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Model-based system engineering in control education using HIL simulators

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Abstract: Nowadays, model-based and knowledge-based system engineering bring completely new demands also to the master degree teaching process and programs. Specifically, it is necessary to establish gluing technologies between individual master degree courses while full STEM education scope is covered. Since huge changes in educational system are often subject to complex, time demanding evaluation and approval process, there is usually significant delay between actual industrial needs and time when universities are able to deliver to the market engineers with required knowledge and curricula. Consequently, solutions which can be implemented in actual courses without huge investments of money and time is what educators should strive for. This paper shows how simple hardware-in-the-loop (HIL) simulators may help during the whole training period while respecting needs of already established courses dealing e.g. with modeling and simulation, control design, industrial IT and communication, control HW and electronics, sensors and actuators. The concept is demonstrated on several examples of already proven procedures in primary and second control courses.

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Keywords: Control education, hardware-in-the-loop simulations, modeling, model-based system engineering, knowledge-based engineering, STEM * education

* Science, Technology, Engineering, Mathematics

1. INTRODUCTION

Nowadays, industry is entering a new era based on full *digitalization*, *industrial IoT*, product *quality monitoring*, *lifecycle management* and *predictive maintenance* of the equipment. Model-based and knowledge-based continuous engineering are one of key enabling principles to manage problems and systems of such complexity. The dynamic model itself is not developed just for initial system design anymore but the final intention is to pack it into stand-alone units and make them executable in more complex simulation setups. Nowadays, the target is to let the model live in real-time parallel to the physical system, i.e. create reliable digital twin. If some parts of complex system need innovation, the re-designed model must pass quickly through all X-in-the-Loop (XIL) stages. This brings new demands on modeling and simulation tools standardization. Such concepts are followed even by SMEs which are suppliers for end-producers e.g. in automotive industry. New engineers entering their professional career are immediately becoming part of continuous engineering process either in SW, HW, mechanical, electrical design, etc. Obviously, their good knowledge of mentioned principles will help to save time and money of the employers.

From academic and research perspective, a lot of large scale applied research projects are being executed by EU under H2020 [1] or are scheduled for next decade *(Horizon Europe)*. Those large consortia must be well balanced between universities, research centers, SMEs, and large enterprises hence create multinational innovation environment. Obviously, the entire value chain of certain product or technology must be covered by project partners and reflected in project results. In order to cooperate effectively (algorithm, data exchange, validation, etc) the XIL [2] principles have been adopted by many of those research initiatives. Point out, that XIL is nowadays not just an umbrella for MIL-SIL-PIL-HIL [3] cycle, but a real new standard to exchange models and algorithms between different vendors and also university teams. It exploits ideas of FMI [4] standard. Consequently, master and Ph.D. degree students need deeper background in referred technologies in order contribute effectively to those projects with their own research and transfer the theoretical results to industry in faster and more convenient way [5].

Parallel to that, impressive number of control education advances have been documented in last decades (Sánchez et al., 2002; Reitinger et al., 2013; Čech et al., 2013; Reitinger et al., 2014; Zimenko et al., 2014; Bazylev et al., 2016), in particular in the field of virtual and remote labs (Gomes and Bogosyan, 2009; Heradio et al., 2016), lab experiments (Carballo et al., 2018; Horacek,

[1] Horizon 2020, EU Framework Programme for Research

[2] X-in-the-Loop
[3] Model/Software/Processor - in the Loop
[4] Functional Mock-up Interface
[5] True especially when higher TRLs (technology readiness level) are requested

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2018; Docekal and Golembiovsky, 2018; Hoyo et al., 2015; Karra, 2018; Kaluz et al., 2014) and open educational resources (De La Torre et al., 2013; Rossiter et al., 2018). Unfortunately, they are still not sufficiently reflecting latest industrial needs mentioned above. In some regions and areas, the gap between theory and practice is even growing as technology innovation goes faster that control education advances (Čech et al., 2019). There are few papers available following a direction of bringing virtual plant to the lab (Riera and Vigario, 2017) while others aim to make that glue via dual education (Kozak, 2016).

