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Digital Twins and HIL Simulators in Control Education – Industrial Perspective ⋆

M. Čech *, M. Vosáhlo **

* University of West Bohemia, NTIS research center, Univerzitni 8, 30100, Pilsen, Czech Republic (e-mail: mcech@ntis.zcu.cz).
** ZF Engineering, Univerzitni 1159, 30100, Pilsen, Czech Republic (e-mail: milan.vosahlo@zf.com)

Abstract: Novel concepts like digital twins and X-in-the-Loop (XIL) simulations are being adopted in many new application areas by all entities in supply chains, including enterprises of all sizes as well as research institutes. However, they are not sufficiently addressed during control education in standard bachelor and master courses. The main cause is the high price of required equipment and SW toolchains. In addition, clear vision and common understanding of the role of digital twins in individual XIL stages should be created. In this paper, cost effective tools are presented and their utilization is demonstrated with a simple gantry crane model with special focus on load swinging attenuation. The authors believe that the presented tools and ideas would bring wider competences to the students and thus bridge the gap between industrial needs and academic practice and shorten the way towards 4th generation universities.

Keywords: Digital twin, XIL standard, HIL simulator, control education, feedback control, vibration damping, overhead crane, STEM, 4th generation university

1. INTRODUCTION

Decades ago, control experts were typically treated as a last 'piece of puzzle' in the supply chains, *i.e.* they were forced to work with existing machines or plants with limited influence over the design process. As a result, such systems were then considered primarily as *black boxes* and system identification (Ljung (1999)) was performed to obtain a simplified model and to tune the controller. Nowadays, it is increasingly obvious that people with feedback control knowledge are integrated also into the machine/plant/product design. This trend allows to optimize machines and plants (*e.g.* dimensions, weight, materials) in virtual modeling phase and to make them *e.g.* more energy efficient, select proper position and performance of sensors and actuators, *etc.* Hence, together with growing modeling and simulation capabilities of computers, the controlled objects became more *gray* and *white boxes*, and topics like controllability and observability Gramians (Yasuda et al. (1988)) and other multi-KPIs [1] are getting substantial attention.

Such trend implies a set of new requirements also on education process and content. The students should have at least some competence in several STEM [2] (Leshner (2018)) fields in order to work effectively in multi-disciplinary teams in practice. This reflects quite nicely the concept of *'T-shaped'* education [3] (see Fig. 1). Note, that the lack of those wider competence (horizontal topics) is still reported by industrial partners as one of the main drawbacks of current educational programmes.

From the vast array of papers focused on control education, some are dealing with virtual and remote laboratories (De La Torre et al., 2013; Docekal and Golembiovsky, 2018; Gomes and Bogosyan, 2009; Ramli et al., 2022; Alptekin and Temmen, 2019), while others provide extensive surveys (Heradio et al., 2016; Horáček, 2018). Other studies deal with special control aspects (Zimenko et al. (2014); Santo et al. (2022); Reitinger et al. (2014)) or with a teaching methodology and evaluation (Rossiter et al. (2018); Bazylev et al. (2016)). Some authors try to motivate students *via* low-cost tools for home automation (Singh et al. (2022); Rani et al. (2022); Riera and Vigario (2017). Those tools are typically quite similar to industrial edge computing architectures (see the survey in Sitton-Candanedo et al. (2019)). However, there is insufficient effort in top-down approaches required by the industry.

In authors' previous work Sobota et al. (2019), the concepts and tools for adopting HIL [4] simulation principles to control courses were described. They were proven profitable in various fields like energetics (Čech et al. (2017)) or mechatronics (Čech et al. (2019a)). Here we go a bit further and will elaborate on *Digital Twin* paradigms (Desai et al. (2019)) from the perspective of control engineers. All the ideas provided here were conceived while working

⋆ The authors would like to thank to REX Controls company (www.rexcontrols.com) for providing Rexygen licence and Monarco HAT free of charge for teaching purposes and for working on master thesis.

