Methods and approaches for creation of digital twins of cyber-physical systems

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***Abstract**: The idea of creating and using digital twins has been strongly influenced by the process of integrating artificial intelligence methods with big data analytics of data from Internet of Things (IoT) devices. The concept of "Digital Twin" has become increasingly influential and culminating in the field of CPS. The main objective of the study is to define the basic requirements to the digital twins for cyber-physical system and based on the different definitions and components of digital twins, to summarize and analyze approaches, methods and tools used for their development. This analysis should serve as a basis for the development of a methodology for creating digital twins for cyber-physical manufacturing systems in the process industry.*

***Keywords**:* DIGITAL TWIN, CYBER-PHYSICAL SYSTEMS, INTERNET OF THINGS, MODELING, SIMULATION

1. Introduction

Transforming industrial production by merging digital technologies and the Internet with conventional industry is crucial to increase its competitiveness. This transformation is possible only on the basis of the development and validation of the theory of cyber-physical systems (CPS). Cyber-physical systems (CPS) are the integration of computational and physical processes. They use embedded computers and networks for the purpose of monitoring and feedback control of physical processes [1]. Through cyber-physical systems, the physical world connects with the virtual world to form the Internet of Things, Data, and Services. Some of the most promising applications of CPSs are cyber-physical production systems. The advanced CPSs are characterized by high dimensionality and complexity, including a variety of decision-making capabilities and control logic. The degree of communication of these systems with physical processes is also increasing, based on algorithms with increased efficiency and robustness. The amount of program code based on logic significantly exceeds traditional control algorithms.

In recent years, the concept of "Digital Twin" (DT) has become increasingly important and culminating in the field of CPS. The digital twin is a digital copy of the physical part of the CPS in real time and represents a bridge between the digital and physical worlds. The idea of creating and using digital twins has been strongly influenced by the process of integrating artificial intelligence methods with big data analytics of data from Internet of Things (IoT) devices.

The main goal of the research, presented in this paper, is to develop an approach and methods for creating digital twins of cyber-physical production systems. The project includes several main tasks related to some of the biggest challenges facing cyber-physical systems and their digital twins, such as: (1) defining the requirements for digital twins of cyber-physical systems; (2) analysis of the existing approaches and methods for the development of digital twins, as well as of the proposed software tools.

The paper is structured in 4 parts. After the introduction, in part two, a short analysis of the currently used definitions of the concept "digital twin" is presented and basic characteristics of digital twins are discussed. In order to achieve highly efficient, reconfigurable and resilient CPPS, in Part 3 the basic requirements to their digital twins are summarized and the basic tasks for their fulfillment defined. Part 4 presents an analysis of the currently used approaches, methods and tools for creation of digital twins for CPPS. The analysis should serve to create a methodology for creating digital twins of cyber-physical production systems for process industry.

2. Digital Twins – basic definitions and characteristics

2.1. On the definitions of digital twin

In recent years, the concept of "Digital Twin", which first appeared in aerospace technology and was proposed by NASA in 2010, has become increasingly influential and culminating in the field of CPS [2]. For the time being, there is no established definition of the term "Digital Twin", as there is a great variety among them, both in terms of functionality and areas of application. In [3] an analysis of the literature references on the topic of "Digital Twin" is done and their application in various fields discussed. A total of 29 definitions of the term "Digital Twin" are presented, cited in 75 literature references, most of which are scientific publications after 2016. It is noteworthy that the vast majority of definitions are applicable to the digital twins used in manufacturing. The analysis of the definitions shows that the concept "digital twin" is represented by the keywords "Virtual, mirror, replica" in 11 definitions, as "Integrated system" - in 5 definitions, as "Simulation, test, prediction" - in 4 definitions and such as "Clone, counterpart", "Ties, links" and "Description, construct, information" - in 3 definitions.

A similar study was conducted by Semeraro et al. in their systematic literature review of DT paradigm in [4]. They analyze the concept of Digital twins and define 5 clusters based on 30 different definitions. The key expression on which the definitions in cluster C1 are based is "life cycle phases", emphasizing the connections between the physical and virtual parts in all phases of the product life cycle. To this cluster belongs the first definition of the term "digital twin", published in 2004 by Grieves [5]. Definitions in cluster C2 define the DT as "the cyber part of Cyber-physical system", but unlike CPS, which focuses on the 3C capabilities (computing, communication and control) DT is focused on virtual models. At the heart of DT are models and data while at the heart of the CPS are sensors and actuators. The definitions in cluster C3 use the terms data, information and knowledge, while those in Cluster C4 reflect aspects of modeling the physical part and especially behavioral models. Cluster C5 brings together definitions that view DT as a "virtual system".

