Smart Agents in Industrial Cyber–Physical Systems

This paper surveys and analyzes the current state of the industrial application of agent technology in CPSs, and provides a vision on the way agents can effectively enable emerging CPS challenges.

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ABSTRACT | Future industrial systems can be realized using the cyber–physical systems (CPSs) that advocate the coexistence of cyber and physical counterparts in a network structure to perform the system's functions in a collaborative manner. Multiagent systems share common ground with CPSs and can empower them with a multitude of capabilities in their efforts to achieve complexity management, decentralization, intelligence, modularity, flexibility, robustness, adaptation, and responsiveness. This work surveys and analyzes the current state of the industrial application of agent technology in CPSs, and provides a vision on the way agents can effectively enable emerging CPS challenges.

KEYWORDS | Artificial intelligence; cyber–physical systems (CPSs); internet of things; multiagent systems (MASs); service-oriented architectures

I. INTRODUCTION

Production activities face a growing set of sustainability challenges that will soon bring current industrial automation practices to their limit. At the core of these challenges [1] lie the ambitious goals of satisfying a continuously changing market with a growing demand for customized and complex products and the need to support their production in a competitive but also sustainable way. Cyber–physical systems (CPSs) are perceived to be a core ingredient in the so called 4th Industrial Revolution [2], and several efforts are pursuing its goals, e.g., Industrie 4.0 [3] and Industrial Internet [4].

A cyber–physical entity is one that integrates its hardware function with a cyber-representation acting as an virtual representation for the physical part. CPS combines two worlds: 1) embedded systems, exhibiting real-time and strictly deterministic behavior; and 2) cloud systems, highly probabilistic and optimized behavior without firm time constraints [2]. From an industrial point of view this concept opens wide the door for the development of smart products that are uniquely identifiable, localizable, and able to take autonomous actions as a function of their internal state and their perception of the environment where they are immersed. It also enables the creation of sophisticated functions in complex systems like production systems or power grids. In production systems the CPS perspective partly breaks with the traditional automation pyramid [5], introducing a more decentralized way of functioning into the traditional hierarchical structure [6]. In fact, such systems would be extremely decoupled and would collectively have the ability to self-organize in order to overcome unexpected disturbances. They also support dynamic system resizing and reconfiguration to meet distinct business opportunities.

Complementing intelligent CPS with the Internet of Services (IoS), new interaction patterns and business models can be realized which may lead also to smarter products and sophisticated System-of-Systems (SoS). This disruptive vision is supported by the convergence of

several developments in artificial intelligence (AI), information and communication technologies (ICT), and the constant increase and pervasive availability of computing, communication, and storage. It must be noted that the novelty of CPS is not in establishing a new technology per se, but instead in combining existing technologies, such as multiagent systems (MASs), service-oriented architectures (SOAs), Internet of Things (IoT), cloud computing, augmented reality, big data, machine-to-machine (M2M), etc., most of which are identified as emergent technologies today [7].

There are however important challenges, such as safety, security, and interoperability, which must be effectively tackled before this vision can become a reality especially in an industrial context. Some of these topics have been partially covered by the industrial MAS community [8], and there are seeds of knowledge and isolated developments that could support an industrial CPS. Industrial MASs [9] are seen as playing a key role in the development of CPSs, allowing to design control systems in a decentralized manner based on the distribution of control functions by autonomous and cooperative agents [10], offering important characteristics, such as modularity, flexibility, robustness, reconfigurability, and responsiveness.

However, these knowledge clusters are not consistently aggregated, nor may be adequate to fully cover CPS needs. In particular, there is not a clear connecting path between the high level design principles (e.g., holonic, bionic, fractal, or reconfigurable) that set high abstraction guidelines for building what could be industrial CPS and their implementation with the hardware in the loop. This means that there is a subsequent and poor articulation with any precedent reference architectures, their system specific instantiation and the design of agents that may be used as a vehicle for the implementation. In the same line of thought, up to day there is no tangible way to measure the properties or quantify the specific behaviors of these emerging systems. Nevertheless, the feasibility of some key ingredients which overall render this a very active and relevant research area have been demonstrated, and may form the basis towards tackling the CPS challenges.

In this context, a fundamental part of the upcoming challenges is to connect the dots between the existing knowledge isolated parts in order to bring it one step closer to the vision. The objective of this work is to discuss the use of MASs in CPSs, for implementing the next generation of industrial systems in light of key requirements such as modularity, flexibility, robustness, scalability, reconfigurability, and self-adaptation. For this purpose, the paper surveys existing applications of industrial agents in CPS context and discusses the current efforts and challenges for their wider applicability.

The paper is organized as follows. Section II overviews the initiatives and programs promoting the digitalization of future industrial systems and derives their requirements, and Section III reviews existing agent-based applications for industrial systems. Section IV introduces the design principles for these systems, and Section V lists important standards for their realization. Key challenges of using agent-oriented approaches in CPSs are discussed in Section VI, and Section VII rounds up the paper with the conclusions.

II. FUTURE INDUSTRIAL SYSTEMS

Future industrial systems are being reshaped and redesigned to address the continuous globalization and digitalization of economy, and the growing demand for increasingly complex and customized products.

A. Initiatives, Programs, and Roadmaps

The 4th Industrial Revolution that is unfolding is not based on a single technology but rather on the concept of aggregating existing system-related technologies around the cyber–physical formulation of systems. This requires a joint, convergent, and multidisciplinary research effort that is currently motivating different research initiatives and agendas. For example, aiming the development of the next generation of industrial systems, at European level the main research activities have been developed under the umbrella of "Horizon 2020—The European Framework Programme for Research and Innovation." In particular, CPS is a key pillar in the Factories of the Future public private partnership providing a financial envelope of 1.15 billion euros, with the general objective of developing and integrating the main enabling technologies supporting novel and adaptable machines and systems.

The European member states have themselves supported several national initiatives; for instance Germany has one of the most prominent research programs called "Industrie 4.0" [3], grounded on the vision whereby intelligent objects collect, store and process all their own relevant information throughout their life-cycle, and systems composed by these objects benefit from all the information and knowledge that is actively generated. A similar direction can also be found for example in Sweden, with the "Made in Sweden 2030" research agenda, and more recently in Spain, with strategies and initiatives following the Industrie 4.0 philosophy that support the digital businesses transformation, especially for small and medium enterprises.

