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The Concept of Virtual Laboratory and PIL Modeling with REX Control System

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***Abstract*—This paper deals with the description of concept of a virtual laboratory designed for educational purposes and deployment of processor-in-the-loop (PIL) concept with the use of the REX Control System. It also presents the case study regarding control of a simple inverted pendulum on the cart. The below mentioned techniques represent modern, accessible and adaptive teaching methods supporting a distance education.**

I. INTRODUCTION

State-of-the-art new information technologies provide alternative tools for improving teacher-student interaction. A web-based, multi-user virtual lab is also possible without necessity of reprogramming the experimentation interface code [1]. It helps to study dynamic simulations, it supports user interactivity, the generation of new experiments, and the opportunity to practice with classical or advanced control strategies applied for different systems. The virtual laboratory is an interactive environment for creating and conducting simulated experiments: a playground for experimentation [2]. The idea of virtual laboratory is very clearly described in [3]: virtual laboratory is a computer-based activity where students interact with real apparatus via a computer link, yet the student is remote from that apparatus. We should distinguish the latter case from a computer-controlled experiment, where a student will directly control an apparatus in his or her vicinity via a computer interface, see Fig. 1 (adopted and modified from original sources [3]).

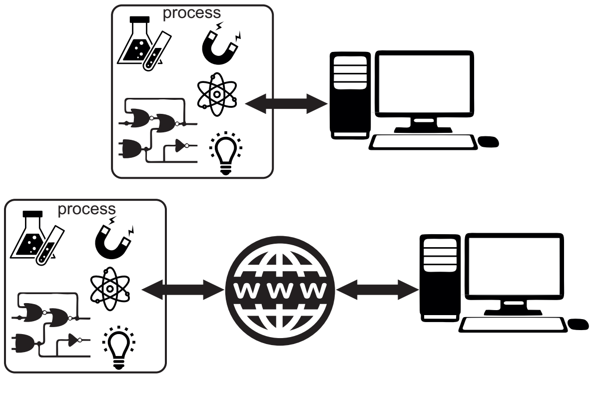

Fig. 1. Distinction between a computer-controlled experiment and a remote controlled experiment

The reference [3] also introduces a definition of virtual lab in technical sense: a virtual laboratory is one where the student interacts with an experiment or activity which is intrinsically remote from the student or which has no immediate physical reality. The latter part of this definition may seem to imply that virtual laboratory can have no physical reality behind it at all. However, the entire concept of virtual laboratories supports as close connection to reality as possible, having the real apparatus present at the laboratory. The reference [4] defines the key idea behind this concept as a design and development of laboratories which have real hardware set-ups and can be virtually accessed by users (students or researchers) via the Internet. Once a virtual laboratory has been set up, users will be able to conduct actual experiments from remote computers anywhere in the world 24/7 as if they were working in actual laboratories. However, some of the references distinguish between two terms: a virtual laboratory (no presence of real physical setup) and a remote laboratory. REX-based solution proposed allow both of these concepts, however the paper is primarily aimed at a virtual lab.

Assuming a high-fidelity mathematical model of controlled process, the concept of virtual laboratory can be modified in the way that real apparatus may be replaced by this mathematical model. This approach closely relates to the techniques of real-time simulations such as HIL (hardware-in-the-loop) or PIL (processor-in-the-loop). The latter will be demonstrated with the REX Control system, being adopted for the real-time synchronization.

There are several solutions mentioned in literature based on different technologies. In [9], authors described the solution Remote Electronic Lab (REL), which uses the LabVIEW for interaction with real experiment and for its simulation via Internet Explorer browser (ver. $\geq$5.0) with ActiveX Control and Visual Basic scripts. Similar solution is described in [10], [11] and [12] where the experimental part is carried out in LabVIEW. The solution in [13] is based on MATLAB, introducing two alternatives for remote access: MATLAB Web Server and WinCon software. Other virtual labs [11], [12], [14] use standard web browser with various components (Java applets, JavaScript, HTML, Flash, XML) for virtual laboratory purposes. The possibility of connection with widely used Moodle learning management system is mentioned in [11].

