A Meta-Model of Cyber-Physical-Social System: The CPSS paradigm to support Human-Machine collaboration in Industry 4.0

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Abstract. The 4-th industrial revolution (Industry 4.0) heavily relying on the concept of Cyber-Physical systems(CPS) has transformed the manufacturing industry into an intelligent environment. Advances in manufacturing and automation industries created hyper-connected industrial ecosystems that are not limited to smart production but also facilitate organizational integration. Hence, fostering the creation of collaborative, networked and intelligent industries. One of the emerging advances in the digital transformation of industries is the creation of environments where humans work in close collaboration with sensor enabled smart machines and robots. Particularly the close involvement of humans in such smart environments challenges system designed methodologies mainly because human aspects are not considered in CPS design frameworks. In this paper we present an approach to support this aspect of Industry 4.0 taking a Cyber-Physical-Social system (CPSS) paradigm to incorporates human aspects with the existing notion of CPS. We propose a meta-model of CPSS that can serve as a framework to design systems involving human and CPS collaboration.

Keywords: Industry 4.0 · Cyber-Physical-Social system · Meta-model · Human-Machine collaboration.

1 Introduction

The introduction of Cyber-physical systems (CPS), linked with advances in Information and communication technologies (ICT) has been the major driving force for the 4th industrial revolution [10]. These advances are empowering an era of digital transformation by offering connectedness and intelligent computation. Thus, promoting collaboration in production systems and organizational integration. Industry 4.0 particularly in manufacturing and automation fields forecasts promising solutions for the the future of digitized industrial ecosystem. One of the major expected outcomes of this revolution is the allocation of tedious and repetitive tasks to intelligent machines and robots [8, 12]. According to (Derler et al., 2013) "CPS describes a broad range of network connected, multidisciplinary, physically-aware engineered systems that integrate embedded computing (cyber) and technologies into the physical world. Such design approaches mainly incorporate the orchestration of physical devices and phenomena with computational nodes". The era of digital transformation is evolving faster than expected. One aspect of this evolution is to enhance advanced collaboration mechanisms in industries; particularly collaborations involving humans and machines [6, 7, 11, 13]. In these industrial contexts the nature of relation between humans and CPS is demanding not only task execution but also cognitive interaction. However, the current design approaches of industrial systems heavily rely on the core concept of CPS lacking efficient means to link technical and social prospects. This degrades quality of collaboration and can also compromise safety[5] resulting challenges to deliver and cope with the speed of evolution in Industry 4.0. Particularly the main challenge originates from the complexity of human nature, as people usually do not follow rules that are not matching with their way of thinking, preferences, needs and capabilities. Additionally each individual is unique and her behaviour under different circumstances is driven by complex phenomenon which has not yet been fully understood.

As Industry 4.0 is enhancing such collaborative industrial environments, the need for a design framework that goes beyond CPS is not far fetched. Hence, a system design methodology that incorporates human aspects will be complementary to the future of digitized industrial ecosystem. In this work we propose an approach to support this prospect by taking a Cyber-Physical-Social system (CPSS) paradigm. CPSS is an emerging concept developed by integrating a social aspect to the existing CPS notion. We first conceptualise the notion of CPSS through a definition that is grounded on a generic framework provided by the theory of systems. Then we illustrate all kinds of relationships that may occur between systems, subsystems and components in a system of CPSSs. Ultimately we present a meta-model of Cyber-Physical-Social systems which can serve as a base framework for the designing of complex systems that involve close collaboration of humans and CPS for the future Industry 4.0 applications. Finally we provide a case study example to demonstrate how the extended meta-model can be used to obtain a compact model, which can then be used for further analysis.

2 Cyber-Physical-Social System (CPSS)

From a general perspective CPSS is the co-joining of Cyber-Physical System (CPS) and Social system. CPS refers to a generation of systems with integrated computational and physical capabilities strongly related to the 4-th Industrial Revolution [1]. The Social aspect refers to interacting individuals, having each their own cognition, preferences, motivation and behaviour [2, 4]. The development of CPSS is still in its infancy. In this work we adopt the definition and conceptualisation of CPSS proposed in [2] that is grounded on a generic framework provided by the theory of systems and formally defined as follows.

