Insights into SoRa: A Reference Architecture for Cyber-physical Social Systems in the Industry 4.0 Era

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Abstract: Reference architectures for Industry 4.0 tend to have a techno-centric orientation; their social dimension is usually restricted to specifying that users exist, and they have concerns that impact the architecture of desired systems. We take a step further to make the social element the core of future systems. A first step is to propose a reference architecture for Industry 4.0 cyber-physical social systems (CPSS), that builds upon proposals from well-known initiatives. Key differentiator in our design is the explicit consideration of the human – cyber-physical relation and the way the two sides influence or adapt to each other. The final aim is that architecture descriptions derived from this reference architecture, will enable the development of CPSSs capable of harnessing the power of the Internet of Things (IoT), while respecting the importance of their human members.

1 INTRODUCTION

The engineering of cyber-physical systems (CPSs) has always been guided by architectures that took into account, more or less, the concerns of their stakeholders. Some argue that one essential component of the systems - the actual user - has often been just partially considered (Dressler, 2018).

As we progress in the Industry 4.0 age, more and more complex reference architectures (RAs) are being put forward, striving to accommodate the development of new technologies and IoT related capabilities. This is even more the case with the advent of approaches such as Society 5.0 in Japan (Hitachi-UTokyo Laboratory, 2020), a model describing a people-centric super-smart society in which humanity is a key trait for this ideal society.

In this particular context, cyber-physical social systems (CPSSs), which are computing systems adding social characteristics and interaction to CPSs having key features such as: integrality, sociability, locality, irreversibility, adaptivity and autonomy (Pirvu et al., 2016), are considered to still be in their "infancy", as recent studies lack a systematic design methodology or are application specific (Zeng et al., 2020). More importantly, there is room for giving a more socio-centric orientation to reference architectures, such that the architectures derived from them will serve in developing improved CPSSs in approaches such as Society 5.0.

This research analyses a number of reference architectures, from FITMAN, to OSMOSE, IoT-A or BEinCPPS. The findings led us to propose improvements in order to explicitly consider the relation between the social side of a system and its cyber-physical counterpart. Furthermore, we suggest that establishing equilibrium between the two sides can be achieved if we facilitate the adaptation of one to the other. To this end, we propose a first effort to elaborate a reference architecture for CPSS – the Socio-centric RA (SoRA), as part of our ongoing research. Please note that in this article only the structural perspective of SoRA will be detailed, as well as to propose an instantiation of a functional perspective.

The remaining of this paper is structured as follows. Section II presents the relevant work regarding RAs. Section III describes SoRA from the structural perspective as well as an instantiation from a functional perspective while section IV discusses

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some key aspects of this RA. In section V concluding remarks are formulated, while in the final section the outlook for SoRA's development is presented.

2 RELATED WORKS

There are numerous RAs for CPSS, some more detailed, others succinctly presented, some more generic, others tailored to specific types of systems, etc. In the following we are going to briefly look at a number of RAs that we consider representative and are sufficiently documented in order to be evaluated.

The OSMOSE project delivered a RA (Felic, et al., 2014) (Felic, et al., 2016) intended to enable the development of sensing-liquid enterprises. These two attributes were inspired from the FInES Research Roadmap 2025 (FInES Research Roadmap Task Force, 2012), which identified nine qualities of being (QB) of Future Internet-based Enterprises. These nine QBs are: 1) Humanistic Enterprise, 2) Inventive Enterprise, 3) Agile Enterprise, 4) Cognisant Enterprise, 5) Sensing Enterprise, 6) Community-oriented Enterprise, 7) Liquid Enterprise, 8) Global Enterprise and 9) Sustainable Enterprise. Key to the OSMOSE reference architecture is the identification of three worlds (real, digital and virtual) to which an enterprise's assets belong; communication between worlds is mediated by a "membrane", which allows osmotic processes to take place (information entering the membrane is processed and routed to the other worlds according to complex event processing and knowledge links mechanisms). From a socio-centric perspective, the OSMOSE reference architecture considers the human users only in terms of the data and multimedia information the system stores for the users, or in terms of avatars that may be used in "what-if" simulations pertaining to the virtual world.

