets. Vol. 48, No.4, July-August 2011

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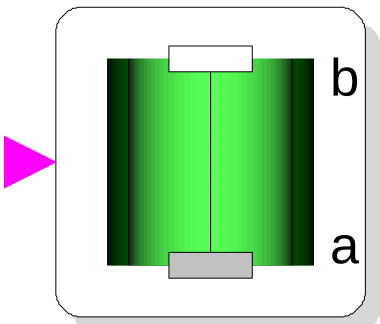
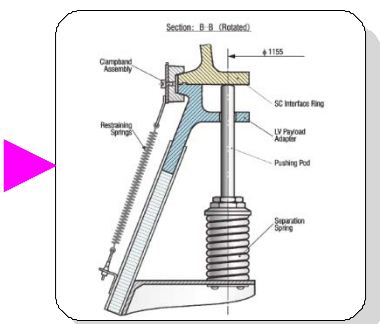
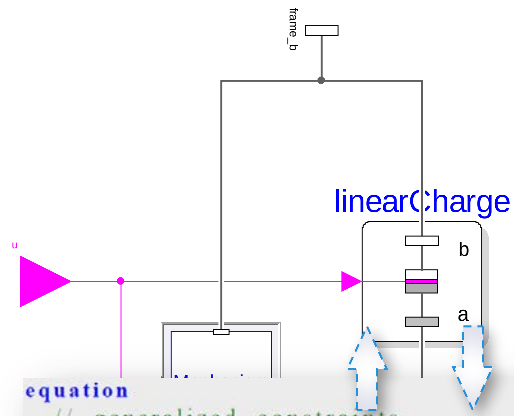
Multibody Dynamics Model

Automatic joint loads computation

physical models of separation mechanisms





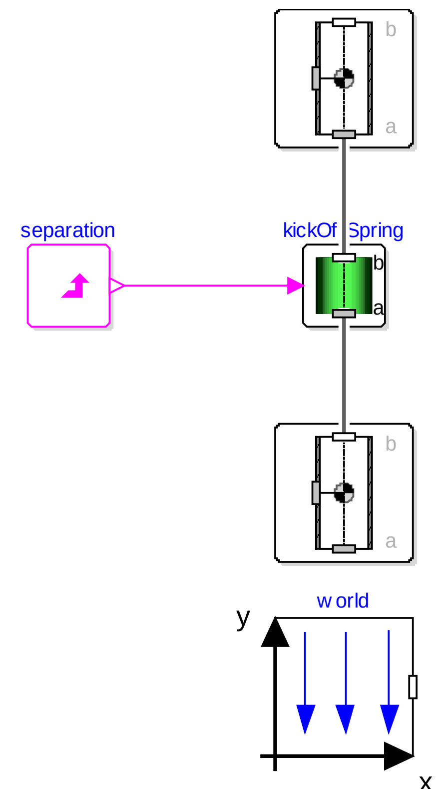



```
equation
  // generalized constraints
  g_con = frame_a.r_0 - frame_b.r_0;
  G_con = Frames.relativeRotation(frame_a.R
    ,frame_b.R);

  // generalized velocity constraints
  g_con_dot = der(g_con);
  G_con_dot = Frames.angularVelocity2(G_con
    );

  // generalized acceleration constraints
  g_con_ddot = der(g_con_dot);
  G_con_ddot = der(G_con_dot);

  // CFE generalized joint constraints
  g_con_ddot = {0,0,0};
  G_con_ddot = {0,0,0};
```



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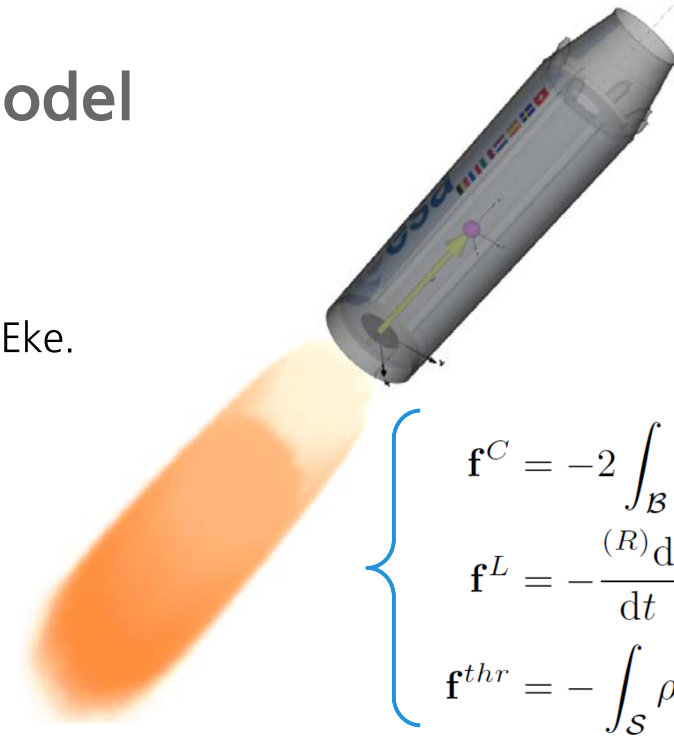
Multibody Dynamics Model



Variable mass dynamics

Kane's equations as obtained by F. O. Eke.

