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SOME ASPECTS OF MODELING CPS FOR PEDAGOGICAL REHABILITATION IN SPECIAL EDUCATION

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Abstract: *The paper presents some aspects of modeling of Cyber-Physical Systems (CPS) in general and particular for pedagogical rehabilitation in special education. The challenges in CPS modeling are described. Model – based design of CPS in ten steps from the literature is given. Some specificity of modeling CPS for pedagogical rehabilitation in special education are discussed and description of training process from a linear control system point of view is given.*

Key words: *Cyber Physical Systems, special education, robots*

1. INTRODUCTION – CPS MODELING

Cyber-physical systems (CPS) are composed of physical systems that affect computations, and vice versa, in a closed loop. By tightly integrating and interacting computing with physical systems one can design CPS that are smarter, cheaper, more reliable, efficient and environmentally friendly than systems based on physical design alone. By adding a computer in a new system we can act (recording data, processing data, control action etc.) into a physical system and can actually give it properties that cannot be given with a pure physical system design alone [1]. CPS is a new and extremely interesting emerging class of [2,3,4,5]. The presence of feedback loops supported by a pervasive sensing infrastructure is the common characteristic of all proposals of CPS. The CPS enables the physical world to be monitored, controlled and influenced both adaptively and intelligently. CPS are already everywhere around us, they are affecting our daily life. Examples include modern automobiles, aircrafts and trains, power systems, medical devices and manufacturing processes. In the future it will certainly become even more pervasive in everything we do – help us become healthier, live longer, have better interactions with friends, even further - explore new worlds, they will allow us to help save the planet - whole big issue of climate change [1].

Recently, the humans are added in the CPS monitoring and control loop in order to be more productive, more efficient and more reliable. The systems that consider humans as part of the physical world are known as Human-in-the-loop systems. Three types of Human-in-the-loop systems are considered [4] - (i) systems where humans may control the operation; (ii) systems where humans are only passively monitored and (iii) hybrid systems of the previous.

In the CPS more and more computing components and sensors are added to achieve higher level functions of physical systems and the problem of modeling and control becomes really complex.

The basis of CPS is integration and interaction of the computer system and the physical system. It is known that computer systems are based on logical operations, discrete mathematics and digital data, while the physical systems are based on the continuous variables, analogue data, continuous, dynamics, continuous mathematics and differential equations. Different disciplines are integrated in CPS - mechanics, electronics, engineering, control, computation, etc. There is, therefore, a need for new interdisciplinary theories, models, methods, tools and contexts to support CPS developments and in order to create bridges between mechanics, electronics, engineering, control and computation. The main challenges [3] in CPS modeling are related to:

- How to model the components of the different disciplines;
- How to model the interfaces among components drawn from different disciplines with a common terminology;
- Model integration - established techniques exist to model the dynamics of the physical components (i.e. a continuous model) and the discrete behaviors of the computing components (i.e., the discrete model), but the interface to join the continuous model and discrete model has not to date been given significant attention [3].

How to generate solution concepts based on customer requirements or market survey results and how to evaluate the different solution concepts proposed;

- Finally, because of the complexity of a CPS, it is impossible to find the optimum solution concepts without iteration and there is a requirement to optimize solution concepts during the early part of the design process.

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In [5] a model – based design in ten steps is given. The steps are not necessarily sequential but necessarily codependent that facilitates the co-evolution of a model of a cyber-physical system with its realization. The steps are:

Step1: Problem definition

By using simple language the problem to be solved is described, without the use of mathematics or technical terminology. In this step the developers, collaborators, colleagues and experts are included. Given the multidisciplinary nature of cyber-physical systems, this step is necessary to effectively communicate design requirements.

Step2: Modeling Physical Processes

A first iteration of physical modeling should establish basic observations and insight into relevant physical systems, such as the environment in which the cyber-physical system resides, or the physical processes to be controlled. Models of physical processes are simplified representations of real systems. What may begin as simple mathematical models may need to be refined following development of a control algorithm, specification of hardware, and testing of components and subsystems?

