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Industrial Agents and the Holonic Paradigm

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1.1. Introduction

Traditional control approaches are based on centralised and hierarchical structures, following the well-known ANSI/ISA-95 (2010), also known as automation pyramid, which presents good production optimisation, but a weak response to condition change and reconfigurability due to the rigidity, monolithic and centralisation of their control structures (Colombo *et al*. 2021). These control approaches are not designed or prepared to respond to the current demanding requirements of responsiveness, scalability, reconfigurability and robustness (Leitão 2009*a*).

The advent of Industry 4.0 (Kagermann *et al*. 2013 ; Leitao *et al*. 2020), led to the use of distributed control structures, the use of the decentralisation of control nodes

Digitalisation and control of Industrial Cyber-Physical Systems,
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and the introduction of intelligence to transform the existing assets into smart processes and machines, and also considering smart products (Barbosa *et al*. 2016) as important players in this ecosystem. Multi-agent Systems (MAS) and holonic systems are suitable to face these demanding requirements since they offer an alternative way to design and implement such innovative control systems taking advantage of their capability to decentralise the control over distributed structures towards modularity, scalability, robustness, fault-tolerance, reconfigurability and re-usability (Leitao, Karnouskos, Ribeiro, Lee, Strasser and Colombo 2016 ; Karnouskos and Leitao 2017). The development of Industry 4.0 compliant solutions will constitute a new opportunity to use MAS and holonics to realise these innovative, and emergent industrial CPS (Colombo *et al*. 2015 ; Leitão and Karnouskos 2015 ; Leitao, Karnouskos, Ribeiro, Lee, Strasser and Colombo 2016 ; Colombo *et al*. 2017 ; Karnouskos *et al*. 2020).

This chapter introduces the main conceptual foundations of MAS and holonic systems and presents the framing of industrial agents as an instantiation of such technological paradigms to face industrial requirements. The alignment of industrial agents with RAMI 4.0 (Deutsches Institut fuer Normung (DIN SPEC 91345) 2016) is also addressed and in particular, it is discussed the use of industrial agents to realise industrial Cyber-Physical Systems (CPS) and concretely Asset Administration Shells (AAS), which play an important role in the development of Industry 4.0 components (Boss *et al*. 2020). At the end, the chapter discusses some research challenges and directions that current raise from the deployment of industrial agents.

1.2. Overview of Multi-Agent Systems and Holonics

1.2.1. *Multi-Agent Systems*

MAS is a technological paradigm derived from the distributed artificial intelligence field that is suitable to implement flexible, adaptive and responsive industrial CPS, based on a set of intelligent autonomous entities, called agents, that cooperate to achieve the system goals.

There is not a unique or universal definition for agents, e.g. Russel and Norvig (1995) ; Wooldridge (2002), but a suitable definition is that an agent is an "*autonomous component that represents physical or logical objects in the system, capable to act in order to achieve its goals, and being able to interact with other agents, when it does not possess knowledge and skills to reach alone its objectives*" (Leitão 2009*a*). From such definition, it is clear that autonomy (i.e. the capability to perform their own decisions without the direct intervention of external entities) and cooperation (i.e. the capability to interact with other agents to achieve their own objectives) are important characteristics of agents. However, according to Wooldridge and Jennings (1995) an agent may also exhibit other characteristics as intelligence (i.e. the capability to reason and perform cognitive procedures), reactivity (i.e. the capability to sense the environment and quick response to changes), proactivity (i.e. the capability to take the initiative) and social capabilities (i.e. the capability to interact with other agents, and possibly humans, via a communication language).

Rare applications consider agents in an isolated manner, but instead, they consider a set of agents to solve complex problems, constituting a MAS, that can be defined as a society of agents that may represent physical or logical objects of a system, capable of interacting, in order to achieve their individual goals, when they have not enough knowledge and/or skills to achieve their objectives individually (Leitão 2009*a*).

As illustrated in Figure 1.1, a MAS system comprises a society of agents, each one representing one object, having a set of goals and possessing a set of skills and local knowledge. Each agent is regulated by internal behaviours that are responsible for performing the required actions towards the execution of its goals, being its functionalities encapsulated as services.

