Co-simulation of Mechanical Systems with Hydraulic Actuators

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***Abstract*— Co-simulation can be used to couple subsystems that present different time-scales, such as hydraulics. However, numerical stability of the co-simulation setup can be compromised by discontinuities and time delays of the coupling variables. Here, we use a reduced-order model of the mechanical subsystem in order to obtain a prediction of these variables and allow for larger communication steps.**

Co-simulation allows for coupling numerical simulations of different subsystems by exchanging interface variables at discrete communication time-points, which makes this approach modular and convenient for developing complex models. However, coupling subsystems through interface variables can affect simulation stability due to discontinuities and time delay of these variables. Although iterative co-simulation schemes exhibit good numerical stability [1], they can be prohibitive in real-time applications due to their high computational cost. In non-iterative co-simulation schemes extrapolation is often used to predict input variables between communication updates. However, extrapolations can easily give wrong predictions if variables change rapidly, especially in nonsmooth systems with unilateral contact. Here, a reduced-order model of the multibody system at the coupling interface is proposed, or interface model (IM) from here on. Such a model can then be integrated efficiently at higher time rates and is used to obtain a physics-based prediction of the interface variables inside the macro time-step [2]. The interaction between the elements in the system is represented by constraints that can include unilateral contact and friction, and the dynamics of the model at the interface is characterized by effective mass and force terms. This model can then be used in multirate co-simulation setups where it can provide a prediction of the multibody system outputs between communication points.

The interface of the multibody system can be parametrized with the r velocity components $\mathbf{w}_\mathrm{i} = \mathbf{D}\mathbf{v}$, where $\mathbf{D}(\mathbf{q})$ is the $r \times n$ interface Jacobian matrix and $\mathbf{v}$ is the array of n generalized velocities. Then, the r interface force components can be arranged in array $\boldsymbol{\lambda}_\mathrm{i}$, and used to define the generalized interface force as $\mathbf{f}_\mathrm{i} = \mathbf{D}^\mathrm{T}\boldsymbol{\lambda}_\mathrm{i}$. Using the parametrization given by $\mathbf{w}_\mathrm{i}$, the dynamic equations of the IM can be written as

$$\widetilde{\mathbf{M}}_\mathrm{i}\dot{\mathbf{w}}_\mathrm{i} = \widetilde{\boldsymbol{\lambda}}_\mathrm{i} + \boldsymbol{\lambda}_\mathrm{i} \qquad (1)$$

where $\widetilde{\mathbf{M}}_\mathrm{i}$ is the *effective mass* matrix of the system at the interface, and $\widetilde{\boldsymbol{\lambda}}_\mathrm{i}$ is the *effective force* that takes into account the forces applied to the system. However, the effective mass and force terms can change quite significantly in nonsmooth systems due to contact detachment and stick-slip transitions.

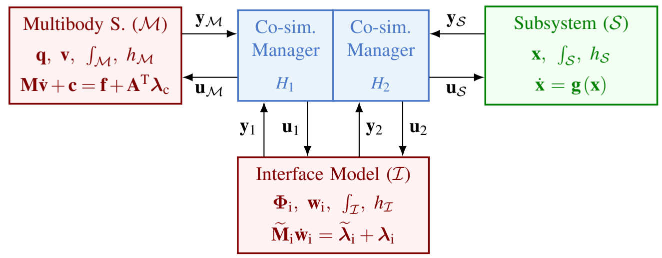

Fig. 1. Block diagram of a multibody system $\mathcal{M}$ and subsystem $\mathcal{S}$ coupled in a co-simulation setup via an interface model $\mathcal{I}$ of the multibody system.

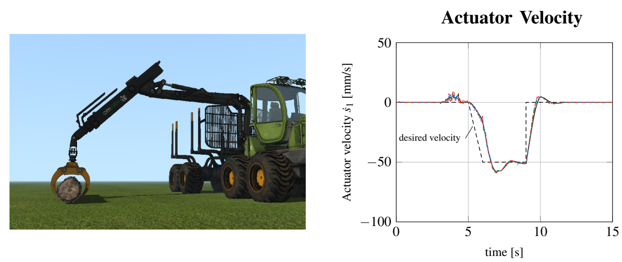

Fig. 2. Numerical results with a co-simulation setup of a hydraulic crane model with two actuators using an interface model.

Figure 2 shows the results of the numerical experiments using the proposed IM in a co-simulation setup of the model of a crane with two hydraulic actuators and a log gripper. A total of 18 bodies and 22 joints constitute the model, which includes spherical, revolute, and prismatic joints. The manoeuvre consists in grasping a log of 500 kg and lift it up to a certain height. For this, a desired velocity was provided as an input of the PD controller of the valve displacement of the hydraulic system. The step-size of the hydraulic system was 0.2 ms in all the numerical experiments, whereas several values were used for the step-size of the multibody system, and the communication (or macro) step-size was set equal to the one of the multibody system, which was increased up to 16 ms without losing stability.

References

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