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Raspberry Pi-based HIL simulators for control education

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Abstract: Excluding hands-on experience with physical plants from control education is tempting in many aspects, but at the same time it is very dangerous. This paper explains why and recommends a compromise between demanding maintenance of physical plants for students to control and relying on pure numeric simulations within the whole curriculum. The golden mean might be the use of real-time simulators with physical inputs and outputs, i.e. hardware-in-the-loop (HIL) simulators. Three examples of HIL simulators are presented, covering a coupled tanks model, a quarter-car model and a nuclear reactor model.

Keywords: Control education, real-time simulation, hardware-in-the-loop, HIL, Raspberry Pi

1. INTRODUCTION

Over the last decade, we have been enthusiastic to watch and accept new features in software tools for simulating dynamic systems. Creating a simulation model of complex electrical, mechanical or hydraulic systems or complete technological units has never been easier, packages like MATLAB/Simulink/SimScape or OpenModelica are available. Alongside this progress, a number of virtual laboratories appeared as well, making the simulations available with a single mouse-click (Gomes and Bogosyan, 2010; Heradio et al., 2016).

These unsurpassed possibilities, however, are gradually changing the way in which automation and feedback control is taught at universities. Physical models of controlled plants (e.g. countless variations of coupled tanks with pumps and valves, mechanical setups with motors, springs and masses, models of heating or ventilation systems, etc.) one by one disappear from the laboratories, being replaced by pure software simulation models which are used for demonstrating feedback control in action.

From the educators' point of view, this is not surprising. The operation of physical models not only poses problems with students' safety during labs, but also requires maintenance of models and their repairs (pumps get stuck, bearings wear out, motors get burned, etc.). From this perspective, simulation-based control education seems like the ideal approach – no risks, zero maintenance, repeatability and sustainability guaranteed.

But isn't this escape into the world of pure simulation hurting students? And consecutively the whole field of control and automation?

2. SIMULATION IS ONLY ONE PIECE OF THE PUZZLE

As always, choosing the easy way has its drawbacks. If the students of feedback control work only in the simulation environment, right from the beginning of their studies, they are often unable to combine the subject matter with the real world:

- A student who has never seen a compact controller or a PLC has problems understanding the basic structure of the feedback loop.
- A student who has never waited for the plant output to settle, is missing the feeling for plant dynamics and easily forgets the simple fact that nothing happens immediately in the real world.
- A student who has neither seen a sensor nor a record of the data we get from it, can hardly imagine what measurement noise is. Not to mention the meaning of the sensitivity function for the quality of the control loop.

In short, who has never personally tried to measure the step response of a physical plant can hardly fully understand what feedback control is about.

This paper is by no means intended to criticize or reject the use of simulation tools, just the opposite. But simulation needs to be used not sooner than the students are ready for it. The students should be first exposed to hands-on experience with physical feedback control loop. The knowledge needed to implement a simple comparator algorithm is minimal while the benefits of observing it in action in real time are enormous. What is a better motivator for studying feedback control theory than practical experiment clearly showing that minimizing the hysteresis band of a relay controller simply does not do the trick?

Without personal experience with physical feedback control loops, students may leave the university prematurely because they do not actually understand what they are studying. Or even worse, despite the misconception of the field of study, they leave the university with a bachelor or master's diploma, only to find out that in the industrial practice they are unable to apply anything from what they have studied so hard.

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3. HIL SIMULATORS MIGHT HELP BRIDGE THE GAP

What better can we do than show and teach the students all the steps in control system design? The simulation-based control education mentioned in the introductory Section 1 leaves the graduates in feedback control theory half-blind and unprepared for the industrial practice.

It would be naive to expect that all educational institutions will at once include physical models in their curriculum. The reasons were mentioned earlier, not to forget the financial aspects. A solution (or at least a partial one) to the problem can be the use of simulated systems, but running in real time and with physical analog and digital inputs and outputs. Such a physical real-time simulator with display and animated objects, e.g. coupled tanks with moving liquid levels and controllable inflow, gives the students at least the feeling of controlling a real plant.

