Guest Editorial: Industrial Cyber–Physical Systems—New Trends in Computing and Communications

CYBER-PHYSICAL systems (CPS) are defined by integrating computation and communication facilities on the one hand and the monitoring and control of physical processes on the other hand. Industrial cyber–physical systems (ICPS) refer to the science and art of designing and using cyber–physical systems for industrial and process control applications, for example in smart factories, smart energy grids, smart transportation systems, smart cities, and several other areas. Many of these applications are time- and mission-critical and hence often require low latency and high reliability. In parallel, there has been a strong growth in integrating intelligence, often in the form of machine/deep learning, into applications, which also leads to vastly increasing computational requirements. These innovations then will be integrated into complex systems, which need to be properly engineered to become safe, reliable, trustworthy, and secure while at the same time being cost-efficient.

In recent years, we have witnessed the emergence of new technologies that are well-suited to address the computational and networking challenges posed by ICPS and to revolutionize their design. In the realm of communication technologies, the upcoming 5G and 6G mobile broadband systems will enable communications at very high data rates, very high reliability, and very low latency (with some tradeoffs between these that need to be carefully understood). They will enable edge computing, which allows to bring computing power close to the physical process, to achieve low latency for compute-intensive tasks, and to provide a smoother integration with cloud computing systems. They will furthermore enable network virtualization techniques, which allow for a flexible and demand-driven provisioning of communications and computing resources. In addition, the ongoing development of industrial Internet-of-Things (IIoT) extends the range of accessible data sources and is a key technology to immerse computing into our physical environment. In the realm of computing, approaches like edge or fog computing provide flexibility in *where* computing can take place and in coordinating distributed computations, whereas the recent revolution in big data computing, artificial intelligence, and machine learning (in particular deep learning) will push the boundaries of what can be computed, enable new control strategies and allow for a flurry of new "smart" applications.

The aim of this special section is to provide a sample of recent developments in computing, communications and machine learning for ICPS. We have received 72 submissions, out of which 18 have been selected for inclusion into this special section. The authors of accepted papers cover a wide range of geographic locations, including Brazil, Chile, China, Germany, India, Italy, Russia, South Korea, Spain, Sweden, and the United States.

We briefly summarize the contribution in the following.

A. Machine Learning, Estimation, and Control

The last years have witnessed a revolution in the field of machine learning. The availability of big data sets and the ever increasing computing power allowed to use a new family of algorithms, generally referred to as deep learning, which achieved significant breakthroughs in fields such as image recognition, language processing, etc. While these methods are now established in many consumer applications, their application in ICPS is still under investigation and represents an exciting direction of research. Machine learning algorithms can be applied to different aspects of ICPS (communication, computing, control, etc.), as shown by some of the papers accepted in this special section.

The article "CLPM: A Cooperative Link Prediction Model for Industrial Internet of Things Using Partitioned Stacked Denoising Autoencoder" by Rui *et al.*, describes how a deep learning algorithm (stacked denoising autoencoder, SDAE) can be used to select the links to be used in a wireless mesh network connecting mobile devices and edge servers in a smart production line. Specifically, SDAE is used by mobile end devices to cooperatively predict which wireless links have to be used. The approach is tested on an industrial dataset, showing higher accuracy, precision, and recall as compared to other link prediction algorithms.

Another example of how machine learning can improve communication in ICPS is given in "Learning-based Online Transmission Path Selection for Secure Estimation in Edge Computing Systems," authored by Wang *et al.* In this case, a wireless mesh network is deployed to connect field devices and edge computers performing a state estimation application, and machine learning is used to achieve robust routing against denial of service attacks. Specifically, the extreme learning machine method is used to select the best paths in a simulated synthetic network, showing both a lower complexity and a higher accuracy as compared to other machine learning methods.

Collaboration in multiagent industrial systems is another area that can be impacted by machine learning. In "Interactive-Imitation-based Distributed Coordination Scheme

Digital Object Identifier 10.1109/TII.2020.3033818

for Smart Manufacturing" by Yang *et al.*, imitation learning is proposed for agents performing collaborative tasks in a production line. Specifically, two learning algorithms are combined: generative adversarial imitation learning to learn from expert demonstrations, and self-imitation learning for self-learning. The approaches are tested in an event-driven simulation, showing faster assembly times and a reduced need for expert supervision as compared to other strategies.