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II. REX-BASED CONCEPT

A. Basic Information About REX

The REX Control System is a family of software products for automation projects. It can be used it in all fields of automation, robotics, measurements and feedback control [5]. Main features of the REX Control System are as follows:

- Graphical programming without hand-coding
- Programming control units on a standard PC or laptop
- User interface for desktop, tablet and smartphone
- Wide family of supported devices and input-output units
- Industry-proven control algorithms
- Easy integration in business IT infrastructure (ERP/BMS)

REX Control system supports both computer-controlled and remote controlled experiments, including MIL, SIL, PIL, HIL as described in [6]. A typical case study concerning virtual lab and PIL technique is demonstrated in next subsections.

B. General PIL Concept Versus Virtual Laboratory Concept

The basic idea of PIL is to provide possibility to test functionality of the designed control system with the plant model instead of the real plant. The control system with its algorithms is running on so called embedded target. Under real condition it controls the real plant via I/O interface. PIL technique makes it possible to substitute a plant model instead, providing that all I/O signals are emulated at a communication line as described in Fig. 2. The embedded target is usually connected to a so called host computer so the entire block scheme can be expressed by Fig. 3.

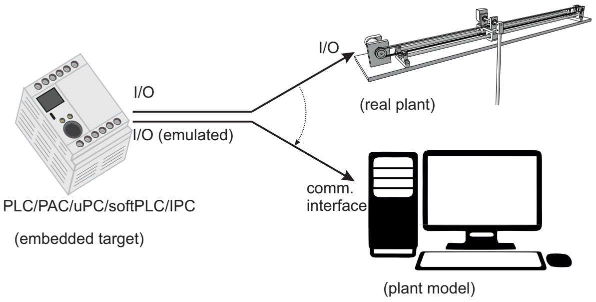


Fig. 2. Idea of PIL simulation

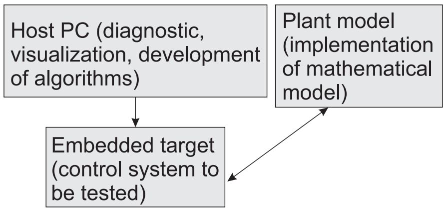


Fig. 3. Block scheme of PIL simulation components

The basic idea of a virtual laboratory is to provide almost the same feeling and results as if one was in the laboratory in-situ. Reference [7] states: the advances in computer graphics and multimedia technology allow construction of virtual physical environments that are representative, detailed and realistic. Original virtual lab definition supposes presence of a real setup connected to control system via I/O signals and accessibility of the variable through the network. However, a real setup may require some special conditions and there is always a potential risk of its malfunction. Having a precise mathematical model adopted for PIL technique, it is possible to use it instead of the real setup while the concept of virtual lab can stay unchanged.

C. PIL Concept with REX

Definition of PIL claims that simulation of the plant model is synchronized with the control algorithms running on the embedded target at full rate (as fast as possible). It is in accordance with one of the reasons why PIL is designed for, namely choice of appropriate sampling period and verification if the needed performance of embedded target is achieved. However, the real-time synchronization on both sides (embedded target and simulation of the plant model) does not clash the definition. It is secured by RexCore - a runtime core running on the target device (Linux IPC, WinPAC, Raspberry Pi etc.). It handles timing and execution of all algorithms and provides various services. The individual tasks are executed using preemptive multitasking.

From REX point of view, the following configurations cover these typical situations, see Fig. 4:

- two targets (A,B) linked via a communication line, both with REX run-time, A considered as embedded target hosting control algorithms (C), B considered as a plant model (S) (with the monitor or touch-screen attached to simulate real feeling similar to observation of a real plant)-determined for situations where REX control system is used both for control and for simulating a mathematical model of the real plant
- two targets (A,B) linked via a communication line, A considered as embedded target hosting control algorithms (C) with no need of REX run-time of any type (PLC, IPC, ...), B considered as a plant model (S) (with the monitor or touch-screen attached to simulate real feeling similar to observation of a real plant)-determined for situations where control algorithms (C) are implemented in non-REX platform and should be tested with a mathematical model (S) of the real plant made created in REX
- two targets (A,B) linked via a communication line, A considered as embedded target with REX run-time hosting control algorithms (C), B considered as a plant model (S) implemented on PC and Simulink (with the monitor attached to simulate real feeling similar to observation of a real plant)-determined for situations where control algorithms (C) are implemented in some REX platform and should be tested with a mathematical model (S) of the real plant created in Simulink (+ additional Simscape-family blocks for physical modeling) or any other simulation software environment

