Industrial Cyber–Physical Systems

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I. INTRODUCTION

In recent years, we have been witnessing rapid changes in the industrial environment, mainly driven by business and societal needs toward mass and extreme customization. This is supported by new disruptive advances in the cross fertilization of concepts and the amalgamation of information-, communication-, and control-technology-driven approaches in traditional industrial automation and control systems. In this industrial context, industrial cyber–physical systems (ICPSs) combine the progress achieved by the application of large distributed computing systems on product and production system planning, engineering, and operation with the power of digital data that are produced during manufacturing processes and also the data collected by the Internet of Things such as sensors and actuators embedded into the products. All these are strong signs that a new generation of "networked smart systems" is embedded into the industrial environment. The technological, economic, and social impacts of these developments are so enormous that the whole process is labeled as the Fourth Industrial Revolution. Advances in these interconnected capabilities affect virtually every engineered industrial system. Future ICPS applications are expected to be more transformative than the IT revolution of the past three decades.

This Special Issue presents the latest developments and achievements in industrial cyber–physical systems (ICPSs). The papers in this issue cover key areas on architecture, design, enabling technologies, and applications of ICPSs. Additionally, they present emerging trends and visions of ICPSs for future investigations.

There are many challenges ahead that need to be addressed in the convergence of computing, control, and communications for ICPSs. There is a need for the investigation of a wide spectrum of foundations and research fields relevant to ICPSs to address the unique scientific and technical challenges of ICPSs. This Special Issue presents some of the latest developments and achievements on several fronts, i.e., the architecture, the design, the enabling technologies, and a representative set of applications of cyber–physical systems introduced and used in the industrial environments. It is an attempt to provide an international forum for a diverse group of researchers, industrialists, and practitioners from different areas that

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discuss the latest achievements and identify critical issues, challenges, and emerging trends for future investigations related to ICPSs.

This Special Issue is intended to complement and build upon the special issue of the PROCEEDINGS OF THE IEEE, vol. 100, no. 1, published in January 2012, and covers two major topics:

1) cyber–physical systems as an innovation backbone for supporting the penetration and proliferation of smart digitalized and networked HW/SW components and systems into an industrial ecosystems;
2) identification of ongoing strategic research, development, and innovation activities and associated results addressing cyber–physical systems in industry and their implications in the structure and the behavioral policies of a digital society.

The papers of this special issue are grouped under four major sections:

a) ICPS architectures and standards;
b) ICPS interoperability;
c) ICPS engineering methods and tools;
d) ICPS applications.

A. Architecture of ICPSs

This section consists of four papers that focus on the architecture of ICPSs, presenting some new advances and prominent challenges in ICPSs.

In the first paper, titled "Formal verification of fault-tolerant startup algorithms for time-triggered architectures: A survey," Saha *et al.* survey various formal verification efforts for checking the correctness of the startup algorithms in the distributed computing platforms with time-triggered architectures. The startup algorithm runs on each distributed computing node when the system is powered up, and again after a failure occurs. Three popular time-triggered architectures, i.e., TTA, FlexRay, and TTCAN, are studied, compared, and contrasted. Besides, the gaps and possible improvements on the verification efforts are also discussed.

ICPS integrates various applications where some applications work in a time-triggered manner while some others work in an event-triggered manner. Thus, an architecture supporting unified designs of both manners can better facilitate the integration of ICPS applications. In the second paper of this category, titled "MixCPS: Mixed time/event-triggered architecture of cyber–physical systems," Yao *et al.* present a mixed time/event-triggered architecture called MixCPS to make ICPS applications work in an integrated and optimized manner. The assignment of computation tasks and the packet transmissions are optimized via the system-level time-triggered scheduling. The authors further discuss the scheduling policy for event-triggered tasks after the resource reservation for time-triggered tasks.