CPSs and "Industrie 4.0" are also a very important research topics in Austria where in 2015 a corresponding association with representatives from industry and research has been founded to foster innovation in this domain. The Austrian government has reserved about 250 million euros for research and technology development until 2017 for this area.

In the United States, CPS was identified by the President's Council of Advisors on Science and Technology report of December 2010 as national priority for the federal R&D due to its potential scientific and technological impact to reach security and competitiveness in a number of United States' critical sectors [11]. For this purpose, the CPS program under the umbrella of the Directorate for Computer & Information Science & Engineering (CISE) from the National Science Foundation (NSF) is the U.S. Government's response to funding R&D projects in CPSs. In this line, the Industrial Internet consortium [4] was announced in 2014 as a not-for-profit open organization created by AT&T, Cisco Systems, General Electric, IBM, and Intel. The consortium defines Industrial Internet as "the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes" and aims to "catalyze and coordinate the priorities and enabling technologies of industry, academia and the government around the Industrial Internet." Further north, in Canada, there is no governmental program exclusively dedicated to funding R&D projects in CPSs. Nevertheless, within the multiple programs offered by the Natural Sciences and Engineering Research Council of Canada (NSERC), several initiatives in the area of CPSs are being supported. The same panorama can be found on Japan, sponsored by the Japan Science and Technology Agency (JST), an independent administrative institution for research and development framed by the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

Recently, China announced its own research initiative "Made in China 2025" to support the development of more intelligent and greener manufacturing with a special focus in quality, adaptation and integration with the Internet. The China's support to R&D projects in CPSs is managed by the National Natural Science Foundation of China (NSFC), also materialized in grants awarded to researchers working in the CPS field. Finally, in Korea, private institutions and research groups related to CPSs are supported by the Ministry of Science, ICT and Future Planning (MSIP).

B. Requirements

Key requirements need to be fulfilled before the vision of an integrated and convergent Industrial Internet and all its benefits can be attained. In particular, it is important to consider that even in highly development countries there are asymmetries on the degree of digitalization of local industries and even within the same company certain areas have been prioritized with respect to computerization. As a result an "Industrie 4.0 shop-floor" as envisioned is challenging, but more importantly due to the rapid technology pace, the main paradigms that are still used in automation and control have not been able to keep up with the progress in relevant domains, e.g., computer science, artificial intelligence and engineering.

In order to overcome these challenges, companies need to understand and embrace the forthcoming technologies and principles, the networked and distributed philosophy promoted and advocated by the 4th Industrial Revolution and initiate a process of change towards the development of a more cyber–physical shop floor. Current productive systems and technologies do not adequately support this view yet and until recently, for example, object orientation was completely absent from industrial programming languages. At the same time the scale of system integration required is unprecedented in industry and requires a collaborative standardization effort, that although common in other sectors, e.g., in telecommunication, has not been attained in the industrial sector.

The technical challenges are complemented by a lack of widely acceptable models on how to design and manage and cyber–physical industrial systems. There is the need for integrated design methodologies and models that identify the relevant data to be collected and turned into knowledge that can, subsequently, be communicated to the different systems, supporting a cycle of continuous improvement. Knowledge generation, from the massive amount of data generated, will, to a great extent, have to be handled in an automated manner. The challenges therein far extend beyond the physical limitations related to data storage and require the design of intelligent systems that generate knowledge, which when retrofitted to the different systems, causes them to react in a "human compatible" way. Here, there are important legal and ethical implications that result from the use of advanced artificial intelligence for which there is, currently, no supporting framework.

Education needed in order to design, implement, and operate complex CPSs in the emerging infrastructure is much more versatile. However, current engineering curricula are not sufficiently preparing engineers with the needed multidisciplinary background required to understand large-scale, interconnected industrial CPSs. Although this challenge may affect companies in a medium to long term there are more immediate education challenges toward the decision makers and employees within companies that may not be able to understand and assess the role of new industrial systems driven by CPSs, and subsequently downplay its potential.

III. INDUSTRIAL APPLICATIONS OF SMART AGENTS IN CPS CONTEXT

MAS technology is being applied to several industrial applications in a CPS context, namely smart production (see, for example, [9] and [12]–[16]), smart electric grids [17]–[20], smart logistics [13], and smart healthcare [21], [22]. This section briefly surveys and discusses

existing industrial agent-based applications focusing on the smart production, smart electric grids, and smart logistics domains.

A. Industrial Applications in Smart Production

Agent-based solutions for smart production have been developed and installed in industrial environments during the last two decades, as surveyed, e.g., in [13], [14], and [16]. Table 1 categorizes them according to the ISA 95 levels, i.e., automation control (L1), supervisory control (L2), manufacturing operations management (L4), and business planning and logistics (L4).

In the mid-1990s, Rockwell Automation developed an agent-based solution to increase the utilization of steel milling process at the steel rod bar mill of the BHP Billiton in Melbourne, Australia [23]. Some years later,

the same automation provider developed an agent-based real-time control system for the chilled water system onboard the U.S. Navy ships [23]. In 2001, another early industrial application of MAS technology, developed by Schneider Automation, was installed in a factory plant of Daimler Chrysler producing engine cylinder heads [26]. The solution was in operation for five years, up to the end of the life-cycle of the targeted product, with a reported increase of 20% in productivity. One year later, the ExPlanTech agent-based production planning framework was deployed by CertiCon at LIAZ Pattern Shop producing patterns and forms for automobile industry, and at SKODA Auto, Mlada Boleslav, for the production planning in the engine assembling workshop [27]. The Agentsteel system was installed in the steelwork Völklingen of Saarstahl for the online planning and