1. **Translational equations of motion**
   - Coriolis force
   - Linear momentum decrease rate
   - Thrust force
   - External forces: aero, gravity, etc.

$$m\mathbf{a} = \mathbf{f}^{C} + \mathbf{f}^{L} + \mathbf{f}^{thr} + \mathbf{f}^{ext}$$

$$\begin{cases} \mathbf{f}^{C} = -2\displaystyle\int_{\mathcal{B}} \rho(\boldsymbol{\omega} \times \mathbf{v}_r)\mathrm{d}V, \\ \mathbf{f}^{L} = -\dfrac{{}^{(R)}\mathrm{d}}{\mathrm{d}t}\displaystyle\int_{\mathcal{B}} \rho\mathbf{v}_r \mathrm{d}V, \\ \mathbf{f}^{thr} = -\displaystyle\int_{\mathcal{S}} \rho\mathbf{v}_r(\mathbf{v}_r \cdot \mathbf{n})\mathrm{d}S, \end{cases}$$

2. **Rotational equations of motion**
   - Jet damping, Coriolis
   - Angular momentum decrease rate
   - Moment of the thrust force
   - External moments: aero, grav. gradients, etc.

$$\mathbf{I}\,\boldsymbol{\alpha} + \boldsymbol{\omega} \times \mathbf{I}\,\boldsymbol{\omega} + \left(\frac{{}^{R}\mathrm{d}\mathbf{I}}{\mathrm{d}t}\right)\boldsymbol{\omega} = \boldsymbol{\tau}^{C_1} + \boldsymbol{\tau}^{C_2} + \boldsymbol{\tau}^{H} + \boldsymbol{\tau}^{thr} + \boldsymbol{\tau}^{ext}$$

$$\begin{cases} \boldsymbol{\tau}^{C_1} = -\displaystyle\int_{B} \rho[\mathbf{r}_p \times (\boldsymbol{\omega} \times \mathbf{r}_p)](\mathbf{v}_r \cdot \mathbf{n})\mathrm{d}S \\ \boldsymbol{\tau}^{C_2} = -\displaystyle\int_{B} \rho\big[\boldsymbol{\omega} \times (\mathbf{r}_p \times \mathbf{v}_r)\big]\mathrm{d}V \\ \boldsymbol{\tau}^{H} = -\dfrac{{}^{R}\mathrm{d}}{\mathrm{d}t}\displaystyle\int_{B} \rho(\mathbf{r}_p \times \mathbf{v}_r)\mathrm{d}V \\ \boldsymbol{\tau}^{thr} = \displaystyle\int_{S} \rho(\mathbf{r}_p \times \mathbf{v}_r)(\mathbf{v}_r \cdot \mathbf{n})\mathrm{d}S \end{cases}$$

Ref: Eke, F. O.
Dynamics of Variable Mass Systems.
NASA CR-1998-208246, NASA Ames Research Center, January 1999.

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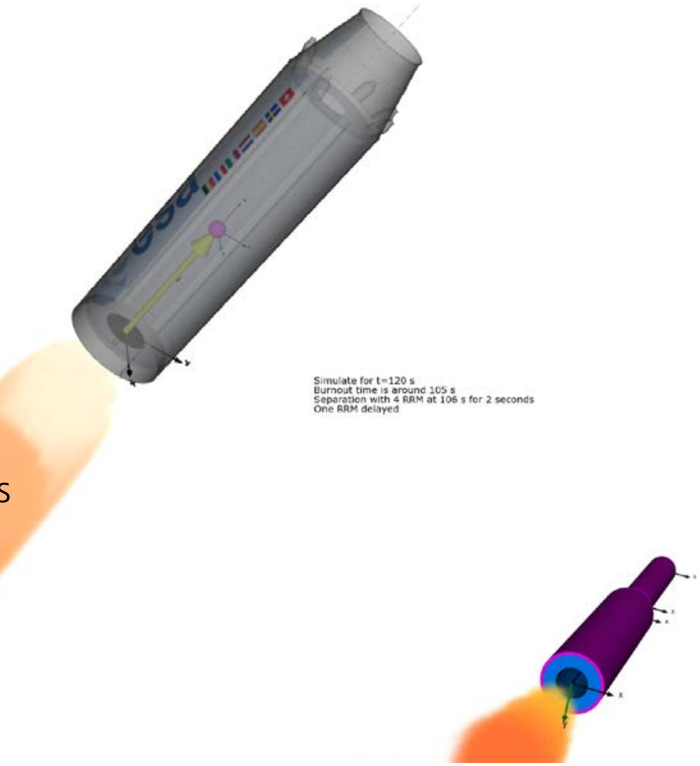
Application example