Authenticating and authorizing users at Internet-of-Things (IoT) endpoints is inherently vulnerable to replay, man-in-the-middle, and denial-of-service attacks. The third paper, "Using smart edge IoT devices for safer, rapid response with industry IoT control operations" by Condry and Nelson, presents a choice of combining the capabilities of smart IoT devices with control system gateways to build an advanced solution with real-time challenge response for more secure control operations. The proposed solution based on Intel endpoint and gateway devices offers the right mix of computing, cryptography, signal/image processing, and communication capabilities for authentication and authorization functions at the edge. The security, the scalability, and the resiliency with real-time performance are validated through a demonstration model.

Industrial automation systems are continuously getting more complex and growing over time. This leads to an ever-growing demand for an efficient integration, bridging the gaps between technologies and tools used across the enterprise and alongside the value chain. With the new challenges imposed by the introduction of CPSs into industrial applications, the matter of integration is becoming even more crucial for the introduction of new technologies and their acceptance by customers. In the paper "Integration of classical components into industrial cyber–physical systems," Bangemann *et al.* summarize integration tasks to be tackled and describe up-to-date technologies used in today's automation industry. Investigations are also made regarding the exploitation of integration strategies for future systems.

B. System Design of ICPSs

This section includes seven papers highlighting the design issues related to ICPSs, discussing the engineering methods for CPS automation systems, user interface for Industry 4.0, aspects-based design, and communication protocols for ICPSs.

System design is critical to the realization of ICPSs. To date, the plethora of different types of systems has resulted in a fragmented space of theories and tools. The advent of ICPSs has urged researchers to rethink systems and system design, with model-based methods gaining acceptance. In the paper "Compositionality in the science of system design," Tripakis describes some of the challenges in the domain of CPS design, expanding on the key principle of compositionality.

In the paper titled "Engineering methods and tools for cyber–physical automation systems," Harrison *et al.* consider the industrial context for the engineering of CPSs. It reviews engineering approaches that have been proposed or adopted to date, including Industry 4.0, and provides examples of currently adopted engineering methods and tools. This article then focuses on a specific component-based CPS engineering toolset. An industrial case study demonstrates the integrated approach of designing automation systems through their life cycle.

The complexity of today's and future technical systems is hidden from the user. Thus, from the users' side, in the paper "Empowering user interfaces for Industrie 4.0," Pfeiffer *et al.* discuss a vital problem on how to empower users to understand, monitor, and control the automated processes of Industrie 4.0. This article presents a survey of flexible but powerful methods for usability and user experience engineering in the context of Industrie 4.0.

In the paper "Systems engineering for industrial cyber–physical systems using aspects," Akkaya *et al.* consider the quality loss of model-based design (MBD) in the case when the model is too complicated. They show how to use aspect-oriented (AO) modeling techniques in MBD as a systematic way to segregate domains of expertise and crosscutting concerns within the model. Concepts are demonstrated on actor-oriented models of an industrial robotic swarm application. The use of AO modeling techniques for managing the complexity is illustrated. AO modeling in design-space exploration is also presented.

In the paper "Real-time wireless sensor-actuator networks for industrial cyber–physical systems," Lu *et al.* spot the challenges of adopting wireless sensor-actuator networks (WSANs) in supporting industrial wireless control systems. They survey the recent advances in real-time WSANs for industrial control systems from four aspects: real-time scheduling algorithms and analyses for WSANs; implementation and experimentation of industrial WSAN protocols; cyber–physical codesign of wireless control systems that integrate wireless and control designs; and a wireless cyber–physical simulator for codesign and evaluation of wireless control systems. Future research directions in ICPSs are also presented in this paper.

Further, in the paper "Industrial wireless IP-based cyber-physical systems," Watteyne *et al.* emphasize the importance of low-power wireless solutions for industrial control systems and survey the 6TiSCH, an emerging family of standards for IP-based industrial communication over low-power and lossy networks. The state of the standardization work, the major issues being discussed, challenges in implementation, and open questions recently identified are described in this paper. They also outline major requirements, present insights from early interoperability testing and performance evaluations, and provide guidelines for chip manufacturers and implementers.