Table 1 Application of Agents in Smart Production

Name	ISA95 level	Scope	Year
BHP Billiton	L2	Process control [23]	1995
Yokogawa	L1	Machinery control [24]	1998
MASCADA (Daimler-Benz pilot)	L2	Manufacturing control [25]	1999
Daimler Chrysler	L2	Manufacturing control [26]	2001
LIAZ	L3	Production planning [27]	2002
Skoda	L3	Production planning [27]	2002
Cambridge packing cell	L2	Manufacturing control [28]	2003
Watchdog Agent	L1	Machinery monitoring [29]	2003
FABMAS	L2	Process control [30]	2003
PABADIS	L1–L4	Manufacturing control [31]	2004
ABAS	L2	Manufacturing simulation and control [32]	2005
Saarstahl	L3	Production process planning and monitoring [33]	2005
SOCRADES	L1–L4	SOA-ready devices, SOA-based cross-layer integration (device-to-ERP) [34–36]	2007
NovaFlex	L2	Manufacturing control [37]	2007
AGP	L2	Manufacturing execution system [38]	2008
ADACOR-FMS	L2	Manufacturing control, and reconfiguration [39]	2008
Axion-Holding	L3	Manufacturing scheduling [40]	2010
IMC-AESOP	L1–L4	SOA-ready devices, cloud-based SCADA/DCS, SOA & cloud -based services [12, 36, 41]	2010
Kuznetsov	L3	Manufacturing scheduling [42]	2013
GRACE (Whirlpool pilot)	L2	Self-adaptation [43]	2013
IDEAS	L2	Reconfiguration and plug-and-produce [44]	2013
ARUM (Airbus and IHF pilots)	L3	Production planning and scheduling [45]	2015
ADACOR2	L2	Manufacturing control and reconfiguration [46]	2015
PRIME	L2	Manufacturing plug-and-produce [47]	2015

monitoring of the steel production process [33]. A real-time MAS scheduling and optimization tool, developed by Magenta Technology, was deployed for the factory workshop of Axion-Holding, Russia [40], and later, Smart Solutions deployed a similar smart MAS for the real-time scheduling in the aircraft jet engines production at Kuznetsov, Russia [42]. A holonic manufacturing execution system (MES), implemented using MAS technology, was developed for the American glass product (AGP) [38].

MASs were also applied in prognostics and health management. The Watchdog agent toolbox, developed by the Center for Intelligent Maintenance Systems (IMS), provides intelligent data processing tools for the assessment of the degradation process of machines and components. These analytical agents have been successfully implemented in several applications, such as monitoring and diagnosing air compressor equipment and machine tools components [29]. Also at the machinery level, Yokogawa Electric Corporation used agent technology to develop a control system for the Shape Deposition Manufacturing (SDM) Laboratory of the Robotics Institute at Carnegie Mellon University [24].

Several large-scale R&D initiatives were conducted along the years to research that promote the use of MASs in industrial applications. The main test case of the European Union (EU) MASCADA project was the development of a PROSA-based agent system for a section of the painting center in the Daimler-Benz plant in Sindelfingen, Germany [25]. Another PROSA-based agent system, entitled FABMAS, was installed for production control of a semiconductor wafer fabrication facility [30]. Also FP5 PABADIS and FP6 PABADIS'PROMISE [31], [48] targeted a distributed, agent-based manufacturing control. The test case of the EU FP7 GRACE project deployed a MAS for integrating process and quality control in the washing machine production line of Whirlpool [43] in Naples, Italy, showing benefits in terms of production efficiency and product quality, as well as a reduction of the scrap costs. The EU FP7 IDEAS project focused on the application of key enabling technologies, and particularly MAS, to enable instant/plug and produce deployment of modular equipment without reprogramming, being demonstrated by using the Masmec System for dynamic part assembly [44].

EU FP6 SOCRADES has aimed toward service-enabled factories [49], and has utilized agent technology in various test cases, e.g., for simulating simple web-service-enabled devices [34], large infrastructures of SOA-ready devices [35], up to more complex cooperative industrial systems [36]. This line of thought was further followed within the EU FP7 IMC-AESOP project, where the focus on SOA-ready devices was heavily shifted toward cloud-ready approaches [12]. A cloud-based service-oriented architecture was proposed with the aim to enhance cloud-centric interactions among disparate systems including agent-based ones [6]. Smart agents would then use these services and driven by their internal logic could take and enforce decisions, e.g., energy monitoring in a plant and usage of excess energy in electric vehicle charging or trading it in an energy market [41]. PABADIS, SOCRADES, and IMC-AESOP are among the rare projects that have tackled a cross-layer CPS infrastructure i.e., L1–L4 as shown in Table 1.

The EU FP7 ARUM project combines MAS and SOA to develop knowledge-based applications that support mitigation strategies to respond faster to unexpected events in ramp-up production of complex and highly customized products, such as airplanes or shipyards [45]. The developed strategic planning and operational scheduling tools were tested in the Hamburg factory plant of Airbus producing the new A350 and in the Ferentino factory of IHF producing products for the airplane in-flight equipment, such as coffee machines and trash compactors. The EU FP7 PRIME project proposes a MAS framework to enhance assembly systems with standardized plug and produce process and control solutions to allow rapid reconfiguration and deployment, performance monitoring, self-awareness, and evolutionary system adaptation [47]. These principles were validated using two MAS-based industrial demonstrators, namely one placed at the University of Nottingham, considering "plug and produce" for reconfiguration of production systems with a minimum human intervention.

Some lab prototypes using MASs have also been realized. A large-scale industrial agent-based control testbed for assembling Gillette packages into customer-tailored gift boxes was deployed at the lab packing cell of the University of Cambridge [28]. MAS shop floor control systems were developed for the Novaflex manufacturing system at Uninova, Portugal, using the CoBASA architecture [37], and for the flexible manufacturing system at the Polytechnic Institute of Braganca, Portugal, using the ADACOR holonic architecture [39]. An evolution of this approach, named ADACOR^2, was deployed in the AIP-PRIMECA system installed in the University of Valenciennes, providing a dynamic control system reconfiguration by combining structural and behavioral self-organization [46]. At last, ABAS was deployed on a highly dynamic, reconfigurable micro-assembly station at Tampere University of Technology in Finland, aiming at the 3-D simulation and visualization of assembly processes [32].

B. Industrial Applications in Smart Electric Grids

ICT is being applied in smart electric grids to enhance the achievement of intelligent and collaborative control systems that cope with the increasing complexity, volume of data, and nonlinearity exhibited by these systems. The use of ICT, and particularly agents and SOA, in intelligent energy systems is reviewed, e.g., in [17] and [18], and is summarized in Table 2.