Definition 1: ***CPSS*** *is a system strictly composed of a Cyber-Physical system (CPS) and a Social System (SOS), in which the system's components interact in a virtual and physical environment*, where CPS and SOS are defined respectively as follows.

A ***CPS*** *is a system encompassing all the systems and subsystems of Cyber and Physical Systems, their components and the interaction between them, as well as integration of computation with physical processes*

A ***Social System*** *is a system that comprises interacting individuals, having each their own cognition, preferences, motivation and behaviour.*

Digitized industrial ecosystems emerging as a result of rapid advances in Industry4.0 are environments where humans and sensor enabled smart devices cohabit a physical space of collaboration. Hence, can be seen as CPSS environments. Following this we present a meta-model of CPSS that can support such collaborative system design approaches in Industry 4.0.

3 A Meta-Model of CPSS

In this section we illustrate all kinds of relationships that may occur between CPSSs, CPSs, SoSs and their components (cyber, physical, Social). Then we ultimately formalise the CPSS paradigm through a meta-model by extending the one proposed by (Lezoche and Panetto, 2018) for CPS.

3.1 Towards a meta-model for CPSSs

We define a system of CPSSs as a tuple
CPSSs = $\langle\, \mathcal{CPSS}, \mathcal{CPS}, \mathcal{SOS}, \mathcal{P}, \mathcal{C}, R^P,\ R^C,\ R^S\,\rangle$, $\mathcal{CPSS}$ is a set of CPSS. Each individual CPSS of the set $\mathcal{CPSS}$ is a combination of $\mathcal{CPS}$ and $\mathcal{SOS}$, (i.e, a single CPSS = $\langle\, \mathcal{CPS},\ \mathcal{SOS}\,\rangle$), where $\mathcal{CPS}$ is a set of CPSs and $\mathcal{SOS}$ is a set of one or more humans. The set $\mathcal{CPS}$ has at least one CPS (i.e, $\mathcal{CPS} \neq \emptyset$), the same is true for the set $\mathcal{SOS}$. Each individual CPS of the set $\mathcal{CPS}$ is a combination of cyber components $\mathcal{C}$ and physical components $\mathcal{P}$. An atomic CPSS is one that is composed of atomic CPS and SOS (i.e, containing one cyber, one physical and one human component). R^P, R^C, R^S represent physical, cyber and social relationships between system's components as discussed below.

Relationships :
Here we define the main types of relationships that may exist within/ between systems, subsystems and components of CPSS and it's environment.

$\mathbf{R^P}$ (Physical relation):- refers to the relation between systems, subsystems and components to be physically connected and the transmission of physical objects between components.

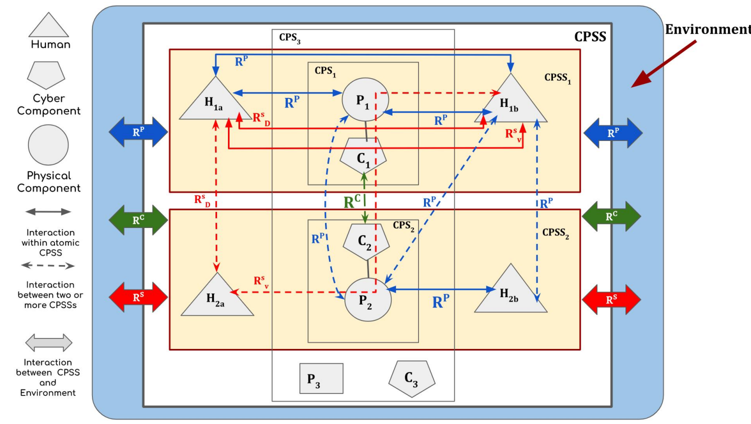

Fig. 1. A composite CPSS

$\mathbf{R^C}$ (Cyber /Virtual relation):- refers to the presence of an information flow /control or sharing of computational node between/within systems, subsystems and components.

