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Brno University of Technology

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FOREWORD

Dear authors, conference participants and readers,

It is with deep satisfaction that I write this Foreword to the Proceedings of the 14th IFAC International Conference on Programmable Devices and Embedded Systems, PDeS 2016, held in Brno/Lednice, the Czech Republic in October 5 - 7, 2016.

The conference series was initiated in 1995, and since then the PDeS workshops have been organized every 18 months by the Institute of Electronics of Silesian University of Technology in Gliwice (Poland) and by the Faculty of Electrical Engineering and Computer Science of the Technical University of Ostrava (Czech Republic). The idea of the PDeS has been appreciated by the International Federation of Automatic Control (IFAC). In 1999 the PDeS Workshops assumed the status of the IFAC Workshop.

This year it was the third time the Faculty of Electrical Engineering and Communication of Brno University of Technology was in charge of preparation and organization of the PDeS conference. The International Programme Committee of PDeS 2016 received 131 authors' registrations, and 131 papers were submitted to a review process. For the conference, 93 papers were accepted. After careful analyses and the review process, 50 papers were selected to be presented in oral sessions and 43 in two poster sessions. These proceedings provide a record of the papers presented at the conference.

This year's conference continued the tradition of series of workshops and presentations devoted to all aspects concerning design, implementation and utilization of electronic digital programmable logic devices, controllers and systems. Underlining the importance of cooperation between the industrial sector and the academic world, a round-table discussion focused on Industry 4.0 was organized within the conference in order to reflect recent crucial development in industrial production and associated modern technologies, such as IoT, IoS and IoP. We believe all participants enjoyed their stay in Brno/Lednice, where, in addition to the outstanding conference programme, they were encouraged to discuss their current work also in an informal setting during accompanying social activities.

The conference organizers owe a debt of gratitude to the following sponsors. The traditional meeting was sponsored by IFAC (The International Federation of Automatic Control) and co-sponsored by Czechoslovakia Section of IEEE (The Institute of Electrical and Electronics Engineers). The conference was also sponsored by several international partners and local municipality. We are pleased to express our thanks to the following companies and organizations for the conference sponsorship:

- IFM electronic Ltd. Průhonice CZ
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- RS Components Sp. z o.o. Warszawa Poland
- MEgA - Měřící Energetické Aparáty, a.s. Česká CZ
- City of Brno.

The organizers would like to thank as well the Department of Control and Instrumentation, the Faculty of Electrical Engineering and Communication of Brno University of Technology for its support. We also address our thanks to the International Federation of Automatic Control and The Institute of Electrical and Electronics Engineers for scientific support of the conference. Last but not least we thank all authors and participants for their contributions.

Prof. Ing. František Zezulka, PhD.
Vice-Chair of PDeS 2016 IPC

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Cyber-Physical System Implementation into the Distributed Control System

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Abstract: The purpose of this paper is to present the *Single inverted pendulum laboratory model with LSM* as a cyber-physical system (CPS). The implementation of the model application into the Distributed Control System infrastructure at the DCAI, FEEI, TU is first described. Pre-prepared program modules from the custom Simulink library *Inverted Pendula Modeling and Control*, developed by the authors of this paper, are used in subsequent modeling and control design. The contribution to the simulation model level of the DCS infrastructure is described in detail - the nonlinear mathematical model obtained from the library is modified to include the velocity loop, and the necessary parameters are obtained via experimental identification. Finally, a control strategy based on a hybrid control structure is designed and swing-up/stabilizing control algorithms are verified on the laboratory model.

Keywords: distributed control system, cyber-physical systems, hybrid control, inverted pendulum, linear synchronous motor.

1. INTRODUCTION

The concept of cyber-physical systems (CPS) integrates physical processes with computations and provides modeling, abstractions, design and analysis techniques for the integrated whole. CPS require networking technologies and computing to embrace not merely the physical dynamics, but also information. The interactions among computing, control, physical and network systems require new design technologies (Pande et al. (2015)). We can comprehend the CPS from two aspects. From the perspective of method, it uses a feedback mechanism to control the physical environment, and from the point of view of composition, it is composed of an embedded system and network components (Švéda and Ryšavý (2013)).