Thanks to standard industrial signal ranges the real-time simulator can be controlled by any PLC or compact controller, as shown in Figure 2. This approach is known as HIL testing (Hardware In the Loop) and it is used for testing control systems especially in the automotive and aerospace industries (Zinnecker et al., 2014), (Brembeck, 2017).

3.1 Advantages of using HIL simulators

As indicated above, including HIL simulators in control education has the following advantages:

- Students work with real devices (PLCs, PACs, compact controllers) that they will meet in industrial practice after completing their studies.
- At first glance it is clear where the controller is, where the controlled plant is and what the interface in between is.
- Students will naturally learn about problems such as sensor calibration and measurement noise.
- There are no problems with maintaining the mechanical parts of physical models and the safety of their operation is ensured.There is no water flowing out of the simulator onto the lab floor, there are no expensive components which could get damaged etc.
- The developed algorithms are immediately applicable so that the students can immediately observe the results of their work. This builds student's trust in the theoretical apparatus included in the curriculum.
- Experiments are repeatable and comparable. No more papers about coupled tanks control, which nobody is able to verify and compare simply because the given physical setup is unique.
- The simulated system can be monotonous, oscillating, integrating or even unstable.
- Any plant or technology can be simulated. Models can be designed and targeted for a particular field of study. The days of modeling plants with equivalent RLC circuits are over.
- Model parameters can be customized if needed. Each student can thus control a different plant, which avoids plagiarism.
- For very slow process, the model can be scaled in time, so that the students can work with it during the lab, but still feel the pain of e.g. waiting for steady state. This gives them a clear understanding of why math-physical modeling and simulation save time and resources.

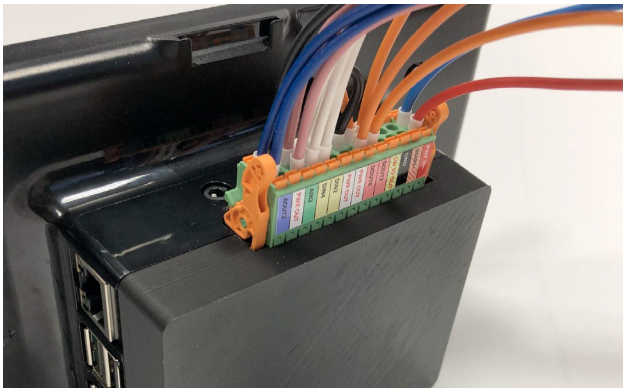

Fig. 1. Hands-on experience includes wiring of input and output signals

There's no sense in questioning the position of software simulation tools in control system design and control education. They just need to be accompanied by additional tools and devices, linking the simulation world with the physical world. Once the students have experience at least with a HIL simulator of a controlled plant and a real PLC or controller, let them go for the simulation, by all means. The difference is that they will work with full understanding of the subject and this has huge positive consequences.

3.2 Model-Based System Engineering

The use of HIL simulators is fully in line with the current trends in industrial practice. In the pursuit of maximum productivity and efficiency, plants and machines are running 24/7. Downtime is reduced to absolute minimum, leaving very little room for experiments with the real plant.

Model-based system engineering is becoming more and more important and the industry is looking for graduates who are able to cover all the phases of model-based control system design:

(1) Formulation and understanding of the problem
(2) Mathematical modeling
(3) Experimental gray-box identification
(4) Model-based design and validation of control algorithms
(5) Implementation of control algorithms in real-time environment
(6) Validation of all design phases using offline and real-time simulations.

Control education focused solely on phases 2 and 4 produces graduates, who need to take additional training prior to working in industrial practice, lowering the trust of both the industry in academia as well as the graduates in themselves.

