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# Co-simulation in the vehicle development process

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**Micro Abstract**
Modern vehicles are highly complex systems consisting of many subsystems in various physical domains that dynamically interact. In this context, co-simulation strategies are particularly attractive as each subsystem is solved via tailored simulation tools with appropriate numerical methods. Industrial applications induce enormous numerical challenges regarding efficiency, accuracy and stability. We present co-simulation strategies by means of selected application examples in vehicle engineering.

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## Introduction

Modern vehicles are highly complex systems consisting of many subsystems in various physical domains. For instance, in a passenger car, besides the mechanical structure, there are electric, electronic, hydraulic and control systems that dynamically interact all together. For any subsystem there are tailored simulation tools with specifically developed and adapted numerical solvers and modeling techniques to address the required complexity and the strongly differing dynamical properties (e.g. different time-scales, different eigenfrequencies). In particular, one has to build and to simulate complex coupled models in order to analyze these multi-domain systems in the computer. In this context, co-simulation strategies allow to simulate each submodel within an appropriate numerical framework, the data of coupling quantities is only exchanged at certain macro time points, while each subsystem solver is able to run with its own stepsizes. In industrial applications, one is hereby confronted with enormous numerical challenges with respect to efficiency, accuracy and numerical stability in order to realize acceptable simulation times; especially in online applications. In this talk, we discuss and present co-simulation strategies as well as administration, prediction and stabilization methods that can be used to set up and to simulate a coupled numerical model. We illustrate these approaches by means of two application examples from the field of vehicle engineering.

## 1 Coupling scheme

Within the prescribed application scenarios, we apply a parallel scheme for efficient co-simulation by realizing a force-displacement coupling as illustrated in Figure 1. *Subsystem 1* provides kinematic states $\boldsymbol{q}_i = \boldsymbol{q}_{Sub1}$ as input for *Subsystem 2* which, vice versa, provides section forces $\boldsymbol{F}_i = \boldsymbol{F}_{Sub2}$ as input for *Subsystem 1*. In particular, we obtain the following situation:

$$\dot{\boldsymbol{x}}_{Sub1} = \boldsymbol{f}_{Sub1}\left(\boldsymbol{x}_{Sub1},\, \boldsymbol{u}_{Sub1} = \boldsymbol{F}_{Sub2}\right) \tag{1}$$
$$\boldsymbol{q}_{Sub1} = \boldsymbol{g}_{Sub1}\left(\boldsymbol{x}_{Sub1}\right) \tag{2}$$
$$\dot{\boldsymbol{x}}_{Sub2} = \boldsymbol{f}_{Sub2}\left(\boldsymbol{x}_{Sub2},\, \boldsymbol{u}_{Sub2} = \boldsymbol{q}_{Sub1}\right) \tag{3}$$
$$\boldsymbol{F}_{Sub2} = \boldsymbol{g}_{Sub2}\left(\boldsymbol{x}_{Sub2}\right) \tag{4}$$

with states $\boldsymbol{x}_{Sub1}$, inputs $\boldsymbol{u}_{Sub1}$ for *Subsystem 1* and states $\boldsymbol{x}_{Sub2}$, inputs $\boldsymbol{u}_{Sub2}$ for *Subsystem 2*.