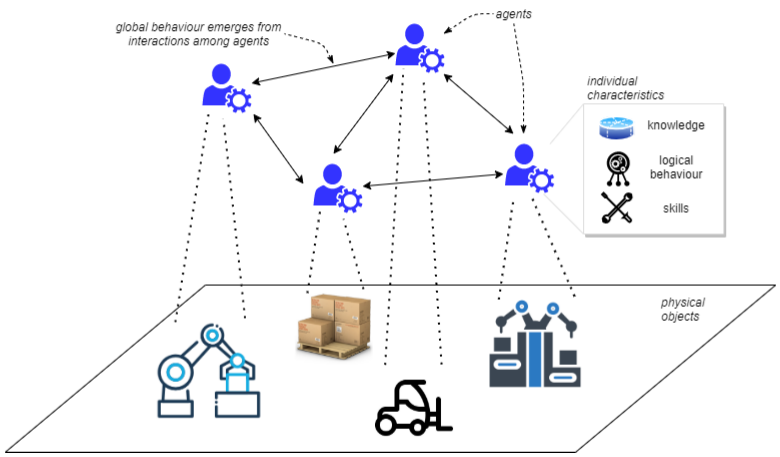

Figure 1.1. *Multi-agent systems technological paradigm*

In such systems, since each agent has a partial view of the system, as well as partial knowledge and skills to execute its goals, agents need to interact with each other, performing different forms of cooperation, e.g., collaboration and negotiation, to achieve its goals. The global system function emerges from the interaction among the distributed agents, each one contributing with its own knowledge and skills. For this purpose, agents follow a heterarchical structure organisation characterised by the high-level of autonomy and cooperation, which ensure modularity, plugability, robustness, scalability and reconfigurability on-the-fly.

Compared to traditional centralised control strategies, MAS offers an alternative way to design large-scale and complex systems by decentralising the control of the system, and distributing the control by autonomous and cooperative agents, ensuring the capabilities to adapt to emergence without external intervention (Wooldridge 2002). In fact, MAS replaces the centralised control with a distributed functioning where the interactions among individual agents lead to the emergence of "intelligent" global behaviour. This ensures a high degree of autonomy without a fixed client-server structure.

Agents are computational pieces of code that exhibit the described characteristics, namely intelligence, autonomy and cooperation, based on a distributed system infrastructure. An agent-based system can be developed using a programming language, but the development of agent-based applications requires the implementation of features that are not supported by usual programming languages, such as message transport, encoding and parsing, yellow and white pages services, and agent life-cycle management services, which increases the programming effort and complexity. In order to simplify their development, debug and maintenance, they are usually developed using agent development frameworks that provide these features. As an example, the Java Agent Development Framework (JADE) (Bellifemine *et al*. 2007) is a well know agent development platform that provides a set of services, namely, naming service and yellow-page services, message transport and parsing services, a library of the Foundation for Intelligent Physical Agents (FIPA 2002) interaction protocols, agent life cycle management services, and debug tools, to develop agent-based FIPA (2002) compliant systems.

1.2.2. *Holonic Paradigm*

Holonic paradigm translates the Köstler's observations and Herbert Simon's theories into a set of appropriate concepts for distributed control systems.

In the mid-1960s, Köstler (1967) introduced the word holon to describe the basic unit of organisation in living organisms and social organisations. Based on Simon's theories, that refer that complex systems are hierarchical systems formed by intermediate stable forms, which do not exist as auto-sufficient and non-interactive elements but, on the contrary, they are simultaneously a part, and a whole, Köstler concluded that, although it is easy to identify sub-wholes or parts, wholes and parts in an absolute sense do not exist anywhere (Leitão 2009*b*).

Having this in mind, Köstler proposed the word *holon* to represent this hybrid nature, being a combination of the Greek word *holos*, which means whole, and the suffix *on*, which means particle. Similar to agents, autonomy and cooperation are the major characteristics of holons, which are autonomous and cooperative entities that can represent physical or logical objects, e.g., a robot, a machine, an order or a product. As illustrated in Figure 1.2, it may comprise a communication part, an information processing part and a physical processing part, the last one only if the holon represents a physical device, such as a product, a transport module, a machine or an industrial robot (Colombo *et al*. 2001 ; Leitão 2009*b*). This feature can be considered as the inspiration for the CPS concept in the sense of combining cyber and physical counterparts.