Clearly, complex education innovations are needed where all stakeholders, including government, are involved (see Fig. 1). This paper shows that simple HIL simulators (Sobota et al., 2019) may help to deal with inner feedback loop emphasized in Fig. 1 without huge investments and in short time. Consequently, they allow the universities to play an expected societal role (4th generation university) (Pawlowski, 2009; Lukovics and Zuti, 2015). The paper explains how those simulators can be used during the whole training period while respecting annotations of already established courses dealing e.g. with modeling and simulation, control design, industrial IT and communication, control HW and electronics, sensors and actuators.

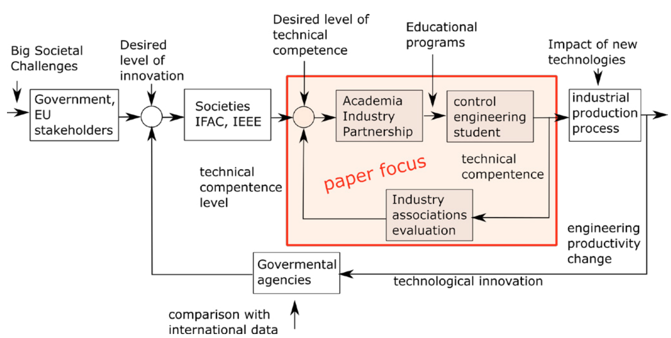

Fig. 1. Overall scheme of engineering education system with highlighted focus where HIL simulators can play crucial role

The rest of the paper is organized as follows: Section 2 highlights several new paradigms which are worth to being followed in control education and are related to HIL simulations. In Sections 3 and 4, it is summarized how HIL simulators are implemented in primary and second control course. Conclusions and ideas for future work are given in Section 5.

2. NEW PARADIGMS WORTH TO FOLLOW IN CONTROL EDUCATION

This section summarizes several novel industrial paradigms which are not yet sufficiently reflected in control education to promote automatic control technology and attract new students and investors. Further, each subsection comes with the position of HIL simulators in that context.

2.1 Continuous Engineering

Every product, system, technology will in the near future utilize continuous engineering technology covering the whole lifecycle and allowing easy engineering re-design or update of specific sub-component of the complex system.

Example 1 New fragment control SW code for ECU in automotive industry must pass directly through complex HIL tests (even remote) where all relevant interacting environment is simulated in real-time including physical I/Os.

Example 2 Re-design of particular mechanical part should imply initial FEM tests followed by model reduction which results into new control oriented dynamical model that is deployed onto real-time HIL simulator for testing against control system and all relevant environment.

2.2 Digital Twin

Digital twins are one of leading industrial technologies (Raileanu et al., 2019; Desai et al., 2019) of the future and should clearly affect also future control education and our labs (Wuttke et al., 2019). A fundamental step ahead, compared to traditional view of model, is that the dynamical model must be executed in real-time and has a potential to live in parallel with its real counterpart. Obviously, HIL simulators could help students in understanding that underpinning concept, i.e. dynamic model in the simulator lives in real-time even if it is disconnected from the higher layers (e.g. laptop in Fig.4).

2.3 Edge Computing

Edge computing has been identified as next driver after the period when cloud infrastructure was established (Sitton-Candanedo et al., 2019; Um et al., 2019). The idea is well understood in the IT community. Automatic control educators should clearly refer to the mapping of complex control system structure to the cloud-edge positioning as depicted in Fig. 2. If we add to the HIL simulators 'top-level' computer with development tools, simple system behaviour layer and diagnostics (see also Sections 3 and 4) the students can clearly distinguish cloud-edge directions and understand how the intelligence is distributed. Specifically, it should be understood that embedded control systems are smart edge nodes which may help to pre-process a lot of information for predictive maintenance of machines and process technologies and propagate relevant information to higher layers of automation pyramid.

