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A problem-solving ontology for human-centered cyber physical production systems

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ABSTRACT

Cyber physical social systems (CPSS) tend to integrate computation with physical processes as well as human and social characteristics. The fusion of cyber, physical, and socio spaces through Industry 4.0 emerges a new type of production systems known as cyber physical production systems (CPPS). CPPS enriches communications among cyber-physical-socio space in the production environment. Utilizing human-centered CPPS in smart factories (ideally) results in a mutual transition from human-machine cooperation to active collaboration, which is characterized by cyber-physical-socio interactions, knowledge exchange and reciprocal learning. The shift from data workers or producers to problem-solver is, therefore, triggered to both humans and CPPS, respectively. Hence, their job roles and responsibilities cannot be independently defined. This paper approaches the collaboration of human and CPPS in problem-solving from the angle of complementarity whereby “human competences” and “CPPS autonomy” together derive supplementary capability and reciprocal learning. In this research, “Problem” is an umbrella term that refers to both categories of “human-CPPS task” (i.e. a specific piece of work required to be done) and “failure event” (i.e. a state of difficulty that needs to be resolved). A holistic ontological framework is proposed, entitled PSP Ontology (Problem, Solution, Problem-Solver Ontology), which represents the logical relations between the three super-concepts of “Problem Profile”, “Problem-Solver Profile”, and “Solution Profile”. Related entities are formalized by introducing (i) contingency vector, (ii) vector of competence and autonomy, and (iii) solution maturity index, respectively. PSP Ontology is utilized for semantic representation of the super-concepts and reasoning out the competence questions, i.e. in which situation and under which conditions human and/or CPPS is dominant or eligible to solve a problem (to accomplish a given task and/or to detect or eliminate a failure), which is qualitatively exemplified in the use-case of maintenance 4.0.

Introduction

Cyber-physical-socio space: terminologies and definitions

The trends of Industry 4.0 and industrial internet evolve human-technology interactions [1], whether technology guides human or human guide technology [2–5]. CEDEFOP’s European skills and jobs survey (ESJS) revealed that “across the 28 European Union (EU) Member States, 43% of adult employees have seen the technologies they use change in the past five years, making some people’s jobs vulnerable to automation” [6]. In particular, 49% of adult employees in the manufacturing sector have anticipated changes in their jobs, i.e. working practices and methods [7]. The technological enhancement is strongly related to the rapid development and application of cyber physical systems (CPS). A CPS “is an integration of computation with physical processes whose behavior is defined by both cyber and physical parts of the system” [8]. CPS is a class of systems that “feature a tight integration between computation, communication, and control in their operation and interactions with the task environment in which they are deployed” [9]. The task environment not only comprehends the physical environment which can be automatically sensed by the cyberspace, but also considers the semantic linkage of cyber-physical-socio space [10]. The cyber-physical-socio space is the coalition and union of the physical space, the cyberspace, and the socio space [10].

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Cyber physical social systems (CPSS) inherited many characteristics from CPS while "tightly conjoined, coordinated, and integrated with human and social characteristics" [9]. Thus, the definition of CPSS emphasizes on a holistic exchange of data, information, and knowledge across the cyber-physical-socio space [11].

Fig. 1 depicts the information exchange, interactions and reciprocal learning among the aforementioned spaces. The physical space encompasses interaction between machines and physical assets (e.g. machines-servers). The socio space covers human interactions, i.e. experiencing and learning. The cyber space connects and interfaces physical and socio spaces. Using various sensors and actuators, the cyber space senses and actuates in the physical space and socio space, facilitates exchange of information and machine learning for improving existing computational models, and executes the models implemented or configured by humans for managing the aforementioned tasks in this space [10]. Human's and machine's behavior, and their social interactions can be sensed and fed back to the cyber space for further processing [10]. Physical and socio space interacts directly as well whereby a machine and human receives signal and stimulus, and responds to it in a distinctive manner, i.e. sensing. For the purpose of processing and computation, the cyber space employs two types of semantic operators as horizontal and vertical. Horizontal operators exploit existing knowledge and explore new knowledge through integration of heterogeneous data, and mapping multimodal physical, cyber and social data into "concepts to support semantic integration" along the spaces [11]. "Vertical operators translate observations from low-level data to a high-level knowledge" [11]. In other words, information processing and computational models deployed in the cyber space employ the horizontal and vertical operators to integrate, interpret, and provide contextually relevant concepts not only to human, but also to CPSS. This endeavor encompasses, therefore, cyber-socio and cyber-physical interactions and information exchange. It also supports the construction and implementation of advanced computational models (algorithms) in the cyber space using human and CPSS feedback (i.e. intersectional learning of human and CPSS).