Step3: Characterization of the Problem

The fixed parameters, adjustable parameters and variables to be controlled are characterized in this step. Identification of quantities that provide characterization of physical processes, such as configuration spaces, safety limitations, input and output sets, saturation points, and modal behavior. Understanding how a physical process may interact with a computation, including end-to-end latency requirements, fault conditions, and reactions to noise and quantization.

Step4: Find Control Algorithm

Determine conditions under which physical processes are controllable and derive a suitable control algorithm to be executed by an embedded computer. Use the problem characterization to specify delays, sampling rates, jitter, and quantization so that the physical dynamics of interest can be accurately measured and suitably controlled;

Step5: Selection of Computational Models

A model of computation is a set of allowable instructions used in a computation along with rules that govern the interaction, communication, and control flow of a set of computational components. A formal model of computation defines semantics that often result in greater analyzability and the potential to simulate cyber-physical systems through the use of heterogeneous modelling tools.

Step6: Hardware specification

Select hardware that is capable of withstanding the environment, interacting with the modeled physical systems, and implementing the control algorithm. For each component, consider its input and output bandwidths, delay from input to output, power usage, measurement resolutions and rates, and mechanical parameters such as form factor, rejection of electrical interference, durability, and lifespan. This step may require several iterations with software design and simulation before an embedded computer can be selected with confidence.

Step7: Simulation

Solve the problem using a desktop simulation tool. If multiple models of computation are to be used, simulation and synthesis tools must allow the compositions of and interactions between multiple models of computation. Depending on the robustness of the development environment, incorporate models of sensors, actuators, and physical processes.

Step8: Construction

Building the device according to specifications, taking note where exceptions have been made that may impact earlier modeling. Planning construction in a way that allows individual components and subsystems be tested against theoretical models.

Step 9: Software Synthesis

Code synthesizers are sometimes incorporated into desktop simulation environments, examples of which are LabVIEW and Ptolemy II. They may directly support the embedded computer used, or generic code may be synthesized and tied to handwritten, architecture-specific code.

Step10: Verification, Validation and Testing

Configure adjustable parameters to create test environments that are as simple as possible, and test each component and subsystem independently. Computational systems may be isolated from physical systems via hardware-in-the-loop testing, where programmable hardware such as embedded computers or FPGAs simulate the feedback from physical or other computational processes. Verification and validation are perhaps the most difficult aspects in the design of a cyber-physical system.

2. CPS FOR PEDAGOGICAL REHABILITATION IN SPECIAL EDUCATION

The education & rehabilitation frameworks have emerged recently yet have been employed widely for implementing information technology and robotics in clinics and special education [7]. In CybSPEED - the H2020-MSCA-RISE-2017 project [8] CPS for Education & Pedagogical Rehabilitation is proposed as emerging and rapidly acquiring influence CPS type in present day society. The problems of modelling, synthesis and implementation of CPSs for pedagogical rehabilitation in special education are defined and are subject of research. The robots are a central component in the CPS for pedagogical rehabilitation in special education - *Autonomous CPS*, *Semi-autonomous CPS* and *Assistive CPS* [7]. The latter are systems with robots like Aldebaran's NAO and Pepper for enhanced, natural language based collaboration with the human. In modelling *Assistive CPSs* both levels of the human counterpart are accounted – as *physical presence* of the human and as *social presence* of the human, thus triggering different decision making algorithms [8]. The main applications of the *Assistive CPSs* are: education, pedagogical rehabilitation, mental health, playing games, socializing, elderly care (as well as in other interactive domains). Robots interacting with children are being considered in several projects and publications.

CybSPEED project is preceded by METEMSS project [6] in which children with several kinds of learning difficulties enjoyed playing with both humanoid and nonhumanoid robots such as NAO and BigFoot.