The *Multipurpose Workplace for Nondestructive Diagnostics with Linear Synchronous Motor* was introduced in (Jadlovský et al. (2016)) as a testbed model application for solving a variety of problems in control and diagnostics at the Center of Modern Control Techniques and Industrial Informatics (CMCT&II, *http://kyb.fei.tuke.sk*) at the DCAI, FEEI, TU. In this paper, it will be treated as an example of a CPS. One of the applications of the model workplace is the *Single inverted pendulum model on a cart with LSM*, which is a benchmark example of an underactuated mechanical system. Our research group has dealt with modeling and control of the underactuated systems since 2011 and the most significant results were published in e.g. Jadlovská and Sarnovský (2013b) and Jadlovská et al. (2015). The results, such as modules for automatic generation of n-link inverted pendula models, implemented control algorithms and demo simulations are included in the custom MATLAB/Simulink library *Inverted Pendula Modeling and Control (IPMaC)*. The library is constantly being expanded with additional benchmark models and modern control design methods for CPS.

This paper describes the implementation of the *Single inverted pendulum laboratory model with LSM* into the distributed control system infrastructure at the DCAI, FEEI, TU. Subsequently, mathematical model of the system is obtained via analytical and experimental identification, and hybrid control based on the swing-up and stabilization control algorithm (Jadlovská and Sarnovský (2013a)) is designed and verified for the laboratory model.

2. DISTRIBUTED CONTROL SYSTEM AT DCAI

In this part of the paper, we will introduce the principal framework for dealing with CPS which is used by the CMCT&II at the DCAI, FEEI, TU. The pyramidal scheme in Fig. 1 depicts the infrastructure of the Distributed Control System (DCS) as a model of a complex Cyber-Physical System, built over the collection of laboratory models and providing experimental verification of practical problems in accordance with international standards (Jadlovský et al. (2016)). The proposed infrastructure of the DCS was gradually built while solving research projects at DCAI with the support of significant international companies, e.g. Rockwell Automation, ORACLE, Mathworks, Wonderware and others. The DCS is integrated into the five-level architecture, which allows solving complex control problems with an emphasis on the connections between individual levels (see Fig. 1).

The lowest *Level of Models, Sensors and Actuators* comprises two basic types of model applications. Production

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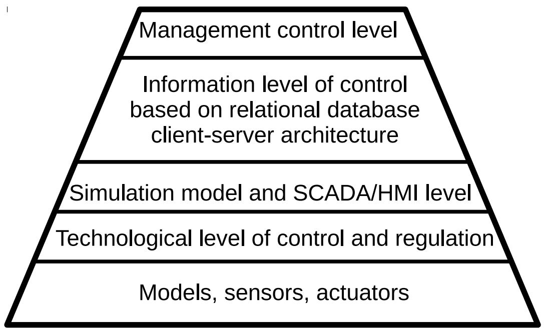

Fig. 1. Distributed control system (DCS) as a pyramidal model of CPS implemented at the Department of Cybernetics and Artificial Intelligence (DCAI)

lines simulate typical situations in manufacturing industry, which provide opportunities to verify control algorithms on individual levels and inter-level communication. Laboratory models, equipped with sensors and actuators, are used as testbed systems for practicing model-based control design for physical systems. The *Technological Level of Control/Regulation* is composed of control facilities such as programmable logical controllers (PLCs) and technological computers, which provide control of physical systems at the level below. Sensors and actuators are standardly interconnected via technological interfaces or through industrial networks. At the *Simulation Model & SCADA/HMI Level*, SCADA/HMI ensures supervisory control, data acquisition and archivation from industry processes, while simulation models are used in the process of design and validation of control algorithms, implemented at the level below. Connection to this level is mostly made via TCP/IP protocol. The following, combined level is represented by the Manufacturing Enterprise System (MES), designed for tracking and documenting production tasks, and the Enterprise/Manufacturing Resource Planning (ERP/MRP), which covers production planning, scheduling, delivery and other functions. At these levels, large amounts of data are collected, archived and managed via a relational database system. Finally, multidimensional databases enabled by the OLAP technology are used to aid the decision-making process at the *Management Control Level*.