In order to clarify the concept of "digital twin", it is extremely important to draw a parallel with the concepts of "digital model" and "digital shadow". The digital model is a digital representation of a specific physical object, and there is no automatic data exchange between them. A change in the state of a physical object does not cause a change in the state of the digital object. The digital model can use manually entered data for the physical object, as shown in Fig.1. Manual data flows are illustrated in Figure 1 with dotted lines. Dense lines show automatic data flows. In the digital shadow, there is a one-way automatic data exchange from the physical to the digital object. In this case, the change in the state of the physical object causes changes in the digital one as well. Finally, with the digital duplicate, there is a two-way automatic data exchange, and any change in the state of the physical object causes a change in the state of the digital and vice versa.

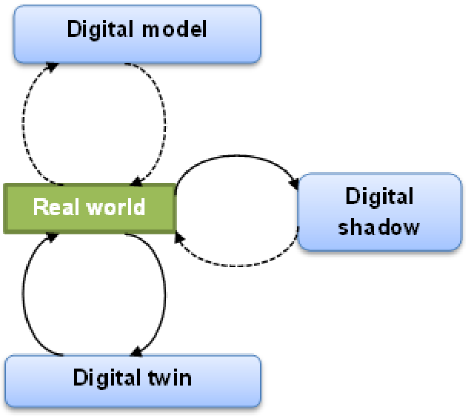

Fig.1: *Digital model, Digital shadow and Digital twin*

The digital twin involves the creation of digital simulation models of physical and technical objects that are dynamic, updated and changed according to the life cycle of the physical object [6]. Such dynamically updated models are able to constantly receive new information about the measurements from sensors of the physical part of the CPS, from sensors of the control devices and from the environment. The digital twin differs from traditional CAD / CAM models and is not just a simulation model, but a living, intelligent and constantly evolving model that follows the life cycle of physical part and covers various functionalities such as monitoring, control, optimization of processes, prediction of states and simulation of new configurations in connection with the maintenance and production of new products. The DT processes are possible through its continuous interaction, communication and synchronization with the physical twin. Higher hierarchical systems summarize new and past data and change model parameters [7]. The dynamically updated CPS model is essentially its digital twin.

2.2. Basic components of digital twins

The five-dimension digital twin model is illustrated in fig.2 and includes the following components: Physical entities (PE), Virtual entities (VE), DT data, DT services and Connections in DT. PE may be seen as the foundation of the DT and consists of devices and/or equipment and/or products. VE are counterparts of the PE and their different models such as geometric, physical, rule and behavioural adequately reflect the PE. The digital twin handles a wide variety of data with different backgrounds, different time scales and degrees of importance. DT data are the main driver of the digital twin. Services are an important component that significantly expands the functionality of digital twins, offering services related to modeling, simulation, optimization, monitoring, diagnostics, planning, forecasting and more. Finally, the digital twin is characterized by six connections, namely: (1) PE – service connection, (2) PE - Data connection, (3) PE – Model connection, (4) Model – Data connection, (5) Model – Service connection and (6) Service – Data connection. Through these connections the communication between the other four components is realized.

The Fourth Industrial Revolution uses device connectivity to make the concept of digital twins a reality for manufacturing processes. The digital twin creates a testing environment for products and control systems that impacts real-time data, which is critical to production accuracy, efficiency and security.

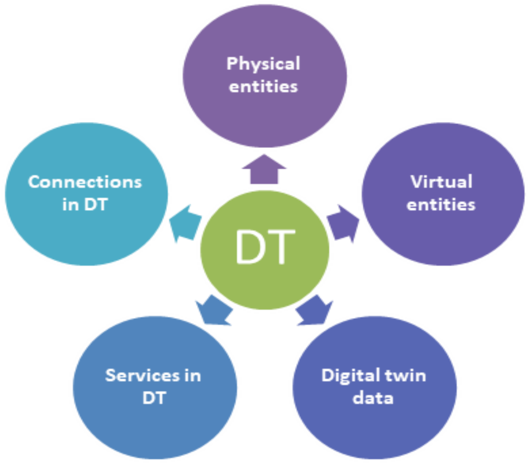

Fig.2: *Basic components of DT*

3. Requirements to the digital twins of CPPS

The main objective of the study is to summarize, analyze and apply approaches, methods and tools used in the development of digital twins of cyber-physical production systems that meet the following basic requirements [8]:

• Able to adapt to heterogeneous environments;

• They are able to work in the conditions of distributed networks: i.e. they must collect, transmit and store in a reliable way all the information provided by intelligent sensors and actuators through the use of the Internet of Things;

• Use modular open architecture;

• Include human-machine interfaces to provide access to specific information, to provide information analysis and to integrate easily accessible and reliable services to inform decision makers in real time;

• Be error tolerant: provided by encapsulating forecasting models in the control loop and checking the correctness of automation systems.