The article "Neuroevolutive Control of Industrial Processes Through Mapping Elites" by Langarica and Núñez, deals with the problem of nonlinear control of industrial process and tries to solve it with a neuroevolution algorithm. In the proposed approach, a population of deep neural networks is created and the best one is selected through an evolutionary algorithm. The proposed control approach is compared with alternative ones (classic PID control, model-predictive control, and reinforcement learning) on both a synthetic application and a pseudoreal one, showing the best performance in terms of set-point tracking and disturbance rejection.

Besides the emerging algorithms based on machine learning, more classical approaches based on geometry and statistics still remain important to solve problems in industrial applications. For example, the article "INDFORG: Industrial Forgery Detection using Automatic Rotation Angle Detection and Correction" by Hurrah *et al.*, applies an approach based on the Pythagorean theorem to estimate and correct artificial rotations in images. The approach is robust to different disturbances (compression, noise, filtering, cropping, and resizing) and can be applied to several industrial processes including image analysis. The approach is validated on datasets of medical and industrial images, showing higher accuracy than other state-of-the-art methods.

The article "A Novel Heavy-Tailed Mixture Distribution Based Robust Kalman Filter for Cooperative Localization" by Bai *et al.* applies statistical filtering to improve cooperative localization of autonomous underwater vehicles. Specifically, to cope with the heavy-tailed and nonstationary measurement noise caused by the underwater environment, the authors propose a novel distribution (heavy-tailed mixture) and use it to model one-step prediction in a robust Kalman filter. The approach is tested in a real lake experiment and compared with other robust estimation methods, showing a reduced localization error and only a minor increase in computational time.

B. Computing

Programmable Logic Controllers (PLCs) are essential components in industrial automation and control systems. The article "Programmable Logic Controllers in the Context of Industry 4.0" authored by Sehr *et al.* gives an overview of PLC development and critically analyzes the fundamental strengths and weaknesses of the programming models for the current PLC-based automation systems, as well as provides suggestions for improvement towards future automation platforms.

Although COVID-19 has seriously affected several industries, intelligent robots exhibit more advantages in manufacturing including a reduced dependence on workers and contributing to meeting social distancing rules. The article "Value-Driven Robotic Digital Twins in Cyber-Physical Applications" authored by Kaigom *et al.* develops a value-driven robotic digital twin (vdRDT) to farm and harness data. The results show reduced operational efforts and costs and increased visibility and agility by using vdRDTs, which can contribute to achieving better digital proficiency and beneficial business outcomes.

In recent years, the Open Platform Communications Unified Architecture (OPC UA), as a higher layer platform-independent, service-oriented protocol, became ubiquitous in industrial automation systems. In "An OPC UA-compliant Interface of Data Analytics Models for Interoperable Manufacturing Intelligence" authored by Shin, an OPC UA-compliant interface for data analytic models to allow inter-operable manufacturing intelligence is proposed. A prototype based on the proposed model is implemented, which indicates its feasibility in reality.

The article "Evaluating Docker for Lightweight Virtualization of Distributed and Time-Sensitive Applications in Industrial Automation" by Sollfrank *et al.* examines the effects of Docker containerization on a soft real-time application. The experimental results show that it is possible to apply Docker virtualization in industrial automation, since soft real-time requirements can be met.

The article "Fog Nodes Deployment Based on Space-Time Characteristics in Smart Factory" authored by Wang *et al.* proposes a fog node deployment strategy based on space-time characteristics to improve the performance and efficiency of intelligent manufacturing, as well as a fog node deployment system model for minimizing response time and balancing the load of fog nodes. Both simulation and experimental evaluation approaches are used to verify the effectiveness of the proposed strategy, and the improvement of response time and load balancing is demonstrated.

C. Networking and Communications

Communication technologies represent a cornerstone for cyber–physical systems applied to industrial and process control applications. Indeed, ICPS pose substantial networking challenges related to the requirements of very high reliability and very low latency, coupled with very high data rates. In the last years, significant effort has been spent on the design and the analysis of solutions to accomplish an improved convergence over common networking technologies both for the wired and the wireless domain. A significant example is provided by the IEEE Time-Sensitive Networking (TSN) project, aimed at enabling deterministic services support over IEEE 802-compliant networks, while maintaining convergence with other best effort services. Another notable case is the amount of studies for upcoming 5G and 6G systems, particularly their definition of the so-called ultrareliable low-latency communications, to be applied to the ICPS realm. Additionally, we are observing a growing interest toward the development of IIoT solutions, with the aim of improving accessibility of data sources and allowing for a whole new set of "smart" applications. Some of the papers included in this special section take up the efforts and deal with some of the open issues within the aforementioned communication technologies.

