A Digital Twin Model-Driven Architecture for Cyber-Physical and Human Systems

Milad Poursoltan, Mamadou Kaba Traore, Nathalie Pinède, and Bruno Vallespir

Abstract The cyber-physical and human system (CPHS) is widely recognized as a key infrastructure to support the future developments in healthcare, industrial manufacturing as well as in many other areas. In consequence, there is an increasing interest in tools, techniques, and technologies to advance the understanding and provide unchallenging improvement of CPHS. Digital Twin is a growing research topic that can equip the CPHS with high-fidelity mirroring, monitoring, controlling, and active functional improvement. The central question in this study asks in what way Digital Twin should be designed and developed for a CPHS. An architecture was required to answer this question and build upon model to define guidelines and requirements for valid Digital Twin. Thus, this study provides much new knowledge about the emerging role of Digital Twin in CPHS by using a model-driven architecture (MDA) approach with the perspective of SD logic. In addition, in the presence of human roles, the given MDA is beneficial for providing abstractions of Digital Twin from different viewpoints, communication with non-technical experts, and decision support, system design, and improvement.

Keywords Cyber-physical and human systems · Digital Twin · Model-driven architecture · SD logic

1 Introduction

CPHS comprises cyber, physical, and human components designed for controlling, monitoring, and improving through an integrated system. As a complex system, CPHS understanding is hard for humans, and intervention in such a system is even more difficult. Digital Twin has represented itself as a new concept in the history of smart technologies' developments that has been thought of new solutions for

M. Poursoltan (✉) · M. K. Traore · B. Vallespir
University of Bordeaux, CNRS, IMS, UMR 5218, 33405 Talence, France
e-mail: milad.poursoltan@ims-bordeaux.fr

N. Pinède
Bordeaux Montaigne University, MICA, 33600 Pessac, France

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cyber and real-world fusion. As an emerging CPHS enabler, Digital Twin is able to depict, pause, resume, save and restore the current states of human and real objects in the cyber world, make the simulation of real-world scenarios in a cyber world and apply decisions in the real world. To benefit from these advantages, Digital Twin has an increasingly important area in CPHS. However, a major problem with the application of Digital Twin in the CPHS is the lack of a framework in order to build, conduct and develop it in the CPHS. A considerable amount of literature has tended to focus on Digital Twin as a techno-centric concept and study Digital Twin for physical assets rather than integrated systems. Some other studies structured the Digital Twin for specific aspects of the cyber-physical system (CPS) and considered humans as a side factor. This paper gives thought to Digital Twin as a cyber-human and service-centered system that benefits a bilateral data flow with human and physical parts in order to mirror and controlling of CPHS.

Embedding Digital Twin in CPHS encompasses some areas of concern. It raises several open research questions about process design, development process updating, synchronization and configuration of models, as well as the role of humans that have not yet been thoroughly explored. Due to the fact that the Digital Twin uses the meta-model concept to merge different cyber tools together in a seamless environment, the architecture-focused concept of MDA seems to be an appropriate way to decompose and develop Digital Twin. In contrast to the MDA of software development that focuses on code generating, the provided MDA zooms in on process flow and model management. In other words, it is applied to show how to map needs to the submodels at the appropriate level of automation and how to make models at appropriate level of self-synchronization and self-configuration.

This study is a part of work with the purpose of providing a methodological framework and platform for learning, validation and improvement of CPHS based on modeling.

The overall structure of the study takes the form of five sections. Section 1 provides literature review, Sect. 2 describes the position of Digital Twin in the CPHS and its subsystems, Sect. 3 illuminates the role of human in the Digital Twin, Sect. 4 is concerned with our proposal MDA, finally, the conclusion gives a brief summary and areas for further researches.