3. SINGLE INVERTED PENDULUM LABORATORY MODEL WITH LSM - IMPLEMENTATION INTO DCS

The technical solution of the *Single inverted pendulum laboratory model with LSM* was designed so as to reflect the DCS pyramid infrastructure. The individual subsystems of the model application will now be analyzed with respect to their relationship with the defined levels of the pyramid model.

The *Level of Models, Sensors and Actuators* is represented by the mechanical construction of the inverted pendulum system with LSM. Motor position is captured by an incremental position sensor with the precision of 1000 impulses/mm. The cart is assumed to be part of the motor armature (stator). The end positions of the stator are captured by a pair of induction position sensors. The angle of the pendulum rod, attached to the cart, is captured by the KINAX-2W2 programmable angle converter with the precision of 220 impulses/degree.

At the *Technological level of control/regulation*, control of the motor position is performed via the KINETIX 6500 servomotor with frequency converter connected to the CompactLogix PLC via the Ethernet. Since the stabilization of inverted pendulum systems requires fast controller responses, motor and pendulum position sensors are connected to the programmable inputs of KINETIX 6500. Implementation of control algorithms at the PLC level is performed via RSLogix 5000. The connection between the simulation model of the Single inverted pendulum with a velocity control of the linear drive and *Technological level of control/regulation* is implemented via DDE protocol utilizing the RSLinx environment under Windows OS.

The *Simulation Model & SCADA/HMI Level* contains a simulation model of the single inverted pendulum with a velocity control of LSM implemented in MATLAB/Simulink. Parameters of the simulation model are determined either by measuring the mechanical characteristics of the inverted pendulum (e.g. rod length, weight mass) or, in the case of motor velocity control, obtained by experimental identification. Using a suitable control algorithm, the sequence of control input values is next computed and transferred into the PLC, which defines the real-time control of the laboratory model. Interconnection of the Simulation model level with the lower (technological) level, as well as the higher levels of DCS infrastructure (MATLAB/Simulink vs. the ORACLE database system) takes place via the OPC server using the RSLinx module.

The whole implementation of the model application into DCS infrastructure is shown in Fig. 2 (Jadlovská (2015)).

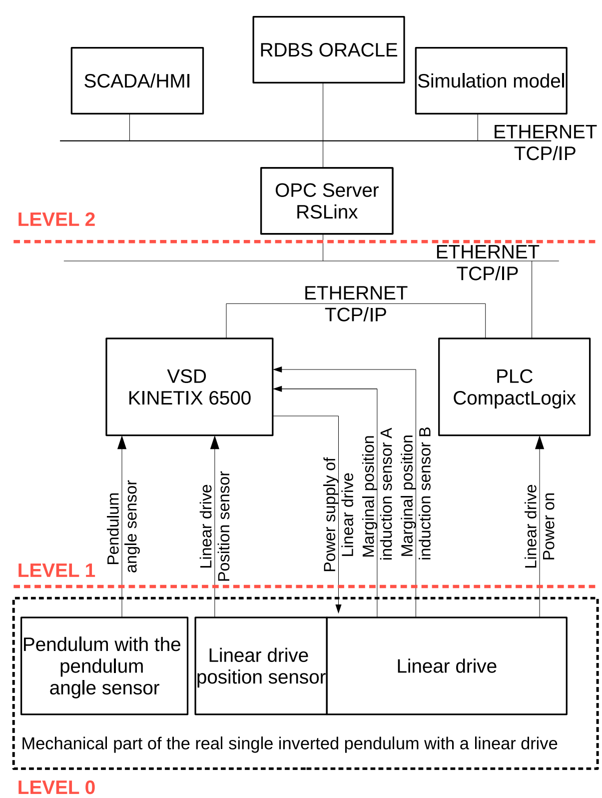

Fig. 2. DCS architecture for the *Single inverted pendulum laboratory model with LSM*

4. DEVELOPMENT OF THE *SIMULATION MODEL LEVEL* FOR THE SINGLE INVERTED PENDULUM MODEL WITH LSM USING THE *IPMAC* LIBRARY

From this part on, we will demonstrate the application of our previous results in the area of modeling/control of underactuated systems (Jadlovská and Sarnovský (2013b)), (Jadlovská et al. (2015)) in the analysis and control design for the *Single inverted pendulum laboratory model with LSM*. The current version of the *IPMaC* library contains the *Inverted Pendula Model Equation Derivator_v3* GUI application, which generates nonlinear differential motion equations describing a classical or rotary inverted pendulum system with a given number of links and displays them in an user-friendly LaTeXformat (Fig. 3). The implemented algorithm of model derivation is based on Lagrangian mechanics and includes the option of the attached weight and the change of pendulum reference position/direction of rotation. Classical inverted pendulum systems covered by the *Derivator_v3* are assumed to have a force input act on the cart (see Vošček (2015), Jadlovská (2015)).