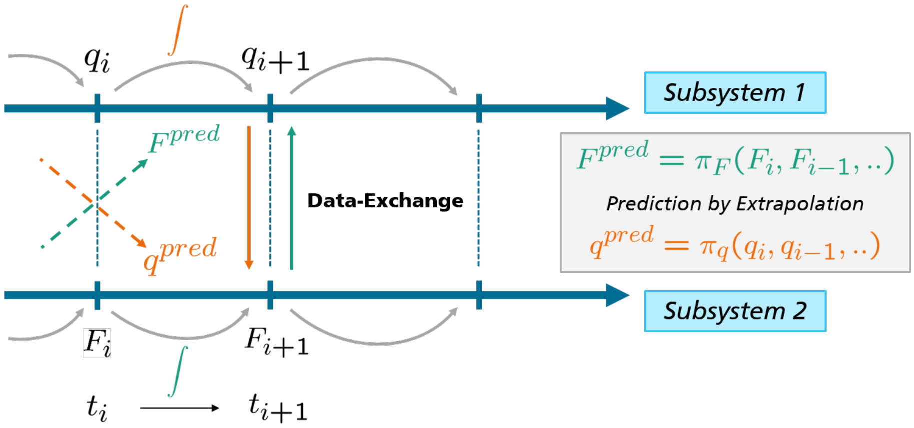


**Figure 1.** Parallel scheme for efficient co-simulation.

The data exchange takes place at each macro time point $t_i$ together with data-based prediction $\boldsymbol{q}^{pred} = \boldsymbol{\pi_q}(\boldsymbol{q}_i, \boldsymbol{q}_{i-1}, \ldots)$ for the kinematic states and $\boldsymbol{F}^{pred} = \boldsymbol{\pi_F}(\boldsymbol{F}_i, \boldsymbol{F}_{i-1}, \ldots)$ for the section forces, respectively. In the subsequent macro time step $t_i \rightarrow t_{i+1}$ both subsystems operate with the predicted coupling quantities $\boldsymbol{u}_{Sub1}(t) = \boldsymbol{F}^{pred}(t)$ and $\boldsymbol{u}_{Sub2}(t) = \boldsymbol{q}^{pred}(t)$. In the following, we introduce two typical application examples and describe the respective co-simulation realizations.

## 2 Tire-vehicle-simulator coupling

In the first application scenario we have a developed a coupled simulation of a tire model and a vehicle model that is integrated into Fraunhofer's interactive driving simulator RODOS®. In this connection, realtime capability is essential in order to achieve the motion feedback together with the visualization with acceptable latency. The parallel co-simulation scheme allows to simulate the vehicle model and all four tire models simultaneously, on a separate core each. With a macro time step size of $\Delta t = t_{i+1} - t_i = 1\,\text{ms}$, both – the tire models (CDTire/Realtime) and the vehicle model (SIMPACK) – are realtime capable so that the entire co-simulation scenario is also realtime capable.

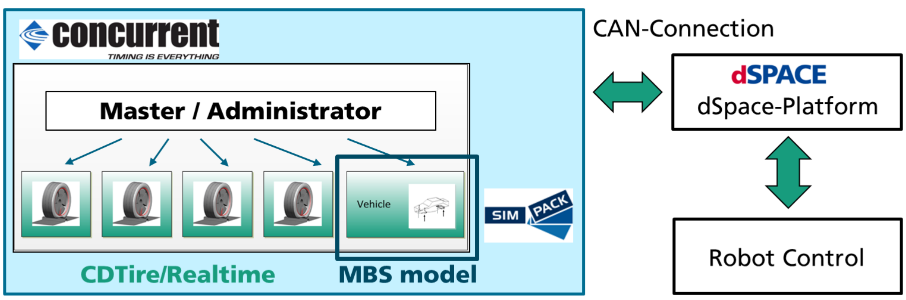


**Figure 2.** Realization of co-simulation scheme for coupling RODOS®, tire models and vehicle model.

The multibody vehicle model (*Subsystem 1*) receives tire forces $\boldsymbol{F}_i = \boldsymbol{F}_{\text{TIRE}}$ as input data, while vehicle kinematic states $\boldsymbol{q}_i = \boldsymbol{q}_{\text{VEHICLE}}$ are provided as input for the tire models (*Subsystem 2*). The realization of the coupled simulation at the driving simulator RODOS® is depicted in Figure 2 where the data exchange between the tire models and the vehicle model is organized by a tailored co-simulation master algorithm. More details and numerical experiments revealing that higher order prediction of the exchanged data is necessary to avoid unphysical oscillations are presented in [2, 4].

## 3 Material-machine coupling

In the second application scenario we have developed, in cooperation with Volvo Construction Equipment AB (Sweden), a co-simulation framework in the construction equipment development context that serves to simulate and analyze the interaction of construction equipment machines with material. In particular, the communication interface involves Volvo CE's multibody machine models and Fraunhofer's software package entitled »GRAnular Physics Engine (GRAPE)« for modeling and simulating soft soil that is based on the discrete element method [5–7].