The FITMAN project delivered three RAs (Rotondi et al., 2013) that define what a smart, digital or virtual enterprise should consist of. From a socio-centric perspective, humans are identified as end-users, that only control the system from a logically remote location. While the RAs benefit from the identification of a collection of reusable components, mainly dedicated to information processing or to abstracting out details of lower-levels of abstraction, the information relevant to the socio-centric perspective is not abundant here as this is not the focus of the FITMAN RAs.

The IoT-A project produced a comprehensive piece of work (The Internet of Things – Architecture project, 2013) that not only defines a RA, but also provides the underlying architectural reference model (ARM), as well as guidance for using the RA in order to generate specific architectures. While the work itself is not complete (the information model, for example, is only partially defined), the ARM contains eloquent descriptions of the domain, functional and communication model, while the RA itself complies with the framework of already established architectural views and perspectives, such as those denoted in (Rozanski and Woods, 2005). That said, the overall approach is techno-centric: the RA is composed of functional groups and functional components, with the user interacting with the system via the top-level applications functional group.

More recently, the Industrial Internet Consortium (IIC) delivered the industrial Internet Reference Architecture (Industrial Internet Consortium, 2017), which is strongly based on the ISO/IEC 42010 (ISO/IEC/IEEE, 2011). This RA, in fact, instantiates ISO/IEC 42010 for the Industrial Internet domain, selecting four relevant viewpoints (i.e. business, usage, functional and implementation) and detailing the elements that need to be defined in order to generate views for each viewpoint; in addition, the RA specifies a number of cross-cutting concerns, while also providing architectural patterns (i.e. topologies for interconnecting physical devices or logical layers within an enterprise) that may be applied when constructing specific system architectures.

In a similar timeframe, the BEinCPPS project finalized its RA, oriented on cyber-physical production systems (CPPS). While initially the BEinCPPS RA (Fischer, et al., 2016) was a cross-breed between the OSMOSE and RAMI 4.0 RAs, the final version (Isaja et al., 2017) adopts a simplified approach, that makes use of four perspectives in order to define a semi-reference semi-concrete architecture. Its simple structural perspective divides the elements of a system into design-time and runtime, while runtime systems are considered at different hierarchical levels. Again, the approach is techno-centric, the human element being either implicit (hence undefined) or explicit only at the top-level cloud level (similar to the FITMAN approach of representing humans only as end-users).

Table 1 below provides a synthetic view over the mentioned architectures, describing the types of systems they were intended for, as well as the scope that they can be associated with. A detailed review of recent reference architectures for cyber-physical systems in industry 4.0 is presented in (Ghetiu, 2018).

Table 1: Some existing reference architectures and their scope and applicability.

Reference Architecture	Intended system	Scope
OSMOSE	Sensing-Liquid Enterprise	Individual enterprise
FITMAN Smart Factory	Smart Factory	Shop floor
FITMAN Digital Factory	Digital Factory	Factory (data analytics)
FITMAN Virtual Factory	Virtual Factory	Supply chains
IIRA	IoT CPSoS	General applicability
IoT-A	CPSoS	General applicability
BEinCPPS	Cyber-physical production systems	Field devices, Factory, Cloud

3 PROPOSED WORK

SoRA adopts the BEinCPPS structural perspective as a starting point. One of the main aspects that lead to this decision is the structural simplicity and clarity of this RA, in its final format (Isaja et al., 2017), which is highly suitable for being adapted in order to present functions and technologies that could be used in concrete architectures; in comparison, other RAs can be considered either too complicated (e.g. FITMAN or OSMOSE) or too abstract (e.g. the 5C architecture (Lee et al., 2015)). Additionally, the BEinCPPS RA makes a clear distinction between the design and operation concerns of an architecture, so it represents a good foundation for creating an improved, yet not too complicated RA.

