Teaching a Course on Modeling and Simulation for Cyber-Physical Systems using Modelica and FMI Technologies with Hands-on-Laboratories

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Abstract

This presentation gives an overview on a modeling and simulation course using Modelica and Flexible Mock-up Interface technologies that has been offered at Rensselaer Polytechnic Institute in Fall 2018 and 2019 and at the King Abdullah University of Science and Technology in Summer 2019, for both undergraduate and graduate students. The main goal of this presentation is to provide the basis for the introduction of this type of course in the North American-style course curriculum. This helps in providing a template that can be replicated in other institutions with the goal of students use Modelica and the FMI for CPS design and analysis, and to expand the existing Modelica community in North America.

Keywords: Modelica, FMI, Higher Education, Teaching, Hands-on-Laboratories, Arduino

1 Summary

1.1 Motivation

Currently, most modeling and simulation courses in university studies are domain specific, and largely they depend on non-standardized languages (predominantly MATLAB/Simulink). In addition, courses on numerical computing methods do not use object-oriented modeling languages for instruction and largely focus on traditional numerical techniques, thereby not addressing issues related to the application of solvers for differential-and-algebraic equation systems which are relevant for complex multi-domain systems.

With computation and communication means becoming evermore pervasive, traditional physical systems, such as industrial plants and power networks, are being transformed into complex and hybrid system-of-systems where the traditional means for modeling and simulation have limitations to understand the interplay between such different domains. According to the National Science Foundation, such types of systems are called Cyber-Physical Systems (CPS) which “are engineered systems that are built from, and depend upon, the seamless integration of computation and physical components.” The development of CPS requires the integration of multiple domains, and thus, to design and study CPSs models of physical systems need to be coupled with models of computation, networking, and other cyber-assets, in order to perform design activities (e.g. trade-off analysis). This also requires engineers from multiple disciplines to perform collaborative design, which in turn necessitates for engineers to cooperate without enforcing domain specific tools or design approaches. In this context, Modelica and the FMI standard provide a suitable foundation for design and analysis of CPS, which is already showing success in areas such as the automotive, aerospace, heat ventilation and AC (HVAC), etc. The Modelica standard provides rich language features allowing to interface multiple domains and means to easily replace component models with different levels of complexity, while the growing family of Modelica tools allow users to focus on complex CPS modeling tasks. Meanwhile the success in the adoption of the FMI standard allows engineers to share models between tools, facilitating collaborative design.

Despite these advantages, Modelica and the FMI have limited adoption in the academic community, with most of the expertise concentrated in Europe. In the case of North America, very few institutions provide students with this specific knowledge and skills, which is desirable for CPS development. This poses both a challenge for the North American industry seeking for talented students with the right skills set, and at the same time for universities to be able to train students to supply the required workforce. This is an important issue to address, the National Academies of Sciences, Engineering and Medicine have highlighted in a 2016 report (https://www.nap.edu/read/23686/chapter/1) the need for students to gain the knowledge and skills to engineer CPS. Among the different foundations required, this course addresses some of the needs related to Foundation 5: Modeling of Heterogeneous and Dynamic Systems Integrating Control, Computing and Communication.

This presentation will give an overview of the efforts of the author in developing, piloting and integrating into the curriculum a new course on modeling and simulation for CPS based on Modelica and FMI technologies that aims to partially address the aforementioned challenges.