2.4 Gamification and virtual reality

Gamification is a well established broad set of ideas helping to boost education innovations (Yordanova, 2019). In particular in engineering education, it is tightly related to augmented and virtual reality (VR) (Alptekin and Temmen, 2019). HIL simulators with real-time models merged with VR state-of-the-art technologies will enable the development of training equipment for both students and industrial practitioners. Such attractive tools are mostly developed in aerospace domain. The prediction is that they will be adopted by many other sectors in next few years.

To sum up, previous top-down analysis aimed to warn about nice links between several latest engineering drivers and HIL simulation principles. In upcoming bottom-up sections, it is shown how simple HIL simulator could be implemented in primary and second control course.

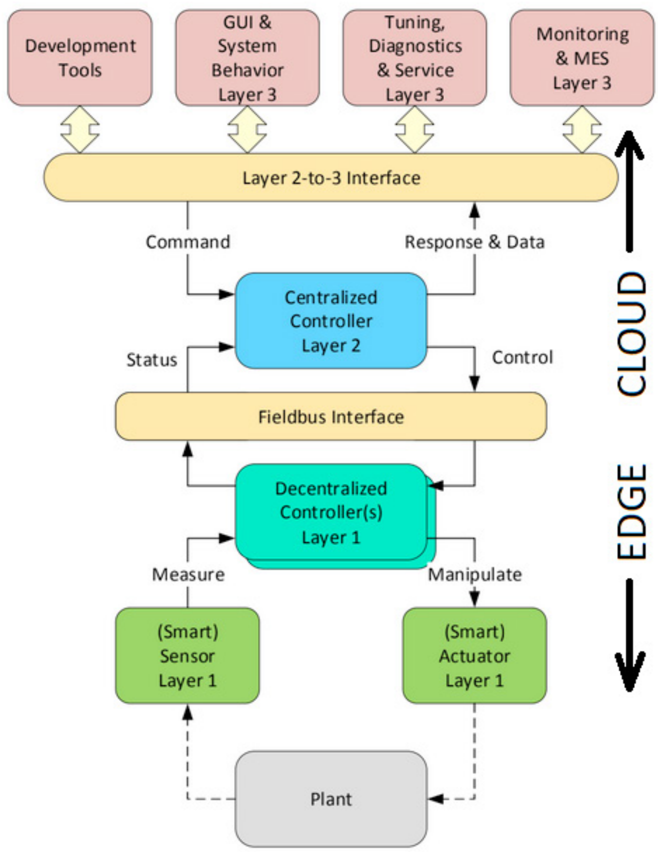

Fig. 2. Complex control system structure which can be understood with the help of HIL simulators

3. COUPLED TANKS USE CASE – PRIMARY CONTROL COURSE

3.1 HIL platform

Nowadays, the ecosystem of the Raspberry Pi offers everything which is needed to build an industrial-grade HIL simulator [6]. The authors chose following components:

- Raspberry Pi 3 B+ with 1 GB of RAM and 1.4 GHz quad-core CPU [7]
- 7" touchscreen display for the Raspberry Pi
- Monarco HAT add-on board with analog and digital inputs and outputs [8]
- REXYGEN software tools to build the HIL simulator without hand-coding [9]

Such HIL simulator accepts inputs and provides outputs in standard industrial ranges (digital signals in 24V logic, analog signals in 0-10V range), therefore it can be controlled by almost any PLC or compact controller on the market.

The CPU of the Raspberry Pi provides sufficient computational power, the complexity of the simulated plant is thus mainly limited mainly by the available I/Os on the Monarco HAT board. It provides 4x digital input, 4x digital output, 2x analog input and 2x analog output. Achievable refresh rate is 500 Hz.