If the BEinCPPS RA is composed of two domains and three layers, SoRA has a more elaborate structure, as shown in figure 1 where we present the structural perspective of SoRA; we highlight in green the new elements added on top of the BEinCPPS structural perspective. The design-time and runtime domains remain but, in order to adequately transition between the two, a third buffer domain is needed; this approach reflects to an extent the OSMOSE philosophy, where the distinct worlds are separated by a "membrane".

The new buffer domain is dedicated to representing the relation between the social and cyber-physical elements within the intended system; its role is to explicitly define how the cyber and the social actors will work well within the CPSS. The domain consists of two layers, one dedicated to training, the other to adaptation. The training layer defines how the human users will be prepared for using the CSP efficiently, whereas the adaptation layer refers to the adaptation of the CSP to the humans inside the CPSS.

Furthermore, the design-time domain needs to be split into an upper layer dedicated to capturing information pertaining to the social realm, whereas the lower layer remains restricted to the standard design of a CPS. The motivation for this separation stems from the need to explicitly consider the social factors that will influence the CPSS design.

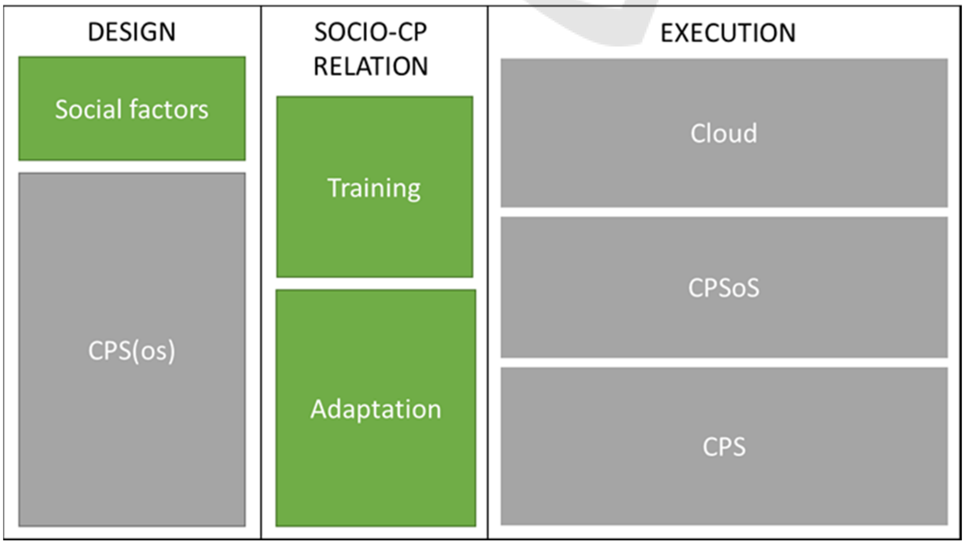

Figure 1: Structural view of the SoRA for CPSS.

In addition, the runtime domain (named "Execution" in figure 1) contains three layers, as that of the BEinCPPS architecture; the two RAs different in the sense that in the SoRA, the layers have generic titles, whereas the BEinCPPS is focused on CPPS. Consequently, at the bottom of the hierarchy we have CPSs (analogue for the shop floor level of the BEinCPPS runtime domain), which are the building block for CPSoSs and ultimately the Cloud (analogue for the enterprise level of the BEinCPPS runtime domain). Note that the Edge is not explicitly depicted in this version of the architecture, but is expected to be contained within each runtime layer.

While it is still under development, figure 2 offers a glimpse of what may be a functional view implementing the SoRA. Here we identify components, technologies or processes that may be used in each layer of the architecture.

The Training layer, for example, can be defined by training processes and training systems; this implies that a CPSS, designed with the social-factor in mind, should come equipped with documentation supporting the training of personnel, but also (if the complexity of the systems deems it necessary) with explicit training systems that may be used in the training process (Gellert et al., 2020). If we were to take the case of an Industry 4.0 production facility, in order to support the social factor, apart from training processes, a VR or AR enabled training system could be developed or purchased.

