Industrial Cyberphysical Systems: A Backbone of the Fourth Industrial Revolution

Armando W. Colombo, Stamatis Karnouskos, Okyay Kaynak, Yang Shi, Shen Yin

***Abstract*—Cyberphysical systems (CPSs) are perceived as the pivotal enabler for a new era of real-time Internet-based communication and collaboration among value-chain participants, e.g., devices, systems, organizations, and humans. The CPS utilization in industrial settings is expected to revolutionize the way enterprises conduct their business from a holistic viewpoint, i.e., from shop-floor to business interactions, from suppliers to customers, and from design to support across the whole product and service lifecycle. Industrial CPS (ICPSs) blur the fabric of cyber (including business) and physical worlds and kickstart an era of system-wide collaboration and information-driven interactions among all stakeholders of the value chain. Therefore, ICPSs are expected to empower the transformation of industry and business at large to a digital, adaptive, networked, and knowledge-based industry with significant long-term impact on the economy, society, environment, and citizens.**

I. BACKGROUND

The increasing penetration of Information Communication Technologies (ICT) in industry is transforming the industrial environment into a multifaceted system featuring a tight combination and coordination between the computational and physical elements, including their digital (virtual) representation e.g., in the cloud, resulting in the formation of the so-called Industrial Cyber-Physical Systems (ICPS) [1]. Digitalization and interconnection of products, services, enterprises, and people are expected to generate significant opportunities and benefits [2], assuming the risks and challenges are properly addressed.

Society is inexorably shifting in form and nature, influenced by many powerful factors such as the aging population, climate changes, uncertain economic situation, demographic transition, globalization, digitalization, and so on. Nowhere is this more apparent than when digital technologies help tackle many of the challenges that derive from those societal changes such as better and more easily accessible healthcare, energy savings, smart transportation, and efficient production and services [3]. Up to now, industrial systems had long-lasting lifecycles (spanning several decades in some cases); however, in the last few years, we have witnessed an increasingly rapid pace of change, mainly because of adoption of emerging Internet concepts, technologies, tools, and methodologies. The rapid advances in computational power, communication, and storage, coupled with the benefits of the cloud and services, have the potential to give rise to a new generation of service-oriented architecture (SOA)-based industrial systems whose functionalities reside on-device and in-cloud and interact seamlessly [1,4]. Their realization brings new opportunities as well as additional challenges that need to be researched, analyzed, and efficiently tackled.

Similar to the societal changes, the manufacturing domain is also undergoing a significant transition [5,6]. On the current industrial shop floor, behavior and (machine) intelligence programming are concentrated on a handful of large monolithic computing resources, accompanied by large numbers of dumb devices, that are tailored and individually programmed for each process step. With the increasing penetration of CPSs, however, significantly more sophisticated scenarios are realized that can enable production efficiency and collaboration with internal and external stakeholders while also adhering to the requirements for flexibility, energy efficiency, and operational excellence imposed by business competition. The same trend is evident also in other domains such as energy, health care, manufacturing, military, transportation, consumer, enterprise, robotics, and smart cities. It is also apparent in complex solutions where CPSs forge the backbone and are the enabler of connectivity and interaction between those seemingly disparate sectors, like transport and energy or health and economic growth [7,8].

The aim of this article is to briefly present aspects of the emerging era of ICPSs, shed some light on the high-level supporting programs and countrywide activities carried out, as well as present key challenges that they pose. In the effort to do so and to set the context of this diverse domain, it is unavoidable to utilize many modern labels that understandably are not fully distinguishable in the community and do not have clearly defined and widely accepted boundaries. Nevertheless, the views presented here may kick-start discussions on the different characteristics that ICPSs bring to the table and, we hope, the ambiguity of the terminology will not hinder the effort.

II. FROM CPS TO ICPS

A decade ago, around 2006, the term CPS was coined to "refer to the integration of computation with physical processes" [9]. CPSs can be described as smart systems that encompass hardware, software, and computational and physical components, seamlessly integrated and closely interacting

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A. W. Colombo is with the Institute for Industrial Informatics, Automation and Robotics (I2AR), University of Applied Sciences Emden/Leer, Germany and also as a consultant for Schneider Electric, Industry Business Unit. Email: awcolombo@ieee.org

S. Karnouskos is with SAP, Germany. E-mail: stamatis.karnouskos@sap.com

O. Kaynak is with Boğaziçi University, Turkey, and Harbin Institute of Technology, China. E-mail: okyay.kaynak@boun.edu.tr

Y. Shi is with University of Victoria, Canada. E-mail: yshi@uvic.ca

S. Yin is with Harbin Institute of Technology, China. E-mail: shen.yin@hit.edu.cn

to sense and control in real time the changing state of the real world. These systems involve a high degree of complexity at numerous spatial and temporal scales and highly networked communications integrating their computational and physical components. As such, CPSs refer to ICT systems (sensing, actuating, computing, communicating, and so on) embedded in physical objects, interconnected through several networks, including the Internet, and providing citizens and businesses with a wide range of innovative applications based on digitalized data, information, and services. Therefore, CPSs are also ubiquitous embedded cyberphysical applications that are surfacing (emerging) and are now bridging the physical and virtual worlds and share all kinds of collaborative networks [1,10,11].