Table 2 Application of Agents in Smart Electric Grids

Name	Automation functions	Year
CRISP	Active Control, Distributed Control and Monitoring [50]	2005
GridAgents	Distributed Control and Monitoring, Demand Response [51]	2008
Fenix	Demand Response, Distributed Control and Monitoring, Active Control [52]	2008
IDAPS	Distributed Control and Monitoring, Demand Side Management [53]	2009
SmartHouse/ SmartGrid	Demand Side Management, Demand Response, Distributed Control and Monitoring, Active Control [19, 50, 54, 55]	2009
OPTIMATE	Distributed Control and Monitoring [56]	2010
More Microgrids	Demand Side Management, Distributed Control and Monitoring, Active Control [19, 54, 57]	2010
Integral	Distributed Control and Monitoring, Active Control [58]	2011
MASGrid	Distributed Control and Monitoring, Active control, Self-Optimization [59]	2011
BeyWatch	Demand Side Management, Demand Response, Distributed Control and Monitoring [60]	2011
EcoGrid	Demand Side Management, Self-optimization [61]	2012
UNLV pilot	Demand Side Management, Peak Load Management [62]	2012
GRID4EU	Demand Side Management, Peak Load Management [63]	2013
NOBEL	User-bidding in Energy Marketplace [64, 65]	2013
E2SG	Distributed Control and Monitoring, Network Reconfiguration [66, 67]	2014

The CRISP project developed the PowerMatcher tool aiming at the supply–demand balancing by using an agent-based electronic market [50]. This tool was used in several followup projects, e.g., Integral and SmartHouse/ SmartGrid projects. Integral focuses on the development of a MAS application to coordinate a cluster of devices to match its electricity supply and demand [58], and SmartHouse/SmartGrid utilized agent technology to autonomously monitor and control a power grid according to enterprise dynamically communicated needs [19], [50], [54]. In addition, during the last case, agents have been used for simulation of energy behaviors at the system level, e.g., smart grid cities [55]. The EU FP7 Eco-Grid project also reused the PowerMatcher tool to implement a real-time energy market [61] for the Danish Bornholm island, which comprises around 2000 residential consumers.

The More Microgrids project used MASs to implement the intelligent control of microgrid loads to maintain the balance between the energy demand and supply through a selective shedding of nonpriority loads [19], [54], [57], and the Intelligent Distributed Autonomous Power Systems (IDAPS) project aims to supply the critical loads when a failure with the utility grid connection is detected [53]. The MASGrid project [59] applies MAS technology for the self-optimization in active power distribution grids aiming to reduce line losses and to maintain the power quality impacted by a high amount of fluctuating distributed generators.

The GridAgents tool was designed to support the development of large-scale distribution network control solutions comprising large amounts of distributed energy resources [51] and was tested in the Fulton Corridor Network and Madison Square Network in New York City.

The NOBEL project created a cloud-based platform offering energy services including a market where energy could be traded by agents representing their users [64], [65]. The E2SG project developed a decentralized and embedded agent-oriented architecture for the optimization and management of intelligent buildings [66], and an asynchronous leaderless MAS-based approach that coordinates the reactive power outputs of a set of power capacitors [67]. The GRID4EU project uses MASs for surveillance and automated control of medium voltage grids [63], the OPTIMATE project uses MASs to ease the analysis and validation of market designs [56], and FENIX applies MASs to prevent electric imbalance in commercial clusters of distributed energy resources [52]. The University of Nevada, Las Vegas (UNLV) developed an intelligent agent software system to integrate residential customers aiming potential energy savings, contributing to decreasing the peak demand in the Desert Southwest [62]. The BeyWatch project presents an innovative energy-aware and user-centric solution, where intelligent agents provide

intelligent energy monitoring/control and power balancing to residential customers [60].

Other examples found in literature use MASs to support the balance of supplied and demanded energy (e.g., [68] and [69], the microgrid operation (e.g., [57]), and the self-healing capability of a smart grid (e.g., [70]–[72]).

C. Industrial Applications in Smart Logistics

Several applications of MASs in scheduling and logistics optimization are also reported in literature, illustrated in Table 3.

Nutech Solutions developed a MAS solution for Air Liquide America LP, enhanced with ant-based strategies, to reduce the distribution costs by managing the truck routes for delivering industrial and medical gases [76]. The Southwest Airlines used a software solution, developed by BiosGroup, integrating ant-based algorithms to get planes to available gates faster at the Sky Harbor International Airport in Phoenix, AZ, USA [73]. Magenta Technology has implemented a series of MAS applications for the real-time scheduling and logistics for different domains, namely taxi scheduling implemented for the Addison Lee taxi company [78], routing and scheduling for the GIST logistics company [75], rent a car optimization for Avis, U.K. [79], and real-time scheduling of cargo assignment to vessels for Tankers International [75]. In a similar manner, Smart Solutions has implemented a series of MAS applications for the scheduling and logistics for different domains, namely adaptive real-time train scheduling for the Russian railways [84] and real-time truck scheduling and routing for Prologics and RusGlobal [81]. The achieved benefits are related to the reduction of the needed resources, reduction of the reaction time in response to disruptive events, and increased effectiveness of resource management.

Whitestein Technologies has introduced a MAS real-time transport optimization solution for ABX Logistics, with an overall cost saving of 11.7% and an improvement in the process efficiency of around 30% [74]. Multi-Agent Technology Group designed a real-time MAS scheduling for the LEGO Company supply chain, which during the yearlong trial period provided the following achievements: reduction of lost sales from 16% to 40%, increase in service level from 66% to 86%, and increase in profitability from 56% to 81% [82]. MASDIMA was prototyped in the Portuguese airline TAP company aiming to monitor and solve problems in real time after disruption during the execution of the airline operation [83]. University of Castilla-La Mancha prototyped a MAS decision support system for the airport ground handling management at the Ciudad Real Central Airport in Spain [80]. Knowledge Genesis in collaboration with Cologne University of Applied Sciences and Airbus developed a MAS for planning airport ground service operations, such as air-catering, luggage delivery, and aircraft cleanup [77].