There is some specificity that we need to take into account when dealing with modeling CPS for pedagogical rehabilitation in special education:

- Progress in learning a motor or cognitive skill is important, but is secondary to the therapeutic process. The most important in special education is the entertaining role of the technology and the emotional involvement of children;
- By empowering the child to be in control of complex technological devices and giving instructions in a 'natural' manner – speech and gestures - the child learns how to react to environments. This is expected to result in better adaptation to the outside world and the social environment of each individual child;
- When modeling CPS, the personal information and information about child motor skills, cognitive skills, social skills etc. must be available and individuality must be taken into account;
- It is very important that CPS are such that not to bore or tire children, or be too demanding because their emotionality is very fragile and emotional outbursts are possible;
- The task of working with the child requires patience and multiple repetitions and is very tiring for the educational therapist;
- Strict observance of all ethical norms and principles relating to processing personal data is mandatory;
- CPS allows detailed measurements and monitoring of the training process. In combination with the expertise of the therapist and the parents, it can produce satisfactory results in the educational process.

In the next section we will try to describe the model of the training process during the experiments in the frame of METEMSS project [6]. This explanation can be used as initial point in modeling CPS for pedagogical rehabilitation in special education.

3. MODELING AND CONTROL OF THE SKILLS TRAINING PROCESS

This section describes the training process of game design for enhancing the development of motor, cognitive and social skills via succession of experiments.

First, it is necessary to explain the pedagogical situation of game validation in several successive experiments. Each individual child is under special care and being attended by a designated member of the pedagogical/clinical staff, according to the specific therapeutic need of the child. Members of staff are psychologists, speech therapists, ergotherapists, and kinesi-therapists. The three groups of games represent a palette of options to engage the child and train a skill according to the current need of the child as assumed by the designated teacher.

In Fig. 1 Experiment 0 denotes the pilot test of the set of games in the laboratory with the participation of children from typical schools. After the piloting and based on the observations of the designer team, the improvements are incorporated in the games (U^0) and these are then tested in real life settings (day care centers) in Experiment 1.

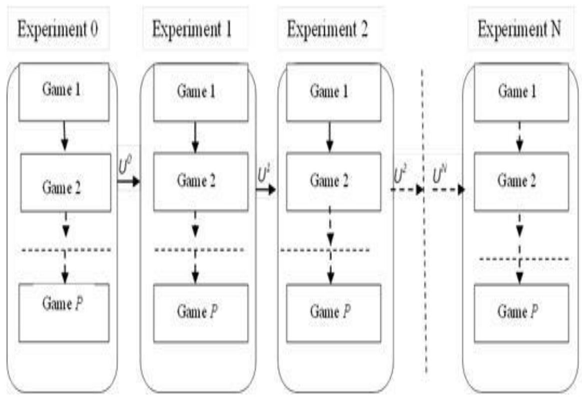

Fig. 1.Experimental succession of games validation in the METEMSS framework

The main challenge in validating games for special education is the fact that children in day care centers suffer from a diversity of symptoms; they are engaged in individual programs designed for each of them and play in small groups. Therefore, it is not possible to attempt to collect big samples of experimental data. Yet it was necessary to find the best approach to validate in quantitative terms the design of games to be included in special education as useful tools for the pedagogical staff. This is why we propose a novel framework for describing the training process inspired by the control systems theory.

Procedure. The procedure of the experiments is the following. The 3 types of games are being organized in 3 scenes (including the installation of the robotic and Kinect technologies). A teacher brings a child to one of the scenes and helps understand the rules of the game. The child plays the game with the constant assistance of the teacher, who is being attentive to the skills the child attempts to master. The focus in our approach is on the teacher, who is responsible for the child and is the only one to assess the game and the condition of the child at every moment of the trial. The main advantage of this approach is that it works with small groups of children, who can engage in a set of games, not being the same as the other child engages in, and being timed by the teacher's assessment only, so there is no need to make sessions equal, too.

Right after each trial the teacher gives assessment of the game on scales from 1 to 5. Eight of the dimensions are set to be addressing skills of the children, whereas one of them is "difficulty" of the game and one referring to its role in formation of new policies. We assume it an extrinsic factor to the evaluation process, so we do not include it in the multidimensional analysis, leaving the number of game dimensions to 8, given in Table 1.