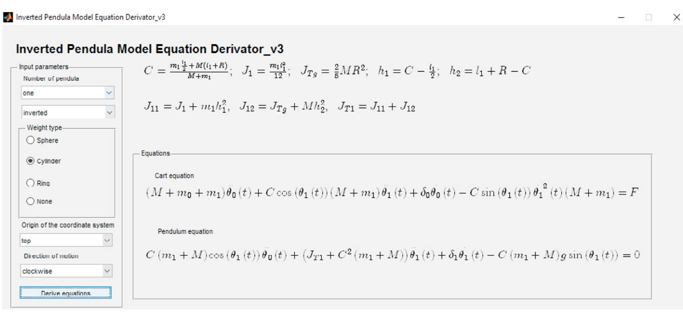

Fig. 3. Inverted Pendula Model Equation Derivator_v3

The generated motion equations of the single inverted pendulum force model with the attached weight (Fig. 4) have the form of a cart equation:

$$(M+m_0+m_1)\,\ddot{\theta}_0(t)+C\cos(\theta_1(t))\,(M+m_1)\,\ddot{\theta}_1(t)+ \\ +\,\delta_0\,\dot{\theta}_0(t)-\,C\,\sin(\theta_1(t))\,\dot{\theta}_1^2(t)\,(M+m_1)=F(t) \tag{1}$$

and a pendulum equation:

$$C\,(m_1+M)\,\cos(\theta_1(t))\,\ddot{\theta}_0(t)+J_1\,\ddot{\theta}_1(t)+ \\ +\,\delta_1\,\dot{\theta}_1(t)-C\,(m_1+M)\,g\,\sin(\theta_1(t))=0 \tag{2}$$

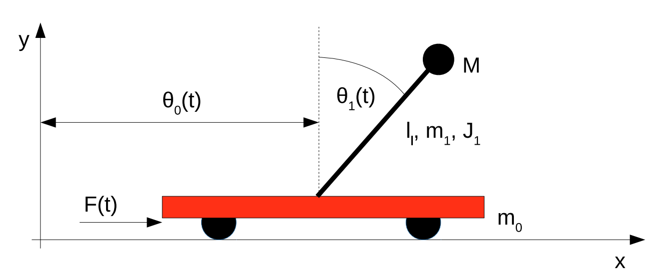

Fig. 4. Single inverted pendulum on a cart with an attached weight - scheme and parameter nomenclature

The parameters m_0, m_1 respectively denote the mass of the cart and the pendulum, l_1 is the length of the pendulum, M is the mass of the weight, δ_0, δ_1 respectively represent the friction and damping coefficients of the cart and the pendulum, $C=\dfrac{m_1\frac{l_1}{2}+M(l_1+R)}{M+m_1}$ stands for the distance between the center of gravity (CoG) and the pivot point, R for weight radius and J_1 denotes the inertia of the pendulum with respect to the CoG. Generalized coordinate $\theta_0(t)$ represents the cart position and $\theta_1(t)$ is the pendulum angle. The system has one external input $F(t)$ which stands for the force applied on the cart. To obtain the state space representation of the single inverted pendulum system, motion equations are usually rearranged into the standard minimal (ODE) form, as in (Jadlovská et al. (2015)).

The generated model (1) and (2) is only appropriate for control design if the drive control unit allows the force input on the cart. Because the *Single inverted pendulum laboratory model* contains the LSM, it does not satisfy this condition. This problem can be solved by modeling the motor-cart subsystem with the included motor velocity controller as a velocity control loop (Mertl et al. (2005)) where the reference velocity becomes the input of the modified mathematical model of the single inverted pendulum system. We will now describe the procedure in more detail.