Ontologically, the term CPSs means "hardware–software systems that tightly couple the physical world and the digitalized (virtual) world." However, CPSs are not merely networked embedded systems but software-intensive, intelligent systems with the capability to collaborate, adapt, and evolve. In a CPS ecosystem, on one hand, every real physical object has one or more cyber representations, and, on the other hand, a cyber component or system can be linked to a physical representation, i.e., an object in the three-dimensional human-tangible world. For both, the physical and cyber parts will form views from the mechatronics, information, communications, and control perspectives. Moreover, these objects are increasingly interconnected, networked either permanently or in an asynchronous manner from time to time [1,11,12]. In this context, ICPSs address the penetration and proliferation of such ecosystems into the industrial environments.

ICPSs forge the core of real-world networked industrial infrastructures having a cyber representation through digitalization of data and information across the enterprise, along the product and process engineering lifecycle and from suppliers to customers along the supply chain. As such, the competitive performance of ICPSs mainly depends on the ability to effectively collect, analyze, and use large-scale digitalized data and information from many different and often heterogeneous sources to sustainably and efficiently manage, supervise (control, monitor, diagnose, provide maintenance), and operate in the industrial environments. This effective information-driven interaction of ICPSs with other CPSs and enterprise systems, extending to all business processes, is viewed as vital to modern industries and the rapid paces at which they operate [13].

ICPS operate at multiple levels in an open and collaborative manner [10,14], forging the next generation of industrial systems that are highly sophisticated and strongly coupled with the technical and business objectives pursued by the enterprise [13,15]. As such, the engineering and industrial communities witness the emergence of a new generation of CPS-based industrial systems that are multidisciplinary in nature, with functions that encompass several layers of an enterprise, with wide applicability in several domains and capable of forming large and complex ecosystems. For example, in industrial automation, the future shop floor is being transformed to a multifaceted ICPS ecosystem featuring, in various degrees, a wide variety of components, e.g., from individual sensors and mechatronic components to complex monitoring and control systems. The latter perform functions related to Supervisory Control And Data Acquisition (SCADA), Distributed Control Systems, and Manufacturing Execution Systems (MESs) and operate in sync with other enterprise-wide systems, such as Enterprise Resource Planning (ERP) and business objectives in real time [1,16]–[18].

The applicability of such ICPS-based infrastructures covers a wide spectrum of domains, such as manufacturing, intelligent transportation, real-time health care, smart grids, smart cities, cyber defense, aerospace, and enterprise systems, just to name a few. The resulting ICPS infrastructure is continuously evolving and depicts emergent behavior empowered by its underlying complex capabilities of the ICPS. Hence, it can address problems that the individual components operating alone would not be able to realize, no matter how computationally powerful or intelligent they are (in a world of limited resources [19]). In addition, it yields sophisticated control, automation, and management functionalities because of interaction, cooperation, composition of individual capabilities, and orchestration of existing and emergent features.

From an economic viewpoint, the disruptive technologies emerging from combining the cyber and physical worlds are already providing an innovative ecosystem for a broad range of industries, creating new markets and platforms for growth [2]. New products and services, mainly based on the use and application of existing big data (now digitalized, easy to assess, and tailored for specific contexts), are facilitating the creation of new functionalities based on the collaboration of heterogeneous systems in cyberspace as well as the creation of new and retention of existing high-value jobs and supporting the continuous quality of life improvements for the citizens of the digitalized society.

Since the Internet of Things (IoT) combines the power of ubiquitous systems, such as sensors, actuators, networking, and in-network (collaborative) processing, with modern CPS technologies, all (heterogeneous) things exhibit the capability to interact with each other and actively participate in global business processes [13]. These interactions build on an array of capabilities, such as information exchange concerning the identity, location, states, and functionalities of physical objects that are made available (á la carte) by their cyber part over the Internet and cloud [20], anytime and everywhere for those stakeholders (e.g., other things) that need them. However, while the ICPS acts as an enabler for building sophisticated information-driven interactions, the fact is that the complexity of the involved stakeholders increases (e.g., of production and supplier networks), and, therefore, automated intelligent approaches are needed to effectively deal with it. Higher-level concepts of autonomous and self-X systems fit well with the evolution taking place in the infrastructure and the services they offer.

ICPSs supervise, monitor, control, and manage real-world physical infrastructures and, therefore, have a real-world impact, especially in industrial infrastructures, as demonstrated by the analysis and lessons learned from the Stuxnet virus [21]. This also implies a tremendous paradigm shift in the behavior of the society that is in a symbiotic relation with

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ICPS ecosystems:

- The workforce is not only interacting with CPSs but also becoming an integral part; i.e., transforming into another CPS that, in turn, interacts over Internet technologies with the ICPS ecosystem.
- Subject matter experts transform into knowledge workers that analyze complex information at the right time in the right place and make decisions.
- Although the subject matter expert continues to be autonomous, via the CPS interaction, his capabilities and effectiveness are increased.
- The workforce now collaborates and offers its services, which can be requested by any other CPS (including other machines).

