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Cyber-Physical Systems, Modelling Framework and Application into Distributed Control Systems

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***Abstract*—This paper introduces cyber-physical systems (CPS), their applications and challenges in the real environment, as well as characteristic features. One of the defining characteristic of the CPS is the hybrid description and the most general hybrid modelling via discrete hybrid automata (DHA) is presented. Subsequently an example of hydraulic CPS is written in the form of DHA and set into distributed control system (DCS) in the possibilities of DCAI, FEEI, TUKE. Study and enrichment of the CPS research field is the content of my dissertation thesis *Hybrid Models of Cyber Systems and their Application into Distributed Control Systems*. Moreover, DCS, which can be considered as CPS, is compared with DCS implemented at CERN, as it is also part of my dissertation thesis.**

***Keywords*—cyber-physical system, embedded system, hybrid system, discrete hybrid automata, distributed control system.**

I. Introduction

Cyber-physical systems refer to the tight integration of computational and physical resources [1], [2]. Research advancement in the area of CPS will surely transform our world with systems that are more precise (robotic surgery, nanotechnologies), work in dangerous and inaccessible environments (fire-fighting, autonomous systems for search and rescue), respond more quickly (autonomous collision avoidance), provide distributive coordination (automated traffic control), are highly efficient and augment human capabilities (assistive technologies, health-care monitoring) [3]. From this point of view many research challenges emerge: CPS composition, security, safety and robustness of CPS, architecture of CPS, sensor and mobile networks, control and hybrid systems, model-based development and verification of CPS, etc. [4].

Dealing with the challenges that CPS provide is a crucial part of my dissertation thesis, precisely, model-based development and verification of CPS.

Next topic in my dissertation thesis is the implementation of CPS into distributed control systems (DCS). DCS are large scaled and complex systems composed of layers from the lowest, which is represented by real processes and dynamical systems, up to the coordination/management layer.

II. Cyber-physical systems

Cyber-physical systems perfectly integrate computation with physical processes and provide abstractions, modelling, design and analysis techniques for the integrated whole. CPS require computing and networking technologies to embrace not merely information, but also the physical dynamics, see

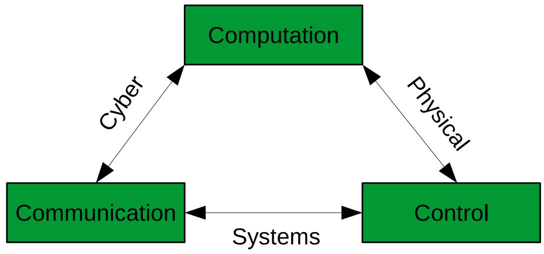

Fig. 1. Overview of a cyber-physical systems [7]

Fig.1. The interactions among control, computing, network and physical systems require new design technologies [5].

Embedded computers and networks monitor, evaluate and control physical processes based on a feedback control, where physical processes affect computational process and vice versa. An overlap occurs among embedded systems and CPS, as well as real-time systems as illustrated in Fig. 2.

We can comprehend CPS from two aspects. From the perspective of composition, it is composed of embedded system and network components. From the perspective of method, it uses a feedback mechanism to control the physical environment [6].

Defining characteristics of CPS are [5]:

- *cyber-capability in every physical device and resource constraints* - software is implemented in every embedded system and system resources are constrained as well, e.g.

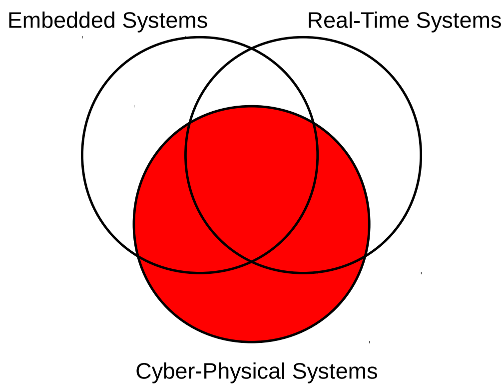

Fig. 2. Overlap between cyber-physical systems, embedded systems and real-time systems [8]