The first step of the procedure is an assumption of the perfect reference velocity tracking:

$$\dot{\theta}_0(t)=\dot{\theta}_0^*(t),\quad \ddot{\theta}_0(t)=\ddot{\theta}_0^*(t) \tag{3}$$

which implies that the pendulum angle $\theta_1(t)$ has no backward impact on the position of the cart $\theta_0(t)$ and the cart motion is clearly described by the reference velocity $\dot{\theta}_0^*(t)$. Based on this assumption, the motion equation of the cart (1) in the single inverted pendulum model will be replaced with the modified second-order transfer function (Schlegel and Měšťánek (2007)) in the form:

$$\frac{s\Theta_0(s)}{s\Theta_0^*(s)}=\frac{p_0}{s^2+q_1 s+q_0},\quad \mathcal{L}(\dot{\theta}_0^*(t))=s\Theta_0(s) \tag{4}$$

The estimated parameters p_0, q_0, q_1 can now be obtained by experimental identification using the regressive ARX model where the input to the motor-cart subsystem is the reference velocity $\dot{\theta}_0^*(t)$ and the measured output is the actual cart velocity $\dot{\theta}_0(t)$.

The next step involves a rewriting of equation (4) into the state space form, which will become part of the complete, modified state-space representation of the single inverted pendulum laboratory model with velocity control:

$$\frac{d}{dt}\begin{bmatrix}\theta_0(t)\\ \dot{\theta}_0(t)\\ \ddot{\theta}_0(t)\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & -q_0 & -q_1\end{bmatrix}\begin{bmatrix}\theta_0(t)\\ \dot{\theta}_0(t)\\ \ddot{\theta}_0(t)\end{bmatrix}+\begin{bmatrix}0\\ 0\\ p_0\end{bmatrix}\dot{\theta}_0^*(t) \tag{5}$$

4.1 Experimental identification of the linear drive velocity loop parameters

The procedure of experimental identification of the linear drive velocity loop consisted of these steps:

- first we generated a symmetric rectangular signal, which represents the reference velocity $\dot{\theta}_0^*(t)$ as the input to the velocity loop. Next, we measured the system output $\dot{\theta}_0(t)$, as seen in Fig. 5. The generated signal was implemented in RSLogix 5000 and the obtained data were sent to the MATLAB/Simulink environment via the DDE protocol,

- subsequently, we used the *arx function* from the *System Identification Toolbox* over the measured I/O data to obtain the unknown parameters p_0, q_0, q_1 of the velocity loop transfer function (4).

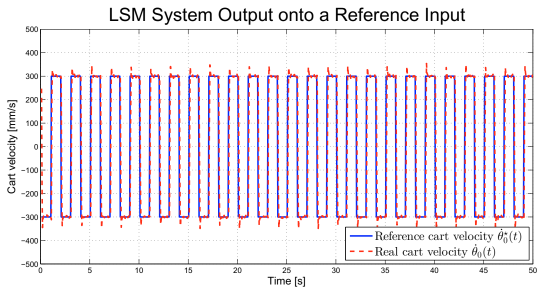

Fig. 5. Input/output training data obtained from the laboratory model

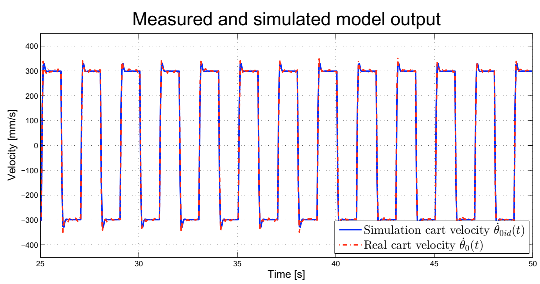

Fig. 6. Validation of the outputs from the simulation linear drive velocity loop $\dot{\theta}_{0id}(t)$ against the laboratory model output $\dot{\theta}_0(t)$

Fig. 6 depicts the comparison of the output from the *Single inverted pendulum laboratory model with velocity control* $\dot{\theta}_0(t)$ and the output of the velocity loop $\dot{\theta}_{0id}(t)$ identified with the 95.99% precision, computed via normalized root mean square measure of the goodness of the fit. Based on the successful validation of the linear drive velocity loop, the identified parameters of the velocity loop can be implemented into the modified state-space model of the single inverted pendulum with velocity control and subsequently used in stabilizing control design.