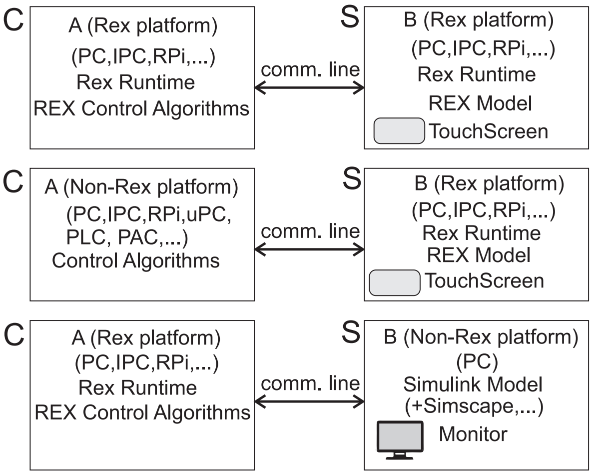


Fig. 4. Typical REX PIL Configurations

D. Virtual Laboratory Concept with REX

The following features of REX Control system determine the possibility to use it for the concept of virtual laboratories:

- it is capable of generating and performing web-based and customized visualizations
- it contains its own embedded webserver, therefore the only thing one need to perform remote experiment is a web browser
- the web visualization can be password-protected and secured
- from technical point of view there is no difference between computer-controlled and remote controlled experiment
- it is multiplatform and it allows wide possibilities to attach various I/O modules

Apart from web access, REX also allows remote access by windows-based RexView diagnostic tool providing hierarchical information about the running control algorithm.

III. NOVELTY OF THE SOLUTION, METHODOLOGY OF USAGE, APPLICABILITY

The most important novelty of this solution lies in:

- independence on platform
- excellent price/performance ratio
- no need of extra SW equipment
- ease of use, transfer to other platforms, integrated ”under one roof” approach

With this proposed approach, both control algorithms and model of the plant can run on PC, miniPC (such as Raspberry), PLC or IPC, moreover under different operating systems. Model of the plant is supposed to be created in REX control system, but control algorithms can be implemented in various SW environments running on various HW platforms, while communication between these two parts is established via standard protocols such as RS, I^2C, Modbus, Profinet and others. As for visualization, the only tool needed to display visualization is a standard web browser running on PC, smartphone, tablet, or touchscreen. Moreover, there are more types of visualization at disposal. The basic visualization can be auto-generated via a single-click based on the block scheme created in REX environment (RexDraw). It is displayed within a web browser, showing the same block structure as in the source scheme, displaying live values of inputs and outputs of the blocks and allowing setting blocks' parameters on the fly. In case of more advanced visualization screens, so called RexHMI Designer is at disposal. It makes it possible to use both embedded and custom graphical elements, and let them be easily bound to particular REX variables. Composition of the entire visualization is carried out in the same environment (RexDraw) as both all algorithms and visualization are integrated into one common project. Last but not least, transfer between SIL (software in the loop, thus modeling control algorithms and the plant in the same environment running on the single target) and PIL is extremely easy.

Methodology of usage of the concept described in this paper is as follows:

- setting up the mathematical model of the plant and control algorithms
- REX implementation of the mathematical model of the plant using REX blocks
- implementation of control algorithms on a chosen platform (it is also REX-based platform, SIL technique is very useful to try before final PIL)
- implementation of PIL technique (emulating all physical signals to communication protocol)
- implementation of web-based visualization, bounding of individual visualization variables to REX signals
- testing PIL model, changing control algorithms, changing plant's parameters on the fly
- transfer of the solution towards control of real plant

The proposed solution is especially useful for education process due to favourable licensing and technical capabilities. It is widely applicable in analysis and synthesis of control systems.