4. AN IDEAL CONTROL COURSE

When HIL simulators are included in the course, the students typically start with simple experiments with the real-

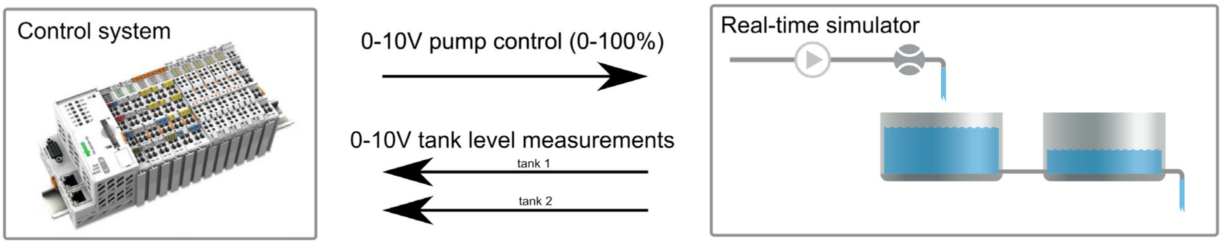

Fig. 2. HIL simulator emulates the plant and its sensors and actuators in real-time

time simulator, observing the plant response to various external signals. The natural behavior and dynamics of the plant is quickly recognized. Plant linearity or nonlinearity can be observed by measuring static characteristics and response to harmonic excitations with varying amplitudes. The simulator can include all imperfections of the real plant and its actuators like saturation, rate-limits, backlash, dead zones etc. The output signals can be corrupted by artificial noise and other parasitic effects including offset or drift to mimic real physical transducers.

As soon as the students understand the plant which they are about to control, the mathematical model can be derived. Model reduction and linearization techniques may be applied. The resulting errors of such approximation can be evaluated by comparing the responses of individual mathematical models in time and frequency domains. The goal is to set the structure of the mathematical model for the consecutive identification.

The phase of data-driven identification follows. The goal is to derive the unknown parameters of a gray-box model with the structure defined in the previous step. The students are led to select suitable excitation signals and execute identification experiment on the HIL simulator and collect input-output data. System identification methods are employed for the computation of the parametric model. The output of the mathematical model is then compared to the behavior of real-time simulator.

Once a verified mathematical model of the controlled plant is available, any control design technique can be applied. This part is intentionally reduced to a minimum in this paper.

The course ends with implementation of the control algorithm on the final hardware platform. An important message here is that programming of control systems no longer requires detailed knowledge of programming techniques and tedious hand coding.

5. LOW COST PLATFORM FOR BUILDING A HIL SIMULATOR

Great news is that today there are hardware platforms and software tools available, which make the implementation of HIL simulators not a matter of EUR 10,000 and above, but it can go lower than EUR 1,000.

The gamechanger in this field was the Raspberry Pi minicomputer (The Raspberry Pi Foundation, 2018). Originally designed as a platform to attract kids to STEM education[1] and teach basic programming, it has quickly spread and found its place in all levels of education, including control courses at universities (Hoyo et al., 2015; Docekal and Golembiovsky, 2018; Kaluz et al., 2014; Karra, 2018; Sobota et al., 2013; Carballo et al., 2018; Schvarcbacher and Rossi, 2017). Nowadays, the ecosystem of the Raspberry Pi offers everything which is needed to build an industrial-grade HIL simulator:

- Raspberry Pi 3 B+ with 1 GB of RAM and 1.4 GHz quad-core CPU (The Raspberry Pi Foundation, 2018)
- 7” touchscreen display for the Raspberry Pi
- Monarco HAT add-on board with analog and digital inputs and outputs (REX Controls, s.r.o., 2016)
- REXYGEN software tools to build the HIL simulator without hand-coding (REX Controls, s.r.o., 2018)[2]