4.2 Identification of laboratory system damping coefficient

To verify the identified velocity control loop parameters p_0, q_0, q_1 in the context of the whole system, we needed to obtain a nonlinear mathematical description of the laboratory model. The last unknown parameter in the motion equation of the pendulum (2) is the damping coefficient δ_1. According to (Feynman et al. (2013)) the relationship between the damping coefficient δ_1 in the mathematical model of the single inverted pendulum on a cart and the identifiable damping coefficient b of a simple pendulum is given as $b = \delta_1/(2J_1)$.

The laboratory model contains a rod with a weight attached on the one end, as shown in Fig. 7. After the omission of the rod rims, the inertia J_1 can be derived according to (Jadlovská et al. (2015)).

To identify the value b of pendulum damping, we neglected the cart and considered only the pendulum motion equation in the form:

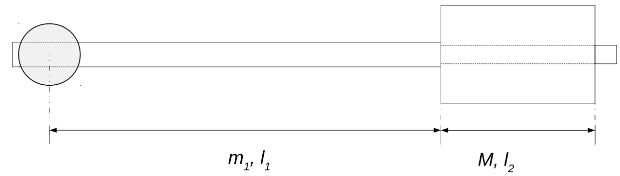

Fig. 7. The cross section of the laboratory pendulum rod

$$\ddot{\theta}_1(t) + 2b\dot{\theta}_1(t) + \omega_0^2 \sin(\theta_1(t)) = 0 \quad (6)$$

where the oscillation frequency ω_0 is defined as

$$\omega_0 = \sqrt{\frac{mgC}{J_P}} \quad (7)$$

and J_P is the inertia of the rod with respect to the pivot point, m is the combined mass of the rod and the attached weight, C is the distance between the pivot point and the CoG, g is the gravity acceleration. Assuming the angle $\theta_1(t)$ to be less than 6°, the equation (7) leads to a linear equation and therefore we can obtain the damping coefficient b according to (Feynman et al. (2013)) as:

$$b = \frac{1}{nT} ln\left(\frac{A(t)}{A(t+nT)}\right) \quad (8)$$

where T is the period of oscillation, $A(t)$ is an amplitude at the time t, n is an unsigned integer. Using (8) and the data measured from the laboratory system, we obtained the value of the damping coefficient b. Verification was performed in MATLAB/Simulink and is shown in Fig. 8.

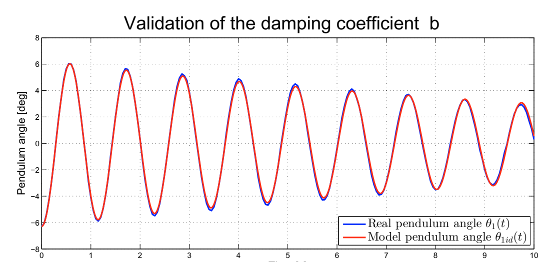

Fig. 8. Comparison of the pendulum angle time behavior for the simulation model with added damping ($\theta_{1id}(t)$) and for the laboratory model ($\theta_1(t)$)

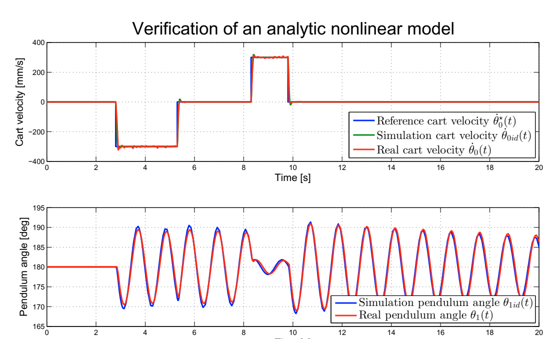

Fig. 9. Validation of the cart velocity $\dot{\theta}_0(t)$ and pendulum angle $\theta_1(t)$ for the simulation model vs the laboratory model of Single inverted pendulum with LSM

The behavior of the now complete nonlinear mathematical model is validated in Fig. 9. The system input $\dot{\theta}_0^*(t)$ has the same magnitude as the signal used in the parameter identification of the velocity transfer function (4), describing the motion of the cart with velocity control. We can observe that the nonlinear simulation model of the inverted pendulum system closely follows the behavior of the laboratory model, and can therefore be considered to be correct. The verified nonlinear model of the laboratory single inverted pendulum with velocity control was implemented into the *IPMaC* library to be next used in control design.