D. Discussion

The analysis of the surveyed applications allows to extract some important conclusions related to the adoption of agent technology to develop industrial large-scale CPSs.

The areas of interest covered by MASs are growing, covering the span of CPS application domains. In fact, initially, industrial applications were more focused in manufacturing domain, started in 1995 and consolidated

TABLE 3 Application of Agents in Logistics

Name	Scope	Year
Southwest Airlines	Ground floor operations optimization [73]	2001
ABX Logistics	Real-time transport optimization [74]	2005
Tankers International	Real-time scheduling [75]	2006
GIST	Real-time routing and scheduling [75]	2007
Air Liquide America	Logistics optimization [76]	2008
Airport ground services operations	Planning and scheduling [77]	2008
Addison Lee	Real-time taxi scheduling [78]	2009
Avis	Rent a car optimization [79]	2009
Ciudad Real Central Airport	Airport ground handling management [80]	2012
Prologics	Real-time truck scheduling and routing [81]	2012
RusGlobal	Real-time truck scheduling and routing [81]	2012
Lego	Real-time scheduling [82]	2013
MASDIMA	Monitoring & real-time adaption in airline operations [83]	2014
Russian railways	Real-time train scheduling [84]	2015

in 2001 with the Daimler Chrysler application, but lately new application fields are emerging, namely smart electric grids, logistics, and smart health (illustrated by an increase in the number of industrial applications in the last years).

In terms of application scope, initially, the industrial application of MASs was more focused in planning and scheduling. Currently, an expansion to other topics like monitoring, control, self-adaptation, and simulation is noticed. Another observation is the discrepancy of the number of industrial applications found in manufacturing and continuous processes, which may be justified by the harder technical requirements found in the last one.

The review also shows that the adoption of agent technology in industrial applications demanding hard real-time constrains is still not expressive. For this purpose, other technologies that ensure real-time control can be combined, e.g., IEC 61131-3 and IEC 61499, being MAS more focused with higher levels to provide intelligence and responsiveness. In the same line, recently, MAS has been combined with other complementary technologies, notably SOA, cloud computing, data mining, augmented reality, and wireless sensor networks. Currently, applications in smart electric grids frequently combine these key technologies. An emerging topic, noted in the most recent applications, is the integration of data mining algorithms to develop distributed big data analytics.

An important issue when reviewing the industrial application of a technology or solution is to analyze the technology readiness level (TRL), which reflects the technology's maturity. From the spectrum of analyzed industrial applications, the majority of applications developed for smart production are centered in TRL 6–7 (mainly those related to demonstrators of R&D projects), but some applications have reached TRL 9, namely the application deployed in Daimler Chrysler. In logistics, the level of maturity is higher, being centered mainly in TRL 7–9, probably justified by the fact that these applications are operating at scheduling and optimization level, not facing some industrial constraints, e.g., real-time control or integration with physical automation devices.

At last, it is important to note that several commercial software companies, such as Magenta Technology, Smart Solutions, NuTech, Certicon, Almende, Multi-Agent Technology, and Whitestein Technologies, as well as some automation provider companies, such as Rockwell Automation and Schneider Electric, are already offering industrial solutions based on MAS technology.

IV. DESIGN PRINCIPLES

The requirements imposed on future industrial systems challenge the cyber–physical conceptualization, and the design of any system is fundamentally different from
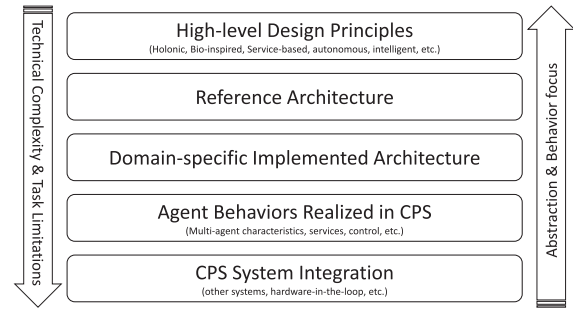

Fig. 1. *Design principles for agent-based CPSs (adapted from [85]).*

its counterpart, more conventional design practices. Although it is possible to argue that all automated systems are cyber–physical in a way, since they result from the coupling of computing elements with physical elements, the vision promoted by the 4th Industrial Revolution requires smaller, more intelligent, and modularized cyber–physical entities that are function oriented and required for their realization.

It is fundamental to consider a connected and integrated approach to system design that links high-level design abstractions and principles, such as holons, services, agents, emergence, self-organization and self-adaptation, with the final, other systems-in-the-loop, implementation [85]. The harmonization of these dimensions is an important challenge that can be better appreciated by considering the design along five different stages as illustrated in Fig. 1, and the specific challenges associated to each one [85].

High Level Design Principles: The cyber–physical formulation of a system has been traditionally inspired by biological or physical systems displaying through-life properties that are highly desirable in engineered systems. These include a persisting ability to react and adapt to quickly changing environmental conditions by dynamically adjusting their structure or operational mode and gracefully recovering from disturbances. This results in an extreme case of robustness that ensures the survival of the system. The key ingredients that grant such behaviors to natural systems relate to the number of system components, the existence of functional redundancy in association to a highly decoupled control structure, and a convergent response that collectively allows the system to explore different solutions for a given disturbance. These ingredients have, for a long time now, been incorporated as high level design principles on most agent-based industrial systems but their implementation at industrial level has been rather elusive.

Reference Architectures: A considerable number of high level design properties are lost during the formulation of reference architectures. System architectures, acting as

blueprints for the creation and generalization of agent-based systems have to incorporate, in a technical framework, not only the high level design principles as well as the specific engineering and technical details of an industrial system. In [86], the authors distinguish between the primary, value adding, functions of an architecture and its life-cycle properties, and this is a crucial point in design. The primary function of a natural system is to survive, and certain natural systems will take or promote significant losses in order to attain its goal. In an engineered system, although one is interested in the life-cycle properties of natural systems, losses have to be avoided. In addition, and contrary to natural systems, engineered systems are fairly heterogeneous. The implementation of the desired life-cycle properties requires the identification of the classes of value-adding components, their functions, interactions, and structural organization. This must ensure a minimum level of harmonization that enables the design of self-organizing patterns resulting in the desired life-cycle properties. The reference architecture should be as technology and system agnostic as possible to maximize range of systems in which it can be instantiated.