Effectively, the personnel are in a symbiotic relationship and work in tandem with the ICPS, as both are part of a larger collaborative CPS ecosystem. As such, design [22,23], implementation, and operation of ICPS and management of the resulting infrastructure are aspects of key importance for educating and forming the human–CPS [24] within this industrial environment.

As analyzed, a new generation of smart systems is increasingly embedded into the industrial environment, transforming them into sophisticated infrastructures. The technological, economic, and social impacts of these developments are so enormous that the whole process is labeled as the Fourth Industrial Revolution, often referred to as Industry 4.0 in Germany [8]. Networks and processes have so far been limited to one factory, but in an Industry 4.0-compliant scenario, these boundaries of individual factories are no longer a constraint, and they are lifted to allow interconnection of multiple stakeholders, e.g., factories, suppliers, and customers, even in different geographical regions or operated via (sometimes competing) stakeholders according to their business needs. This evolution shows that changes in the emerging Industry 4.0 economy are likely to come more from the introduction of new business models, new organizing principles, and best practices around which business is built, mainly capitalizing on 1) the knowledge generated during the development and utilization of services, exposed and/or consumed by the networked things and 2) increasing ratio of technology time-to-market to technology time-on-market [25].

III. GLOBAL INTEREST IN ICPS

CPSs and their penetration into the industrial environment have been widely investigated and are the focus of an enormous set of research and innovation activities around the world. Several labels have been used in recent years such as ICPS, (industrial) IOT, Industry 4.0, and the like, and, although differences exist, at their core, similar aspects prevail. In this article, the focus is on the area they cover at large and not on their differences.

Several programs with significant research budgets have been devoted in the last decade to CPSs in the United States, Europe, and all over the world. In the United States, the National Science Foundation (NSF) has identified CPSs as a key area of research, and a multi-million dollar budget has been devoted to funding CPS activities [26]. Multiple other agencies of the federal government have been promoting and accelerating the research and development of CPSs. In the United States, the Smart Manufacturing Leadership Consortium (SMLC) [27] aims to design a smart factory featuring adaptability, resource efficiency, and ergonomics as well as the integration of customers and partners in business and value processes. The Industrial Internet Consortium (IIC) features several heavyweight companies active in the ICPS domain and aims to create common interoperable and open architectural frameworks encompassing initiatives that connect and integrate objects with people and processes [28].

The European research, development, and innovation program HORIZON 2020 (with a total budget of approx. €80 billion [29]), features several CPS-related actions, which are viewed as key enablers for several domains [30]–[32]. This is also done in conjunction with the Private-Public-Partnership (PPP) program of the ARTEMIS Industry Association [33], where industry-specific aspects are addressed and, as discussed in the Strategic Research Agenda (SRA) [25], ICPS are considered as a key multi-disciplinary enabler of the industrial digital revolution.

In 2015, the CPS Public Working Group [34] completed and released the Framework for CPSs, and, at the same time research and developments institutions from several European countries are carrying out Road2CPS [12], creating a joint action plan, for the future development of CPS through roadmaps, impact multiplications and constituency building. The German government has recently initiated the implementation of the Industry 4.0 Platform [35], which mainly promotes the ICPS as the Fourth Industrial Revolution [7,8]. Similar activities can be found in several other European countries e.g., in Spain with the initiative Industria Conectada [36] and the Netherlands' program on Smart Industry [37].

Corporate research and development programs, such as the Industry 4.0 from Bosch [38], the EcostruXure program from Schneider Electric [39], the Mitsubishi Electric IoT / Industry 4.0 initiative [40], the Siemens Industrie 4.0-related programs [41], the SAP Industry 4.0 [42], or the Rockwell Automation Connected Enterprise initiative [43], are all addressing the digital interconnection of humans, machines, products and systems as cyberphysical objects forming a holistic solution ecosystem.

The stakes are high, and efforts are not expected to be isolated to the ICPS domain, as their impact relies on building up collaboration and interoperability. While we are still at the dawn of the era, after an initial introduction of initiatives at the country level, global cross-nation collaboration is needed, as ICPSs have the potential to transform the lives of billions of people. For instance, U.S. and European universities are collaborating in the Trans-Atlantic Modelling and Simulation for CPS (TAMS4CPS) project [44], with the aim to develop a strategic research and collaboration agenda to foster trans-Atlantic research in modeling and simulation for CPSs. Another example is the Industrial Internet Consortium and the Industrie 4.0 platform collaboration, which are working together toward assessing their respective architectures, i.e., the Reference Architecture Model for Industrie 4.0 (RAMI4.0

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[45]) and the Industrial Internet Reference Architecture (IIRA) in order to align them and make them interoperable [46].

Based on expert analysis [47], as well as input from advisory and consulting companies [48]–[50] and international industry consortia [28], it is evident that new smart ICPS and related technologies [6,51] and infrastructures are currently driving research, innovation, competition and disruptive business opportunities in a broad set of sectors such as agriculture, energy and smart grid, transportation, collaborative and networked organizations, smart city, building design, industrial automation, healthcare, and manufacturing.