5. HYBRID CONTROL DESIGN FOR THE SINGLE INVERTED PENDULUM WITH LSM

The principal control objective for the single inverted pendulum is defined as stabilization of the pendulum link in the unstable equilibrium, i.e. in the vertical upright (inverted) position, as a result of the nonzero initial conditions, or a disturbance input signal (Jadlovská and Jadlovská (2013)). As far as the single inverted pendulum does not meet the Brockett's necessary condition (Ceragioli (2002)), the hybrid control structure, as seen in Fig. 10, has to be used (Lunze and Lamnabhi-Lagarrigue (2009)).

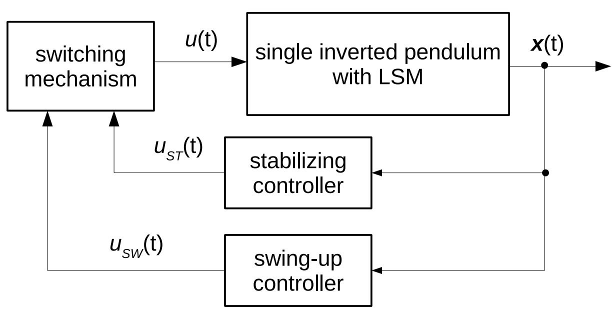

Fig. 10. Hybrid control structure for the Single inverted pendulum system with velocity control

The resulting control law consists of two controllers, namely a swing-up controller and a stabilizing controller (Jadlovská and Sarnovský (2013a)). The swing-up controller is used to bring the pendulum into the vicinity of the unstable equilibrium point (Tanaka et al. (2011)), where the control is delegated onto the stabilizing controller. The switching mechanism between the control algorithms is set by *if-then* rules and can also be implemented via *StateFlow Toolbox*. To design a swing-up controller based on the methods implemented in the *IPMaC* library (Furuta's energy-based approach, partial-feedback linearization (Vošček (2015), Jadlovská (2015))), a nonlinear mathematical model, described by the motion equations (2) and (5) is used.

Since the stabilizing procedure only takes place in the small vicinity of the unstable equilibrium point, the linear approximation of the system in the unstable equilibrium point is sufficient to design the stabilizing controller. To obtain the state space model of the whole system with velocity control, we rewrote the motion equation of the pendulum (2) into the state space and performed its linearization around the equilibrium point via the Taylor series expansion. Then we joined the state space model of the pendulum with the state space representation of the velocity loop (5). As a result, we obtained the modified state space model of the *Single inverted pendulum system with velocity control* in the form:

$$\dot{\mathbf{x}}(t) = \underbrace{\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & a_{25} \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & a_{54} & a_{55} \end{bmatrix}}_{\mathbf{A}} \mathbf{x}(t) + \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ b_5 \end{bmatrix}}_{\mathbf{B}} u(t), \qquad (9)$$

where $\mathbf{A}$ is the dynamics matrix (Jacobian), $\mathbf{B}$ is the input matrix, $a_{ij} = f(q_0, q_1)$, and $b_i = g(p_0)$ are functions of identified parameters q_0, q_1, p_0, the state space vector $\mathbf{x}(t)$ is defined as:

$$\mathbf{x} = [x_1\, x_2\, x_3\, x_4\, x_5]^T = [\theta_1(t)\, \dot{\theta}_1(t)\, \theta_0(t)\, \dot{\theta}_0(t)\, \ddot{\theta}_0(t)]^T \quad (10)$$

and the system input $u(t)$ corresponds to reference cart velocity $\dot{\theta}_0^*(t)$.

The linear approximation of the modified laboratory inverted pendulum model was next used to design the stabilizing control that brings the cart to the reference point and maintains the pendulum in the upright position. To design the state-feedback control law, we used the standard technique based on the minimization of the quadratic criterion (LQR) with the suitable weight matrices $\mathbf{Q}$, $\mathbf{R}$. The proposed hybrid control approach (Fig. 10) was first tested on the modified nonlinear simulation model using the *IPMaC* library blocks. In addition to the LQR method for the stabilizing controller, the method of maximizing the potential energy was selected for the swing-up controller. Verification of the proposed control design was finally performed in the laboratory setting and the results are depicted in Fig. 11. To improve performance, the control law was implemented into the PLC, which directly controls the KINETIX 6500 servomotor.