IV. CASE STUDY: CONTROL OF SIMPLE INVERTED PENDULUM ON THE CART

Control of the simple inverted pendulum on the cart has been chosen as the case study in this paper for more reasons. First of all, it is a challenging and interesting task, also attractive for students and researchers. It is a very good example of feedback control system, combining classical algorithms (PID) and more advanced algorithms based on so called modern control theory. The topic of inverted pendulum control has been treated so many times, much more than any other physical educational model. This paper does not describe the details of control approach, but yet it shows some novelty. It very clearly shows the concept of the mathematical model and control algorithm through inputs from two encoder signals (pendulum angle, cart position) and a PWM signal representing manipulated value brought to power electronic unit and DC motor. The physical setup used for this case study is shown as its 3D model in Fig. 5.

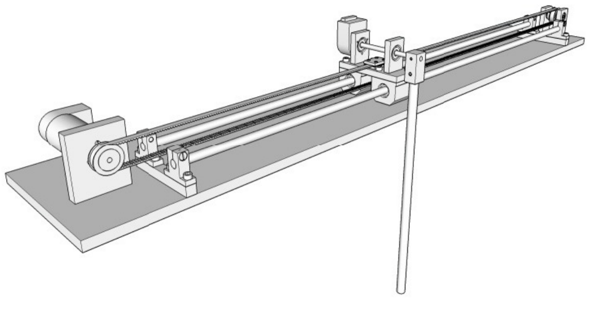


Fig. 5. 3D model of inverted pendulum on the cart

A. Modeling of Control of Inverted Pendulum on the Cart

There are more approaches and equations describing a simple pendulum model. Physical setup shown in Fig. 5 can be adopted for identification in the form expressed by Fig. 6.

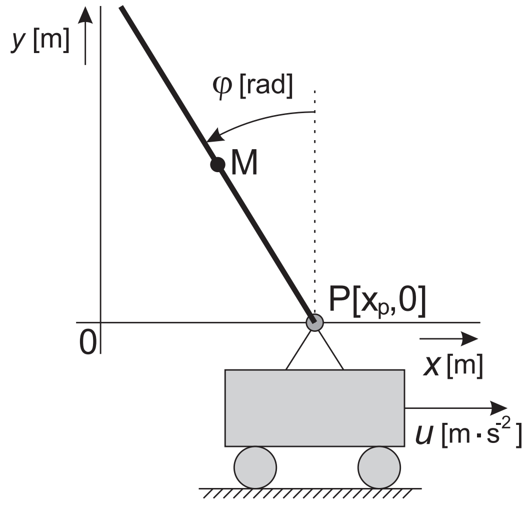


Fig. 6. Situation scheme for analytical identification

It is possible to derive Eq. (1) for a pendulum movement

$$l \cdot \ddot{\varphi} - g \cdot \sin\varphi + b \cdot \dot{\varphi} - u \cdot \cos\varphi = 0 \tag{1}$$

where

l	[m]	pendulum length to the mass center $\lvert MP \rvert$
φ	[rad]	pendulum angle
g	$[\mathrm{m} \cdot \mathrm{s}^{-2}]$	gravity acceleration
b	$[\mathrm{m} \cdot \mathrm{s}^{-1}]$	damping coefficient
u	$[\mathrm{m} \cdot \mathrm{s}^{-2}]$	cart acceleration

In order to get the full state-space description of the system, Eq. (1) can be extended by two state variables representing position and speed of the cart, supposing u as controlled input. The entire state-space description of inverted pendulum (IP block in Fig. 8) can be described by Eq. (2)-Eq. (5).