2 Literature Review

The term "cyber-physical system" has been introduced by the National Science Foundation in the United States in 2006 in order to guide a new generation of engineered systems [18, 21]. In recent years, there has been an increasing amount of literature on CPS, and subsequently, diverse forms of this concept have been developed for different application fields. (e.g., medical cyber-physical systems (MCPS), cyber-physical production systems (CPPS), etc.). CPHS has received more attention as a pivotal CPS form in various fields. There are disagreements in the literature on the term of CPHS, and it has been called by different names like human cyber-physical systems (e.g. [11, 23]), Human in the loop cyber-physical systems (e.g. [9, 28]) and human-centered cyber-physical systems (e.g., [1, 14]) however they are of the same opinion that CPHS is an arrangement of human, cyber and physical parts to perform tasks with the aim of achieving specific goals [17, 24, 33]. We would like to go one step beyond this idea and propose a more comprehensive definition for CPHS. We represent it as a system of systems (SoS) that combines humans as an integral element within cyber and physical systems and links behavioural patterns and human science in the different areas of the cyber and dynamic physical world in order to design or improve CPS with respect of the humans' diverse physical, cognitive and social capabilities. Nunes et al. [24] have presented a reference model to specify processes in order to define the human roles in the CPHS. This model includes three main processes termed: data acquisition, state interface and actuation. The first process refers to gathering data from humans, the second process addresses the processing of acquired data in order to show human physical and psychological states. Finally, actuation deals with the actions that may be performed in the system. Recently, the role of humans in the CPS has been more highlighted in manufacturing than in other fields. (e.g. [8, 10, 12, 31]). This may come from the fact that the current trend of Industry 4.0 tends to change the role of humans in manufacturing systems.

Costa et al. [5] argue that humans have always taken part in the manufacturing processes, and the integration of humans into the cyber-physical production system is a challenging task; nevertheless, the recent advances in technologies introduce several solutions to facile this integration. Krugh and Mears [17] believe that despite the undeniable role of humans in smart manufacturing systems, the human's role has not been clearly defined in CPS, so it tries to build a complementary cyber-human system to provide a unified CHS/CPS architecture for smart manufacturing. Communication within the cooperation between human and technological actors through CPS has been discussed in [2]. Lee et al. [19] have presented a 5-level CPS architecture for developing and deploying the CPS in manufacturing systems and have placed digital models at the cyber level of this architecture as a central information hub.

Digital Twin is a technology that provides high-fidelity mirroring of physical entities in cyberspace for various purposes such as simulation, real-time synchronization, virtualization, and communication [12, 13, 15, 22, 25, 26, 32]. Three subcategories of the Digital Twin have been identified in [16] based on the differentiation in terms of their levels of integration as follows: Digital Model that has no automatic data flow between physical and cyber objects, digital shadow that possesses an automatic data flow from physical to cyber objects and Digital Twin that benefits bilateral automatic data flow between physical and cyber parts.

In the last few years, some frameworks have been brought up for Digital Twin design, application and, development for various purposes. Zheng et al. [32] have proposed an application framework of Digital Twin for product lifecycle management that encompasses physical space, virtual space, and information-processing layer. They have placed bidirectional mapping, intelligent decisions, and interoperability between physical and virtual space into their framework. A unified Digital Twin framework has been proposed in [26] for the real-time monitoring and evaluation of manufacturing systems. This framework has been developed within software-defined control approach using a set of centralized data management infrastructures, a central controller, and a set of applications. Digital Twin has been placed in a central controller as the key piece of a software-defined control. A reference framework has been reported in [15] for developing the Digital Twin of physical entities, which are parts of CPS. This reference regards the high-level purpose of Digital Twin as concrete services and represents four main blocks (virtual entity platform, data management platform, physical entity platform), and service platform, to structure Digital Twin within CPS.

The challenges of Digital Twin development have been discussed in [25], and a Digital Twin structure has been developed within a CPPS. This structure defines "plant model abstraction manager" and "network component models" in order to manage and coordinate between twins, while each twin comprises models and controller.

To the best of our knowledge, there has been no structured study about the architecture of the Digital Twin in the CPHS and far too little attention has been paid to the role of humans in the Digital Twin. To cover these issues, a new architecture using the MDA approach is developed in the current study to take humans into account in order to design and develop the Digital Twin for CPHS.

3 Digital Twin in the CPHS

Multiple, heterogeneous, distributed,and occasionally independently operating systems that are embedded in a network, form of SoS [6]. As a type of SoS, the CPHS consists of humans, cyber and physical systems, and the relationship between these systems are established through three subsystems termed cyber-physical, cyber-human and human-physical system [33]. According to [27], physical systems refer to the natural and human-made systems built through the laws of physics and operating in continuous time. These systems generally are composed of physical objects, sensors, actuators and communication networks. Cyber systems are related to computational systems carried out in cyberspace. As a cyber component, Digital Twin is placed in the cyber space [19] and is able to interact bilaterally with human and physical components with the help of cyber-physical and cyber human systems, as shown in Fig. 1.