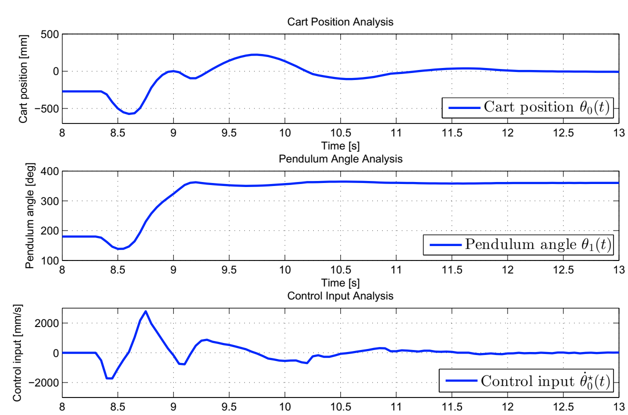

Fig. 11. Time behavior of the cart position $\theta_0(t)$, pendulum angle $\theta_1(t)$ and control input $\dot{\theta}_0^*(t)$ for the laboratory Single inverted pendulum system

It can be seen that the implemented control algorithm succeeds in fulfilling all control objectives for the laboratory model of the single inverted pendulum with velocity control. This also provides the additional validation of the experimentally identified model. The final result has been captured in Fig. 12.

6. CONCLUSION

The purpose of this paper was to present the laboratory model of the *Single inverted pendulum with LSM* as a

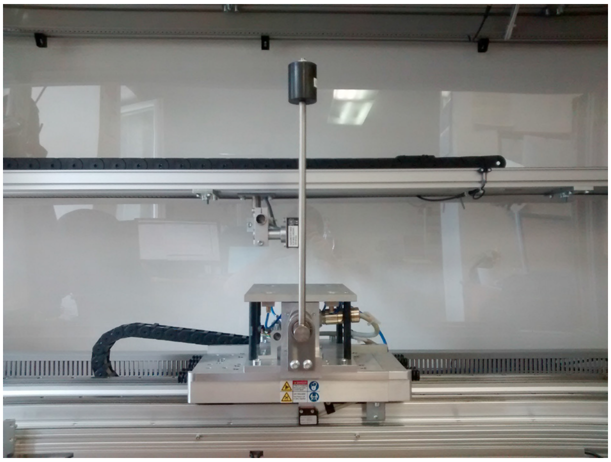

Fig. 12. Hybrid control of the laboratory Single inverted pendulum system with LSM

cyber-physical system and to describe its decomposition into the relevant levels of the Distributed Control System infrastructure at DCAI FEEI TU. We made use of the pre-prepared program modules of the custom-designed MATLAB/Simulink library *Inverted Pendula Modeling and Control*, developed by the authors of this paper, in the process of subsequent analytical identification and control algorithm design. A GUI application which generates motion equations for inverted pendulum systems was used to obtain a mathematical model of a single inverted pendulum system with an attached weight and force input. Since the laboratory model does not allow to apply force input on the cart, the cart motion equation was replaced by the linear model of a velocity control loop, where the parameters were experimentally identified. The modified nonlinear mathematical model was verified against the measured data and included in the *IPMaC* block library. Afterwards, linear approximation of the modified nonlinear model was performed for the close vicinity of the unstable equilibrium point. Finally, a hybrid control structure based on two controllers was designed. The swing-up controller uses the modified nonlinear mathematical model from the *IPMaC* to devise the strategy for bringing the pendulum into the vicinity of the equilibrium point. Once the pendulum is close to the upright position, a switching mechanism delegates control to a stabilizing controller which is based on the linear approximation of the system. The designed control law was successfully verified on the laboratory model. Our further research goals include the design and verification of modern control algorithms for swinging up and stabilization of the single inverted pendulum laboratory model with LSM, adding more pendulum links to the model, as well as research in the area of underactuated systems oscillations and stability, all as part of the research activity *Hybrid Models of Cyber-Physical Systems and their Application into Distributed Control Systems.*

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