Poly-model description of Industry 4.0 cyber-physical systems

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Abstract. An actual task is to project a cyber and physical system (CPS) of industrial purpose based on a set of graphs and analytical models which describe the CPS behavior in the physical device level and in the virtual level. There is a scheme and description of CPS functionality principle as an automatic control digital system. The advantages of subtractive equations to describe a CPS are described and also the restrictions to use automatic models to synthesize the systems of higher order (digital production). There is a scheme and CPS functionality principle as a company cloud environment element is described (digital twin) which is based on a uml-diagram. There are advantages and disadvantages to describe a CPS with a uml-diagram given when they model CPS behavior as a part of digital production. There is a scheme given and CPS functionality principle is described using a Petri net model. It is clear that all three types of CPS description must be viewed together as a poly-model division which helps the CPS designers to create and research the project solutions of the Industry 4.0 digital production components synthesis.

1. Introduction

A cyber and physical system is a new type of technological equipment which is used in the modern industry to automatize the completion of complicated technological processes [1, 2]. Each separate cyber and physical system (CPS) can be integrated into existing digital company production infrastructure and also can be used as a base unit of technological equipment to project a new digital production [3, 4].

To project a cyber and physical systems is a complicated synthesis projection task because there are two components of different grade in existence to describe a functionality principle where an absolutely different mathematical apparatus is used [5, 6]. The CPS physical level is a production machine to complete technological operations automatically [7]. The CPS virtual level is the physical CPS device digital twin or a program model which is equal to the physical device [8, 9].

To realize synthesis project procedures of CPS physical devices separately from the CPS digital model synthesis is equal and vice versa is not reasonable. Consecutive synthesis of CPS components only increases the design project time and decreases the CPS program models quality [10, 11]. The most desirable form of project activity organization to synthesize a CPS is a parallel form of physical and virtual components projection which helps to develop the description accuracy and CPS quality (information similarity) and its digital twin which correspond the technical task (TT) requirements [12, 13].
Today a universal model does not exist which is adequate to the real objects to describe simultaneously all CPS properties in the parameter level of physical and virtual components [14, 15]. So an actual task is to design a poly-model division where each separate model characterize a restricted number of CPS specifications in the CPS physical level of representation but also in the level of its digital twin [16, 17].

A perspective thing to realize project activity of the CPS models synthesizing is a following way of description [18, 19]:

- recurrent equations accepted in the theory of automatic control to describe a CPS as a closed digital system of automatic control;
- a uml (Unified Modeling Language)-diagram accepted in the programming theory to describe the program modules different classes interaction;
- a Petri net accepted in the complicated technical systems projection theory to automatize the object and industrial technological processes synthesizing project activity completion.

2. CPS description as an automatic control digital system

A cyber and physical system as an element of industrial automatizing (physical device) consists of a calculation resources set, digital into analogue and analogue into digital converter, the drive and the system of measuring sensors. Such automatics element is of the digital systems automatic control class which functionality principle is described with subtractive equations.

CPS virtual environment in the digital twin form is placed in the company cloud environment. To represent both CPS components in the mathematical model format it is reasonable to use a homogeneous mathematical apparatus, which is used to form the CPS automatizing projection system algorithmic provision. CPS functional scheme as an automatic control digital system is given in figure 1.

\[
\begin{bmatrix}
\dot{X}_p \\
\dot{X}_c
\end{bmatrix} =
\begin{bmatrix}
A_p & 0 \\
0 & A_c
\end{bmatrix}
\begin{bmatrix}
X_p \\
X_c
\end{bmatrix} +
\begin{bmatrix}
B_p & 0 \\
0 & B_c
\end{bmatrix}
\begin{bmatrix}
U_p \\
U_c
\end{bmatrix},
\]

where \( \dot{X}_p, X_c \) - CPS conditions vectors in the physical (p) and cyber (c) levels; \( A_p, A_c \) - CPS matrix parameters in the physical and cyber levels; \( B_p, B_c \) - CPS control matrices; \( U_p, U_c \) - controlling values.

This equation unites controlling and being controlled influences which make an effect in the CPS physical device level and in the CPS digital twin level. Also it must be considered that values \( X_p \) transit...
not only CPS controller into digital twin virtual machine and values $X$, not only virtual machine are received by the CPS physical device controller. The industrial Internet of Things (IoT) makes the data exchange with the properties of the distribution environment which creates a delay in the CPS physical channel.

CPS automatic system digital control object in the physical level is the item manufacturing technological process work chamber. The CPS control object in the virtual level is the work chamber digital twin. CPS parameters calculation contained in the matrices must be realized with methods of the automatic control digital systems synthesis which are true for digital systems with a delay. The results of such calculation could be used as the base for the digital automatic CPS resistivity evaluation method.

Methods and theories of automatic control application to synthesize a digital CPS has a feature. CPS models unification to describe the digital production functionality in general normally is not used. This is because of automatics element description forms scaling which depend on the being studied system order. A digital production is an automatics system of higher order in comparison with a CPS so to synthesize smart factory controlling rules it is reasonable to use a simplified description for each CPS.