3.2 Implementation in primary control course

The very first task, the students are assigned is to control a plant manually. The plant is an emulator of a coupled tanks system, probably the most typical plant in control courses throughout all continents. There is one controllable pump which defines the inflow of water. The water flows from tank 1 to tank 2 at variable speed, which is given by the difference in water levels in individual tanks. Tank 2 has an uncontrollable outflow, where the water leaves the plant. The goal is to keep water level in tank 2 at the setpoint.

A manual control unit is connected to the plant, allowing the user to control the inflow of water with a potentiometer. The water level in tank 2 is indicated by a voltmeter, see Fig. 3. The changes in voltage naturally correspond with on-screen animations.

By trying to keep the voltage (water level) at given value, the students experience the role of a controller in person. This hands-on experience gives students deep understanding of terms like *input*, *output* and *plant* itself. The HIL simulator allows for data logging and also network connectivity, opening possibilities to organize competitons among students or introduce other gamification concepts. By controlling the plant manually, students gain the feeling for plant dynamics. The plant parameters are intentionally designed so that waiting for the plant output to settle is long enough to cause a bit of pain but short enough to allow for experiments within a standard lab session.

After this initial session students understand the plant and the role of a controller. At this point they are ready to use a real PLC or controller. Just like in industrial practice, the first step is to get reliable sensor readings and control the actuator. In other words, the potentiometer is replaced by analog output of the PLC and the voltmeter is replaced by analog input of the PLC. Students must get familiar with engineering tools of the chosen PLC. We use miniature PLC [10], again built from a Raspberry Pi and Monarco HAT. For programming we use REXYGEN as it allows graphical programming of control algorithms, avoiding the need of detailed knowledge of programming techniques and tedious hand coding at all. Figure 4 shows the full setup, which allows the students to understand and distinguish the roles of three elements in control system design:

(1) Engineering station (desktop or laptop computer)
(2) Controller or PLC
(3) Controlled plant

Once students understand how to design the algorithm and deploy it to the controller, they start with simple experiments. Observing the plant response to various signals they recall what they have intuitively learned while controlling the plant manually. The behavior and dynamics of the plant become visible and measurable using time plots. Plant linearity or nonlinearity can be observed by measuring static characteristics at various working points. Students learn about monotonous and nonlinear

[6] this is not possible to achieve via only Arduino-based approaches, e.g. https://github.com/gergelytakacs/AutomationShield
[7] https://www.raspberrypi.org
[8] https://www.monarco.io
[9] https://www.rexygen.com/

[10] as it executes operating system, Soft PLC is more accurate term

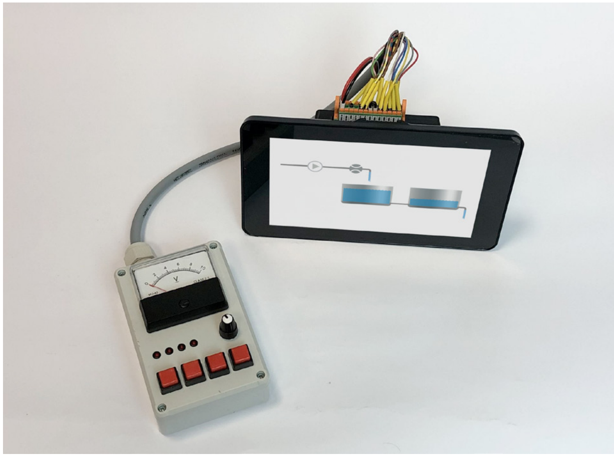

Fig. 3. The first hands-on experience is gained by controlling the plant manually

Fig. 4. Engineering station (left), controller (middle) and the controlled plant (right)

behavior of the plant. Using real hardware and physical input/output signals also immediately exposes problems of real world like saturation of the actuator and measurement noise.

The input-output data recorded during simple experiments allow for deriving a mathematical model in the form of a FOPDT or SOPDT transfer function. In other words, gray-box identification is carried out. The obtained mathematical models are validated by comparing their output to the response of the real plant.