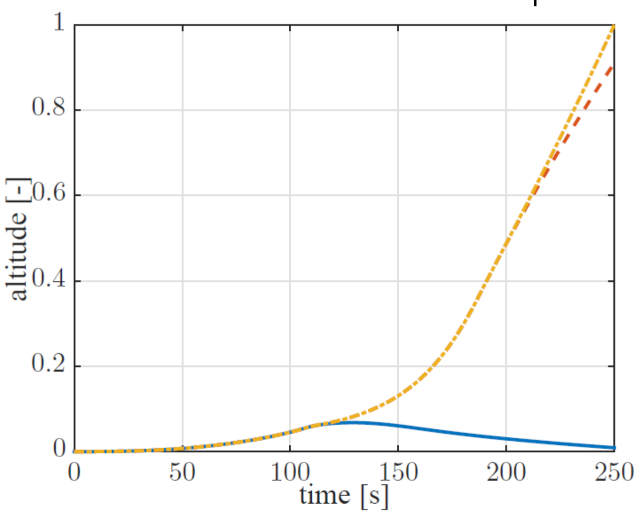
3-DOF open-loop point-mass launcher model

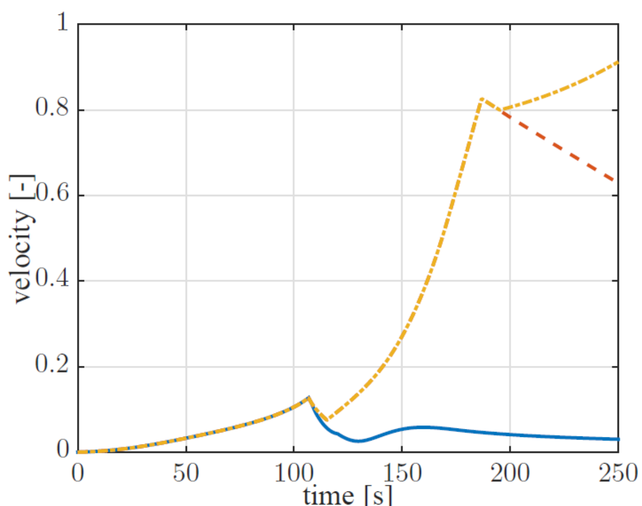
Study

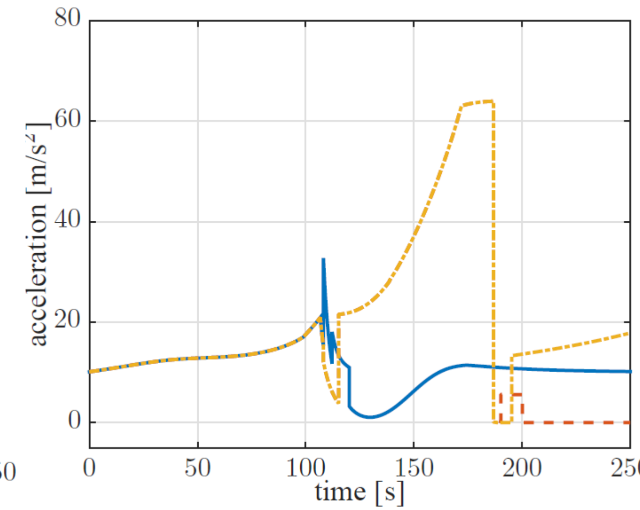
- Separation dynamics: linear charge + retro thrusters
- Automatic joint loads computation with CFE
- Open-loop: no GNC, thrust vectoring
- VEGA User's manual data + assumptions

Results

- Separation dynamics: end-to-end trajectories
- More insight on physics behind separation
- Ease of use and implementation







Summary and Outlook

Objective

- Introduce the first building blocks towards a multidisciplinary launch vehicle dynamics model for preliminary studies

Methodology and Framework

- Equation-based and acausal modeling approach using Modelica
- Object-oriented structure
- Multibody model including variable mass dynamics and joint loads computation

Outlook

- Flexible bodies
- GNC & thrust vectoring
- Optimization (trajectory, stage sizing, etc.)
- Support launcher program lifecycle

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