IV. RESEARCH AND INNOVATION CHALLENGES

A. Major Challenges

Business continuity and agility form the core modus operandi of modern global enterprises [13], and efforts that yield results of more efficient automation systems are well-justified. ICPSs, as a convergence of several complementary technologies, including the larger scope of CPS [1,6], IoT [51] and Internet of Services, can play a pivotal role towards enabling enterprises to achieve their goals. As such, they face several challenges pertinent to their disaggregated technologies, architectures and domains. Considering the key trends identified [9,11,22,52]–[63], including Information Driven Interaction, Distributed Business Processes, Cloud Computing and visualization, Cooperation, Multi-core systems and GPU computing, SOA-ready devices, the key question that arises is how to take advantage of their benefits in order to provide the multi-faceted ICPS envisioned that fully cover the industrial requirements.

The prevalence of digitalization across all layers of an enterprise needs solutions that will support ICPS engineering at device, system, infrastructure, and application levels. This includes the whole lifecycle, from cradle to grave, of all kinds of ICPS components that can be considered as a set of major challenges that need to be tackled. Examples of challenging aspects include multidisciplinary [58] engineering methods and tools for evolvable ICPS-architectures [64]; intelligent monitoring [65]; understanding and managing emergent behaviors in networked ICPSs; designing and implementing human-to-machine, business-to-machine, and business-to-human interactions; improving existing or creating new communication and information technologies guaranteeing connectivity and interoperability among cyber and physical components; and so on.

To achieve the pursued agility and continuity, business processes performed in highly distributed production systems need to be efficiently integrated with a sophisticated shop-floor infrastructure that is capable of responding to dynamic adaptations in a timely manner [15]. As an example, considering envisioned architecture transitions such as the one shown in Figure 1, the high-level changes imposed on engineering of future automation systems are becoming easier to recognize. Figure 1 advocates that, in parallel to traditional hierarchical architectures in industrial infrastructures, selected functionalities at different levels [as defined by the International Society of Automation (ISA)-95 paradigm] can be exposed as a collection of CPS services. The latter exists in the CPSs or traditional systems, as well as the cloud, giving rise to a highly heterogeneous, dynamic, and adequately performing ecosystem of services [4,14,20]. With such services, applications can cherry-pick the functionalities they need to rapidly and efficiently fulfill their goals.

In addition, the role of service-oriented interactions as well as the cloud are changing the way CPSs are designed, deployed, and managed. As shown in Figure 2, the cloud can host a variety of auxiliary services and components that can interact with the CPS and enhance its capabilities. By utilizing the cloud-intrinsic capabilities, such as virtualization, scalability, multi-tenancy, performance, and lifecycle management, better CPSs can be realized that may include more lightweight devices since demanding parts (e.g., computation intensive) can now be hosted in the cloud [1,4,20]. Cloud-assisted CPS is viewed as a key enabler for a multitude of scenarios both in Peer-to-Peer (P2P) scenarios as well as in cross-layer ones (e.g., between SCADA and ERP).

Future industrial infrastructures are expected to be complex System of Systems (SoS) [14,32,67] that will empower a new generation of applications and services that are hardly realizable today or too costly to achieve. New sophisticated enterprise-wide monitoring and control approaches will be possible due to the prevalence of ICPSs and, especially, the formation of systems of ICPSs (SoICPSs). In ICPSs (and SoICPSs), components can be dynamically added or removed, and dynamic discovery enables on-demand information combination and collaboration [54].

Engineering industrial solutions based on SoICPS are offering new challenges and innovation opportunities [32] as the following:

- SoICPSs are continuously evolving, which softens, or even completely removes, the traditional separation between the engineering/design phases and the operational stages.
- The high degree of heterogeneity, uncertainty, and partial autonomy of SoICPSs require new, fully integrated approaches for their design, validation, and operation.
- SoICPSs are highly flexible and thus subject to frequent, dynamic reconfiguration, which must be supported by design support tools to enable efficient engineering.

To this end, supporting engineering tools [23,64] will also need to be networked and integrated with the different phases, from design through development, commissioning, deployment, operation, and maintenance of the digitalized industrial environment.

ICPSs enable monitoring and control of (industrial) physical processes and bridge the cyber and virtual worlds. Their impact across the value chain is increasingly evident [68], especially as they are the key towards digitalization of the industrial environment. Hence, future and emerging technologies [1,15,69] and paradigms for implementing ICPSs, such as SOA, cloud computing, the IoT, big data, and the industrial Internet, need to be deeply investigated, especially in real-world operations. This is by no means an easy undertaking, considering also that nowadays ICPSs are built with highly heterogeneous hardware and software components and depend