$$\dot{x}_1 = x_2 \tag{2}$$

$$\dot{x}_2 = \frac{g}{l} \cdot \sin x_1 - \frac{b}{l} \cdot x_2 + \frac{1}{l} \cdot u \cdot \cos x_1 \tag{3}$$

$$\dot{x}_3 = x_4 \tag{4}$$

$$\dot{x}_4 = u \tag{5}$$

where

x_1	[rad]	pendulum angle
x_2	$[\mathrm{rad} \cdot \mathrm{s}^{-1}]$	pendulum angular speed
x_3	[m]	cart position
x_4	$[\mathrm{m} \cdot \mathrm{s}^{-1}]$	cart speed
u	$[\mathrm{m} \cdot \mathrm{s}^{-2}]$	cart acceleration

Actuator (DC motor and electronic unit for a speed control) can be considered as a part of the system with its dynamic approximated by a fast 1^{st} order system. Though mathematical model gives the information about cart and pendulum speed, PIL concept reflects the number of variables being at disposal under real conditions, therefore only cart position and pendulum angle are measured and thus representing the two outputs, see Fig. 7. The entire model of the system considered for PIL technique and virtual laboratory is then shown in Fig. 8.

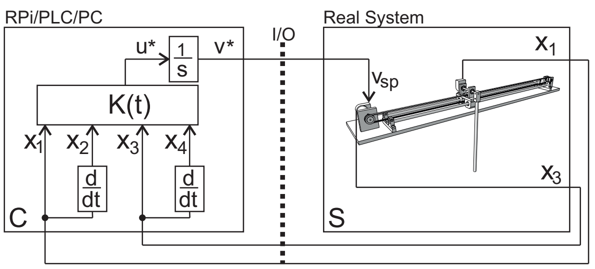


Fig. 7. Control of the real system of inverted pendulum on the cart

The time constant τ has been identified experimentally. It represents dynamical behavior of the inner speed loop implemented as a fast PI controller. Note that control system hosting control algorithms is identical both in control of the real system (Fig. 7) and its PIL representation (Fig. 8). Remaining unmeasured states x_2 and x_4 representing cart and pendulum speed are approximated by numeric derivatives.

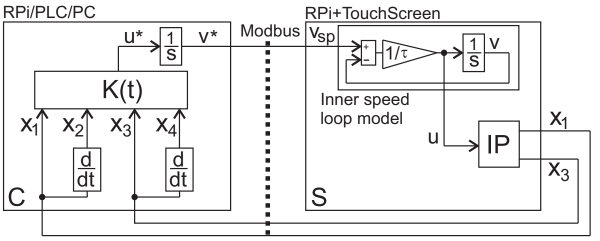


Fig. 8. PIL representation of control of inverted pendulum on the cart

B. Implementation of PIL model with Raspberry Pi3

The concept described by Fig. 8 has been implemented in REX Control system running on two RPi3 single-board computers in accordance with Fig. 3. Fig. 9 shows the picture of PIL testing stand. Upper part of this picture shows Rpi3 as embedded target hosting control algorithms for inverted pendulum while the visualization touch-screen attached to the 2^{nd} Rpi3 (beyond the touch-screen) serves as the mathematical model according Eq. (2)-Eq. (5) . These computers use Modbus communication protocol for the data exchange.