[1] KPI – Key Performance Indicator
[2] Science, Technology, Engineering, Mathematics
[3] In case of two vertical topics, it is often called Π-*shaped education*; in case of more vertical topics *combi-shaped education*
[4] Hardware-in-the-Loop

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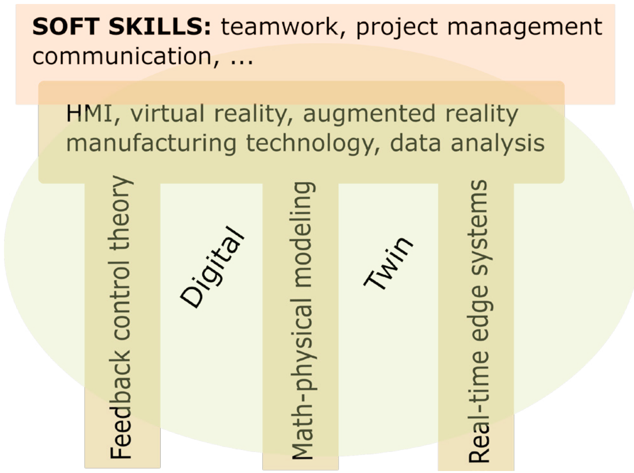

Fig. 1. Proposed concept of digital twin in the control engineer perspective: essential topics structured according to T-shaped paradigm

on the large H2020 projects *I-MECH* [5] and *IMOCO4.E* [6] (Čech et al. (2021), Čech et al. (2019b)) where also substantial amount of industrial partners are taking part in and are a welcomed source of requirements.

The rest of the paper is organized as follows: Section 2 presents the basic approach of digital twins and HIL simulators and discusses in deeper details the required T-shaped skills. Section 3 documents utilization of described tools and ideas on a gantry crane simulator. Potential student exercises are also suggested. Section 4 proposes other suitable models which can be built *via* presented technology. Conclusions and pathways for future development are summarized in Section 5.

2. CONCEPT AND APPROACH

There are specific standards being developed dealing with XIL and digital twins (ISO 23247). However, more discussions are needed in academic, research and industrial communities to polish those concepts. Initial list of proposed horizontal and vertical topics for control engineers is shown in Fig. 1. They reflect actual industrial needs and should be at least partially covered in master control courses. Hence they can help to define the structure of individual courses effectively. In each part of the Figure 1, we tried to identify main drawbacks reported by industry and highlight specific digital twin aspects.

Remark 1. Apparently, the position of topics is dependent on the primary knowledge domain of the students. *E.g.* for mechanical engineers, *industrial technology* will become one of primary vertical topics.

Remark 2. Moreover, those topics will be varying during the whole professional career, *e.g.* horizontal could become vertical or other verticals could be added according to latest technology developments.

In upcoming subsections, the topics are elaborated in more detail and links across courses are proposed. They will be further instantiated in Section 3 on illustrative example.

[5] https://www.i-mech.eu
[6] https://www.imoco4e.eu

2.1 Soft skills

Based on long-term discussions with lots of our industrial partners, soft skills are becoming a primary importance during employee searching process. Without them, it is highly difficult to make a concept of digital twins tangible.

Describing agile/DevOps [7] development is not in the scope of this article, but it needs to be mentioned as it is often overlooked in education, yet it is a crucial part of the work process of an engineer. Three “sets” have to be mentioned here: The mindset, the toolset and teamwork. Any feature mentioned here is shared among those categories though.

The **mindset** – in terms of digital twins, at the beginning of the project, it is necessary to focus on getting the basic functionality running and then add features one by one, while maintaining the project in operational state and a ’backlog’ of tasks that need to be done. Also a daily synchronization call is viable to recognize any bottlenecks, to help a member that is stuck and to allocate members that have any free time to tasks that have priority.