network bandwidth, computation resources,
- *close integration* - physical processes are deeply integrated with the computational processes,
- *extreme scales and networked* - CPS contain many wireless technologies e.g. - GSM, blue-tooth, wi-fi, which allows creation of CPS of vast levels and are considered as distributed systems,
- *complex spatial and temporal scales* - different subsystems of CPS have different time and space requirements,
- *dynamical reconfiguration/reorganization* - CPS require adaptive characteristics because of their size and complexity,
- *high degrees of automation and closed-loop control* - CPS take advantage of easy manipulation and from control, which is realized by feedback control,
- *operation must be dependable and certified in some cases* - this is one of the most important characteristic of CPS, as CPS are complex and spacious, it is needed that the system is secured and reliable.

III. Hybrid dynamical systems

Dynamical system (DS) describes an evolution of a state over time [9]. DS can be influenced by input signals, which can be represented by control signal or disturbance. DS can also have output signals, which might be measured or regulated. Such DS are called control systems. Based on the type of their state, DS can be classified into:

1) *continuous* - if the state of a DS evolves in Euclidean space $\Re^n$, $n \geq 1$,
2) *discrete* - if the state of a DS evolves in the range of a finite set $\{q_1, \dots, q_n\}$,
3) *hybrid* - combination of a continuous and discrete system.

Based on time, DS can be classified into:

1) *continuous time* - $t \in \Re$ and evolution of the state is described by a differential equation,
2) *discrete time* - a set of time is a subset of integers $k \in N$ and evolution of the state is described by a difference equation,
3) *hybrid time* - evolution of a DS is over continuous time but discrete events(instantaneous jumps) occur.

CPS belong to a hybrid systems category with the hybrid time. The most significant representations of the hybrid systems are:

- discrete hybrid automata (DHA) [10]
- piece-wise affine (PWA) systems [11]
- mixed-logical dynamical (MLD) systems [12]
- switching control [13]

DHA is the most general description of the hybrid systems, where if the discrete part preserves its state then the continuous part of DS evolves according to difference equations assigned to that discrete state [14]. When an event occurs and fulfil required conditions, which lead to change of the discrete state, event causes change in the continuous part as well [14]. Modelling of DHA is composed of four parts:

- switched affine systems (SAS)
- event generator (EG)
- finite state machines (FSM)
- mode selector (MS),

which are depicted on Fig.3. These parts of the DHA are defined as:

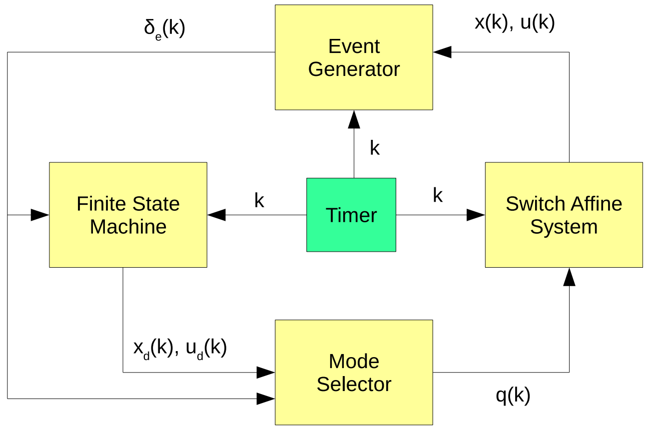

Fig. 3. The DHA framework for modelling CPS

- switched affine systems - describe the continuous part of the hybrid system, which is defined as follows:

$$\begin{cases} x(k+1) = A_q x(k) + B_q u(k) + f_q \\ y(k) = C_q x(k) + D_q u(k) + g_q \end{cases}, \quad (1)$$

where $x(k)$ - state of the system, $y(k)$ - system output, $u(k)$ - system input and $\{A_q, B_q, C_q, D_q\}$ is a set of matrices and vectors $\{f_q, g_q\}$ represent nonlinear vectors for discrete state q of the system.
- event generator - provides a generation of a specific event based on the fulfilment of boundary conditions. Mathematical description of EG:

$$\delta_e(k) = f_h(x(k), u(k), k) \quad (2)$$

$f_h : \Re^n \times \Re^m \times N_{\geq 0} \rightarrow E \subseteq \{0,1\}^{n_e}$
- finite state machines - represent the discrete part of the hybrid systems, which can be described as follows:

$$x_d(k+1) = f_d(x_d(k), u_d(k), \delta_e(k)) \quad (3)$$

$x_d(k+1) \in X_d \subseteq \{0,1\}^{n_d}$, $x_d(k)$ - discrete state vector, $u_d(k)$ - discrete input, $\delta_e(k)$ - output of EG
- mode selector - defines the continuous part of DS in the frame of SAS. Output signal is defined in the form:

$$q(k) = f_m(x_d(k), u_d(k), \delta_e(k)) \quad (4)$$

IV. Example of CPS description in the DHA frame

Consider a hydraulic dynamical system stated in [15], [16]. Structure is shown on Fig. 4. The input to the system represents the inflow $q_0(t)$. Dynamics of this system is dependent on the height of a liquid in the second tank. If the height $h_2(t)$ is lower than the height h, in which the liquid level in the second tank runs over the the height of the bottom of the first tank, the dynamics evolves according to the physical laws for the two tank hydraulic DS without interaction (5), however if the height $h_2(t)$ is above the height h, the dynamics of the system is described as the two tanks hydraulic system with interaction (6).

Mode $q = 1$

$$\begin{aligned} \Delta h_1(t+T) &= \left(1 - \frac{k_1 T}{F_1^s}\right) \Delta h_1(t) + \frac{\Delta q_0(t) T}{F_1^s} \\ \Delta h_2(t+T) &= \frac{k_1 T}{F_2} \Delta h_1(t) + \left(1 - \frac{k_2 T}{F_2}\right) \Delta h_2(t) \end{aligned} \quad (5)$$

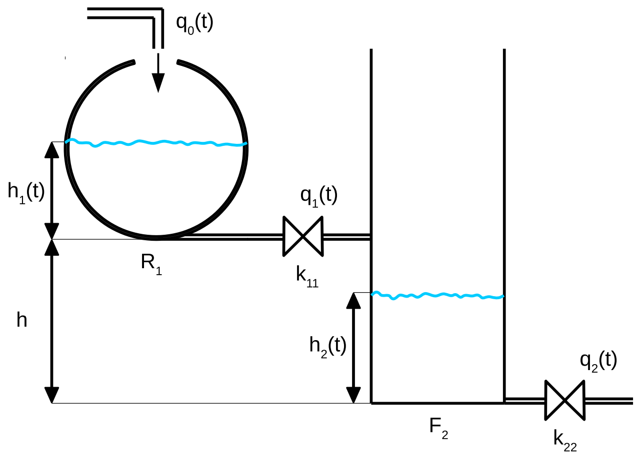

Fig. 4. The system of coupled tanks

Mode $q = 2$

$$\Delta h_1(t+T) = \left(1 - \frac{k_1}{\frac{F_1^s}{T}}\right)\Delta h_1(t) + \frac{k_1}{\frac{F_1^s}{T}}\Delta h_2(t) + \frac{\Delta q_0(t)}{\frac{F_1^s}{T}}$$

$$\Delta h_2(t+T) = \frac{k_1}{\frac{F_1^s}{T}}\Delta h_1(t) - \left(\frac{k_1}{\frac{F_2}{T}} + \frac{k_2}{\frac{F_2}{T}} - 1\right)\Delta h_2(t) \tag{6}$$

Parameters of this system are : F_1^s - cross-sectional area of the first tank in the steady state, F_2 - cross-sectional area of the second tank, k_1, k_2 - modified flow resistances constants, T - sample rate.

These two mods of the dynamics of the stated system represent FSM, to each of these mods is assigned a set of discrete difference equations in the SAS frame. Fulfilment of the condition $h_2(t) = h$ triggers EG and consequently MS selects the dynamics of the system, which is determined by EG.