$\mathbf{R^S}$ (Social relation):- refers to the flow of information/ transfer of knowledge between humans. It also reflects cognitive ties that govern human behaviour. A social relationship within a system of CPSS takes two different forms. *i. A direct communication/ Conversation in the physical world (R^S_D). ii. Indirect communication through a CPS medium (R^S_V)* Figure 1 is an example of a system of CPSS, that is composed of two CPSSs and one CPS. In a system of CPSS three forms of interaction can occur. *i. Interaction within a single CPSS (among subsystems and components), ii. Interaction between two or more CPSSs, and iii. Interaction between CPSS and it's environment.* This example illustrates all types of relationships and forms of interactions that may exist within a system of CPSS.

The first outer yellow box represents a single CPSS ($CPSS_1$) which is composed of a CPS (CPS_1, most inner box) and a Social system of two human components H_1a and H_1b. CPS_1 is composed of a Physical component (P_1) and a Cyber component (C_1). $CPSS_2$ is another CPSS containing (CPS_2, H_2a, H_2b, P_2, C_2) for the corresponding components in $CPSS_1$. CPS_3 is a CPS with it's own components P_3, C_3. The blue region represents the external environment.

I. Interactions within a single CPSS :
Interactions within a single CPSS can be Physical, Cyber or social relations as illustrated on figure 1.
$\mathbf{R^P}$:- Physical relations within a single CPSS can exist between Human and Human (R^P - the top blue line connecting H_1a to H_1b), between Human and Physical components (R^P - the two blue lines connecting H_1a to P_1 and H_1b to P_1), or between two or more physical components. This type of interaction is

visually observable as it involves direct contact in the physical world.
$\mathbf{R^C}$:- Cyber relations within a single CPSS refer to the sharing of computational resources and the flow/control of information among the different components of the system.
$\mathbf{R^S}$:- A social relationship within a single CPSS takes two different forms. *i. A direct communication/ Conversation in the physical world (R^S_D). ii. Indirect communication through a CPS medium (R^S_V), represented by the two red lines connecting H_1a to H_1b respectively.*

II. Interactions between different CPSSs :
$\mathbf{R^P}$:- A direct physical contact between Humans (H-H), Physical components (P-P) or Human and Physical components (H-P) represented by R^P the blue dotted lines on figure 1, connecting (H_1b to H_2b), (P_1 to P_2) and (H_1b to P_2) respectively.
$\mathbf{R^C}$:- Is a virtual information flow/ control between cyber components of two or more CPSSs. Represented by R^C the green dotted line on figure 1, connecting C_1 and C_2.
$\mathbf{R^S}$:- A social relationship between different CPSSs also takes two different forms as it is within a single CPSS (direct communication - R^S_D and through a CPS medium - R^S_V , red dotted lines connecting (H_1a to H_2a) and (H_1b to H_2a) respectively.

II. Interactions between CPSS and external environment :
Physical, Cyber and Social relations represented by R^P, R^C, R^S (Blue, Green and Red arrows respectively) connecting the CPSS to different systems, subsystems and components of the external environment.

3.2 CPSS Meta model

The extended meta-model CPSSs = $\langle\ \mathcal{CPSS}, \mathcal{CPS}, \mathcal{SOS}, \mathcal{P}, \mathcal{C}, R^P,\ R^C,\ R^S\ \rangle$ is presented in UML 2.0 notation on Figure 2. The elaborated meta-model concerties the broad definition of CPSS. It visualises the minimum requirement for the emergence a CPSS as an atomic unit and the formation of a composite CPSS. The emergence of a CPSS requires the combination of triplets, at least one social component and one physical component that is linked to at least one cyber component. Atomic CPSS is one that emerges when this minimum requirement is fulfilled. Accordingly each atomic CPSS is given a single social component which represents a human, a single physical component which models it's mechanical behaviour and a single cyber component for computational functionality. This is presented in the meta model by the relationship *'form a single CPSS'* between the classes 'Social component', 'Cyber component' and 'Physical component'. As an extension to the composition of complex CPSS the aggregate relation *'logically includes'* is introduced to the model. An atomic CPSS *'is physically part of'* a composite CPSS and with inheritance relation it can lend it's functionality. The class of 'Cyber-Physical-Social production system (CPSPS)' can be viewed