Instantiated System-Specific Architecture: The true value of an architecture can only be observed once it comes into operation in a concrete system. A reference architecture, if properly designed, can generate a multitude of different systems. Even if the starting point is an existing system, where the architecture has been previously instantiated, with a specific set of constrains there are often several ways in which the system can be modified. This implies that a good design must be supported by metrics that quantify how the instantiation adheres to the primary goals and to the desired life-cycle properties. Without such a set of metrics, it is indeed impossible to objectively guide decision making of how to build a system. The ability to reconfigure the system is one of the main primary goals of cyber–physical design and is one of the distinguishing factors of systems compliant to the 4th Industrial Revolution. Reconfiguration is understood as multiobjective, not restricted to the physical modification of the system, and could include sustainability aspects, such as energy savings, reuse of equipment, and optimal use of human resources.

MAS Behavior/Control Design: While the previous three design stages develop in an abstract framework, the ability to instantiate an architecture requires the development of an IT platform that can support the cyber-representation of the system. At this stage several technical design decisions should be considered including the choice of the supporting technologies and the development of a concepts for how to manage the interactions between the cyber and physical parts of the system. Historically, there have been two main trends to connect the cyber part to

the physical part [87]: 1) the use of embedded agents whereby each value adding component in the system has its own computing device hosting cyber-representation that takes full control over that equipment; and 2) the use of agents connected to the system, but not necessarily embedded within each component, and where the agents do not exert full control over the equipment but rather influence its behavior in the medium to long terms. The emergence of cloud computing is also opening additional possibilities, such as running the agents in computationally powerful environments with a permanent connection to local controllers. In the former case, depending on the timing requirements of the system, the agent may be able to take full control remotely. When the design moves from the conceptual sphere (first three levels) to the implementation sphere (last two levels), it is fundamental to ensure that the IT platform strictly adheres to the principles formalized in the reference architecture.

Other System-in-the-Loop Implementation: Finally, in the last stage of the design, one must consider the scope of action of the MAS. Most of the existing solutions have focused in control, planning/scheduling, and supervision at a level that positions them on the bottom stages of the ISA 95 model and predominantly at MES level. However, as mentioned before, there is a certain level of harmonization required to generate a convergent and self-organizing response at system level. This requires the creation of several interfaces including: an interface that abstracts the interaction with heterogeneous hardware, ensuring that different components can behave or be abstracted as one of the value-adding cyber–physical entities described in the architecture; an interface that abstracts human–system cooperation and interaction in an easy, safe, and secure way and offers the user an intuitive interaction with the system; and an interface that connects the system with other business tools. These interfaces are seen as difficult to design since they encode the assumptions that the CPS imposes or requires from the external system to operate in accordance to its conceptual design principles. Security is a major challenges and concern given the open nature of the existing supporting technologies.

V. STANDARDS FOR INTEGRATING AGENTS AND CPSs

Standardization is key in order to realize interoperable and scalable solutions based on the integration of smart agents in industrial CPS environments. Since industrial CPS is a new development field, there are not many standards available but supporting approaches from service-oriented, agent, real-time control, and communication domain already exist.

SOA-based concepts and web services are key issues for realizing agent-based solutions (see [9], [34]–[36],

[88], and [89]. In this domain, the devices profile for web services (DPWS) as well as the representational state transfer (REST) provide important approaches [12]. DPWS, defined by the Advancement of Structured Information Standards (OASIS), deals with the ubiquitous device integration using web services embedded in distributed devices. REST can be seen as alternative integration approach emerged out of the world wide web initiative and focuses mainly on the M2M communication.

In the domain of industrial agents, the Foundation for Intelligent Physical Agents (FIPA; www.fipa.org) has established a series of specifications for the development of MAS solutions. Examples are the FIPA Abstract Architecture specifications, which deal with abstract entities that are required to build agent services and an agent environment, and the FIPA Agent Communication specifications, which deal with the definition of the Agent Communication Language (ACL) and interaction protocols. FIPA is currently the only standard for the development of MASs, and is usually adopted by the agent developers community mainly due to the high popularity of JADE agent platform, which is FIPA compliant.

For the realization of (real-time) control tasks used in industrial environments, the following standardized approaches are available: the widely known IEC 61131 standard defines a software model for programmable logic controllers (PLCs) with a corresponding execution model for cyclic and event-driven execution of control tasks [90]. Moreover, five different programming languages have been defined within IEC 61131 to satisfy the domain-specific needs in industrial control. A further standard in the control domain is introduced by IEC 61499 that defines a function-blocks-oriented reference model for distributed, reconfigurable automation and control systems [91]. Compared to IEC 61131, a pure event-driven execution approach is introduced by IEC 61499 which has especially been defined to cover the important requirements of portability, (re)configurability, and interoperability for distributed control. This standard provides basic services supporting the reconfiguration of distributed control applications from third entities like agents or higher level, supervisory control. A domain-specific approach for process control based on IEC 61499 is introduced by IEC 61804, which also uses function blocks in a distributed environment.

A further important part of industrial agent-based CPS approaches is the communication between different devices [9], [36]. In this area, some essential approaches have to be taken into account. The extensible messaging and presence protocol (XMPP) provides an XML-based format for the realization of a message-oriented middleware introduced by IETF as RFC 6120, RFC 6121, and RFC 6122. This open standard allows the near-real-time exchange of data between several network entities in a publish–subscribe manner. XMPP is currently adopted as transport protocol as part of the IEC 61850 interoperability

and communication approach for smart grids. Related approaches are the message queue telemetry transport (MQTT) as well as the simple object access protocol (SOAP). MQTT is a lightwight M2M communication protocol over the transmission control protocol (TCP) applying the publish–subscribe pattern. It is standardized by OASIS and mainly used in IoT applications. SOAP was introduced by the World Wide Web Consortium (W3C) as communication protocol for the exchange of information between web services. Similar to the aforementioned approaches, it uses XML-based syntax for the message format over other application layer protocols like hypertext transfer protocol (HTTP) or simple mail transfer protocol (SMTP). Finally, IEC 62541, called OPC unified architecture (OPC UA) [92], is an interesting communication approach to harmonize the information exchange in industrial systems. It defines a generic data model and web-service based communication protocol suitable for industrial applications. Both OPC-UA and DPWS have been demonstrated in cloud-based CPS industrial environments [9], [36], including interaction of agents with such services [41].