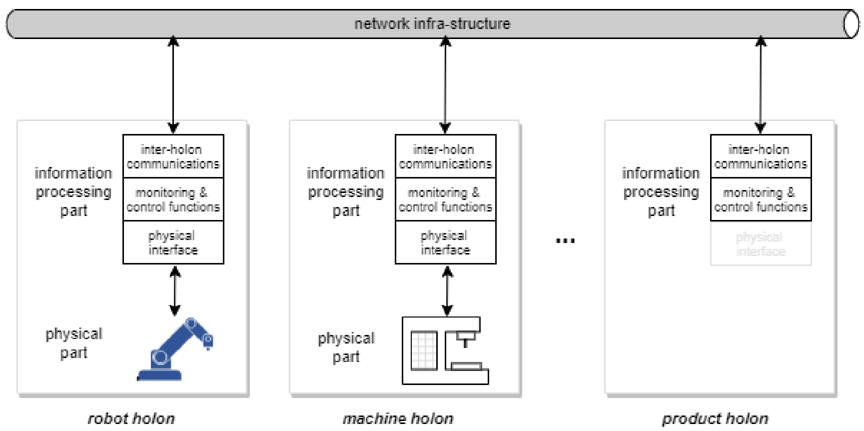

Figure 1.2. *Highlights of the constitution of holons*

A holarchy is a society of holons, organised in a hierarchical structure, operating as autonomous wholes in supra-ordination to their parts and as dependent parts in subordination to controls on higher levels. Holons cooperate with each other to achieve system goals by combining their individual skills and knowledge. In a holarchy, The holons behaviours and activities are determined through the cooperation with other holons, following appropriate interaction patterns, in opposition to being determined by a centralised mechanism.

Each holarchy has fixed rules and directives, and a holon can dynamically belong to multiple holarchies at the same time, which is an important difference from the traditional concept of hierarchies. In fact, each holon can integrate a holarchy and, simultaneously, to preserve their autonomy and individuality. This allows getting the best of two worlds : to preserve the stability of hierarchy while providing the dynamic flexibility of heterarchy structures.

In holonics, the design of complex problems can be simplified by dividing the initial problem into several small problems. This is possible through the inherent recursivity capability associated with the holon, and particularly with the Janus effect, i.e. a holon is simultaneously a self-contained whole to its subordinated parts and a dependent part when seen from the higher levels. As illustrated in Figure 1.3, a holon

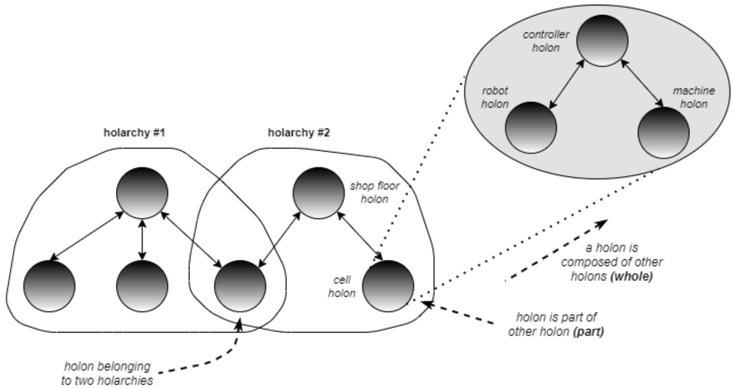

Figure 1.3. *Main features of holonics paradigm*

representing a cell can be simultaneously the whole, encapsulating holons representing the cell resources and the part when considering the shop floor system.

In other words, a holon can be part of another holon or a holon can be broken into several other holons, which in turn can be broken into further holons.