Achieving the above defined requirements to the developed digital twins is connected with solving the following main tasks:

• Creating and deploying a set of simulation models that have a specific purpose and range of validity. For this purpose, it is proposed to use the approach of model-driven development.

• Providing data and information on the various stakeholders.

• Achieving interconnectedness through semantic technologies.

• Automatic transformation of models between the different phases of the life cycle and creation of preconditions for verification of digital twins.

• Ensuring a connection between the real and digital worlds by ensuring synchronization between measured data and virtual presentation.

• The digital twin can be an element of the product itself and delivered with it, or it can be a stand-alone service that forms its own business models.

• Closing the feedback loop, not only in relation to the real system, but also to the earlier stages of the life cycle, can significantly improve the quality of development.

The next section of the report presents an analysis of the existing approaches, methods and tools used to create digital twins for cyber-physical systems.

4. Overview of techniques and platforms for creating digital twins

4.1. Methods and Techniques for sensing and measurements of physical part

To create high-precision digital twins, physical world information obtained through measurements and sensors is needed. It is necessary to use advanced principles and tools to measure a large number and variety of parameters that must be collected in real time. Various algorithms for primary data processing, for indirect estimation of non-measurable parameters, for data reconciliation, structural analysis, etc. can be referred to the used methods.

4.2. Methods and Techniques for improvement of physical part

As discussed in section 2.1 of the paper, the digital twins can improve the performance of PE. The main means for this are the advanced control systems, which are also very diverse in terms of principles of operation, structure, type of energy used by drive and power systems, and more. In addition, various services for planning, scheduling, optimization, etc. can be used, which contribute significantly to the improvement of PE.

4.3. Methods and Techniques for digital twin modeling

The modeling and simulation of cyber-physical systems and their components (embedded, mechatronic, etc.) is considered an important stage in the design, development and operation of CPS and their components. One of the most successful approaches used for CPS design is model-based design [9] and model-driven development [10], where models play a significant role in the design process.

Models and data are the core of the digital twin. However, creating virtual models as well as combining and analyzing data are complex tasks, which require in-depth knowledge in many areas. The following formalisms and tools are used to model and analyze various aspects of the DT:

• Equation-based models in tools such as MapleSim [11] and Modelica [12], suitable for modeling the physical part of the system,

• Function block models in tools such as Simulink [13], suitable for the design of control and simulation systems;

• Finite-state machines and labeled transition systems in tool such as LTSA [14] are best suited for modeling decision logic and communication protocols;

• Hybrid dynamic models in tools such as SpaceX [15] are useful for analyzing abstract unified continuous dynamics behavior and discrete switching modes;

• Network simulation models in a tool such as OMNeT ++ [16], useful for analyzing the properties of communication networks, such as packet loss and communication delay;

• Software models in tools such as SPIN [17], useful for analyzing whether the logic of the solution is implemented correctly.

• Various approaches and tools based on the UML profile for systems engineering SysML [18] and UML profile for real time embedded systems MARTE [19].

• Method for defining the requirements to the digital twin of cyber-physical systems using the "Requirements diagrams" of the UML profile for system engineering SysML

• Methods and models for formal verification and validation of digital twins for cyber-physical production systems - in the field of verification, research is focused mainly on model checking, based on timed logic and different types of automata: timed, hybrid, as well as their combined use. As tool for verification, the use of UPPAAL [20] for verification of the digital twin gives reliable results.