In spite of available standards, standardization is a crucial factor for the industrial adoption of agent technology, and should be addressed in the near future. Actions regarding the compliance of existing industrial standards, the tuning of existing standards in the agents field according to industrial requirements, and the establishment of new standards are mandatory. An example of the last point is the effort conducted by the IEEE Standards Association to establish recommended practices for the integration of agents with low-level automation functions. In fact, there are different ways to connect agents with real-time control tasks, as analyzed [93], and the first potential approaches have been identified as using mainly elements as defined in IEC 61131 (i.e., communication function blocks) and IEC 61499 (i.e., communication service interface function blocks). Apart from the agent interface to real-time control, also the design and deployment methods as well as metrics and benchmarking criteria are examples of important issues which need further standards in order to integrate MAS technology in CPS-based industrial environments.

VI. KEY CHALLENGES OF AGENTS IN CPS CONTEXT

Agents and CPSs share common ground. As such, agents may act as enablers for CPSs to realize their vision goals. Table 4 indicates industrial agent characteristics that may contribute to the CPS demands and challenges [94], pointing out also potential directions that may benefit from using agent features to achieve the CPS demands.

A detailed survey on the key factors that impact the industrial adoption of agent technology [95], shows the way to better understand and act in order to improve

Table 4 Relevant Industrial Agent Characteristics and Potential Contribution to CPS Demands

Emerging CPS Aspects	Relevant Agent Characteristics	Agent Applicability	Utilization Example
Integration, modularity, servification, collaboration	Agents rely on modularization, interaction among other agents, intelligence and adaptation, which can act as enablers	Very Good	Glue disparate systems, wrap legacy infrastructure, enable collaborative interactions, design patterns of distributed systems
Human Computer Interaction	In Agents, significant efforts have been directed towards having them acting as human delegates and running according to their owner's profiles / goals	Good	Act as user representatives in complex processes, adjust operational behavior according to user preferences, provide dynamically customizable user interfaces
Autonomic and self-* features, emergent behavior	Agents can provide intelligence and self-* properties e.g., self-adaptation, self-optimization, self-configuration and self-healing. Based on inherent capabilities of agents, the emergent behavior may appear from the interaction among the individual agents	Very Good	Utilize autonomic and self-* behaviors to act as enablers in CPS, including high-level interactions inspired e.g., from biological systems, complex systems and swarms
Infrastructure and service migration	MAS have been used to capture and expose common functionalities among systems, represent behaviors of legacy systems etc.	Fair	Agents can be utilized to test various migration approaches, to functionally glue legacy and new systems via API migration, etc.
Simulation of CPS and large-scale CPS SoS	Agents have proven to be capable of performing sophisticated simulations, e.g., Agent-based Modeling and Simulation (ABM) is well-investigated.	Very Good	Agents can be used to simulate large numbers of CPS, interactions and behaviors, as well as complex ecosystems, e.g., CPS SoS
Data management, transformation, analytics, knowledge extraction	Agents have been widely used for data mining, and with embedded algorithms they can also support distributed data analytics scenarios	Good	Agents can be used for data mining at the point of action, data filtering and aggregation, initial analysis, distributed processing, derive intelligent autonomous strategies, and support approaches that combine local (fast reaction) and global (optimized and robust) data analysis
Artificial Intelligence	Agents have been widely used in conjunction with Artificial Intelligence, planning, learning, knowledge representation, neural networks, control theory, etc.	Very Good	Capabilities of Artificial Intelligence at large can be supported via agents and empower CPS with these capabilities e.g., to learn, adjust and reconfigure
Knowledge-driven risk analysis and decision making/management	Agents have been used in knowledge representation in ontologies, knowledge extraction, knowledge management, etc., and applied it in decision making scenarios	Good	Agents can be utilized to manage knowledge and analyze risks as well as take decisions on behalf of the individual CPS as well as ecosystems of CPS
Management of (very) large scale CPS and CPS SoS	MAS provide mature robust, scalable and flexible solutions, for managing systems and complex infrastructures	Good	Agent concepts can be used for enhancing management of individual CPS and CPS-SoS, enabling CPS with the capability to implement recursivity using the agent technology and following holonic principles
Real-time control	Agents in proper settings have been utilized for high-speed interactions but hardly for closed-loop real-time control	Weak	Agents can be integrated with IEC 61131-3 and IEC61499 control applications that guarantee the real-time constraints
Security, Trust, Privacy, Resilience, Safety	In MAS, several aspects of distributed systems security, code mobility, operational resiliency, etc., have been investigated	Weak	Agents paradigm can be deployed to carry out security tests, infrastructure analysis, intelligently and autonomously maintain the infrastructure etc.

the industrial adoption level, mainly identifying the associated challenges. Several main challenges can be identified, namely in terms of technology/solution maturity, methodologies and tools, human in the loop, smooth migration, and self-* properties, in addition to the standardization already discussed in the previous section.

The use of proven and well-maturated technology is crucial to convince industrial stakeholders, since they are very conservative and demand-proven technological solutions. In fact, some existing industrial agent-based applications already achieved high TRLs, particularly in logistics domain, but more industrial applications exhibiting higher TRLs are required, particularly TRL 9 (i.e., actual system proven in operational environment).

Based on the inherent capabilities of agents, the emergent behavior will appear naturally from the interaction among distributed and autonomous agents. In this process, the resulting patterns are more complex than the individual behaviors from which they emerge. The complexity is also due to the sensitivity of initial conditions (butterfly effect) and to the nonlinear interactions involving amplification and cooperation processes. Since the emergent behavior is difficult to predict, a pertinent challenge is related to the development of mechanisms that ensure that not expected and not desired properties will not emerge in this complex and nonlinear process. Another similar issue is the digitalization and implementation of self-* properties,

and particularly self-organization, self-adaptation, self-optimization, and self-healing, which are key issues in the Industrie 4.0 philosophy. In fact, the inspiration from nature and biology can bring tremendous benefits in developing more adaptive, responsive, and evolvable CPSs, since very simple mechanisms can solve very complex problems. The challenge is to properly translate these mechanisms to the target application domain, considering the particular characteristics and constraints, and not simply copy them. Additionally, the encapsulation of agents' functionalities as services also allows to hide the associated complexity from the users as black boxes. The composition and orchestration considering self-* properties are also important in the design of such agent-based systems.