1.3. Industrial Agents

1.3.1. *Definition and Characteristics*

In the context of MAS, a software agent can be defined as *"an encapsulated computer system that is situated in some environment and that is capable of flexible, autonomous action in that environment in order to meet its design objectives"* (Jennings and Wooldridge 1998). As previously referred, these agent-based systems provide several benefits, namely flexibility, robustness, reconfigurability and scalability, to develop large and complex systems (Leitão and Karnouskos 2015).

Industrial agents inherit the software agent principles, such as intelligence, autonomy and cooperation, but their application domains are related to industrial environments and then facing industrial requirements, e.g., specific hardware integration, reliability, fault-tolerance, scalability, industrial standard compliance, quality assurance, resilience, manageability, and maintainability (Leitao, Karnouskos, Ribeiro, Lee, Strasser and Colombo 2016). The degree of importance of each requirement if different and dependent on the operational and business contexts. Additionally, Karnouskos and Leitao (2017) elaborate on the key factors, which includes Design, Technology, Intelligence/Algorithms, Standardisation, Hardware, Challenges, Application, and Cost, that play important roles in the acceptance of agent-based solutions in the industry.

In this sense, according to Unland (2015), an industrial agent is an *"agile and robust software entity that intelligently represents and manages the functionalities and capabilities of an industrial unit. While it reveals the common features of an advanced agent, it also has some specifics. It understands and efficiently handles the interface and functionality of (low-level) industrial devices. Usually, it belongs to an agent-based industrial application system within which it acts and communicates in an efficient, intelligent, collaborative, and goal-oriented way. In principle, it is an autonomous and self-sustained unit. Nevertheless, it accepts and follows company guidelines, codes of conduct, general laws, and relevant directives from higher levels. Moreover, especially in emergency and real-time scenarios, its autonomy may be compromised in order to permit fast and efficient reactions."*

The industrial agents context impose strong requirements that may affect the adequacy of the existing agent development frameworks and consequently compromise the industrial adoption of the agent technology. In this context, the development of new, light and industrial oriented agent development frameworks is fundamental to attend to the industrial requirements, considering the communication between industrial agents, the structure to interconnect the physical assets and the legacy systems, and the compliance with industrial standards (Colombo *et al*. 2006).

Another important issue to be addressed is related to the target applications that can better benefit from the use of industrial agents. Due to intrinsic characteristics of industrial agents, and particularly the need for interaction among agents to achieve the global behaviour, they are particularly suited for soft real-time operations, e.g., monitoring, simulation, planning, scheduling and system self-organisation under condition changes. The implementation of hard real-time control strategies usually requires to combine industrial agents with traditional industrial controllers, e.g., PLCs (Programmable Logic Controllers), CNC (Computer Nummerical Control), that maintain the nominal system operation and ensures the system responsiveness (Colombo *et al*. 2001 ; Leitao *et al*. 2021).

1.3.2. *Interfacing with Physical Assets*

Being applicable to industrial applications, an industrial agent, recalling the holonics principles, has usually associated a physical hardware counterpart, which increases the deployment complexity. For example, consider one software agent associated with a punching machine to monitor and optimise its health condition or a software agent associated with a smart metering device to gather the current consumption data. In this context, the interface between the software agent and the low-level automation control devices, illustrated in Figure 1.4, assumes a crucial role. Due to the heterogeneity of the counterparts, this interface can be implemented in different ways, following proprietary or more standard technologies, without having a universal standard that allows the easy, fast and transparent integration (Schoop *et al*. 2002).