The **toolset** – From a wide selection of collaborative tools, usually complementing each other, the team has to choose a set that will fit best their needs. The most necessary tools are:

- *Communication tool* – a quick chat or a call is necessary necessary on daily basis, especially when working remotely.. This typically includes a calendar for scheduled meetings and some file-sharing capability for files that are not part of the product itself.
- *Task tracking tool* – distribution of tasks among team members is effective when it is easy to see how occupied each member is. Also it helps to find when any bug was introduced.
- *GIT* – there is just no alternative these days, as each team member can make changes to project files at the same time without blocking other members ability to work.
- *Knowledge base hub* – Documentations, workarounds, competence and state of the project should all be at one spot with clearly defined structure that is easy to navigate.
- *Tools that connect the above-mentioned tools* – these typically run in the background, but their contribution is nonetheless important. For example, a tool to create a git branch from the task-tracking tool improves the traceability of changes, while it speeds up the work by removing manual creation of branches and shows the reviewer changes done and automatically merges the branch to the master once the task is finished.

Teamwork – sharing the workload, tossing ideas around, managing the backlog of tasks and peer reviewing of changes made are vital parts of teamwork that increase the productivity of the team as long as there is a structure that fits the project needs and communication among team members works. Short daily meetings for synchronizations and sharing new features, and peer reviews for changes made are the necessary grease of modern industry.

[7] Development Operations

For digital twins, this means that not every team member needs to know all of the control theory or how to make HMI as long as everyone knows who has the ability to do so and there are regular workshops to share knowledge of the competences and their requirements. Delegation of workload also plays a key part, so that some members are not over-burdened while others are slacking.

Another important aspect in today's globalized world is language skill. In international teams, it is necessary to find a common language. With most academic works and sources being available in English, it becomes the obvious choice, yet, for some reason, it is still not so hard to meet university graduates who can read and understand English, but struggle to express themselves.

2.2 Vertical technical topics and skills

- **Math-physical modeling:** The message that "a phase of getting a suitable control-oriented model is often more time consuming than controller design phase" is still underestimated and not sufficiently communicated to the students. The exercises mostly start with "given the math model, lets design the controller". Note that such separation leads to misunderstanding of the optimality of the whole application. Specifically, students should be aware of the difference between black/gray/white boxes, when to use identification, when math-physical modeling and how to combine them effectively. Consequently, students will be able to choose between state-space representation, transfer function, *etc.* Clearly, these methods will help also with control system performance evaluation/validation.
- **Feedback control theory:** More advanced control theories should be introduced in master courses, *e.g.* predictive control, repetitive control, iterative learning control, sliding-mode control, H^∞ control, combining feedback and feed-forward control. Moreover, clear guidelines when to use which approach must be provided. Ideally, they should be completed *via* real illustrative examples, success stories and comparison of proper criteria evaluated for each approach.
- **Real-time edge systems:** Novel control solutions are often based on SoC+FPGA [8] (*e.g.* Xilinx [9], Altera [10]), ASIC, HeSoC (heterogenous system on chip) architecture. They allow *e.g.* to solve signal processing tasks with a high sampling rates on the same device as a feedback control algorithm, hence resources are saved up. Other topics like vector processors, multi-threading, hyper-threading, RISC V [11] should be introduced as well. We need to be familiar with the trade-off between performance and energy consumption, understanding 'cost' of information and cost of control action. This allows to decide which control tasks can be done in parallel on individual processor cores, how to combine different sampling rates on SoC+FPGA architectures, role of graphical accelerators *etc.*. Note, that HW control aspects are nowadays underrated both by teachers and students.

[8] System on Chip, Field Programmable Gate Array
[9] www.xilinx.com
[10] https://en.wikipedia.org/wiki/Altera
[11] Reduced Instruction Set Computer

Specific digital twin aspects: Understanding difference between digital twin instance and digital twin aggregate; be aware of type of data which can be extracted from low level feedback loops for further processing; in that context, control loop performance assessment is essential as well as being acquainted with links between 1D and 3D FEM (Finite Element Method) simulation (Goubej et al. (2021)).

