CO-SIMULATION OF CONTINUOUS SYSTEMS: A TUTORIAL

Cláudio Gomes
University of Antwerp
Antwerp, Belgium
joachim.denil@uantwerp.be

Casper Thule
Aarhus University
Aarhus, Denmark
casper.thule@eng.au.dk

Joachim Denil
University of Antwerp, Flanders Make
Antwerp, Belgium
joachim.denil@uantwerp.be

Hans Vangheluwe
University of Antwerp, Flanders Make
Antwerp, Belgium
hans.vangheluwe@uantwerp.be

ABSTRACT

Truly complex engineered systems that integrate physical, software and network aspects are emerging (Nielsen et al. 2015), posing challenges in their design, operation, and maintenance.

The design of such systems, due to market pressure, has to be concurrent and distributed, that is, divided between different teams and/or external suppliers, each in its own domain and each with its own tools. Each participant develops a partial solution, that needs to be integrated with all the other partial solutions. The later in the process the integration is done, the higher its cost (Plateaux et al. 2009). Ideally, the solutions developed independently should be integrated sooner and more frequently (Van der Auweraer et al. 2013).

Modeling and simulation has improved the development of the partial solutions, but falls short in fostering this holistic development process (Blochwitz et al. 2011). To understand why, one has to observe that: (i) models of each partial solution cannot be exchanged or integrated easily, because these are likely developed by a specialized tool; (ii) externally supplied models may have Intellectual Property (IP) that cannot be cheaply disclosed to system integrators; and (iii) as solutions are refined, the system should be evaluated by integrating physical prototypes, software components, and even human operators, in what are denoted as Model/Software/Hardware/Human-in-the-loop simulations (Alvarez Cabrera et al. 2011).

Co-simulation consists of the theory and techniques to enable global simulation of a coupled system via the composition of simulators. Each simulator is broadly defined as a black box capable of exhibiting behaviour, consuming inputs and producing outputs.

Despite the large number of applications and growing interest in the challenges that co-simulation poses (see, e.g., (Gomes et al. 2017, Blockwitz et al. 2012)), the field is fragmented into multiple application domains, with limited sharing of knowledge. For example, the use of dead-reckoning models is well-known in discrete event co-simulation (Lee et al. 2000) and in adaptive control (García, Prett, and Morari 1989), but it was only very recently used in a continuous time co-simulation application (Stettinger et al. 2014).

This tutorial aims at facilitating the exchange of solutions and techniques, by promoting a deeper understanding of co-simulation. To that end, we assume minimal background on continuous systems modeling and simulation, and introduce the following topics:

1. Differential Equations – Scalar and Vector

2. Solution Approximation and Error – The Forward Euler method
3. Decoupling Method – Multi-rate integration
4. Generalized Decoupling Method – Continuous time Co-simulation
5. The FMI Standard

Further references, and a python notebook (http://jupyter.org/), will be provided, so that participants can try the examples, and build their own. Upon successful completion of this tutorial, the participants will have learned the necessary concepts to take their own routes in exploring this broad and fascinating field.

REFERENCES

Alvarez Cabrera, A. A., K. Woestenenk, and T. Tomiyama. 2011. "An architecture model to support cooperative design for mechatronic products: A control design case". *Mechatronics* 21 (3).

Blochwitz, T., M. Otter, M. Arnold, C. Bausch, C. Clauss, H. Elmqvist, A. Junghanns, J. Mauss, M. Monteiro, T. Neidhold, D. Neumerkel, H. Olsson, J.-V. Peetz, and S. Wolf. 2011, jun. "The Functional Mockup Interface for Tool independent Exchange of Simulation Models". In *8th International Modelica Conference*, pp. 105–114. Dresden, Germany.

Blockwitz, T., M. Otter, J. Akesson, M. Arnold, C. Clauss, H. Elmqvist, M. Friedrich, A. Junghanns, J. Mauss, D. Neumerkel, H. Olsson, and A. Viel. 2012, nov. "Functional Mockup Interface 2.0: The Standard for Tool independent Exchange of Simulation Models". In *9th International Modelica Conference*, pp. 173–184. Munich, Germany, Linkoping University Electronic Press.

Garcia, C. E., D. M. Prett, and M. Morari. 1989, may. "Model predictive control: Theory and practice—A survey". *Automatica* vol. 25 (3), pp. 335–348.

Gomes, C., C. Thule, D. Broman, P. G. Larsen, and H. Vangheluwe. 2017, feb. "Co-simulation: State of the art". Technical report.

Lee, B.-S., W. Cai, S. J. Turner, and L. Chen. 2000, dec. "Adaptive dead reckoning algorithms for distributed interactive simulation". *International Journal of Simulation* vol. 1 (1-2), pp. 21–34.

Nielsen, C. B., P. G. Larsen, J. Fitzgerald, J. Woodcock, and J. Peleska. 2015, sep. "Systems of Systems Engineering: Basic Concepts, Model-Based Techniques, and Research Directions". *ACM Computing Surveys* 48 (2), pp. 18:1—-18:41.

Plateaux, R., J. Choley, O. Penas, and A. Riviere. 2009. "Towards an integrated mechatronic design process". In *International Conference on Mechatronics*, Volume 00, pp. 1–6. Malaga, Spain, IEEE.

Stettinger, G., M. Horn, M. Benedikt, and J. Zehetner. 2014. "Model-based coupling approach for non-iterative realtime co-simulation". In *European Control Conference (ECC)*, pp. 2084–2089.

Van der Auweraer, H., J. Anthonis, S. De Bruyne, and J. Leuridan. 2013. "Virtual engineering at work: the challenges for designing mechatronic products". *Engineering with Computers* 29 (3), pp. 389–408.

AUTHOR BIOGRAPHIES

CLAUDIO GOMES is a PhD student at the University of Antwerp (Belgium). His research focus is on the foundations of co-simulation.

CASPER THULE is a PhD student in the Department of Engineering at Aarhus University.

JOACHIM DENIL is an assistant professor in the department of Electronics-ICT at the University of Antwerp. His research interests include model-based systems engineering and embedded software.

HANS VANGHELUWE is a Professor in the department of Mathematics and Computer Science at the University of Antwerp (Belgium) and an Adjunct Professor in the School of Computer Science at McGill University (Canada). He heads the Modelling, Simulation and Design (MSDL) research lab.