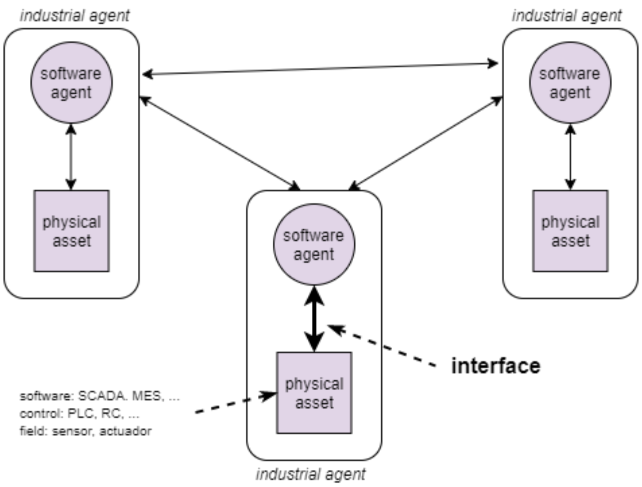

Figure 1.4. *Interface between the software agent and the physical asset*

The recently established IEEE 2660.1-2020 standard on Recommended Practice on Industrial Agents (IEEE 2021) addresses this problem by defining a method to recommend the best interfacing practice for a particular application scenario taking into account the feedback from experts in implementing and using different interfacing practices (Leitao *et al*. 2021). For this purpose, this method scores and compares the existing interface practices according to specific criteria and also indicates their strong and weak points.

1.4. Industrial Agents to Realise Industrial Cyber-Physical Systems

MAS and holonics are being applied in industrial environments, namely in smart production, smart grids and smart logistics, for more than 20 years (Lastra and Colombo 2006 ; Leitão and Karnouskos 2015 ; Leitao, Karnouskos, Ribeiro, Lee, Strasser and Colombo 2016). Nowadays, industrial agents can play an important role in the industrial CPS context since they can provide naturally in these emergent solutions autonomy, proactivity and cooperation. In fact, industrial agents are potentially suited to realise industrial CPS, by adding a brain set of capabilities that include knowledge, decision-making algorithms and negotiation algorithms to the AAS, and thus contributing to the realisation of more autonomous and intelligent I4.0 Components.

1.4.1. *Supporting the Development of Intelligent Products, Machines and Systems within Cyber-Physical Systems*

Through using Industry 4.0-compliant digitalisation and networking technologies migrate the traditional hierarchical industrial architecture and associated technologies (Colombo *et al*. 2010 ; Colombo, Bangemann, Karnouskos, Delsing, Stluka, Harrison, Jammes and Lastra 2014 ; Leitao *et al*. 2020), implemented on the basis of IEC 62264 / IEC 61512 into a completely distributed, asynchronously networked and functional flat infrastructure driven by interaction among the different services (Colombo *et al*. 2005). This infrastructure is composed of a set of cyber-physical nodes, also identified as I4.0 components and systems. Each node is fussioning Mechatronics, Communication, Information and Service-based Business Technologies (Colombo, Bangemann and Karnouskos 2014).

According to the DIN Specification 91345 (Reference Architecture Model for Industry 4.0 - RAMI 4.0) (Deutsches Institut fuer Normung (DIN SPEC 91345) 2016), an initial physical object, positioned within the ISA'95 / ISA'88 standard enterprise architecture, is called an "asset". Each of these assets can be digitalised and networked following the 6-layer-specifications addressed by the 3D-RAMI 4.0 model's vertical dimension. Such digitalised and networked asset becomes a Cyber-Physical Component / System, recognised as I4.0-Component / System.

The concrete specification and implementation of a cyber-physical component or I4.0-component are done by means of the Asset Administration Shell (AAS), as illustrated in Figure 1.5 (Boss *et al*. 2020). The AAS is a uniquely addressable digital/cyber representation of functionality and data/information for each type and instance of an asset. In this sense, it supports the Internet-based communication and the networking of a digitalised asset with other assets in the Industry 4.0-compliant system.

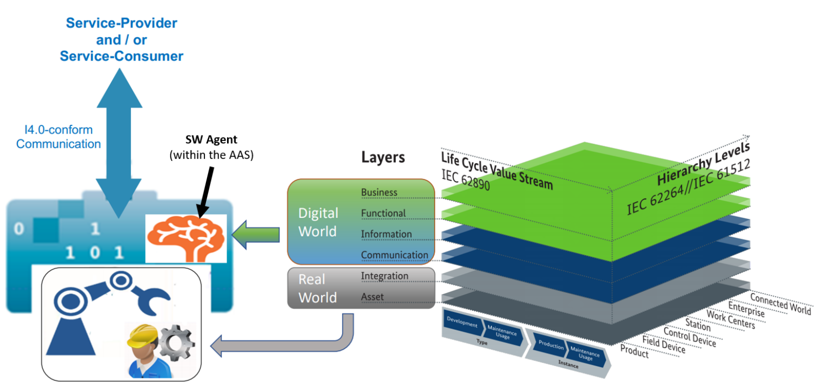

Figure 1.5. *Positioning of Industrial Physical Agents within the RAMI 4.0*

Following the latest reported results about the specification and implementation of the AAS, it is possible to summarise a set of characteristics such as :