Furthermore, industrial application of CPSS emerges a new type of production systems, known as cyber physical production systems (CPPS), which are utilized in smart factories [12,13]. CPPS enriches communications among cyber-physical-socio space in the production environment. CPPS are a class of production systems which are characterized as "Feedback Systems" that are ideally intelligent, real time, adaptive and predictive, networked and/or distributed, possibly with wireless sensing and actuation, and also possibly in loop with human [8]. An example of CPPS is "a high-speed printing press for a print-on-demand service [with several] platforms, sensors, and actuators" [8]. The press is capable "to induce rapid shutdown to prevent damage to the equipment in case of paper jams" [8]. Such an autonomous operational decision prevents disasters in the production plant. In this case, an associated operator who interacts with the CPPS does not necessarily need to deal with initiating and monitoring of the machine, rather he/she should hold "new skills" for customizing machine performance under various technical, environmental and economic requirements and conditions such as maintenance cost effectiveness or energy consumption. The transition of personnel job role is, therefore, assumed from low level operation to (high level) decision endeavors.

From interaction-design principles, CPPS are human-centered systems. In contrast, user-centered systems treat "humans as technology users, persons who work with this system which was designed to be convenient for them" [14]. Human-centered systems aim to preserve "human integrity in a human-machine symbiosis" and include "different levels of interaction, conversation social cohesion" [14]. In other words, CPPS are principally designed to deeply interact and collaborate with human, rather than providing services to facilitate human jobs, towards achieving a common goal, e.g. reducing the failure rate.

Human and CPPS complementarily in problem-solving

Deploying CPPS raises several challenges for industries with regard to (i) integration of human-CPPS interaction and exchanges along production processes, (ii) interoperations with production platforms, infrastructure and information systems, (iii) promoting human competences and CPPS autonomies in problem-solving, (iv) identification of new job roles for human and CPPS across the production system, and (v) advancement of technological resources (Adopted from Refs. [12–16]).

Referring to challenge (i), as mentioned above, human-CPPS interactions and exchanges may entail reciprocal learning, i.e. on the one side CPPS can actively learn new concepts from humans and on the other side humans can receive (new) knowledge from CPPS [14,17]. By considering challenge (iii), we should point out that a "problem" may be caused either by "human or CPPS failure" that should be resolved, or defined as a "task" which is designed for

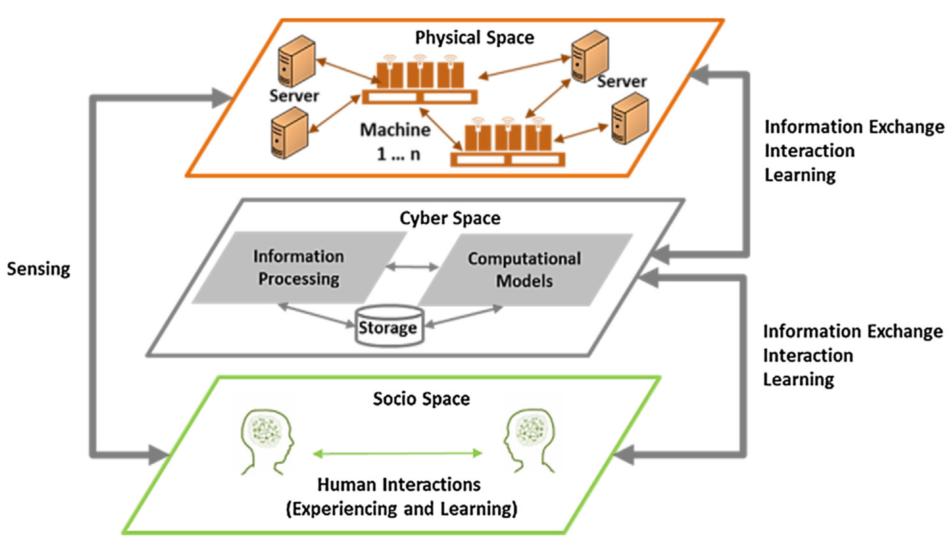

Fig. 1. Information exchange, interaction and learning across cyber-physical-socio space.