2.3 Horizontal technical topics and skills

- **HMI:** The students should be aware of principles of HMI [12] ergonomy and how to adapt it also for tablets and smart phones.
- **Virtual and augmented reality:** Those well-known approaches can bring a lot of innovations, namely to bring an ultra realistic view of physical reality to operators screens, tablets or mobile phones. Additionally, they help with training of new engineers and operators.
- **Manufacturing technology:** Key aspect is understanding of additive and subtractive manufacturing. Specifically, the initial model of the system or plant has clear links to CAD system, manufacturing of the system (which has to be controlled) and with HMIs.
- **AI and data analysis:** Industry needs mastering of basic machine learning principles and related application for zero-defect manufacturing combined with predictive maintenance and how this will affect product lifecycle management systems (PLM).

Specific digital twin aspects: Still, the problem is understanding the difference between manufacturing equipment and product which is produced. Both the product quality and machine lifecycle management are closely related and can be monitored *via* feedback control loops. Deeper knowledge of the whole automation pyramid is required. It seems that also new technologies like blockchain will enter this "game" soon.

2.4 Following XIL cycle

Nowadays, XIL is not just a buzzword, but a real API standard for the communication between test automation tools and test benches [13]. Such standard is mainly adopted by automotive and aerospace industries. However, they are distributed across the whole supply chains hence requested from all cooperating suppliers (being often SMEs). Consequently, XIL toolchains are an inseparable part of more complex digital twin paradigms. Cost-effective solution for education courses is shown in Fig. 2 Typically, it means model/software/processor/hardware-in-the-loop stages defined as follows (Severa and Čech (2012)):

MIL – In this stage, both the model and the control system are simulated in virtual non real-time environment. Typically, the best control structure can be chosen and the input/output signals optimized.

SIL – The control system is coded as it will be on target application. One should often make do without advanced math libraries *etc.* (*e.g.* available in Matlab/Simulink).

[12] Human-Machine interface
[13] https://www.asam.net/standards/detail/xil/

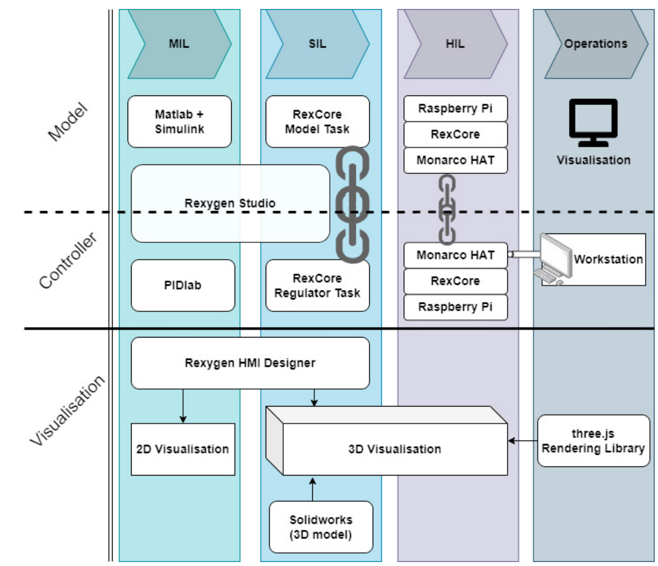

Fig. 2. Overall structure and employment of XIL tools in the illustrative example (see also Tab. 1

PIL – The control system is implemented in real-time on target device (target processor and instruction set) often with limited computational capabilities. The model is implemented on another device and should be executed in real-time as well. Communication between the model and the control system is routed *via* industrial communication (*e.g.* EtherCAT [14]).

HIL – The structure is similar to PIL. In this last stage, also I/O converters and cards are tested if necessary.

Real operation – Control system is linked to physical plant/machine for real operation.

Remark 3. Point out, that nowadays, majority of sensors and actuators are able to communicate directly *via* industrial communications. Hence the difference between PIL and HIL stage often disappears.

Remark 4. For students, it is crucial to highlight that the model is getting simplified while the control system is maturing into its final implementation.