Cyber systems should proactively use the help of humans to perform the operations when needed [29]. The cyber-human system (CHS) aims to acquire data from humans and feedback information to humans in order to enhance control and monitoring of CPS or assist humans in performing their jobs more safely and efficiently in the real-world [17]. Human-physical systems (HPS) are formed when human needs to be equipped with the physical systems to communicate with cyber systems (e.g., when an individual carries a GPS tracker) or human's task must be performed with the help of physical systems (e.g., using the elevator) or physical systems requires human to

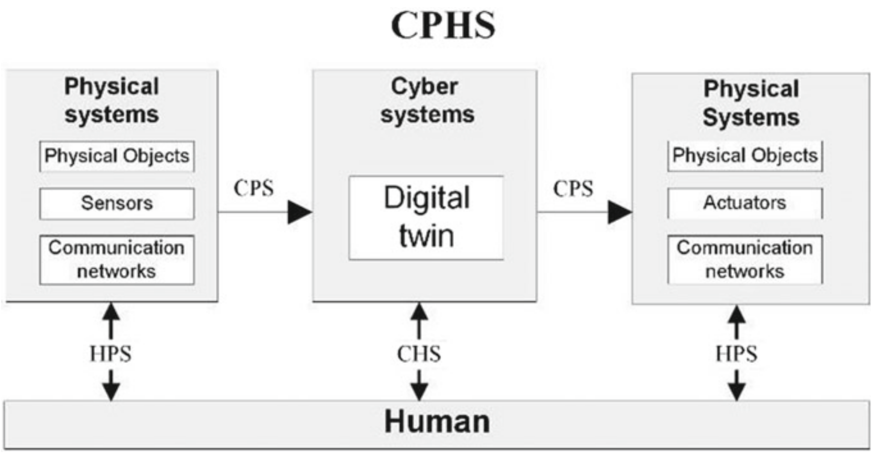

Fig. 1 Position of Digital Twin in the CPHS

complete jobs (e.g. semi-automated robotic systems). Like CHS, the CPS has a two-way relationship between cyber and physical systems for receiving and sending data. Figure 1 illustrates CPHS components and their subsystems.

Every system with a large network of components, many-to-many communication channels, and sophisticated information processing, can be referred to as complex which makes the prediction of system states difficult [20]. Adopting this definition, we can say that Digital Twin is a complex system since it deals with heterogeneous and massive amounts of data and various data processing, multiple models and applications, as well as diverse communication links with physical systems and humans. Humans get involved in many cyber systems by design or implication [7]. This indicates a need to understand the various perceptions of humans that exist for the design and operation of the Digital Twin. Participation of human in Digital Twin can occur through design, computation, communication, and control. To represent and organize our knowledge about human's roles in Digital Twin, we use graphical concept mapping, which comprises concepts (represented by boxes) and relationships between pairs of concepts (represented by labeled links) (see Fig. 2).

Generally, models in Digital Twin are used to communicate an understandable situation of the real world to perform analysis and resolve problems as well as keep knowledge to be used in a current or further situation. Each model differs in some form of functionality, complexity, integrations and, technologies. The goals of models in Digital Twin can be categorized into optimization, diagnostic, and prognostic. It is essential to evaluate how well cyber systems mirror their physical counterparts. One of the most critical processes that human gets involved in is to verify and validate the models in Digital Twin. Given that humans do not perform a task in the same manner and also because of human performance constraints and cognitive limitations, the presence of humans in such a complex system makes it difficult to predict the behaviour of the system. However, Digital Twin needs to be evolved so it should