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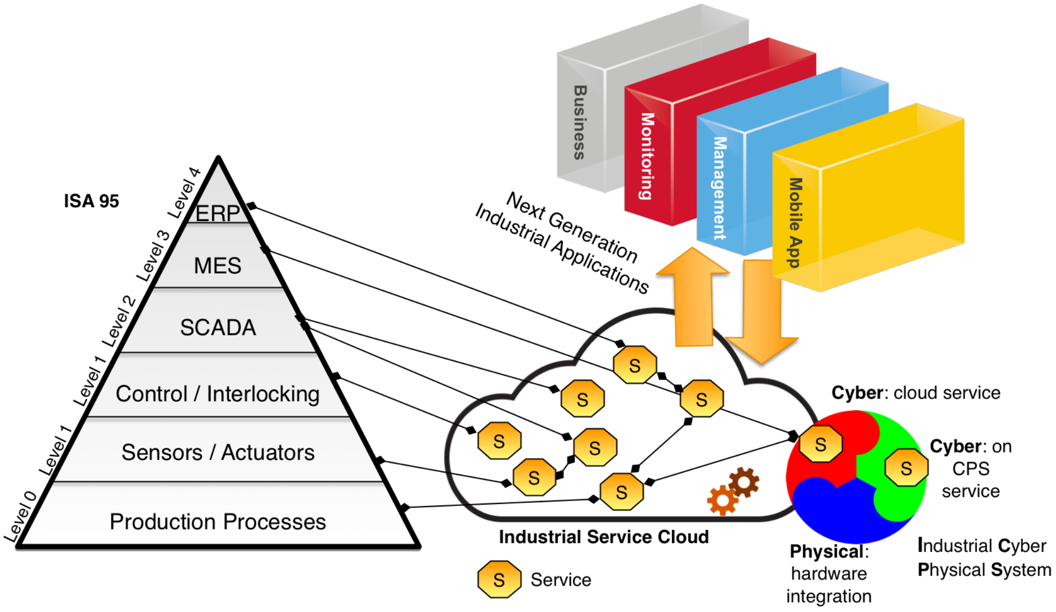

Figure 1. The transitioning towards a SOA-based information-driven architecture [1,66]

on systems and services that are operated by third-party stakeholders. Any research and innovation activity should integrate well with existing prevalent architectures such as ISA-95/ISA-88 [1,70,71]. New platforms for industrial innovation, from physical product to product-as-a-service in cyberspace, will have to be introduced in several industrial domains. However, legacy systems must also be migrated into service-based collaborative ICPS ecosystems, which is not to be taken lightly.

Business becomes digital business, and, as such, ICPSs are playing a pivotal role across the value chain. Empowered by the cross-ICPS collaboration, the supply chain can utilize ICPSs to enhance its operations across all the areas of sourcing, procurement, conversion, logistics, partner coordination, and collaboration within an organization and across organizations. ICPSs can empower the development and application of new business models, where new forms of interactions and relationships between supplier and customer are realized: interaction between products and interaction between services, physical but also cyberinteractions repositioning a partner within the value chain. New innovations toward supply-chain resilience, traceability, accountability, compliance, and so on can be realized across its spectrum. Building new ICPS-dependent cross-stakeholder applications as well as operating them within the necessary service-level agreements is perceived as a challenging task, considering the dynamics and emerging complexity of the ICPS infrastructure.

Collaboration is a major challenge. This has to be done in a cross-layer fashion across the enterprise, as well as with all external stakeholders [1]. The umbrella paradigm underpinning novel collaborative systems is to consider the set of intelligent system units as a conglomerate of distributed, autonomous, intelligent, proactive, fault-tolerant, and reusable units, which operate as a set of cooperating entities [5]. These entities are capable of working in a proactive manner, initiating collaborative actions and dynamically interacting with each other to achieve both local and global objectives along three basic collaboration axes, i.e., enterprise, supply-chain, and lifecycle [14]. From the physical device control level up to the higher levels of the business process management system, as defined in ISA-95 and ISA-88 [70] i.e., from suppliers through the enterprise to the customer [14,72], and from design [58] through operation to recycling phases of an engineering system lifecycle, collaboration will be enabled if, on the one hand, the involved systems act and react on their environment, sharing some principal commonalities and, on the other hand, have some different aspects that complement each other to form a coherent group of objects that cooperate with each other to interact with their environment [10,14].

Overall, creating synergies among ICPS stakeholders, especially in a cross-domain manner, is a major challenge. CPSs are viewed as a key part of critical infrastructures, e.g., the energy domain [60,61]. Future smart cities will integrate multiple such systems in a harmonized way to enable new innovative services for their citizens. Hence, the factory of the future may well be situated within the smart city and alongside smart buildings and smart houses. The latter will take full advantage of the energy available in the grid, and all forms of energy side-products, such as heat, will not be wasted but fully integrated, e.g., for heating houses, public buildings, and so on. As such, a major challenge is to be able to identify synergies among different domains, create interoperable solutions that take advantage of the sophisticated infrastructure, and optimize them according to business, environmental, health, social, and other high-level objectives.