3. EXAMPLE: GANTRY CRANE SIMULATOR

In this part, the work done in Vosáhlo (2020) is described from the digital twin perspective. The aim is just to present a way that students can follow, while the full details of math model and control system are available in the master's thesis. Also potential cross-links to other courses are highlighted.

3.1 Dynamical gantry crane model

For easy understanding, students can start with simplified 'pendulum on cart model' (Fig. 3) described by:

$$m\ddot{x}\cos\phi - ml\ddot{\phi} + mg\sin\phi = 0, \quad (1)$$

$$(M+m)\ddot{x} + ml\dot{\phi}^2\sin\phi - ml\ddot{\phi}\cos\phi = f, \quad (2)$$

where M, m, l, g are cart mass, pendulum mass, pendulum length and gravitational acceleration, respectively. Following exercises can be done by students: verification of equations against component-based model obtained *e.g.*

[14] https://www.ethercat.org

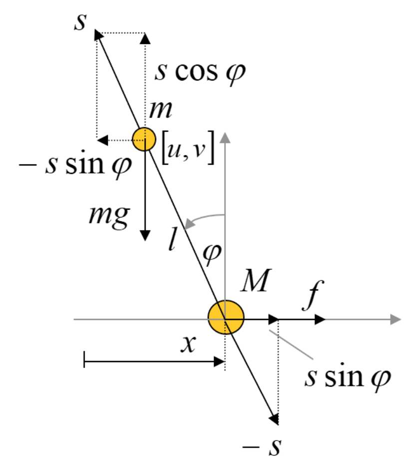

Fig. 3. Simple pendulum model serving for students as an initial step into gantry crane modeling

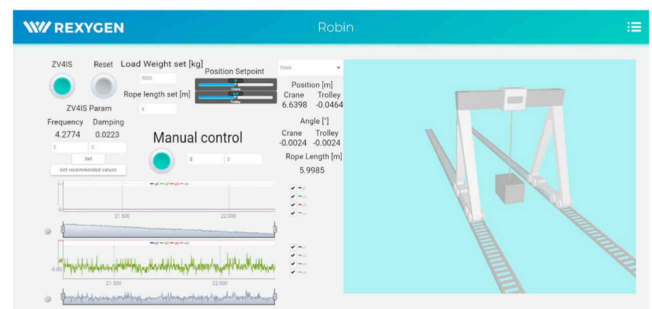

Fig. 4. HMI with key performance parameters and signal trends (executed on laptop) in Rexygen studio.

via Modelica or SimScape; understanding the concept of FMI/FMU [15] and model export into FMU; creating more realistic model with two link pendulum and spherical joints; modeling rope flexibility via springs. All these tasks can be done in cooperation with students specialized in mechanical engineering or courses dedicated to modeling.

3.2 Gantry crane HMI with 3D visualization

Building 3D HMIs is a long-term trend (Severa et al. (2011)). In this example, the process of creating a simple HMI is straightforward, with a basic ability to use a CAD software being the main 'obstacle'. The first step is obtaining a 3D model for visualization, which can be done by choosing one from an open-source model repository for 3D printing (Fig. 8). If several models are suitable, choosing the simpler one is better, since each polygon will have to be rendered on a hardware with potentially limited computational power. Some changes to the model might be required, hence the CAD skills needed. For example: some parts of the model might not be needed so they need to be removed, or the aspect ratio of some shapes has to be adjusted to resemble the desired plant model closely. After these edits, the model is exported to a format compatible with the rendering software, in our case, *threeJS*, a *JavaScript* library for lightweight 3D rendering (see Fig. 4). The coordinate parameters need to be routed to the model and properly scaled and constrained. The last part is the design of the HMI itself,

[15] Functional Mock-up Interface, Functional Mock-up Unit

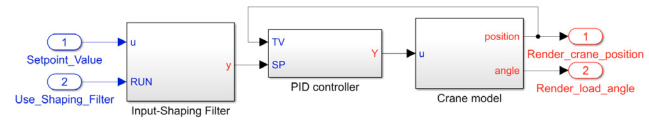

Fig. 5. Control system scheme with a PID controller (feedback) and input shaping filter (feedforward)