4.4. Methods and Techniques for DT data management

The digital twin is driven by data, it is its core. All phases of the data life cycle are included, such as: data collection, transmission, storage, processing, merging and visualization. Data is obtained in different ways - from software applications, from hardware and from the network. When working with data, different technologies and methods are used. This can be classified into groups, corresponding to the life cycle phases. Data storage is inextricably linked to databases, which are finding it increasingly difficult to cope with large volumes of data, their heterogeneity and unstructured character. Big data methods, NoSQL and NewSQL databases, as well as cloud storage are increasingly used. The data processing is related to the selection and extraction of useful information. For this purpose a wide variety of methods are available, such as: the rich palette of statistical methods, methods of machine learning, different types of neural networks, analytical processing systems and more. Data fusion can be performed by digital twin at different levels (raw data, feature level or decision level) by working with data from different sources and using various methods of artificial intelligence, Kalman filters, fuzzy sets, vector support machine, etc. The last phase of the data management life cycle is the visualization of the data, the purpose of which is to present in summary or detailed form specific information. There is a wide variety of visualization forms, such as different types of charts, histograms, charts, boards, and more. The principles of visualization are also different, such as based on geometry, pixels, icons based on layers, images and more.

4.5. Methods and Techniques for DT services

Services in the field of creating digital cyber-physical twins integrates knowledge and engineering principles from the fields of computer science, control theory, electrical engineering, electronics, mechanics, artificial intelligence and a number of engineering disciplines in order to enrich cyber-physical science with appropriate methods and techniques as special attention is paid to their application as services in 3 areas of cyber-physical production systems: (1) As a means of solving various tasks for monitoring, maintenance and increasing the reliability of equipment; (2) As a means of analyzing the behavior and commissioning of equipment and devices, and (3) As a tool for decision making through engineering and statistical analysis.

Different conventional simulation tools are available, such as those using the finite element method, the Monte Carlo method and various CAD / CAE systems, such as Dessault Systemes [21], Matlab / Simulink, Verosim [22] and others. However, the emphasis is on software tools that cover the entire development lifecycle, meet the requirements of Industry 4.0 and are based on semantic meta-models, such as AutomationML [23] and the MAYA project. Among the most popular and used tools are Predix [24], IoTIFY [25], BoschIoT Suite [26], Seebo [27], ThingWorx Operator Advisor [28], etc., which must be analyzed in order to select a suitable tool for the development of digital twin of batch reactor.

4.6. Methods and Techniques for connections in DT

The suggested methods for the six connections in the digital twin are shown in Fig.3.

The development and implementation of digital twins is still in its infancy, so the first tools for their development are owned by large companies such as GE and others. The following well-known digital twin platforms and tools are of the greatest importance for the production area:

• „Predix" of General Electric [24];

• „Mind Sphere" of Siemens [29] – it adopts Industry 4.0's concept of connecting machines and physical infrastructure via the cloud

• „Thing Worx" of PTC [28, 30] – is focused on collecting data from IIoT/IoT devices and presenting a user interface that facilitates data analysis,

• „Watson IoT platform" of IBM [31] – it is available as a universal tool for data from IoT devices that can be used to control systems in real time through data, collected from millions of IoT devices.

All the above mentioned platforms are paid. Also of interest are some open platforms, such as the Ditto project in Eclipse [32] and Imodel.js, developed by Bentley Systems [33] that is a platform for creating, accessing and building digital twins.

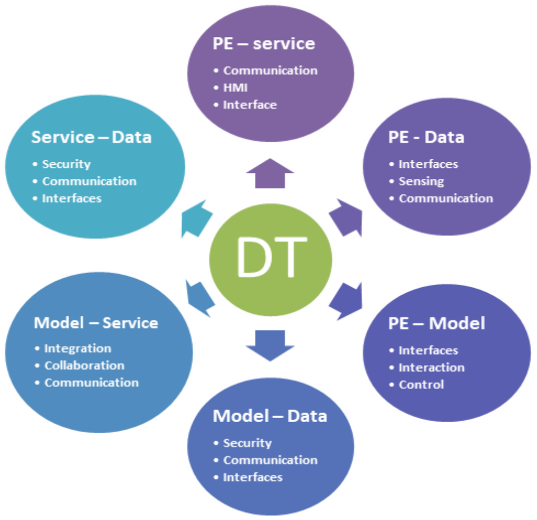

Fig.3: *Connection methods*

4.7. Platforms and tools for digital twins

Conclusions

The study presented in this paper includes an analysis of the requirements for digital twins of cyber-physical production systems, an overview of the approaches and methods for creating digital twins of cyber-physical systems, as well as a comparison of different approaches. The next step is the development of approach and methods for creating digital twins of cyber-physical systems, as well as for their formal verification and validation. An important stage in research project is the creation of a digital twin of a specific cyber-physical system, implemented as a pilot demonstrator.

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