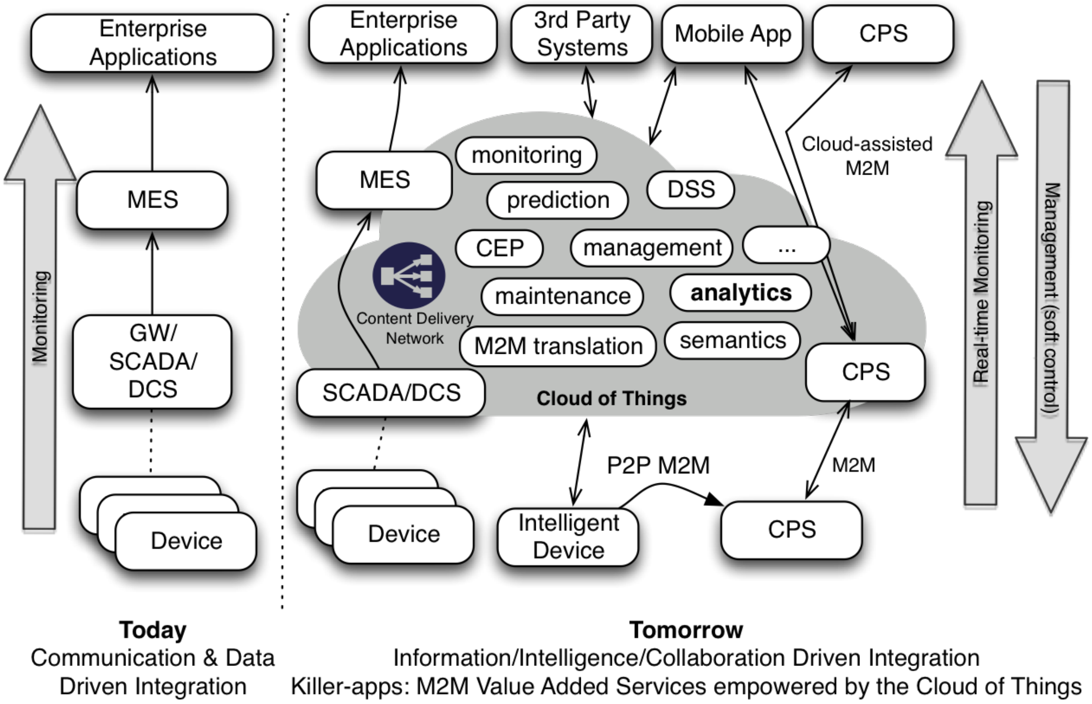

Figure 2. A Cloud-based CPS Infrastructure [1,54]. M2M: machine-to-machine; GW: gateway; CEP: complex event processing; DCS: distributed control system; P2P: peer-to-peer.

B. Cross-Cutting Issues

Several key challenges in multiple domains have been identified for CPSs [9,11,22,52]–[63]. Taking these into consideration along with discussions with CPS experts in industry, as well as empirical experiences building up such systems in a multitude of industry-led research projects, some key issues that arise are shown in Table I. The listed cross-cutting challenges are especially relevant for ICPSs and their system-of-system constellations and can be roughly clustered to six major areas [56]: 1) ICPS capabilities, 2) ICPS management, 3) ICPS engineering, 4) ICPS ecosystems, 5) ICPS infrastructures, and 6) ICPS information systems. It has to be pointed out that Table I provides a rule of thumb with some subjective views on key challenges, their difficulty, industry priority, and estimated time frame to reach maturity, i.e., a technology readiness level (TRL) of at least TRL-7 that assumes the realization of a system prototype demonstration in operational environment (hence, it should be taken with a grain of salt).

In the ICPS capabilities area, several issues related to real-time monitoring, control, and management on ICPSs as well as SoICPSs and their design and optimization [59,73], which are perceived as highly challenging, are presented. The priorities range from medium to high, and the control aspects [73] are crucial for the acceptance of CPSs in industrial facilities. Some of the aspects feature varying degrees of difficulty, and one could claim that they are, in part, even possible today, e.g., the servification of CPSs, energy efficiency, on-ICPS analytics, and so on. However, such efforts represent mostly a transfer of selected functionalities from other higher levels (e.g., from MES or ERP) and do not take in full consideration the intrinsic capabilities of ICPSs as well as their operational context, hence they are perceived as key challenges because they act as enablers and building blocks for further ICPS developments.

On ICPS management areas, methods and tools addressing the management aspects are perceived as a key enabler for industry. Management and coordination not only of standalone ICPSs but also of multilayer large-scale ICPSs are considered as a must to tackle increasing complexity and effectively integrate ICPSs in organizational processes. In addition the security, safety, and trust aspects [18,21,74], not only at the ICPS level but also large-scale systems, are seen as challenging, especially due to the nature of interactions among ICPSs that are no longer a priori known and centrally managed. As an example, while safe and secure standalone ICPSs can be constructed, when put in an ecosystem and via its interactions with other ICPSs, the safety aspects of the system and potential cascading effects can no longer be guaranteed nor be fully tested in lab [75]. Although industrially mature solutions are expected in the mid to long term, tackling challenges they pose, especially when considering very large systems, is also expected to be instrumental to ICPS acceptance.