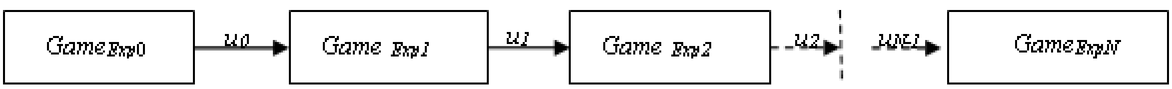

FIG. 2 IMPROVEMENTS OF THE GAMES

Table 1: Evaluation dimensions

	Criterion
1	Appropriateness of the game
2	Motivation of the child
3	Impact on cognitive development
4	Impact on motor development
5	Impact on social development
6	Interest of the child
7	*Level of difficulty of the game**
8	Role of collective participation
9	Role in formation of novel policies

- Not included in the state matrix A

The "difficulty" dimension is necessary in order to allow the teachers to design a strategy for skills training for the children from simpler to more complex games, being one of the aims of the proposal for introducing computerized and robotic technology in special education. The ones, included in the 8 dimensional state matrix ***A*** are the actual evaluation parameters of the game, included in the overall "game appropriateness" indicator.

The fact that scores are collected in a "paper and pencil" manner is not crucial for the proposed evaluation methodology. Scores could be collected by any type of computer interface or via the touch screen of a smart phone. In this way the methodology combines an expert systems approach to game validation with the principles of multidimensional scaling in psychology, providing quantitative evaluation from qualitative type of data. Based on a stochasticity assumption of the game conditions, this approach can produce quantitative evaluation of the output of the entire system as presented next.

A.Process Description of the METEMSS Skills Training System

Consider the training process of children using computerized and robotic methodologies. The potential for improved skills of the children as a result of the games is represented by *m* in number indicators of the games – in particular here by 8 assessment dimensions, represented as Likert scales - so matrix ***A*** of the current state of the game is a 8x8 diagonal matrix. The values of ***A*** are recorded for each child and for each game separately. Information about the values of the 8 indicators is received from the scores of the teachers provided at the end of each game and averaged at the end of each experiment. After each experiment, improvements are being made in the games.

We assume that any game can be improved, and the important aspect is that the degree of change in the game from Experiment 1 to Experiment 2 can vary. Also, an important assumption is that the teachers' assessment is *implicit*, but *objective*, since they know best the children and their learning needs. The improvements in the games after each experiment are considered the manipulated process variables (Fig. 2). The process terminates when the game has no further capacity for improvement.

System Description:

- For each game and each child we define an 8 dimensional state variable $\boldsymbol{x}(k) = [x_1 x_2 \dots x_8]^T$, where the vector elements represents :

x_1 - Appropriateness of the game, x_2 – Motivation of the child; x_3 – Impact on cognitive development; x_4 - Impact on motor development; x_5 – Impact on social development, x_6 –Interest of the child; x_7 – $Roleofcollectiveparticipation$; x_8–Role in formation of novel policies.

- Control variable – $\boldsymbol{u}(k) = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \in \mathcal{R}^2$,

$k = 1,2, \dots, N$is a two dimensional vector, representing the types of improvements on the game. We consider two types of improvements - first, adding new *functions of the games* -$\boldsymbol{u}_1$ and second, adding new *elements in the games construction* - $\boldsymbol{u}_2$. This control variable is tailored to the particular situation of game design implemented in METEMSS. For different situations, the vector and its dimension can be defined as representing different types of game modifications according to the current needs. The brainstorming sessions after each experiment of all involved experts are assumed providing relevant and objective qualitative view on the current game design similar to an expert system approach to game validation. The advantage of our system is in combining both qualitative and quantitative assessment of the designed games.