1.2 Overview of the Presentation

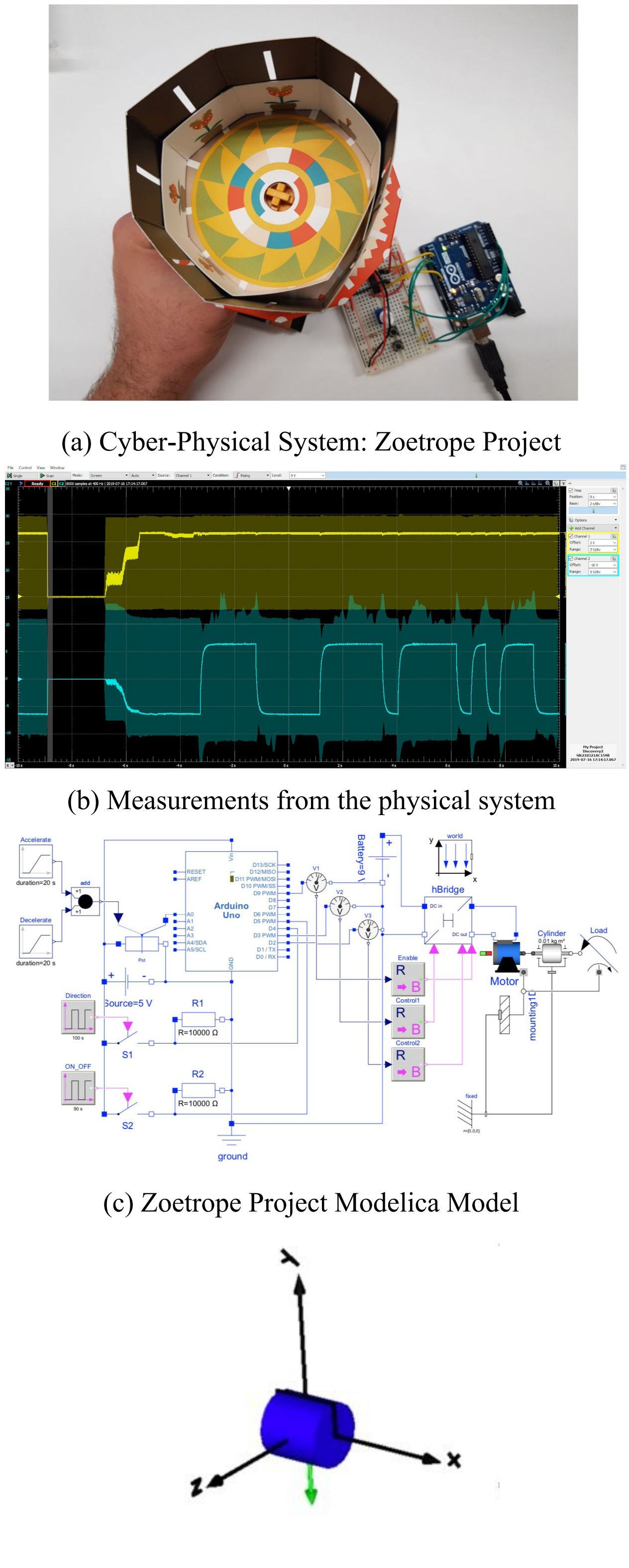
The main goal of this presentation is to provide the basis for the introduction of this type of course in the North American style course curriculum, using the presenter's experience as an example. This helps in providing a template that can be replicated in other institutions with the goal of students use Modelica and the FMI for CPS design and analysis, and to expand the existing Modelica community in North America.

This presentation will cover the different teaching and learning activities carried out in the course. It will provide a list of topics covered in lectures and homeworks, with samples of the activities - an excerpt is shown in Table 1. The mechanisms for course assessment are also discussed. The course makes intensive use of "guided explorations," which are workshops where the students follow specific steps using a Modelica tool when developing Modelica-based models.

Table 1. Excerpt of the list of topics

Lecture no.	*Topics*
1	Course introduction and getting started with Dymola
2	Object-oriented graphical modeling
...	...
5	Equation-based modeling
6	Understanding equation-based modeling
...	...
12	Model architectures, templates and interfaces
13	Model variants and data management
...	...
16	The FMI Standard
17	Real-Time Simulation
...	...

In addition to the workshops, the students carry out two hands-on labs which make the use of the Arduino Starter Kit and a 6 degree of freedom robotic arm in different experiments. The first laboratory consists of building projects from the Arduino Starter Kit both the physical system and in digital form using the Modelica Arduino library, and comparing measurements from the physical system with those of the model. The goal of this laboratory is for students to learn the source of discrepancies between models and reality. An example for the Zoetrope project is shown in Figure 1.



