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Engineering insights from an anthropocentric cyber-physical system: A case study for an assembly station ☆

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ABSTRACT

To effectively cope with the complexity of manufacturing control problems the cyber-physical systems are engineered to work in the social space. Therefore the research in the field of cyber-physical systems needs to address social aspects when this concept is adopted in factory automation. The paper argues for an anthropocentric cyber-physical reference model as the basic decomposition unit for the design of distributed manufacturing control systems. The model assimilates all the required components (i.e. physical, computational and human) of a synthetic hybrid system in an integrated way. This is due to the real need to design cyber-physical production systems where the technological advances are merging their functionalities in a way more and more difficult to distinctly draw between the physical, computational and human components. If this view is almost obvious for advanced technologies, such as brain computer interfaces, controlled assistive robots and intelligent prostheses, it is equally true even for simple automated systems, like context-aware assistive systems that are built with state-of-the-art technologies. This assertion is demonstrated in the context of the *SmartFactory*^{KL} production system, where the manual assembly station exhibits all the key features of an anthropocentric cyber-physical system by employing a seamless augmented reality to guide the human operator.

1. Introduction

In the last decade the advances in factory automation became aware of the fact that any significant improvement may be achieved only by considering the tight integration of computational, physical and social elements [35]. Due to the relevant structural interactions among these elements, the integration presumes the engineering of synthetic hybrid systems that can achieve goals beyond the inherent capabilities of its composite parts. Today, this comprehensive outlook can be found in dissimilar research areas (e.g. aerospace, automotive, chemical processes, civil infrastructure, energy, healthcare, manufacturing, transportation, etc.), including the smart factory concept [64].

The integration of physical and computational elements is well-reflected in the standard view of cyber-physical systems (CPS). A CPS poses some exclusive features that differentiate it from the conventional systems (e.g. embedded systems, sensor networks, etc.) [43,26,59]: *integrality* (the CPS's functionalities are relying on the unified composability of its elements with self-organization capabilities, such as learning, adaptation, and auto-assembly), *sociability* (the ability to interact with other CPSs via different communication technologies, not only device-centred but human-centred as well in an open mixed network environment), *locality* (the computational and physical capabilities of a CPS are bounded by the spatial properties of the environment), *irreversibility* (self-referential timescale, sensed as dynamics, not discrete, nor spatial), *adaptive* (with self-organization and evolving capabilities), *autonomous* (control loop must close over the life-cycle of a CPS, including the assimilation of human factor who is constantly closing the loop of any engineered artefact, despite its automation degree), and *highly automated* (as a key driving-force of eroding the boundaries between its composite elements and favouring their structural interactions). Even if it is not explicitly stated, the human factor plays a crucial role in a CPS to display the above mentioned features. Some recent studies are trying to give a more comprehensive view over the definition of a CPS that, besides the classical computational and physical dimensions,

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includes the social one as an integral part of a CPS. This may be observed in the new emerging concepts, such as smart environments [42], cyber-physical-social systems [63], human system integration [34], and social cyber-physical systems [20], that are paving the way towards the old vision of symbiotic man–machine systems [29].

For most application domains CPS are engineered to work in the social space. Therefore the research in CPS will increasingly address the social aspects when the CPS concept is adopted for the developments in factory automation. The early dreams of control engineers to develop unmanned factories were abandoned not only due to ethical or social reasons, but mainly because the engineering of such control systems proved to be unfeasible. As a result the research in CPS is increasingly addressing the social aspects when it needs to provide real-life solutions [10,62,12]. For that reason, in [59] we defined the anthropocentric cyber-physical system (ACPS) as a reference model for factory automation that integrates the physical component (PC), the computational/cyber component (CC) and the human component (HC). The basic decomposition abstraction serves to naturally reflect the multiple and context-sensitive loci of control for cyber-physical production systems. The key characteristic of an ACPS reference model is its unified integrality which cannot be further decomposed into smaller engineering artefacts without losing its functionality.