1) The AAS creates cross-vendor interoperability because it contains data and information associated with different phases of the life cycle of the digitalised and networked asset ;

2) The AAS specifies the entire life cycle of products, equipment, machinery and production systems, following the standard specification IEC 62890 ;

3) The AAS enables "digital" consistent value chains being considered as the implementation of different "digital twins" of the asset/s.

The AAS is composed of submodels which are the data and information containers associated to different life-cycle phases of the digitalised asset.

Any asset located within the IEC 62264 standard architecture can become a CPS or I4.0 component, i.e., products, sensors and actuators, controllers, stations, lines, IT-/Management systems like MES (Manufacturing Execution Systems), ERP (Enterprise Resource Planning), CRM (Customer Relationship Management), etc. Those I4.0 components and systems, cyber-physical components and systems, are able to perform business in a service-oriented fashion, and for each business to be developed and implemented, I4.0 components have to fulfil a dedicated set of Service-Level-Agreements (SLAs).

An innovative concrete step for integrating agent- and Holonic-technology with I4.0-compliant solutions is to include essential capabilities of agents/holons, such as decision-making functions as well as negotiation services, as a set of new submodels, as schematically depicted in Figure 1.6.

1.4.2. *Implementing an Industrial Multi-agent System as ICPS*

Following the proposal of enhancing the AAS structure by, e.g. a submodel with Agent capabilities, has major consequences. On the one side, the AAS is designed available for non-intelligent but also for intelligent digitalised assets, being also a digital basis for autonomous components and systems. On the other side, the set of I4.0-components with Intelligent Decision-Making and Negotiation capabilities, that is, the set of networked AAS with intelligence, constitutes the basis of an I4.0-compliant "Industrial Multi-agent systems". It is here where MAS and Holonics technologies find their way into the Industry 4.0 and CPS contexts. The AAS are in charge of managing the own Physical Agents, and the SLA-based Business Interaction Protocol manages the whole I4.0 Ecosystem-based on MAS/Holonic systems.