ICPS and SoICPS engineering is viewed as a high-priority endeavor, especially by industry practitioners who will design, deploy, and operate future ICPS-enabled landscapes. As such, methods, tools, models, and practices related to lifecycle management are needed for industrial settings [64,76]. Model-based engineering ICPS solutions, achievement of resilience [77] and graceful degradation, safe programming and validation, as well as simulation [76,78] of complex ICPS infrastructures are high on the agenda. With the high degree of hardware heterogeneity, new developments in operating systems and programming languages tailored to CPSs may

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Table I
KEY CROSS-CUTTING CHALLENGES FOR ICPS AND SYSTEMS OF ICPS (SOICPS)

Area	Key Challenges	Difficulty	Priority	Maturity in
ICPS Capabilities	Real-time monitoring, control & management of ICPS / SoICPS	high	high	4-7 years
	Seamless (real-time) service-based interaction of ICPS with human-actors/users	high	high	4-6 years
	Optimization in ICPSs and their task-specific application	high	medium	4-7 years
	On-ICPS advanced analytics and decision making	medium	high	3-5 years
	Sentient SoICPS: Autonomous collaboration among ICPSs	high	high	8-10+ years
	Energy efficient ICPSs	medium	medium	3-5 years
ICPS Management	Lifecycle management of ICPSs	medium	medium	5-8 years
	Management/coordination of multi-domain large scale ICPSs and SoICPSs	high	high	5-10 years
	Security and trust management for ICPSs and SoICPSs	high	high	5-8 years
ICPS Engineering	Model-based engineering methods covering the full life cycle of ICPSs and SoICPSs	high	high	4-7 years
	Safe programming, validation, resilient, risk-mitigating ICPSs and SoICPSs	high	high	5-10+ years
	Engineering tools and practices for ICPSs' lifecycle support	high	high	3-7 years
	New operating systems and programming languages for ICPSs and SoICPSs	medium	low	3-6 years
	Simulation of ICPSs and large-scale SoICPSs	medium	high	3-6 years
ICPS Infrastructures	Multi-domain ICPS interoperability, management, control, QoS etc.	medium	high	4-7 years
	Migration solutions to full ICPS infrastructure and cohabitation with legacy systems	medium	high	3-6 years
	Integration, resilience, robustness and sustainability of ICPS critical infrastructures	high	high	5-8 years
	Provision of ubiquitous ICPS data & information services	medium	medium	3-5 years
	Economic, social, environmental etc. impact of ICPS infrastructures	high	high	4-8 years
ICPS Ecosystems	Autonomic and self-X featured ICPSs	high	medium	7-10+ years
	Education/training to enable fast assimilation of ICPSs (humans in the loop)	high	high	3-7 years
	Collaborative ICPSs (intelligent autonomous ICPS collaboration)	medium	medium	5-8 years
	Cross-industry knowledge base, best practices & emergent behavior at SoICPS level	high	high	8-10+ years
ICPS Information Systems	Artificial Intelligence in ICPSs / SoICPSs	high	high	7-10+ years
	Cross-Domain large-scale information management in ICPS infrastructures	medium	low	6-9 years
	Transformation of ICPS data and information analytics to actionable knowledge	high	high	4-8 years
	ICPS automated knowledge-driven decision making, management, and risk analysis	high	medium	6-10+ years
	Autonomous smart ICPSs within an ambient-intelligent-ecosystem	high	medium	8-10+ years

arise, which, however, also may be tackled by significantly extending existing approaches [79].

In ICPS infrastructures, the key issues identified are related to management, control, interoperability, migration, quality of service, and so on, which become increasingly important, especially from the operational point of view. Especially for ICPSs in critical infrastructures, resilience, robustness [81], safety and sustainability are preeminent [82]. The difficulty level is perceived as mostly medium, as significant efforts are already underway on how to tackle them. Nevertheless, even if some of them might be more trivial, it is mandatory to resolve them so that they can act as enablers for the ICPS. A typical example is the social, environmental, and economic impact of ICPSs, which have cascading effects and impact the wider adoption of ICPSs in real industrial environments [68]. Migration is also an aspect that must be considered at infrastructure level, as the pace of technology associated with ICPS solutions is increasing.

ICPS ecosystems and the business benefits they bring will increasingly be the focus once sophisticated ICPSs and infrastructures are in place. In this area, the key challenges would be related to design [22], deployment, and operation