From the engineering stance, the ACPS concept emphasizes the adaptive and dynamic division of labor among the ACPS components as a result of their continuous interactions. Consequently, the function allocation cannot be fixed at the design time as in Fitts' list [11], but oscillates between different levels of automation (from fully manual to fully automated). In other words, a priori assumptions regarding the function allocations among the ACPS components are useless when the precise future of the ACPS is known only a posterior. As in the latest Seridan's taxonomy for automation [38], the dynamic allocation mechanism is a consequence of the innate complexity and bounded rationality conditions in which an ACPS operates. In line with the cybernetics Law of Requisite Variety [1], it requires real-time evaluations for the physical/cognitive status of the human operator (in terms of risk, reliability, and costs of automation) to grasp all possible inputs that may affect the ACPS behavior. Moreover, the adaptive and active allocation of tasks between the ACPS components to provide an optimal workload balance is not restricted to the operational requirements – as considered in the research topic of adaptive automation [47], but includes also the symbolic integration of man and machines in a closed-loop – as considered for example in the augmented cognition research field [9]. It means that an ACPS may infer the user's intention by measuring human cognitive activity and translates it into possible actions over the physical environment. These actions are realized either by the user or by the cyber component that will increasingly incorporate distributed artificial cognition complementing or in tandem with human cognition. Consequently, ACPS is "adaptive automation" + "augmented cognition", a view that is obvious in more advanced technologies, such as brain computer interfaces, controlled assistive robots and intelligent prostheses [49], but is not restricted just to them.

This paper contributes to this comprehensive view of a CPS by showing that even simple automated systems, such as a manual assembly module, inherit the key features of an ACPS. The paper is an extension of the paper presented in Zamfirescu et al. [60] and provides detailed insides regarding the interaction-based architectural design of a representative workstation from the *SmartFactory*^{KL} demonstrator, namely the manual assembly module. The work reported in this paper does not necessarily contribute to the "adaptive automation" feature of an ACPS, which will remain for long time an open research problem [23]. Instead, it addresses the "augmented cognition" feature in the form of a so called context-aware assistive system, by providing an integrative engineering approach for the design of cyber physical production systems. If this kind of ACPSs, coined by some authors as "assistive" CPSs [33], have become ubiquitous in cars or smartphones, for the manufacturing environment they are still in the infancy adoption stage, despite the maturity level of the available technology. We believe that their true potential to improve learning and motivation of human operators plays a key role in optimizing productivity.

Consequently, the next section will summarize our anthropocentric cyber-physical reference architecture for smart factories (ACPA4SF) as a composition of four ACPS types that are self-sufficient to describe and engineer any manufacturing control system. ACPA4SF is based on the ACPS reference model, an abstract framework that captures the key components of an ACPS and the mutual relationships among them. The ACPS reference model is supported by the latest technological developments in service-oriented architectures (SOA), semantic Web, human–machine interaction (HMI). The third section details the concrete implementation of ACPA4SF in the *SmartFactory*^{KL} production system, where the main concerns are the inter-ACPS interactions. The intra-ACPS interactions are detailed in the fourth section for a representative station of the *SmartFactory*^{KL} demonstrator, namely the manual assembly station. The last section encapsulates the concluding remarks.

2. ACPA4SF reference architecture

The *ACPA4SF reference architecture* aims to provide a template solution for concrete architectures of cyber physical production systems. It accommodates the latest architectural developments in factory automation, from fully centralized to fully decentralized approaches. ACPA4SF is based on the *ACPS reference model*, an abstract framework that captures the key components and their relationships in an ACPS. The next subsections detail the rationales for the proposed ACPS reference model and the ACPA4SF reference architecture. Since these architectural design concerns are technology agnostic, the enabling technologies to implement a concrete ACPA4SF architecture are briefly summarized in the last subsection.

2.1. ACPS reference model

The ACPS reference model was defined to provide the highest abstraction level for the ACPA4SF definition. It tries to capture the common ground encompassing the meaning of CPSs and to identify the core relationships among its composite entities. The ACPS reference model goes beyond the classical architecture of a CPS [4] that simply embeds the human–machine interface in a mechatronic device. To preserve the key features of a CPS (e.g. integrality, autonomy, sociability, adaptivity, etc.), the ACPS reference model implicitly accounts for the continuous adaptation loops that truly exist among the cyber, physical and social components. In cyber-physical production systems, where the human factor will increasingly play a significant role [39], there is a clear need to consider humans as endogenous interacting components within a CPS [3,49,20].

Therefore the ACPS reference model for factory automation integrates the PC, the CC and the HC (see Fig. 1, depicting in an UML 2.0 composite structure diagram the ACPS reference model). The interactions between these components are usually made via adaptors, optional in many cases, which translate the signals into the specific format of the interacting component. For example: between the PC and HC there are special displays or meters to measure the working parameters of a machine; between the CC and HC there are the classical human–computer interaction (HCI) devices (e.g. screens, mouse, keyboard, etc.), and between the PC and CC