V. Distributed control system

DCS are composed of many different systems (together forming CPS [17]), which determine different approaches to their modelling and control. Hybrid modelling and resultant control of such systems are the main topics of my dissertation thesis *Hybrid Models of Cyber Systems and their Application into Distributed Control Systems*. DCS itself can be represented as CPS, however distinct systems comprising DCS can also represent simpler CPS. Considering this representation of CPS, DCS provides a very good framework to study and implementation of many different modelling and control techniques. Such a DCS infrastructure is realized at DCAI FEEI Center of Modern Control Techniques and Industrial Informatics and is composed of 5 levels, as depicted on Fig. 7 [18].

Techonological level is situated at the lowest level and is represented by real models, actuators and sensors. From the variety of real models, the most important models for my dissertation thesis are under-actuated mechanical systems and hydraulic dynamical systems stated in the section IV. As an example of the under-actuated system can be considered Multipurpose workplace of nondestructive diagnostics with

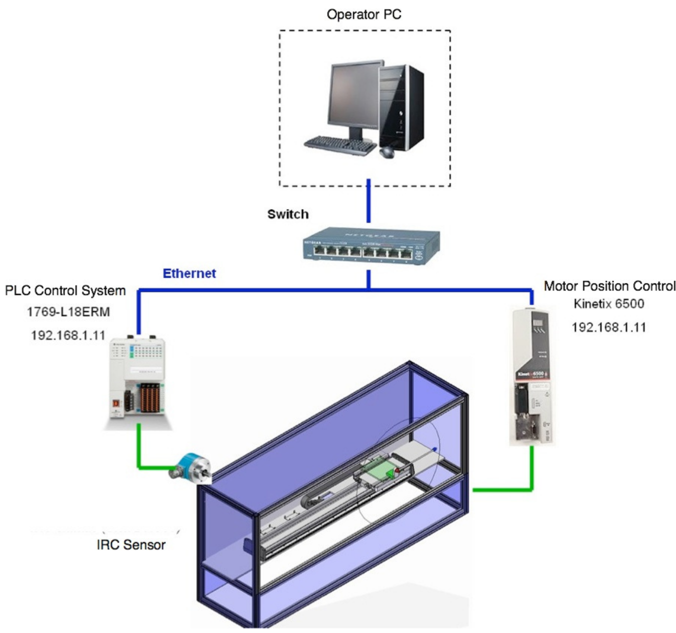

Fig. 5. Multipurpose workplace of nondestructive diagnostics with linear drive [18]

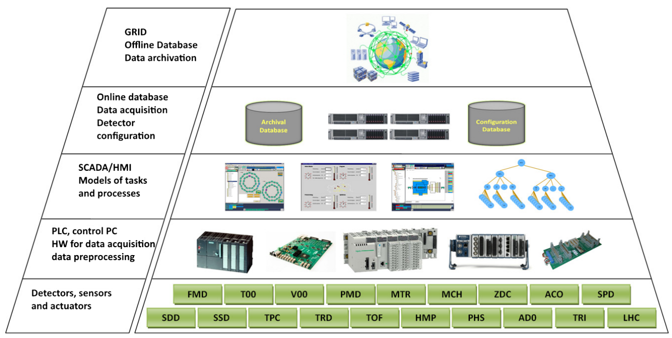

Fig. 6. DCS of ALICE detector control system

linear drive, whose part is a classical single inverted pendulum model, Fig. 5 [19].

Directly above the zero-level of DCS appears *Technological level of control and regulation*, which is denoted as the first level of DCS. Hardware realization of this level is made with the help of programmable logic controllers (PLC) and technological PC′s onto which are connected model sensors and actuators from the first level. In the context of the mentioned models, classical inverted pendulum is controlled by PLC and hydraulic systems by technological PC.