The Adaptation layer refers to the systems capability to model their user and adapt to them, so that quality metrics can be improved. Machine learning (ML) techniques can be employed, but also newer approaches such as generative design or design-space exploration, especially in co-simulated environments, can be used.

The runtime domain can be instantiated with agent-oriented platforms that readily implement logic, not only for executing production functions, but also for interfacing with users in "smart" ways. As (Ocker et. al 2019) suggest, multi-agent systems (MAS) are a solution to modern challenges faced by production systems or other types of complex, human-design systems. Software agents can be mapped to individual devices, users or to aggregates of such entities; they can activate solely within the software domain or become embodied. Furthermore, any MAS comes with a solution for inter-agent communication; if the design of a CPSS tunes this communication so that it is done efficiently, across CPSs and levels of hierarchy, then MASs represent indeed a powerful proposition for the composition of CPSS.

What is more important is that MAS can be employed in defining the functions of the socio-cyber-physical relation domain. Specialized agents can aid or fully execute the training of human users, whereas the adaptation of the CPS to its users can be enacted by other types of specialized agents, embodied or not.

The bottom layer of the runtime domain (CPS) brings together devices and users, that are interfaced through a specific class of MAS. The middle layer interconnects CPSs and users, through a potentially different class of MAS. Finally, at the top-layer we find Cloud functions: data processing (e.g. big data), together with specific applications which support the

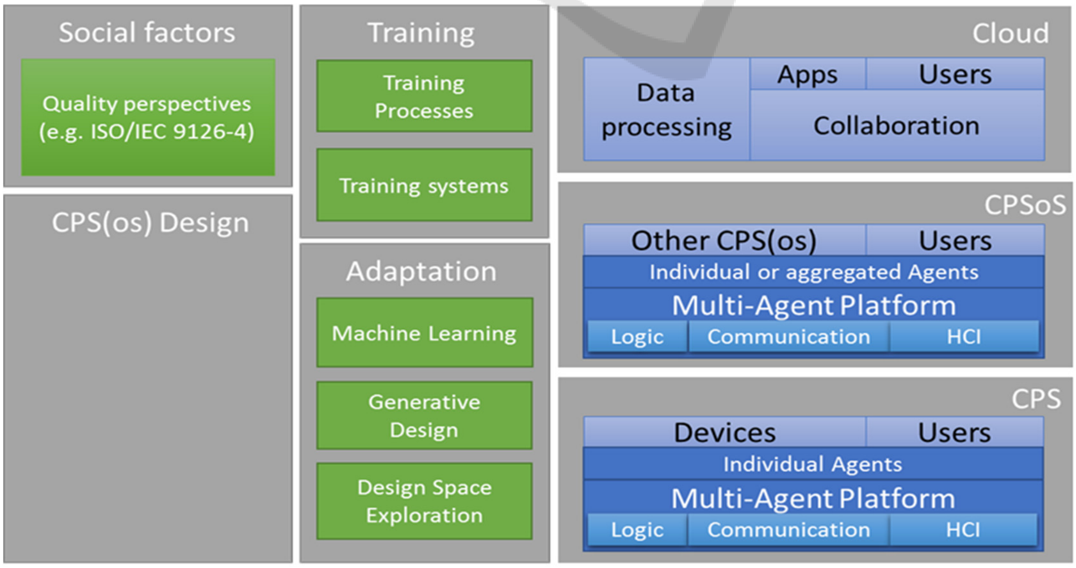

Figure 2: Functional view of the SoRA for CPSS.

collaboration between users or the execution of other system functions.

Going forward, the ARM for the SoRA architecture should be supplied. We take as starting point IoT-A's ARM and identify aspects that should be modified or added so that it becomes relevant. This work will be presented in a follow-up article.

4 DISCUSSION

The information provided in the previous section is just a brief introduction to SoRA - a developing reference architecture for CPSS. In this paper, we only define its structural perspective and sketch what could be its functional perspective.