Once a verified mathematical model of the controlled plant is available, students design a PI and PID controllers using PIDlab [11], using as little theory as possible, focusing on achieving the first success as soon as possible.

The behavior of the designed PI/PID controllers is evaluated at various working points. The topics like gain scheduling, controllers with variable parameters and robustness are briefly introduced.

4. QUARTER-CAR USE CASE – SECOND CONTROL COURSE

Similar HIL simulators were employed also in a second control engineering course at the University of West Bohemia as a semester project to explain full MIL-SIL-PIL-HIL cycle. The students are already familiar with the basics of linear systems theory and they gradually move to more advanced topics such as digital control, state observers, linear state feedback, modal control or frequency domain loopshaping.

A quarter-car suspension model was chosen for implementation in the HIL simulator for several reasons:

- The system is easy to visualize, all the students are familiar with cars from their everyday life
- Oscillatory dynamics can be introduced, importance of several design choices can be explained and the difference between open- and closed-loop behaviour is clearly visible
- The system is simple enough for the purpose of analysis and control design but complex enough to demonstrate all the relevant theory in practice
- The time constants of the system are small so that system responses can be observed immediately
- Nonlinear behaviour can be easily incorporated in the model to explain differences between real plant (represented by the HIL setup) and the idealized model used for the analysis and controller design
- Inherent tradeoffs emerging in control design can easily be explained, e.g. bandwidth vs noise amplification, robustness to unmodelled dynamics, actuator/sensor imperfections etc.

4.1 Modelling and analysis, data-driven identification

The quarter car model is the commonly used simplified model of the car chassis suspension. It consists of two masses connected by spring and damper elements. The higher mass usually represents the car body while lower mass stands for the wheel. The students should design an active suspension control system that keeps the car height constant, maintaining passenger comfort and actively suppressing disturbances due to varying road profile.

The students derive an idealized linear model from the equations of motion of the equivalent two-mass system. Approximate parameter values are given and the model response is studied both in time and frequency domain. Oscillatory behavior is revealed due the occurrence of two flexible modes coming from the chassis and wheel dynamics. This part gives them a basic understanding about the system behaviour. The derived model structure is used in the subsequent step of gray-box identification from the experimental data which leads to exact parameter values.

4.2 Model-in-the-loop

Based on the identified plant model, several approaches to controller design are proposed. The students start with a PID controller and then move to state-space control method using linear state feedback and observers. Practical aspects of PID control such as derivative part filtering or integrator windup problems are studied. Students have to meet several design constraints defined both in time and frequency domain, e.g. maximum settling time, overshoot and actuator effort, bandwidth or robustness margins. The results are validated on the virtual models of controller and

[11] http://www.pidlab.com

controlled system in Matlab-Simulink environment in the Model-in-the-Loop (MIL) setting.

This phase is essential from the theoretical and algorithmic point of view. The students develop understanding of various control design methods and means for their evaluation using closed-loop models.

4.3 Software-in-the-loop

The goal of this phase is to implement the designed controllers in the real-time software environment of the target control platform. The controllers have to be discretized using a suitable method to make the algorithms compatible with the sampled data systems. During the course, the REXYGEN control framework is being used. The main goal is the validation of the *correct implementation* of the algorithms, which were designed in the previous phase.

4.4 Processor-in-the-loop

In this part, the students move the whole control loop to the target hardware, in our case the Raspberry Pi single board computer with Monarco HAT add-on extending it with physical inputs and outputs. This phase is important for understanding the practical limitations imposed by the target hardware. Stability and calculation time of the whole control application has to be evaluated. Correct working on the target devices is a necessary prerequisite before moving to next step.

4.5 Hardware-in-the-loop

This phase introduces the HIL simulator representing the real plant. The simulator is connected to the controller via physical inputs and outputs forming the whole control loop. The feedback and manipulated variable signals are exchanged between the controller and plant simulator devices via 0-10V analog inputs and outputs. The analog IOs come with some inherent errors such as high-frequency noise and bias. Proper scaling of the signal is necessary to put the closed loop into operation. All these practical issues that have to be solved in order to develop deeper understanding of implementation aspects encountered in real-life control engineering problems.