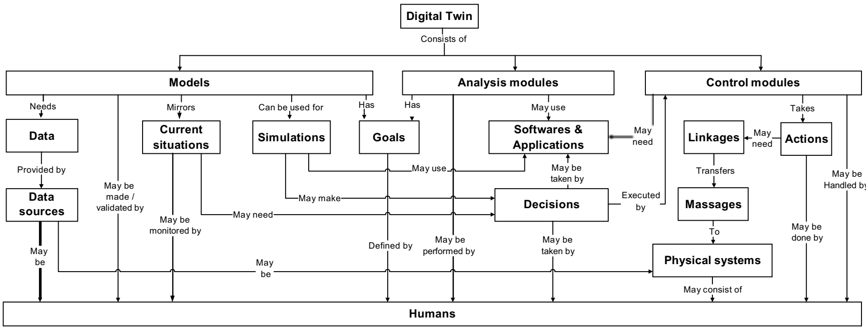

Fig. 2 Digital Twin concept map for CPHS

be flexible and human adaptability can also play a significant role in Digital Twin's resilient system and also keep the CPSH stable.

4 Proposed Framework

The proposed methodological approach for this study is a mixed methodology based on MDA and SD logic. The using of both concepts brings organized model development as well as interactive value creation for CPHS.

The central idea behind an MDA is to separate the specification of system from the platform details that system uses to be executed [4]. Platform is defined as the methods, technologies and subsystems under which system is lunched. Chong et al. [3] introduce reusability, interoperability and portability as three principle goals of MDA through architectural separation. Tyson et al. [30] have used three categories of interoperability for service and data interoperability as technical interoperability, semantic interoperability and process interoperability. They believe that model-driven conceptual architecture can be utilized to deal with interoperability challenges and provides better integration of SoS and also facilitates communication between different components of a SoS.

A Digital Twin is not deployed on a unique platform, so it should be designed and developed from a platform-independent perspective. This reveals that Digital Twin is placed at the level of the platform-independent model (PIM) of MDA. The implementation of such an architecture is performed through heterogonous platform-specific models (PSMs). Thus, developing Digital Twin through the MDA approach provides not only an early evaluation of the overall system and focuses on platform independent solutions before full implementation but also provides interoperable capabilities for its platform dependent models in order to be developed under their specific platform.

In addition, the applied MDA approach allows the Digital Twin structure to be generic enough to do analysis without worrying about technologies and cyber systems in which models and applications will be executed.

The high-level Digital Twin's target is to provide concrete services [15]. The foundational proposition of SD logic for Digital Twin is that cyber and real space are fundamentally concerned with the exchange of service. The key to these services is to create value through mutual cooperation. In other words, human, cyber and physical parts cannot deliver individually the value of Digital Twin to the CPHS but can participate in the creation and offering of value propositions. The successful implementation of Digital Twin will need to create value and require the right mix of data, models and actions.

Provided architecture (see Fig. 3) includes three phases termed feeding, modelling, and servicing comprising data, model and action modules. Each module has a process and actor dimensions. The overall level of participation of cyber actors indicates the degree of automation of the system. The data managing process deals with activities regarding access, storing, updating, and ensuring data reliability. Modelling has various processes to ensure appropriate mirroring and analyzing situations. Each