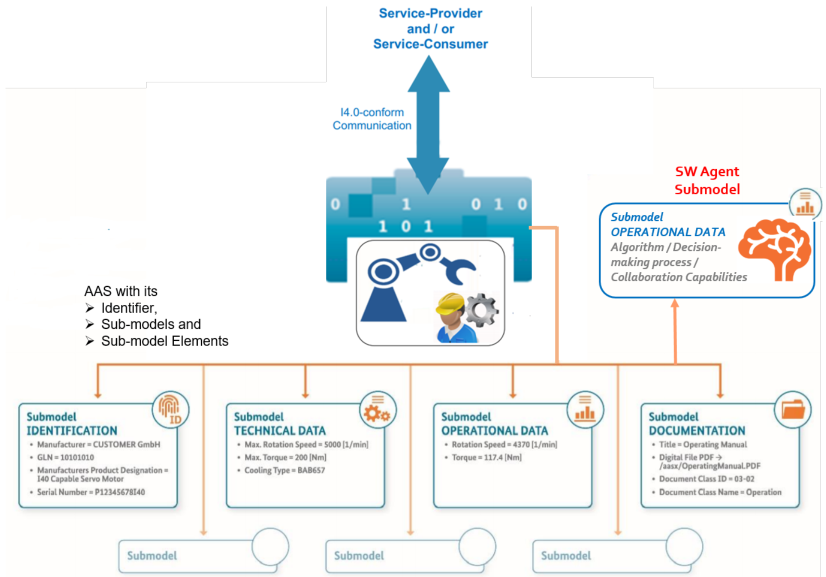

Figure 1.6. *Industrial Agent as a submodel within the AAS*

1.5. Discussion and Future Directions

Concepts and technologies pertinent to Industrial agents and holonic systems have been researched and prototyped over the last decades (Colombo *et al*. 2001, 2006 ; Leitão and Karnouskos 2015 ; Leitao, Karnouskos, Ribeiro, Lee, Strasser and Colombo 2016). However, the influences of each era computing and communication paradigms and associated technologies are evident (Ribeiro *et al*. 2017), and have heavily influenced how this research and prototypes have evolved, and recently this is due to the emergence of Industry 4.0 (Leitao *et al*. 2020), and specifically, the Industrial CPS (Karnouskos *et al*. 2020). The promising directions are in the direction of the power-relation relying in the combination of CPS and Agents that can lead to enhanced capabilities, management, engineering, infrastructures, ecosystems and information systems (Colombo *et al*. 2021).

From a technology viewpoint, there are several horizontal challenges that pertain to Industrial Agents and CPS that are identified, and to a degree also prioritised (Leitao, Karnouskos, Ribeiro, Lee, Strasser and Colombo 2016 ; Leitão, Colombo and Karnouskos 2016 ; Colombo *et al*. 2017 ; Karnouskos *et al*. 2020). Ever-relevant directions that agents can address, include integration, modularity, servification, and collaboration in order to realise the autonomous and intelligent infrastructures envisioned. In addition, the direction of combining the intelligent aspects of Agents with the modern machine learning capabilities can further lead to approaches that deal with better planning, learning, knowledge representation and control, all of which are in the heart of modern CPS systems and services (Ribeiro *et al*. 2008 ; Nagorny *et al*. 2012 ; Karnouskos *et al*. 2020).

Beyond the core technology aspects for the powerful combination of agents and CPS, the operationalisation of these in concrete scenarios is also of research interest. Especially in the direction of human-machine interaction where agents can mediate and bring together both, seem appealing and are under active development via the utilisation of modern technologies with successful realisations as sophisticated chatbots, augmented/virtual reality, personal assistants etc.

Agent-based modelling and simulation have been an active area of Agents, and approaches can be extended to the new CPS-based infrastructures. Simulation of complex CPS-infrastructures, as well as large ecosystems with their own goals and capabilities, is of interest. Additionally, providing monitoring, management, and control solutions for such complex systems while hiding complexity and in parallel offering self-management is also another promising direction.

Finally, because most of the discussed solutions go beyond the traditionally highly-controlled industrial environments, key issues relevant to security, trust, privacy, resiliency, safety, ethics are also promising directions to investigate, as future agent-based systems are expected to be designed, developed and operated in real-world constellations with high uncertainties.

While for engineers, priorities are initially on the technology and product/solution development, it has to be considered that other non-technical aspects may be the determining factors for success. As analysed by Karnouskos and Leitao (2017) the key factors for the acceptance of agents in industrial environments include design, technology, intelligence/algorithms, standardisation, hardware, challenges, application and cost. The case of the agent-based system Production 2000+ at the Mercedes-Benz (now Daimler) factory plant in Stuttgart, Germany (Colombo *et al*. 2006), exemplifies why agents should not be looked only as a technology, but in their entirety, including the business aspects (Karnouskos *et al*. 2020). The agent-based solution introduced enhanced reconfiguration and adaptation in the assembly line, and was in operation for five years, before being decommissioned, and that despite the evidenced robustness and higher productivity increase of 20%, because its technical advantage did not imply an immediate and measurable economic advantage (Schild and Bussmann 2007).

Concluding, it can be pointed out that there are several promising directions (Karnouskos *et al*. 2020) for agents and their associated concepts, which, however, need to carefully balance technological as well as operational and business factors (Karnouskos and Leitao 2017). The current combination of agent concepts, modern technologies, and the emergence of cyber-physical infrastructures provide today the most fruitful ground where agent-based approaches can be designed, realised, operated and assessed. As can be seen, industrial agents and their associated concepts may yet have another chance to enter the mainstream and achieve the long-promised impact (Karnouskos and Leitao 2017).

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