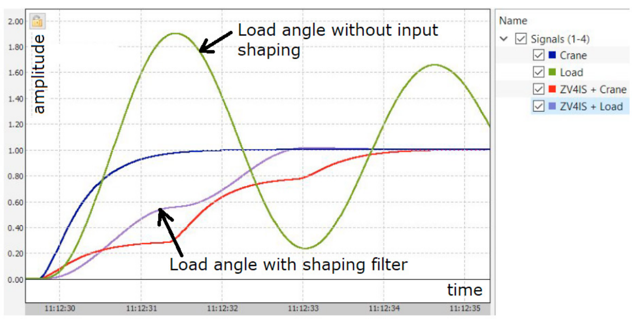

Fig. 6. System response with and without shaping filter (pendulum angle when a step in position is applied on a cart). Data obtained using Rexygen studio

Table 1. Tools and platforms used in the illustrative example

name	*link*
Rexygen studio	https://www.rexygen.com
Rexygen HMI designer	https://www.rexygen.com
Monarco HAT	https://www.monarco.io/
Raspberry PI	https://www.raspberrypi.org/
JavaStript	https://cs.wikipedia.org/wiki/JavaScript
threeJS	https://threejs.org/
Solidworks	https://www.solidworks.com/
Matlab-Simulink	https://www.mathworks.com/

which consists of adding the rendering window to the canvas, as well as a vast array of buttons, graphs, labels and other widgets to build an user-friendly interface. None of these steps requires an in-depth knowledge of programming/rendering/modeling, yet one learns the principles and main hurdles of each aspect in a quick succession, broadening the insight into related disciplines.

3.3 Control system of a cart

The aim of this exercise is to demonstrate benefits of combining feedback and feedforward control to the students. Specifically, input shaping filter (Goubej et al. (2020), Helma and Goubej (2021)) is used for setpoint weighting while the cart position is controlled by a classical feedback PID controller (Fig. 5, 6).

There are lots of topics for consequential student projects: employing cascade control, predictive control; adapting input shaper for more oscillatory modes in case of more precise pendulum model (double-pendulum even with spherical joints, flexible rope); robustness analysis in case when rope length or load mass are unknown in certain intervals.

Finally, students are able to build a final HIL setup as shown in Fig. 7 using technologies summarized in Tab. 1.[16]

[16] The price of the HW setup is about 500Eur including 2pcs of Raspberry Pi

Fig. 7. HIL setup consisting of 1) HMI (workstation), 2) control system HW, 3) Real-time model HW

Fig. 8. Real crane printed on a 3D printer, *i.e.* showing to the students potential of digital twining technologies and links between CAD, HMI and production

4. OTHER USEFUL MODELS

Clearly, students should be aware of applicability of control theory in various engineering segments (at least process control, energetics and robotics/mechatronics). Note that recently other simple simulators were presented in Sobota et al. (2019): Quarter car model, Coupled tanks model, Simplified model of nuclear reactor power controller. Similarly to example in Section 3, these can be decomposed into MIL, SIL, PIL and HIL stages and used in education. Point out that such real-time models were already proven attractive for industry, namely for training purposes.

5. CONCLUSIONS

This paper provides an approach how to explain to control engineers interrelations between digital twins and XIL simulation principles. In this paper, also cost effective tools for teaching digital twins and XIL simulations were presented. The whole approach was demonstrated on a gantry crane simulator example. The authors believe that such approaches will help to bridge the gap between educational, research and industrial practice.

The future work will be focused on improvements of the gantry crane dynamical model and testing it on a real industrial setup. Further, other types of simulators will be developed to cover other modern control concepts (*e.g.* predictive control, repetitive control). Nowadays, this approach is followed mainly when working on bachelor's or master's theses. The goal is to make it an inherent part of the courses for all students.

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