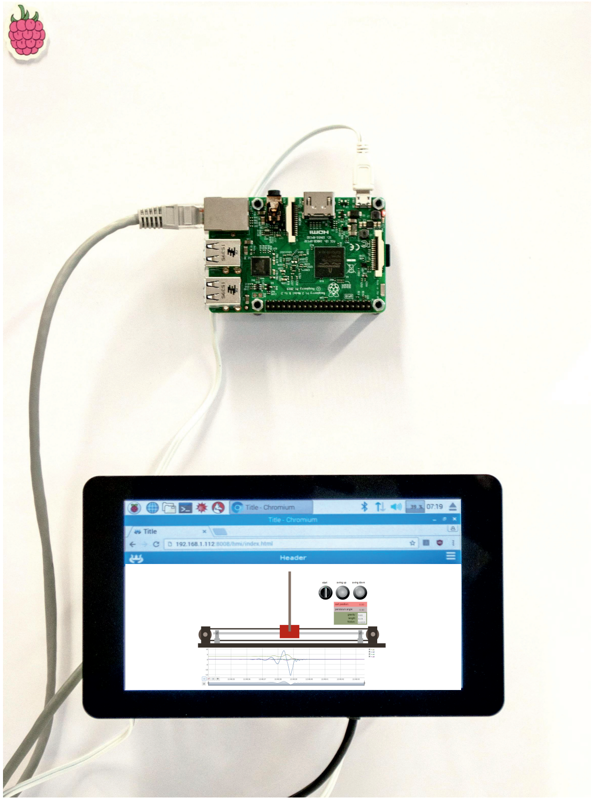


Fig. 9. Photo of the testing stand for PIL model of control of inverted pendulum on the cart

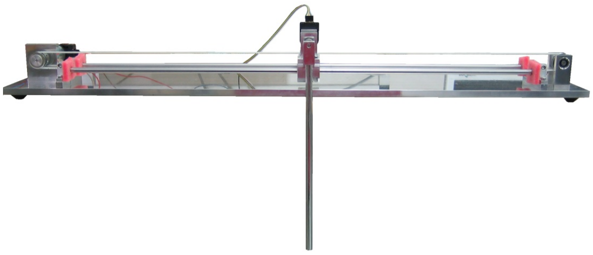


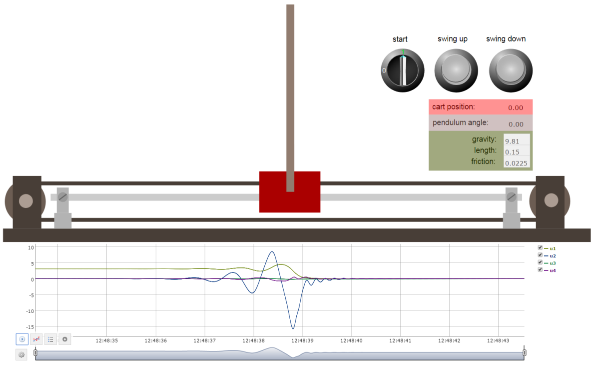
Fig. 10. Photo of the of inverted pendulum on the cart

Once the control algorithms are verified by PIL simulation, they can be deployed for the real system shown in Fig. 10.

C. Web Visualization for Virtual Laboratory

Web visualization contains both text and visual information about position of the cart and pendulum rod, using dynamic graph components and text boxes. Visualization of the movement of both cart and rod positions are displayed in real time. It is composed of two objects representing the cart and the rod. Firstly rotation property of the rod is bound for the x_1 REX variable. Then it is grouped with the cart object, and translation of this group is assigned to x_3 REX variable. This is possible due to RexHMI capabilities of REX Control system, allowing sequential animations and thus there is no need to perform external conversion between particular coordinate systems.

Apart from feeling or real experimentation for a remote user, it is also important for the virtual laboratory to have the possibility of data export and archiving. RexHMI designer makes it possible to use TRND web component capable of selecting signals to be displayed, viewing the current trends or pausing the simulation in order to analyse the time waveforms. The export of raw values can be added to the HTML source code or easily via RexView remote client. The experiment is performed via the switch responsible for swing-up, regulation in the upright position and swing-down. The detail screenshot of the website in a web browser corresponding to Fig. 9 showing regulation in upright position is given in Fig. 11.



cart position: 0.00
pendulum angle: 0.00
gravity: 9.81
length: 0.15
friction: 0.0225

Fig. 11. Web visualization screenshot

Fig. 12 displays the data export representing pendulum angle and cart position during the swing-up and steady states.

V. CONCLUSION

The concepts of PIL and virtual laboratory introduced in this paper have been documented for the particular case study of the most typical control laboratory experiment, that is a simple inverted pendulum on the cart. Description of control algorithms was beyond the scope of this paper. The main relevance of documented approach in case of inverted pendulum model is the thorough design and test of swing-up algorithms as it is quite difficult to compute a functional control strategy concerning constraints given by physical reality, mainly the limits of the range in x-axis and a possible saturation limit for a speed controller.