- For each child we define an output variable $\boldsymbol{y}(k) = [y_1, y_2, y_3]^T$, where the vector elements represents: y_1- motor development of the child, y_2- cognitive development of the child and y_3– social development of the child.
- For each game and each child we introduce the matrix $\boldsymbol{A} \in \mathcal{R}_{8\times8}$, representing the individual characteristics of the child in terms of the game parameters studied ($x_1 x_2 \dots x_8$). Since these parameters are independent, the matrix is diagonal with elements of the main diagonal $a_{11}, a_{22}, \dots, a_{88}$.
- For each game and each child we introduce the matrix $\boldsymbol{B} \in \mathcal{R}_{8\times2}$, representing how the child is influenced by the introduction of changes in the game (control type $u_1 and/or u_2$) .
- For each game and each child we introduce the matrix $\boldsymbol{C} \in \mathcal{R}_{3\times8}$, representing the influence of game parameters (vector $\boldsymbol{x}$) on the motor, social and cognitive development of the child (vector ***y***).
- Initial state – the initial values of the 8 variables are assumed (*implicitly*) known by the teachers working with each child i.e. extent to which a game corresponds to the child's needs;
- ***N***– number of experiments;

$$\succ \quad \boldsymbol{x}(\boldsymbol{k}+1) = \boldsymbol{A}\boldsymbol{x}(\boldsymbol{k}) + \boldsymbol{B}\boldsymbol{u}(\boldsymbol{k}); \boldsymbol{k} = 1, \dots, \boldsymbol{N}$$

$$\boldsymbol{y}(\boldsymbol{k}+1) = \boldsymbol{C}\boldsymbol{x}(\boldsymbol{k}), \boldsymbol{k} = 1, \dots, \boldsymbol{N}$$

Let denote the state after the *i*-th game from the *k*-th experiment by $\boldsymbol{x}(\boldsymbol{Game}_i^k)$.We assume that $\boldsymbol{x}(\boldsymbol{Game}_{i+1}^k)$ depends linearly on the state$\boldsymbol{x}(\boldsymbol{Game}_i^k)$and the magnitude of this dependence is determined by coefficients, drawn from the teacher scores after each game. These coefficients determine the transition matrices from the *i*-th to the *i*+1-th game from every *k*-th experiment, which are denoted as $\boldsymbol{A}_i^k \in \boldsymbol{\mathcal{R}}^{m \times m}$. These matrices are square, with nonzero elements along the main diagonal. Hence, we can describe the process of moving from game to game in the same experiment by a homogeneous linear system:

$$\boldsymbol{x}(\boldsymbol{Game}_2^k) = \boldsymbol{A}_1^k \boldsymbol{x}(\boldsymbol{Game}_1^k$$
$$\boldsymbol{x}(\boldsymbol{Game}_3^k) = \boldsymbol{A}_2^k \boldsymbol{x}(\boldsymbol{Game}_2^k)$$
$$\boldsymbol{x}(\boldsymbol{Game}_P^k) = \boldsymbol{A}_{P-1}^k \boldsymbol{x}(\boldsymbol{Game}_{P-1}^k) \quad (1)$$

After the completion of the *k*-th experiment we have information about the values of the 8 dimensions. If the result is not satisfactory from a designer point of view, we make improvements in the games. The improvements can be of either or both types -$\boldsymbol{u}_1$, $\boldsymbol{u}_2$of the described above.

These improvements are assumed the control actions on the process of designing games for enhancing the motor, cognitive and social skills of children, playing the games, within the proposed model. Therefore, the initial value of the *k*+1-st experiment is determined by a non-homogeneous linear system described by

$$\boldsymbol{x}(\boldsymbol{Game}_1^{k+1}) = \boldsymbol{x}(\boldsymbol{Game}_P^k) + \boldsymbol{B}\boldsymbol{U}^{\boldsymbol{k}}, k = 1,2, \dots, N, \quad (2)$$

where$\boldsymbol{U}^{\boldsymbol{k}}$is the control variable from the *k*-th to *k*+1-st experiment .

Matrix $\boldsymbol{B} \in \boldsymbol{\mathcal{R}}^{m \times 2}$ consists of coefficients, reflecting the expected by the teacher change in the game for enhancing the individual motor, cognitive and social skills of the participating children.

4. CONCLUSIONS

Some aspects concerning modeling CPS are discussed in the paper. The description of the process of game design for enhancing the development of motor, cognitive and social skills via succession of experiments from a linear control system perspective is presented. The authors believe it can be useful for future modeling of Cyber-Physical Systems in special education.

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