3. Cyber and physical systems description based on a uml-diagram

To describe an industrial purpose cyber and physical system with a uml-diagram [17] helps to represent projection object with the language of graphical descriptions being used into object oriented modelling for items controlled with a program. Uml-diagrams are generally accepted standards forms, which use graphical objects and the relations for their connection which helps to project in the system level some automatic cyber and physical systems.

The projection object (cyber and physical system) as a uml-model is a set of diagrams to define content, hierarchy structure, components interaction order, components conditions in each moment of time, behavior characteristics and other properties, which are necessary to make a description adequate for a real CPS production machine in the modelling environment.

CPS description with a uml-diagram helps [20] the cyber and physical systems designer to create and research standardized project solutions for modelling visualizing and projection object properties documentation, which are sufficient to form a fully digital twin model. An example how to describe a CPS with a uml-diagram component is given in figure 2.

![Figure 2. An example how to describe an industrial purpose CPS using components of a uml-diagram.](image-url)

A CPS description uml-diagram is used to represent a cyber and physical component placed in the company cloud environment. A cyber and physical component is a set of program codes specialized in relation to the different program classes which are represented by the procedure and functions libraries,
program modules and other. Each program class reflects CPS physical device behavior in the company virtual environment.

Most types of uml-diagrams (class diagram, components diagram, structure diagram and other) describe CPS cyber and physical component is a statistics form of the projection object graphical representation. Such diagrams can reasonably be used to describe the CPS digital twin architecture and to design CPS representation standardized forms in the digital company virtual environment. Some uml-diagrams (for example, a deployment diagram), which totally counts 13 may help to model CPS digital twin behavior in dynamics.

A uml-diagram as a form to describe a CPS is not a programming language so to design a program code which represents the CPS digital twin in the company virtual environment it is necessary to use specialized software projection environments. Such software projection environments are a part of automatic projection system installed in an instrument PC of the Industry 4.0 smart factories designer automatic work place.

4. CPS description based on Petri nets theory

A cyber and physical system as an industrial automatizing object functions in a discreet time so that why the principles of its functionality can be adequate to the real technological processes described with discreet and event models. Discrete and event models are used in the Petri nets theory [9] and represent the projection object as a set of graphical objects and relations to unite them.

Each technological operation is equal to a net model with a process with a fixed beginning and end. Technological operation completion finishing in a CPS is an event right after which the following system elements are engaged. The Petri nets theory is based on laws of reason and consequences connections which are realized in the event level. A Petri net can be used to describe processes in the CPS physical device and also to describe events in the CPS digital twin. Petri net schemes to describe a CPS are given in figure 3.

![Petri Net Scheme](image)

**Figure 3.** A Petri net scheme to describe the Industry 4.0 cyber and physical system operation.

Petri nets help to describe the behavior of separate CPS and its interaction in a digital production including parallel and recurrent ways of the technological operations completion by a group of CPSs.
The time in a Petri net is studied discretely to the events.

As shown in the figure 3 the technological operation inside the CPS work chamber is studied as an event which completion route (is drawn with arrows) is an inter-connection among operations and the process condition indicator — a marker being moved within a CPS net model.

CPS representation as a Petri net helps to research project solutions in step by step mode of the technological operation completion. A projection environment, which uses Petri nets models gives the CPS designer all research means for processes synchronism being completed in a digital production and production infrastructure resource sufficiency and other model properties which are actual for CPS physical and virtual components.

The significant advantages of Petri nets models, which are used to describe a CPS are:

- cascading ability of CPS separate models to organize technological sections models;
- clear representation for a designer of technological operations completion results.

The clear disadvantages of the Petri nets models to describe the cyber and physical production components are:

- Petri net structure is tightly approximated to a smart factory workshop structure;
- a Petri net cannot represent a self-organizing cyber and physical production because links among smart factory automatics elements change dynamically;
- to start a production of new product type it is required new Petri nets models, which describe the same Industry 4.0 smart factory and the product, which is already being manufactured of a particular type is done with previously applied model.

5. Conclusion

Cyber and physical system synthesis is a complicated project task, which requires from the designer knowledge in different study fields and scientific theories [21, 22]. Today such a project task can be solved only with special automatics means. CPS designer instrument provision include sets of technical provision for automatic work places and automatizing projection systems software the most important CPS projection properties of which are visualization ability and project solutions modeling, which helps to research different structural options and CPS functionality principles.

CPS technical projection in practice is done for the best (optimal in Pareto criteria) project solution in relation to which CPS dynamical characteristics corresponding to the technical task requirements are received. To unite project solutions to describe a separate CPS into a single project solution to describe the digital production functionality principle is the next project stage oriented to design the Industry 4.0 smart factory in general.

It must be taken into account that digital production synthesis is based on multi-operational CPSs private models integration of different classes which is not always a project solution based on models cascading in general technological chain of equipment. Such a property can be found only in a linear model in particular a Petri net model [9] for non-recurrent technological algorithm in a digital production. CPS description with the automatic control theory and with a uml-digram [17] is based on technological operations, technological processes and technological routes of item manufacturing so a digital production model design can be viewed as a separate project task, which use the scaling principles of CPS separate private models.

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