Students often find out that their designed controllers that worked well with model in numeric simulations perform poorly with the physical plant. They need to go back to the previous phases and reconsider all their design choices. The designed controllers are finally tested on a testing trajectory simulating a real road profile. Various time and frequency domain criteria are introduced to compare different variants of their closed-loop controllers.

The main benefit of the whole XIL cycle compared to offline numerical simulations only is the possibility of explanation of the whole model-based control engineering process in the way it works in real-life problems. This allows the students to get much deeper insight to what feedback control actually involves. Moreover, they acquire some practical implementation skills which might be handy when they come to industrial practice after graduation.

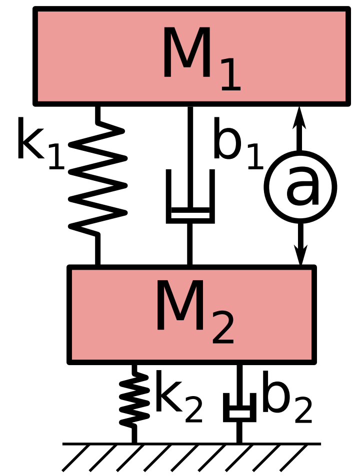

Fig. 5. Modelled double mass system which is executed in real-time on Raspberry Pi

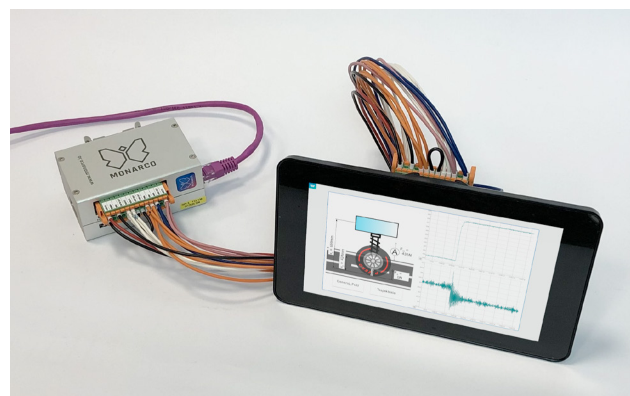

Fig. 6. HIL simulator of quarter car model: controller (left) and controlled plant (right)

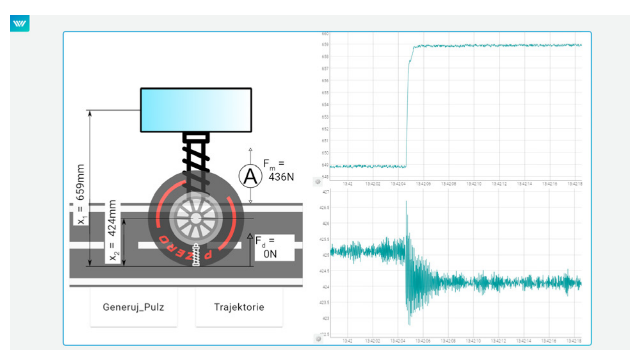

Fig. 7. Controlled simulator interface

5. CONCLUSIONS

This paper showed that simple HIL simulators can be reused in various control courses and may be enablers for more complex and multidisciplinary lab projects. Moreover, they help to emphasize control engineering in the light of modern technologies like digital twins, edge computing, virtual reality, model-based and knowledge based continuous engineering, i.e. finally attract more students to the domain. The experience from primary and second control course showed increased enthusiasm of students (working usually in pairs) as they feel they are mastering practical skills relevant for working career. As a consequence, the technology described is also nicely supporting effective dual education. To cover full XIL cycle, it is planned to finalize complex student project with real physical setup of quarter car model and coupled tanks setup.

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