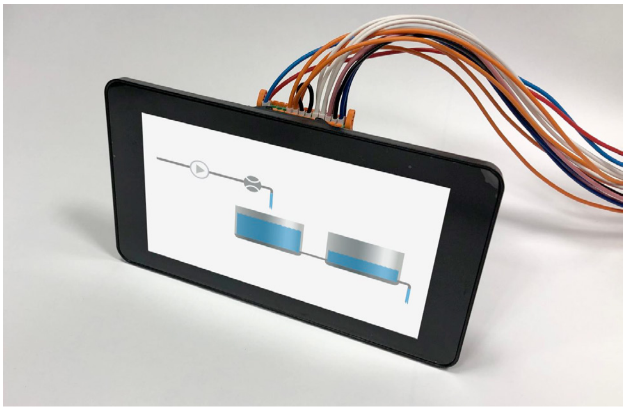

Fig. 3. HIL simulator of coupled tanks model

The 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 by the available I/Os on the Monarco HAT board, which provides 4x digital input, 4x digital output, 2x analog input and 2x analog output. Achievable refresh rate is 500 Hz.

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[1] Science, Technology, Engineering and Mathematics

[2] Basically any software can be used for building the HIL simulator because both the Raspberry Pi and Monarco HAT are open hardware platforms.

6. EXAMPLE HIL SIMULATORS

6.1 Coupled tanks model

The coupled tanks model shown in Figure 3 is probably the most typical in control courses throughout all continents (Wellstead, 1990; Grega and Maciejczyk, 1994; Horáček, 2000; Alvarado et al., 2006; Grygiel et al., 2016). 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.

The pump is controlled by a standard 0-10V analog signal, which defines its power 0-100%. Water levels are indicated by two analog signals, again in the standard range 0-10V. There is one limit switch at tank 1, which stops the pump in case the water level in tank 1 rises too much. This is signalled by one digital output.

Although quite simple to describe and understand, the coupled tanks model offers a wide range of experiments to carry out. Students can observe monotonous and non-linear behavior of the plant and apply PI/PID control strategies or design state-space controllers. In advanced courses, state observer can be designed, where the level in tank 1 is reconstructed from the control signal and tank 2 measurements. Cascading control using PI/PID controllers can be implemented as well.

6.2 Quarter car model

The second example of a plant suitable for HIL simulation is a quarter-car model (Kulkarni et al., 2017; Verros and Natsiavas, 2005; Lauwerys et al., 2005). It represents a simplified car suspension system allowing to study several phenomena of road vehicle dynamics.

The equivalent schematics of the plant is shown in Fig. 4. It is modeled as a two degrees of freedom system consisting of the sprung mass representing the car body and the unsprung mass of the wheel. Parameters of the individual elements can be adjusted to achieve diverse dynamic characteristics. The input to the model is a standard analog signal defining the actuator force. Two analog outputs can be configured to provide the measurements of absolute/relative position or acceleration of the bodies which serve as the feedback for the controller under single-output or multiple-output setup.

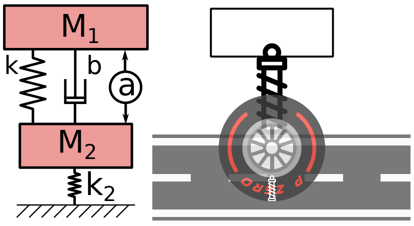

Fig. 4. Quarter-car 2DoF simplified model, M1 - sprung mass (car chassis), M2 - unsprung mass (wheel), k,k2 - spring elements, b - damper, a - actuator

The model is being used in terms of control courses dealing with state of the art modeling, experimental identification and model-based control design techniques. The ultimate goal is to perform a gray-box data-driven identification, design and evaluate several control strategies for active suspension system. Students go through all steps mentioned in Section 4.