The second level of DCS is represented by *SCADA/HMI* technologies and simulation models of the zero-level real models. SCADA/HMI ensures data acquisition, collection and archivation as well as supervisory control of the systems from lower levels of DCS. Simulation models included in this level serve for simulation purposes, control design and verification of algorithms [19]. My dissertation thesis is situated mainly into these three levels of DCS.

The level above SCADA/HMI is *Information level of control* which includes relational databases, ERP/MRP and MES systems. At the top of DCS is *Management control level* based on multidimensional databases and OLAP technology [20].

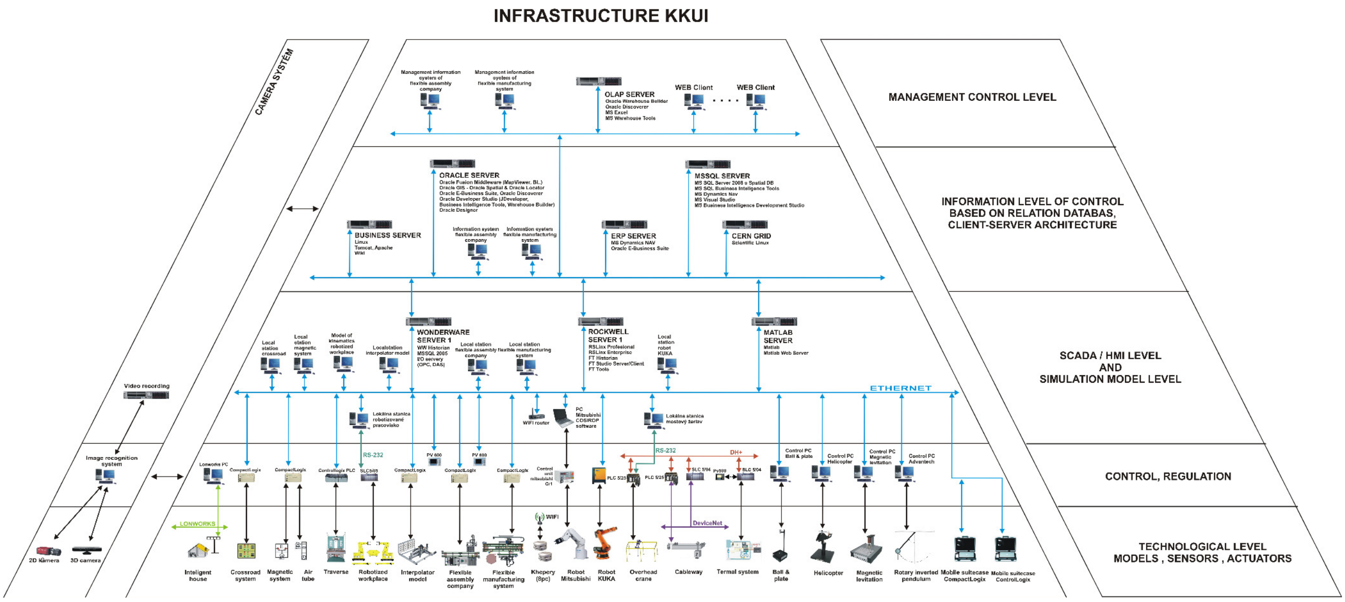

Fig. 7. Distributed control system (DCS) pyramidal model implemented at the Department of Cybernetics and Artificial Intelligence

VI. Conclusion

This paper provides a basic notion of a cyber-physical systems, their specifications and challenges they pose. One of the biggest challenges is to model such a cyber-physical system. Mathematical modelling of CPS is mainly done with the help of hybrid systems framework. This modelling framework can be used to implement CPS into distributed control systems architecture. Such a DCS architecture is also used at CERN, see Fig. 6, where information and experience from our own architecture can be utilized. Moreover, finite-state machines are used to model processes in CERN, which are part of the most general form of hybrid systems - hybrid automata. The author is also a member of Alice Collaboration in CERN Alice experiment and it is one of the main topics of his dissertation thesis.

CPS offer a huge research space and only further research will show us which applications and consequences in real life we can expect.

Acknowledgment

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