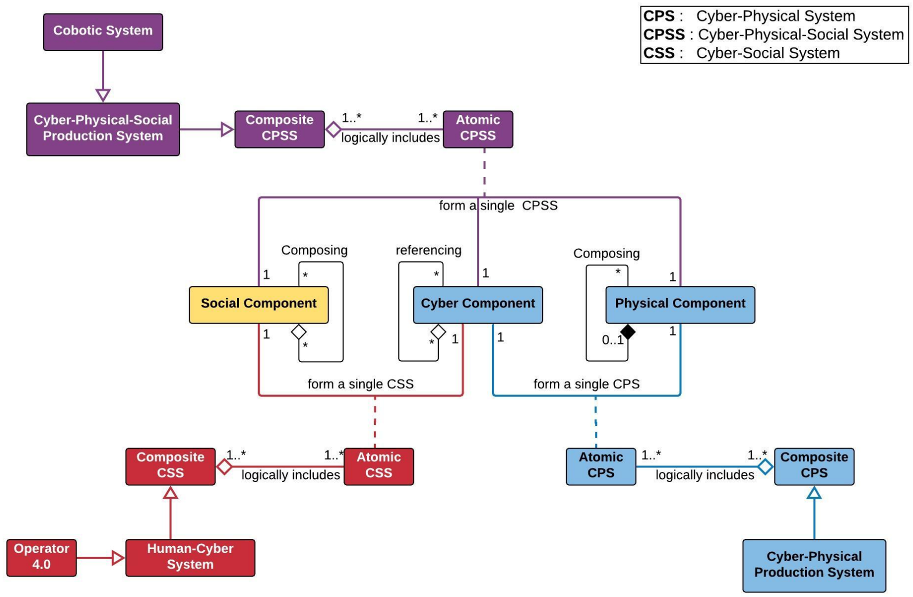

Fig. 2. Meta-model of CPSS *: The blue concepts depict concepts from (Lezoche and Panetto, 2018)*

in the model as a subclass of composite CPSS and Cobotic system is a subclass of CPSPS. Whenever a system is in the relation *'is physically part of'* this also entails that it is being *'logically included'* in that system, similar analogy used in [1]. When the presence of 'Social component' is omitted an atomic CPS can emerge represented by the relationship *'form a single CPS'*. The meta-model we presented in this work is a partial extension and is subject to further extension /modification in an effort to model complex properties and interdependence between components. Additionally we introduce the emergence of Cyber-social system (CSS) in the model, which is not a concept developed currently but possibly in the future. Despite the terminology CSS is currently being used to refer an online social network, in this context the future CSS could imply a system where human cognition is supported through cyber components. This concept is also partially shared by (Romero et al., 2016), automation aiding enhanced cognitive capabilities such as perception, memory, reasoning and decision (Operator 4.0), a sub class of Human-Cyber system. Once having a well developed and operational CSS, there will be a different horizon and additional possibilities to the emergence of the *future CPSS*. This is introduced here with the goal of having a meta model that is flexible and open to accommodate new concepts in the evolution of the domain. However as this is not the scope of this scientific paper it will not be discussed further. The concept of SPS (Social-Physical system) is not included in the model because it is the long existing standard manual system of operation with no actual relevance in this context. In the following section we present a case study to show how the meta model can simulate a Cyber-Physical-Social production system.