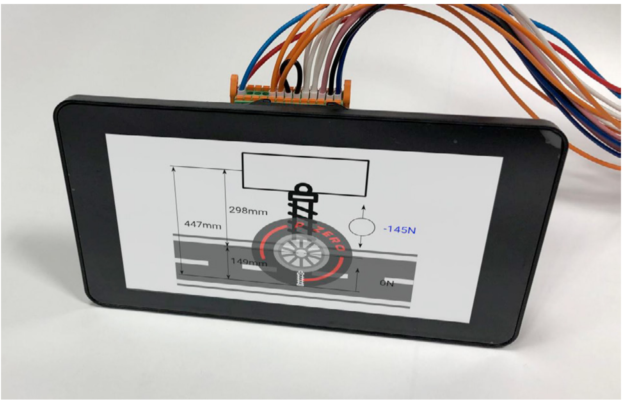

Fig. 5. HIL simulator of quarter car model

Students can start with *simple experiments with the HIL simulator* by observing the plant response to various external signals. Both the external disturbance simulating the variable road condition and actuator force can be injected. Oscillatory behavior is quickly recognized from the measured position and/or acceleration. Plant nonlinearity can be observed from the measured static characteristics and response to harmonic excitations with varying amplitudes when using a model with a more realistic spring and stiffness functions. Parasitic noise signal corrupting the measured outputs can be added to emulate real sensors.

The equations of motion of the linearized lumped-parameter system can be derived in the next step from the equivalent two-mass system representation shown in Fig. 4. The goal is to get more insight into the plant dynamics and derive a suitable structure of the model used in the subsequent step of experimental identification. Principles of modal decomposition can be shown explaining the contribution of two flexible modes of the system to the overall behavior. Model reduction can be performed by observing that the dominant motion characteristics are caused from the first mode leading to the approximation of the plant dynamics by a 1DoF spring-mass-damper system. The discrepancies resulting from this approximation can be evaluated by comparing the response of the reduced and full-scale model in time and frequency-domain.

The next phase of *data-driven identification* can follow. Students perform the identification experiment with the HIL simulator of the quarter-car model with the aim of collecting the input and output data. Various system identification methods can be employed for the computation of the parametric model. Bias, variance and consistency of different estimators can be discussed and explained. Validation of the model with respect to measured data based on a proper testing trajectory can follow. Connections between continuous-time models and their sampled-data equivalents can be established as well.

The next step deals with a *model-based design of various control strategies* which students have learned during courses on the control theory. They usually start with simple low-order controllers such as lead-lag compensators, moving to PID control, state feedback and more complex schemes including observers or high-order compensators. Various design methods can be explained, ranging from pole-placement, root-locus, loop-shaping to quadratic optimal control or norm-based control. Nonlinear control strategies can be evaluated as well. Robust control problems can be formulated easily by setting an uncertainty in one of the plant model parameters, e.g. the variable car mass due to the changing load and amount of fuel. Students typically work with the identified plant model in this case and validate their designs by means of numerical simulations in the Matlab/Simulink environment (model-in-the-loop, MIL).

Selected control strategies can be *implemented in the real-time environment*. Students are encouraged to think about the implementation issues including choice of proper sampling period, scaling of units and most importantly proper discretization of the control algorithms in the form suitable for a sampled-data system. They gradually move from Matlab to industry-relevant platforms (PLC, PAC, etc.). Depending on the selected platform and its development tools, the control algorithms are evaluated under Software-in-the-loop (SIL) scenario. A software emulator of the target controller is typically used. The result of this phase is a validation of the control algorithm in the software tools of the target platform.

The next logical step is to transfer the implemented and *validated software to the target hardware platform intended for real-time control* under the Processor-in-the-loop (PIL) setting. The goal is to validate that the algorithms can run correctly in terms of stability and computational complexity. The workload of the target CPUs can be monitored by means of diagnostic tools of the selected platform. In case the resources are missing, the students are suggested to think about simplification of their controllers (e.g. by model reduction techniques), optimization of the implemented code, change of the sampling period or reformulation of the design requirements. This important step emphasizes that control engineers are often forced to work with limited resources and careful planning and optimization is required.

The last step involves a *full-scale hardware-in-the-loop (HIL) simulation* which should be as close to reality as possible. The students connect their controllers to the HIL simulators running the plant dynamics model in real-time. The goal is to validate the overall control system design including the configuration of the peripherals, input/output drivers and physical connection between the controller and the plant by means of sensors and actuators (represented by analog IOs in this case). Final experiments include evaluation of closed-loop performance by various criteria such as passenger comfort measured by achieved vertical acceleration, relative motions of wheels and car chassis or tire wear from the measured reaction forces generated by the suspension system.