The structural perspective builds on that provided by the BEinCPPS RA; a key differentiator is the addition of an explicit buffer domain, that bridges the design and runtime domains. Its purpose is to expose the importance of the socio - cyber-physical relation, for the development of successful CPSSs. Our initial thoughts go towards the need for defining the way in which the human factor is going to be accustomed to the cyber-physical one (i.e. training), as well as on explicitly allowing (or even requesting) the CPS to adapt itself to the human factor, so that it can better support it.

When looking at the functional perspective, we consider it is necessary to put more focus on the tools and means for designing the social factors into the architectures of CPSSs, in contrast with focusing on the technical aspects of CPS architectures. While existing RAs vary in terms of scope, qualities built into the targeted system or even the level of detail with which they are made public, we aim to obtain a RA that is socio-oriented, builds on existing best practices and conforms to the Future Internet prospects for Industry 4.0.

Another defining trait of the SoRA is the centering on multi-agency as a philosophy for addressing the needs of a modern CPSS. MAS can be employed in order to implement the training and adaptation functions of our buffer defined, as well as in bringing together CPSs and human actors, at all hierarchical levels within a CPSS.

5 CONCLUSIONS

In this work we have introduced SoRA, a new RA aimed at facilitating the development of architecture descriptions for CPSSs, that reflect the importance of the human factor as a key element in the control loop. To achieve this, SoRA builds on previous work that spans decades of research and implementation. Key in making a difference is considering that the relation between the social and the cyber-physical elements needs to be added to the core of all CPSSs architectures.

Previous RAs have been of a predominantly techno-centric nature: the human was the external factor, the user that interacts with the system via a more or less advanced interface; important was achieving the functions of the system. In the best of cases, ISO/IEC 42010 (ISO/IEC/IEEE, 2011) was brought into attention, reminding that architectures have to consider the concerns of stakeholders or, specific to the IoT domain, architectures would need to define an entire business view (Industrial Internet Consortium, 2017). Other architectures were too succinctly defined (such as the SmartFactory or RAMI 4.0 RAs) to evaluate their orientation, but we can go by the rule that if something is not explicitly defined, it does not exist; as such, we cannot attribute a socio-centric nature to such architectures.

There are cases when focus is explicitly laid on other attributes (or qualities of being, as (FInES Research Roadmap Task Force, 2012) considers); the OSMOSE RA (Felic, et al., 2016) aims at identifying architectural constructs that enable the development of architectural descriptions for sensitive and liquid enterprises. RAs need to map out the spectrum of QBs and OSMOSE's approach is valid from this perspective.

In this paper, we have detailed only the structural and functional perspectives of SoRA. Its structural perspective builds on that provided by the BEinCPPS RA, to which it adds a new domain: that of the socio - cyber-physical relationship. The intention is to explicitly consider this relationship from the onset, so that the resulting architecture will lead to the implementation of a CPSS where human users are well trained in efficiently using the CPSS, while the cyber-physical components will continuously adapt to the social factors that interact with them. SoRA's functional perspective is still in a developing stage, but one aspect can be considered defined: its reliance on MAS to achieve functions related to training, adaptation, and human-computer interaction.

6 FUTURE WORK

As part of the research conducted for SoRA, the next step is to further elaborate on the means through which social factors can be (best) taken into account at design time. The current proposal is to look at quality perspectives, using notions derived from standards such as ISO/IEC 9126-4 or ISO/IEC 20510. We need to evaluate if proposals such as IIRA's business viewpoint are satisfactory from a socio-centric perspective, or a more in-depth view is needed, including user modelling, profiling.

Another line of research is that of implementing prototype systems, that reflect the new functions described in the socio – cyber-physical relation domain of SoRA. The first prototype is an adaptive system to correctly learn how to manually assemble products without a human instructor. The adaptation aims at adjusting the instructions for the user according to the previous and current performance in the execution of the task, the chosen components, the physical and emotional state of the operator as well as the detected user profile. The second prototype is a modular production system prototype having a distributed low-level control architecture together with a MAS for the high-level control. Fully automatic the system can produce standard orders (i.e. modular tablets), orders which have limited or predefined customization; in case of highly customized orders, the automated system collaborates with human operators to manufacture the special orders.

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