An important issue regarding the development of CPSs, and often neglected in the past, is the consideration of the human in the loop. This requires the consideration of adequate methods, methodologies, and technologies to develop adaptive and intuitive user interfaces. As an example, maintenance personnel will significantly benefit from using knowledge-based tools, complemented with advanced technologies such as augmented reality, to support the execution of their tasks. Having this in mind, it is important to note that the selection of technologies to support the integration of humans is dependent on the application domain, the type of operation to be performed by the human (e.g.,

availability of hands or level of noise in the environment), and the type of data to be exchanged between the human and the system.

The smooth migration from existing traditional centralized systems to the deployment of new plug-and-produce CPS is mandatory for the industrial adoption of this paradigm, simplifying the use of these principles by system integrators, module and equipment developers, and end users. Note that in this process, existing standard automation devices and/or applications may remain in use, which requires the coexistence and integration of these existing systems. Since the use of CPS principles corresponds with an entirely new way of thinking concerning the design of these systems, it is fundamental to create a plethora of assisted procedures that guide system integrators in deploying these systems which can be rapidly changed over. This transformation cannot be performed in one single step but instead requires the implementation of a sequence of steps. For this purpose, the establishment of migration strategies is mandatory for the industrial adoption, with agents playing a fundamental role through the modularization and decentralization that they provide and the encapsulation of their functionalities as services. In this point, the development of standard interfaces (syntax and semantics) and industrial middleware, based on industrial M2M communication protocols, e.g., OPC-UA or DPWS, are important to support the interconnection of heterogeneous systems and devices, contributing to a smooth migration to the new CPS.

The industrial adoption of agent technology requires the capability to implement scalable, resilience, and fault-tolerant solutions, allowing the management of large-scale CPSs. Agents provide the capability to develop flexible and robust solutions (e.g., due to the nonexistence of a central node), but the industrial applications of agents reported in the literature still misses the complete achievement of scalability, which is crucial in industrial environments that require the simultaneously execution of several hundreds or thousands of agents. For this purpose, the capability to develop industrial agent-based solutions based on the recursive property and following the holonic principles may be useful to achieve scalability. Another important technical issue is related to the connectivity among network components and with legacy systems, being necessary to use infrastructures and protocols that ensure security, safety, fastness, and trust.

A key aspect is the integration of complementary technologies to enhance MAS potentialities and overcome its existing limitations. In fact, agent technology can contribute to the development of modular, interoperable, and collaborative CPSs, by encapsulating their functionalities as services, taking advantage of the use of service-orientation principles. For this purpose, the integration of MAS and SOA technologies is a crucial challenge, as well as the establishment of standard interfaces for connecting CPS components, mainly to interface transparently physical automation devices, software systems, and legacy systems, contributing to support interoperability. Additionally, the use of proper ontologies will simplify the development of knowledge-driven decision-making systems, especially in case of heterogeneous systems.

Recently, we have noticed a tendency toward the integration of MAS with SOA, particularly in manufacturing and electric grids domains, but significant efforts in integrating also other technologies, such as cloud computing, big data techniques, augmented reality, RFID, and M2M should be addressed in order to develop more efficient and robust CPSs. In particular, embedding data mining algorithms and embodying advanced intelligence and learning algorithms will contribute, respectively, to achieving big data advanced analytics (collecting, organizing, and analyzing the vast and diverse sensory data) and enhance artificial intelligence in CPSs. The use of cloud platforms allows to store big amounts of data and run heavy computational algorithms to process these data. Another similar issue is the integration of agents and IEC 61131-3 and IEC 61499 to ensure the achievement of real-time control of CPSs.

Methodologies and tools covering the agent's life-cycle management are being pointed out along the time by several surveys and roadmaps as a crucial challenge for the industrial adoption of agent technology. At the moment, the challenge continues to be valid and there is a demand for methodologies and tools supporting the agents' life-cycle management, especially addressing the industrial requirements. As an example, JADE agent-based development framework is widely used to develop MAS-based systems, particularity because it is FIPA compliant, but more robust and efficient tools need to face the industrial requirements. Namely, the framework should provide [96] security and privacy, real-time interaction protocols for large-scale systems to ensure scalability and latency, light ACL protocols to support scalability in industrial large-scale systems, and truly distributed yellow page service and discovery mechanisms to improve the system robustness.

VII. CONCLUSION

CPS is an emerging paradigm addressing the requirements of future industrial systems. CPS advocates the integration of key technologies to face demanding challenges, in terms of flexibility, robustness, adaptation, and reconfigurability. MAS will play an important role in this perspective by providing a new and alternative approach design of intelligent and adaptive systems based on the decentralization of control functions.

The paper promotes a discussion of the industrial adoption of MAS in the CPS perspective, particularly focusing on the smart production, smart electric grids, and

smart logistics domains, noting a clear increase of the number of industrial applications in the last years. In general, the TRLs of the deployed industrial applications are still far from what is desired, especially in smart production and smart electrical grids.

The paper also discusses the key challenges related to the contribution of agent technology to face the CPS demands in the context of future industrial automation systems. In particular, issues like the modularity, autonomic and self-* features, smooth migration, human in the loop, and simulation can benefit from using agent technology. The standardization issue was also identified as a key aspect in deploying industrial agent-based applications, being necessary to develop solutions compliant with existing industrial standards, but also promoting the establishment of new standards in the field that addresses the industrial requirements.

The complete achievement of CPS will require the integration of MAS with complementary technologies. In particular, MAS can be combined with SOA to reach the system interoperability, with big data techniques and infrastructures for large-scale data analytics, with cloud computing for storage and processing of big amounts of data and augmented reality for the human integration. ∎

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