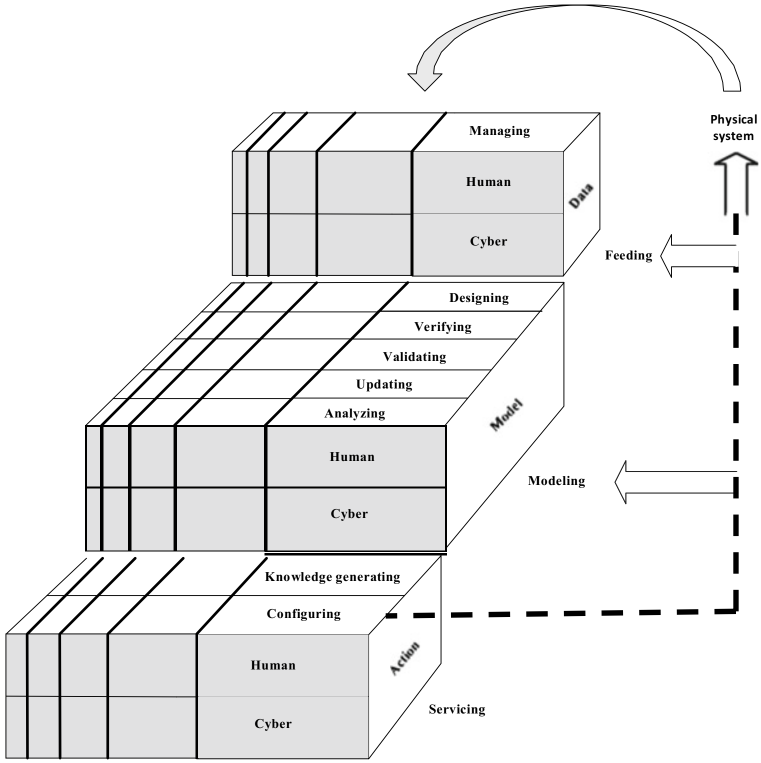

Fig. 3 Digital Twin architecture for CPHS

model in Digital Twin may serve differently so the activities of each process may vary from one model to another. Final services may lead to knowledge generation or reconfiguration of cyber or physical systems. Knowledge generation is related to the result of modelling which do not bring any configuration into systems (e.g., when scenario testing doesn't show desirable result), but the results need to be conserved as knowledge.

Reconfiguration may occur in the cyber or physical systems. Any reconfiguration in physical systems may change the behaviour of physical systems and, consequently, may impact the behaviour of cyber systems.

The usage of the framework can be illustrated briefly by an example (see Fig. 4). Patient, ambulance, nurse and hospital equipped with sensors or/and communication equipment are the sources of data that feed the cloud database. Data is processed in cloud environments. By using real-time data from the cloud, the practitioner runs the digital models of CPHS's components. Analysis may be performed to diagnose abnormalities, predict the future condition of the patient or estimate medical care arrival time. Decisions may lead to adjust electrics patient devices, coordinating services in the hospital, sharing the patient's condition with the hospital, alerting the ambulance and providing recommendations for the nurse.

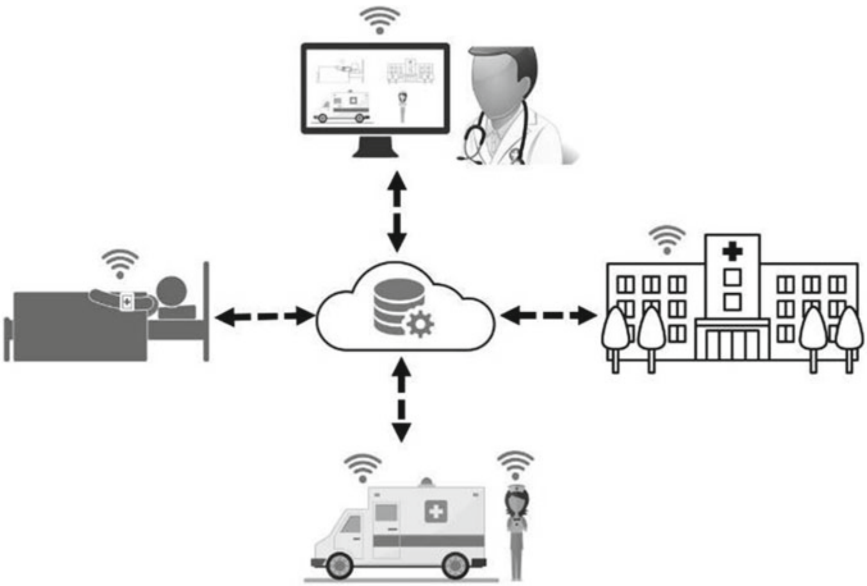

Fig. 4 Illustration of the use of the Digital Twin architecture in a CPHS

5 Conclusion

As pointed out in the first of this paper, the aim was to answer the question of in what way Digital Twin should be designed and developed for a CPHS. This paper has argued the position of the Digital Twin in the CPHS and provided a new Digital Twin concept map. Then we proposed a new framework and illustrated how value could be generated through services in Digital Twin in a cooperative way. The ideas discussed in this article reflect the thinking of humans in the loop. If the debate is to be moved forward, a better understanding of how Digital Twin can be optimized by human. Considerably, more work will need to be done to determine the level of automation of Digital Twin in the CPHS. In addition, it would be interesting to assess the effects future research will explore the role of Digital Twin in a value-producing system within the context of decentralization and autonomy, where humans actor plays a key role.

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