6.3 Nuclear reactor

When it comes to controlling a nuclear reactor, there is no chance to offer hands-on experience with a real one. Still, it is very reasonable to include it in control courses in the form of a HIL simulator. With nuclear technology in mind, students naturally accept that it is more than necessary to verify the designed control algorithm before controlling the real plant, which emphasizes the importance of mathematical modelling.

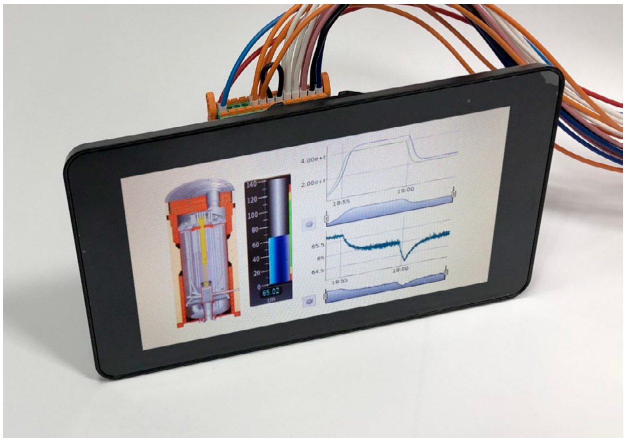

Fig. 6. Real-time simulator of nuclear reactor

With a HIL simulator of a nuclear reactor, students can experience the difficulties of handling unstable plants. Open loop identification methods cannot be used for estimation of the plant dynamics.

In nuclear energetics, the model that is used to describe reactors dynamics is a point kinetic model with six groups of delayed neutrons. This leads to a complex system of ordinary differential equations of 7th order nonlinear with respect to the input reactivity. The reactivity is controlled by the position of control rods, which is the manipulated variable (input) of the HIL simulator. The state vector is represented by neutron density and by concentrations of six groups of delayed neutrons. The neutron density and thermal power are the outputs of the power controller. These variables have to be controlled without significant overshoot and their values can vary in a wide range, for instance from 1kW to 10MW. Other important controlled variable is represented by the relative rate of change in neutron density.

Students are encouraged to apply linearization techniques and compare the behavior of the full model with the linearized ones for different equilibriums. Various control design methods can be explained including mainly techniques of PI/PID control design, loop-shaping, pole-placement methods for the linearized model. One can test different control structures as feedforward control, selector and cascade control or try gain scheduling techniques.

The presented HIL simulator was used during factory acceptance tests (FAT) of the control system for an experimental nuclear reactor in ÚJV Řež, Czech Republic.

7. CONCLUSIONS

This paper explains the importance of hands-on experience in control education, which results in graduates who are much better prepared for the challenges of industrial practice. All students should be exposed to the task of controlling a physical plant as soon as possible. On the other hand, physical plants can be problematic in terms of maintenance, sustainability and funds allocation. A compromise is presented in the paper: real-time simulators with physical inputs and outputs. Such simulators allow students to pass through all steps of control system design while eliminating the downsides of true physical plants.

Compared to conventional control courses, which are often taught only by means of offline numerical simulations, the use of real-time simulators brings some fundamental benefits for the students:

- The utilization of independent hardware platforms for both the controller and the controlled plant subsystems develops deeper understanding of fundamental principles of feedback control. The general feedback loop structure may seem too abstract to some students when working only in the simulation environment.
- Students can learn an important lesson that any mathematical model is only a simplified abstraction of reality.
- The students are exposed to daily problems of the control engineering domain, including plant nonlinearities, imprecise sensors and actuators and limited resources of the controller hardware and software for its programming and tuning.
- The students get in touch with industry-relevant hardware platforms and software tools.
- The students experience the gradual progression from theoretical analysis to equations, numerical models and final implementation of designed control law in real-time environment, which are the essential skills of today's control engineer.

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