4 Case study

Let us consider an abstract scenario of *aerospace engine systems plant* modified and adopted from [14]. This case study is chosen because it simulates the emerging advent in Industry 4.0, which is a collaborative production systems between human and CPS. This is a plant producing parts of engine system for aerospace industry. The production system is organized as job shop. In the production line of the plant there are manufacturing engineers, operators and maintenance technicians that are skilled and able to perform tasks on different machines. In order to improve efficiency robotic cells are introduced at job shops to collaborate with the workers. In this production system there are several machines designated for different task. Most of the activities require similar set of skills but there are few activities that require additional skills for which additional training is needed. However, the company's orientation for task identification and worker involvement follows socio-technical principles which allows collaboration and knowledge sharing between the workers through live chat and virtual assistance. This highlights social interaction between the workers to support each-other.
Figure 3 illustrates a simplified version of this sophisticated process of the plant in an effort to visualise with best possible detail the composition of such complex CPSPS and the interaction between different components. As it can be seen on the figure one can assume a simplified version of the job shop with three different machines equipped with robotic cells to collaborate with the workers. The physical parts of each machine and robotic cells with their embedded computational capabilities form the three CPS units. However since human workers are present at the vicinity of these workstations to work in collaboration with the robotic cells, individual CPSSs can emerge at each work station. Therefore the system design should not only rely on CPS autonomous task execution, as this can compromise worker's safety and degrades collaboration quality. Such systems should be designed taking into account not only cyber and physical components but also important social aspects of humans. We believe the CPSS paradigm with the support of artificial intelligence brings several opportunities for the future of Industry 4.0 facilitating seamless collaboration and support between human and CPS. For instance as human is part of the system design it makes it possible to customise and personalise work spaces matching physical and cognitive characteristics of workers to support special needs, disabilities, aging and other kinds of personal limitations and opportunities. Furthermore it can enable systems to be designed in such a way that the collaborating robots and machines learn complex human behaviours, response patterns, values and needs. Thus, machines and robots pursue important human aspects and perform actions that humans would approve to become better companions. In future studies we aim

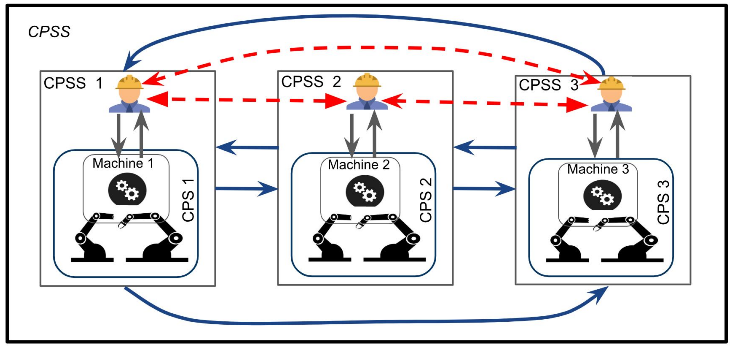

Fig. 3. Cyber-Physical-Social Production System

to further develop the meta model and also validate proposed activities at design phase through experiment at execution phase in selected case studies.

5 Conclusion

In this paper we proposed an approach to support human-machine collaboration in Industry 4.0 through a Cyber-Physical-Social systems (CPSS) paradigm. CPSS is an emerging concept that intertwines human aspects to the existing notion Cyber-Physical systems (CPS). Current system designs approaches in Industry 4.0 heavily rely on the core concept of CPS, which does not incorporate human aspects. Thus, degrading collaboration quality and also leaving room for compromised safety. We believe the CPSS paradigm supports the future of Industry 4.0 in bridging this gap as it effectively integrates human aspects with CPS. In general the emergence of such intelligent collaborative industrial environments together with the complexity of human dynamics make systems more complex. Nevertheless taking a CPSS paradigm offers opportunities to better understand and model complex interactions. We elaborated the emerging notion of CPSS by visualising all kinds of relationships and interactions that may occur with in a system of CPSSs. Additionally the extended meta-mode is a step towards having a generic framework. As it brings human dynamics closer to CPS, it jointly opens opportunities to benefit from artificial intelligence in learning complex human behaviours, values and needs so as to enable machines and robots in becoming better companions during collaboration. This will be investigated in future studies.

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