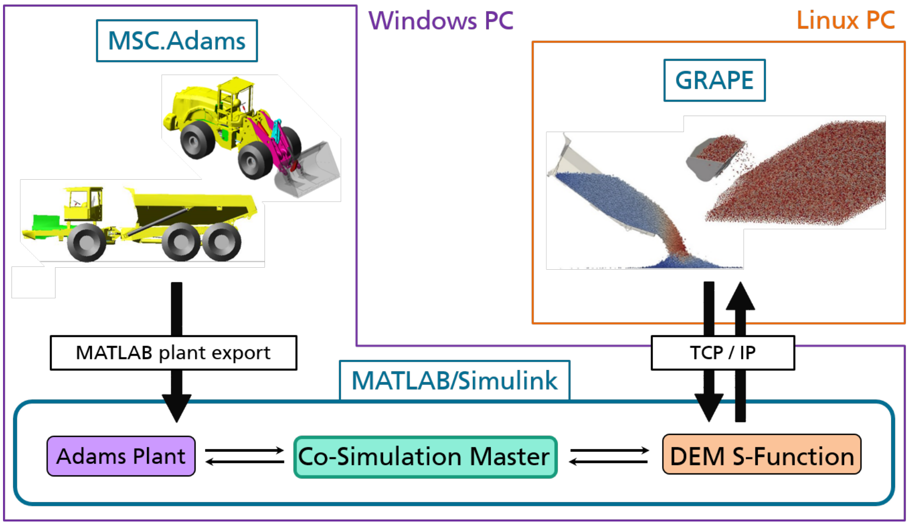


**Figure 3.** Realization of co-simulation scheme for coupling GRAPE to multibody construction equipment.

The multibody construction equipment model (*Subsystem 1*) provides kinematic states $\boldsymbol{q}_i = \boldsymbol{q}_{\mathrm{CE}}$ as input for GRAPE (*Subsystem 2*) which provides section forces $\boldsymbol{F}_i = \boldsymbol{F}_{\mathrm{GRAPE}}$ as input for the multibody construction equipment model. The realization of the prescribed coupling concept requires specific co-simulation interfaces for the multibody construction equipment model and the GRAPE particles, as well as a co-simulation master algorithm organizing the data exchange and the prediction strategies. In this connection, MATLAB/Simulink is chosen as the platform for setting up the co-simulation scenario. One the one hand, we utilize the plant export to MATLAB provided by MSC.Adams (*Adams Plant*) and, on the other hand, GRAPE is integrated as an S-Function into the scheme (*DEM S-Function*). Additionally, the co-simulation master is implemented in a MATLAB/Simulink subsystem (*Co-Simulation Master*). The communication, i.e. the exchange of the coupling quantities, with the GRAPE server is realized via a TCP/IP network protocol so that it is possible to run GRAPE and MATLAB/Simulink together with MSC.Adams on different host PC's, as depicted in Figure 3. More details, numerical results and a verification on the basis of real measurements are presented in [1, 3].

## References


[1] M. Balzer, M. Burger, T. Däuwel, T. Ekevid, S. Steidel, and D. Weber. Coupling DEM Particles to MBS Wheel Loader via Co-Simulation. In *Proceedings of the 4th Commercial Vehicle Technology Symposium (CVT 2016)*, pages 479–488, Kaiserslautern, 2016.

[2] M. Burger, M. Bäcker, A. Gallrein, and M. Kleer. Integration eines detaillierten, flexiblen Reifenmodells in den Fraunhofer Fahrsimulator. In *VDI-Bericht 2211, 14. Internationale VDI-Tagung Reifen-Fahrwerk-Fahrbahn*, number ISBN 978-3-18-092211-9, pages 167–184, Hannover, Oktober 2013.

[3] M. Burger, K. Dreßler, T. Ekevid, S. Steidel, and D. Weber. Coupling a DEM material model to multibody construction equipment. In *Proceedings of the 8th ECCOMAS Thematic Conference on Multibody Dynamics*, Prague, June 2017.

[4] A. Gallrein, M. Bäcker, M. Burger, and A. Gizatullin. An Advanced Flexible Realtime Tire Model and its Integration into Fraunhofer's Driving Simulator. *SAE Technical Paper 2014-01-0861*, 2014.

[5] M. Obermayr. *Prediction of Load Data for Construction Equipment using the Discrete Element Method*. PhD thesis, Universität Stuttgart, 2013.

[6] M. Obermayr, K. Dreßler, C. Vrettos, and P. Eberhard. A bonded-particle model for cemented sand. *Computers and Geotechnics*, 49:299–313, 2013.

[7] M. Obermayr, C. Vrettos, P. Eberhard, and T. Däuwel. A discrete element model and its experimental validation for the prediction of draft forces in cohesive soil. *Journal of Terramechanics*, 53:93–104, 2014.