In the paper "The industrial control systems cybersecurity landscape," Mclauhlin *et al.* discuss the security challenges existing in industrial control systems (ICSs). The authors explain the key concepts and principles of ICS operation, highlight the uniqueness of ICS environment, and provide a timeline of various attacks targeting ICSs. Further, phases of ICS security assessment process are presented and the approach for designing an appropriate evaluation testbed capturing the various layers of ICS architecture is demonstrated. Finally, ICS security issues associated with current trends for both ICS attack and defense strategies are explored.

C. ICPS Applications

This section consists of seven papers on emerging and exciting ICPS applications encompassing smart grid, robotics, transportation, and manufacturing.

Smart grids are electric networks that employ advanced monitoring, control, and communication technologies to deliver reliable and secure energy supply, enhance operation efficiency for generators and distributors, and provide flexible choices for consumers. Smart grids are a combination of complex physical network systems and cyber systems that face many technological challenges. In the paper "Smart grid: A cyber–physical systems perspective," Yu and Xue present an overview of these challenges in the context of ICPSs, outline potential contributions that ICPSs can make to smart grids, as well as the challenges that smart grids present to ICPS research, and bring forward current technological advances to smart grids.

More specifically, modern smart grid allows plug-in hybrid electric vehicles (PHEVs) be a promising candidate for demand response. In the paper "Aggregation and charging control of PHEVs in smart grid: A cyber–physical perspective," by following the CPS design approach, Liu *et al.* propose a general framework for the local aggregator to estimate the charging status and generate the charging control signals for PHEVs. A novel aggregation model is developed for the entire cyber space to inherently guarantee heterogeneous charging requirements. Furthermore, the authors develop a model predictive control (MPC) scheme for the battery charging control. Both the aggregation model and control strategy are designed based on the PHEV population migration probabilities. From the CPS perspective, both the cyber and physical loads of this novel framework are extremely low. The proposed approaches are validated through a comprehensive valley-filling case study.

Multiagent systems (MASs) share common ground with ICPSs and can empower them with a multitude of capabilities to achieve complexity management, decentralization, intelligence, modularity, flexibility, robustness, adaptation, and responsiveness. In the paper "Smart agents in industrial cyber–physical systems," Leitao *et al.* survey and analyze the current state of the industrial application of agent technology in ICPS context, and provide a vision on the way agents can effectively be utilized to tackle emerging ICPS challenges.

In the paper "Intelligent seven-DoF robot with dynamic obstacle avoidance and 3-D object recognition for industrial cyber–physical systems in manufacturing automation," Luo and Kuo present a service-oriented multiagent system (SoMAS) for the control and analysis of the CPSs in manufacturing automation utilizing a noncontact dynamic obstacle avoidance 7-DoF robot arm. The successful implementation of 3-D model-based object recognition, object fetching, and dynamic collision avoidance is demonstrated via experimental results.

Cognitive robots, being able to adapt their actions based on sensory information and the management of uncertainty, have begun to find their way into manufacturing settings. However, the full potential of these robots has not been fully exploited, largely due to the lack of vertical integration with existing IT infrastructures, such as the manufacturing execution system (MES), as part of a large-scale cyber–physical entity. In the paper "A vertical and cyber–physical integration of cognitive robots in manufacturing," Krueger *et al.* introduce the development of the cognitive cyber–physical system and its application in the automotive industry.

Freight transportation is of outmost importance for our society and is continuously increasing. In the paper "Cyber–physical control of road freight transport," Basselink *et al.* review how modern information and communication technology supports the cyber–physical transportation system architecture with an integrated logistic system coordinating fleets of trucks traveling together in vehicle platoons. The efficacy of the coordinated platoon planning is validated based on the fuel savings through a realistic case study and simulations.

In the paper "Cyber–physical systems for open-knowledge-driven manufacturing execution systems," Iarovyi *et al.* investigate the design of an open-knowledge-driven manufacturing execution system (OKD-MES). This article describes and illustrates an approach for designing OKD-MES based on CPSs that controls robot workstations and conveyor-based transportation systems of a pallet-based production system. ■

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