(a) Cyber-Physical System: Zoetrope Project

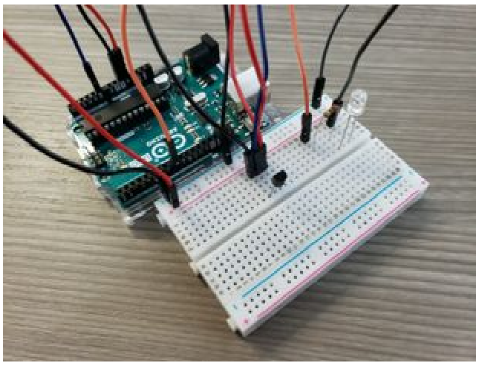
(b) Measurements from the physical system

(c) Zoetrope Project Modelica Model

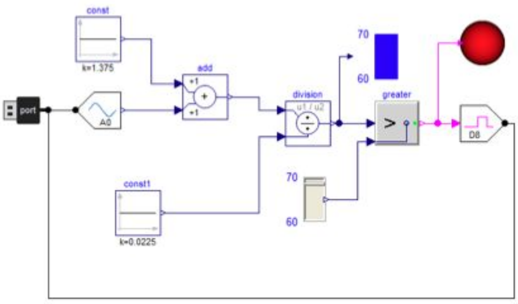
(d) Animated Simulation of the Zoetrope

Figure 1. Zoetrope CPS physical system and model

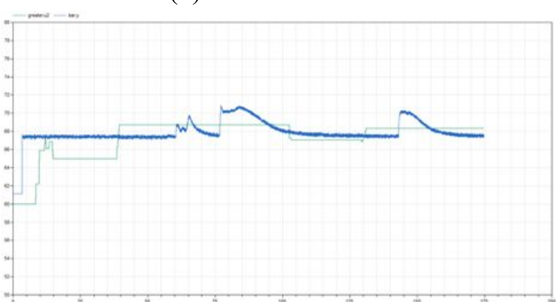
The second laboratory aims on interacting with models via hardware-in-the-loop simulation using three experiments. Again the Modelica Arduino library is used in three experiments. The first experiment consists in dimming a led by varying the voltage from the simulator. This gives the basis on using the Firmata protocol to communicate the real-time simulation model with the Arduino. The second experiment consists in a temperature monitor where a temperature sensor and led are connected in the loop with the Arduino while the simulator performs a threshold check in software, turning on an LED as an alarm when the threshold has been breached. This experiment helps to illustrate the issues when coupling a simulation with noisy measurements and how to use the Modelica User Interaction library to display the measurement and alarm data on the display during the simulation, as shown in Figure 2.



(a) Arduino with the circuit including a temperature sensor and LED



(b) Modelica model



(c) Real-time hardware-in-the-loop experiments when varying the threshold (green) and temperature (blue)

Figure 2. Real-Time Hardware-in-the-Loop Temperature Alarm

Finally, the third experiment consists on sending commands to a 6 degree of freedom robotic arm. This last experiment serves to motivate the importance of feedback for control in HIL.

For their final assessment, the students carry out a project for their final assessment where they have to apply the knowledge and skills gained from the course. The presentation will provide a few examples of interesting projects carried out by the students. Figure 3 shows a screenshot of a project where a student built a model of a drone which is controlled by a joystick and visualized using different features of the Modelica Visualization Library, note that the use of this library was not covered in class; however, the student was able to learn quickly how to exploit it based on his course learnings.

Figure 3. Screenshot of student project

1.3 Conclusion

This abstract gives an overview of the proposed presentation. The goal is to share experiences in bringing Modelica and the FMI into a modeling and simulation course within the North American curriculum. In addition to sharing these experiences, the presenter hopes this presentation will help in developing the interest of other faculty in using Modelica and the FMI for their teaching. From the experience teaching this course in three editions, the majority of the students have shown great interest and their projects show that they have become knowledgeable on the course topics.

The long term goal of this effort will be to share some of the educational resources developed with the Modelica community, in particular, the laboratories. These laboratories are still under development and refinement, in this presentation they will be introduced, with the hope of gathering feedback for their improvement. It is the intention of the author that the developed laboratory activities will be released to the community in their final form if there is sufficient interest.