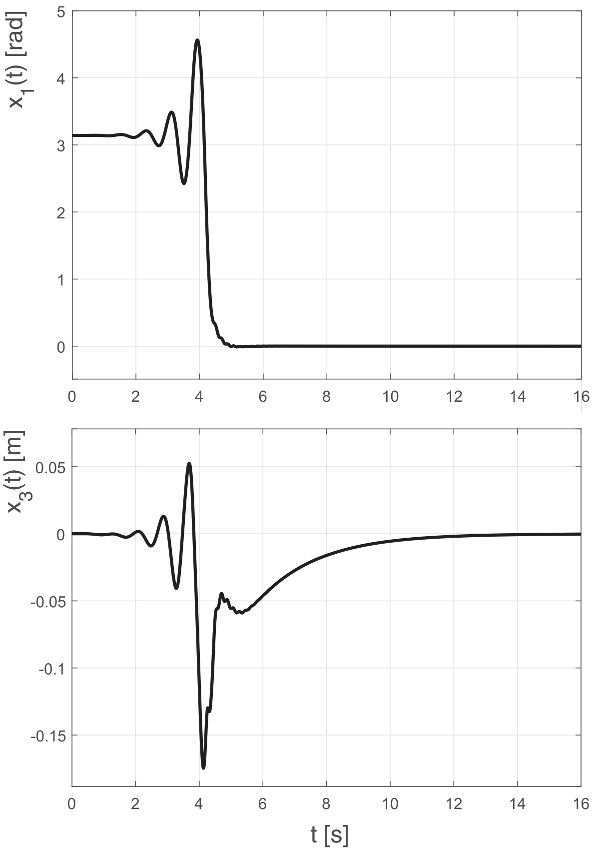


Fig. 12. Pendulum angle and cart position during the swing-up

Unsuccessful attempts during control design applied in the real system without PIL simulation may result in a damage of the real setup. For a double or a triple pendulum, design and verification of control algorithms with the use of PIL or HIL become a necessity.

Virtual laboratory is based on modern HTML5 technology, allowing all the features required for this concept. As it allows secured multi-user access with customizable different levels of user rights, it becomes efficient both for students and researchers. However, it is obvious that certain time slots for particular users should be considered and introduced to the system for efficient remote work to avoid unwanted interference caused by possible concurrent actions.

A very important feature of the proposed solution is a possibility of introducing customizable interactivity of web visualization components. For example, the graphical objects can be draggable, or assigned with other actions allowable by Javascript events. Having applied for this case study, it is possible to simulate a disturbance in the control circuit by dragging the cart or the rod, corresponding to a manual touch of the pendulum in upright position under real conditions. Moreover, important parameters playing a crucial role in the system dynamics (such as gravity, rod length, friction coefficient) can be entered via web edit boxes, see Fig. 11.

Transition between a virtual laboratory and a remote laboratory (control of the real system and its PIL model) is easily possible due to the possibility of connecting I/O interfaces to the various supported HW platforms, such as Arduino board which is currently used to control the real apparatus of inverted pendulum on the cart (Fig. 10) or Monarco HAT for RPi [8]. The proposed solution is currently tested using a different embedded platform hosting control algorithms, namely the PLC SIMATIC S7 that can be easily connected to the Rpi3 hosting a mathematical model of the plant by S7 Comm - a special driver developed by REX Controls, s.r.o.

Current virtual laboratory may be extended by a visual feedback provided by a web camera broadcasting the stream to the website together with the visualization. Considering the idea of replacing real apparatus by its mathematical model, it is possible to host several virtual experiments within one piece of hardware with a single REX run-time used for the models.

The presented case study is supposed to become a template based on which other similar models are planned to be created in the Laboratory of Control Systems at Department of Cybernetics and Biomedical Engineering. As there are several subjects that deal with control theory in different levels, it is planned to adopt the idea for classical PID algorithms and algorithms based on modern control theory with the use of current physical educational linear and nonlinear SISO and MIMO models (helicopter, ball on beam, ball on plate, ball on spool, rotary inverted pendulum, magnetic levitation).

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