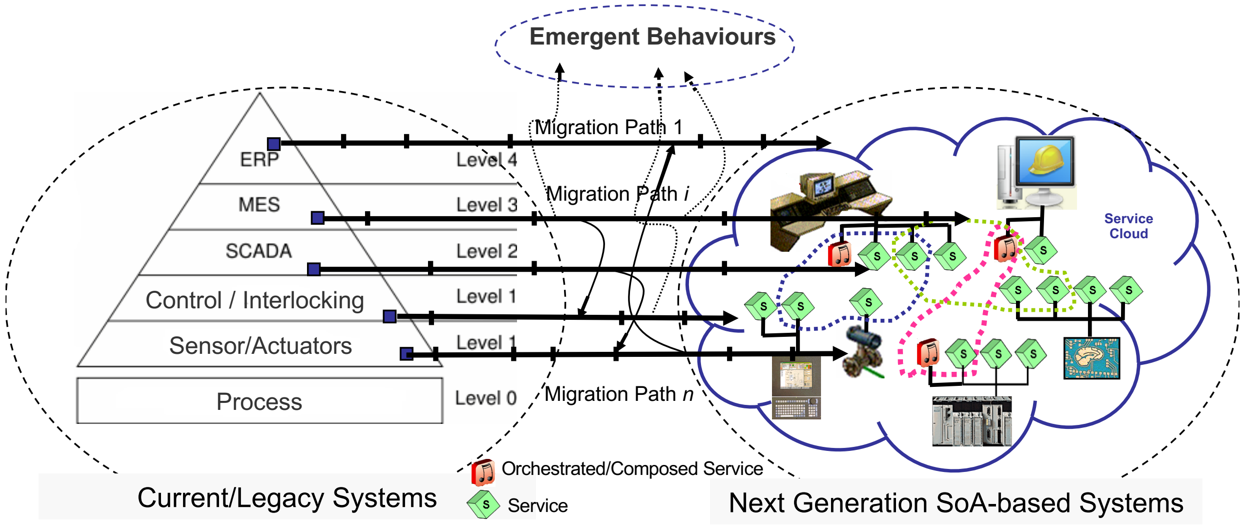

Figure 3. The migration to SOA-based Infrastructure [1,80]

of collaborative, autonomous and self-X [19] features of ICPS ecosystems. Such ecosystems build upon intelligent ICPSs and enhance all possible interactions with the environment and the involved stakeholders, including the ICPS-to-human interaction [24] that may lead to enhanced workforce performance and satisfaction. For the latter to be achieved, education and training to enable fast assimilation of ICPSs need to be properly tackled. Although many of the aforementioned aspects are expected to mature only in the long run, e.g., the capability to exploit cross-industry information derived from the big amounts of generated and associated data and transform it to knowledge at ICPSs/SoICPSs level, the path to dealing with these challenges is viewed as highly challenging, and the technologies to do so have not been adequately investigated yet.

ICPS information systems are also viewed as integral parts in realizing the ICPS vision and being able to capitalize on the data, information, and knowledge acquired within the organization, as well as from the (collaborative) cross-organizational interactions. The revolutionary progress is coupled with the highly intelligent ICPSs, as well as the emergent behaviors stemming from their interactions at the SoICPSs level. Understanding and transforming information to knowledge in an automated fashion [17,23], so that operations, such as management, risk analysis, and decision making, can be realized by ICPSs are perceived as challenging, especially when one considers that these are not predefined tasks but, rather, emerge from machine intelligence and operation of ICPSs in real-world dynamic environments (e.g., self-driving cars).

Migration is often not given adequate attention in CPS solutions, but for ICPSs, it is highly prioritized. Since most industrial infrastructures are brownfields, any ICPS has to be capable of operating, co-existing, and integrating legacy systems [71], while in parallel transition to the new infrastructure. Considering the migration to an information-flat and service-based infrastructure as shown in Figure 1, a high level view of the steps that need to be undertaken is depicted in Figure 3. Migration could be evolutionary, with incremental migration of features to the new infrastructure, i.e., capturing of functionalities as these are described in each ISA-95 layer and making them available as ICPS services. As there are several interdependencies, the potential migration paths must be assessed, and a migration should be done stepwise. Such migration will also unleash at system level emergent behaviors because of the dynamic interactions among the different devices and systems. Top-down and bottom-up approaches will need to be analyzed in detail [1,71,80], and the resulting migration strategies can be highly complex, depending on the preconditions, requirements, and goals. Figure 3 makes it clear that the migration is not a one-time operation but, rather, a continuous one that the industry will have to get accustomed to. As ICPSs, their services, and infrastructure evolve, it is expected that migration will be part of the daily development and operational aspects in such systems. In addition, any migration strategies have a multitude of goals that go beyond technology and include cost effectiveness, resource efficiency, agility, deterministic behavior, operational easiness, business continuity, and so on [13].

V. CONCLUSIONS

ICPSs are perceived as a promising approach that extends the CPS's overall activities to the industrial domain and considers predominantly their requirements such as safety, migration, compliance, agility, business continuity, performance, and collaboration. Although we are still at the dawn of an era described as the Fourth Industrial Revolution, the contributions of ICPSs toward the vision are pivotal and have far-reaching impact on industry, the economy, society, and the environment. This is attested by several ICPS efforts carried out worldwide, tackling design and operation of ultralarge-scale systems [83], as well as assessment of their impacts.

Although the promises of ICPSs are significant and the opportunities they bring are multifaceted, these can be realized only if key challenges are addressed to ease their industrial adoption. The prevalent focus ought to be placed on the integration and collaboration of ICPSs not only within an organization but at large scale and within a global ICPS ecosystem. Added value can be generated based on collaboration among disparate ICPS systems and services, and innovation can be accelerated. Therefore, collaborative ICPS are perceived as enablers towards future society vision realization and goal achievement.

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