The article "LoRa beyond ALOHA: An Investigation of Alternative Random Access Protocols" by Beltramelli *et al.* considers LoRaWAN, a recently emerging and widely adopted technology for low-power wide-area networking enabling new implementations in the IIoT domain. The article, in particular, deals with the topic of medium access control protocols for LoRaWAN, and presents a stochastic geometry-based model to investigate alternative solutions to the pure ALOHA access scheme adopted by LoRaWAN. The obtained results are then compared in terms of achieved reliability and power efficiency.

The topic of remote state estimation, central in several industrial systems, is considered in the article "Joint Scheduling and Channel Allocation for Kalman Filtering over Multihop WirelessHART Networks," by Chen *et al.* Communications reliability over wireless channels in harsh industrial environments is still an open challenge for ICPS, and this may strongly impact on the performance of wireless condition monitoring systems, reducing their efficiency in capturing machine state variations. The authors consider the widespread WirelessHART protocol in multihop networks and set the goal of allowing channel reuse for improving efficiency in a multisensor system. To this aim, they propose an error-aware scheduling and channel allocation framework, which also takes into account the effects of interference and collisions, to accomplish a high reliability and consequently a high state estimation accuracy.

We have received several manuscript submissions related to TSN networks. The paper "CSRP: an Enhanced Protocol for Consistent Reservation of Resources in AVB/TSN" by Bujosa *et al.* focuses on a key component of the TSN framework, the stream reservation protocol (SRP). This protocol provides a mechanism for resources reservation over the end-to-end path from a transmitter to one or more receivers, to satisfy specific quality-of-service requirements. Considering the context of ICPS with its plethora of critical applications requiring strictly bounded frame delays and no frame losses, the authors focus on the distributed version of the SRP protocol, arguing that it lacks some properties such as termination and consistency. To achieve this, the authors adopted a formal model checker, UPPAAL, that has been subsequently used to verify the effectiveness of the enhanced version of SRP proposed by the authors, called consistent stream reservation protocol (CSRP).

The article "w-SHARP: Implementation of a High-Performance Wireless Time-Sensitive Network for Low Latency and Ultra-Low Cycle Time Industrial Applications" by scar Seijo *et al.* focuses on the application of the TSN concept to the case of wireless networks. In particular, the authors consider the w-SHARP (Wireless Synchronous and Hybrid Architecture for RT Performance) system, which builds upon the IEEE 802.11 framework, and enhances its design including features like orthogonal frequency division multiple access and the optimization of the interframe spacing, aiming at providing support for submillisecond cycle times and ultrahigh reliability over wireless networks. A prototypical implementation exploiting a software defined radio (SDR) platform is also evaluated, and the performance of w-SHARP is compared experimentally to the performance obtained by other wireless systems.

The convergence of the TSN framework and wireless IEEE 802.11 systems represents a timely topic in the current literature. The article "A Precise Synchronization Method for Future Wireless TSN Networks" by Romanov *et al.* addresses the subject of high-precision time synchronization, which is a central requirement to achieve a TSN-compliant system and which represents an issue for currently available IEEE 802.11 wireless networks. The authors propose an innovative method to achieve the required time synchronization accuracy in wireless systems through the adoption of low-cost solutions. The results, which have also been validated experimentally through the use of integrated wireless chips and low-cost FPGAs, are encouraging and comparable with modern wired real-time fieldbus solutions.

Besides the aforementioned emerging communication technologies, more classical approaches still provide important solutions to solve problems in specific industrial applications. As an example, the article "Cyber-Physical Healthcare System with Blood Test Module on Broadcast Television Network for Remote Cardiovascular Disease (CVD) Management" by Guo *et al.* deals with the hot topic of ICPS applied to healthcare and smart home applications. Specifically, leveraging the potential of the Internet of things, this work presents a remote monitoring systems able to gather data from different biomedical sensors implemented within widespread home appliances (like television controllers) and to provide prompt and reliable distance medical assistance.

A further key aspect for communications in the field of ICPS is represented by security. This is addressed by the article "Clone Detection Based on BPNN and Physical Layer Reputation for Industrial Wireless CPS" by Pan *et al.* The article considers a type of malicious attack known as clone node attack, where confidential information is captured by a legitimate network node and then used to create and spread clone nodes. The authors propose a new clone detection method applying physical layer reputation coupled with back propagation neural networks, and they implement it in an edge-based network. After a thorough mathematical analysis, the article presents the outcomes of an experimental assessment, providing a realistic picture of the achieved improvements compared to other clone detection techniques.

Acknowledgment

The guest editors would like to thank the authors who responded to the call and spent several efforts in providing significant contributions. The guest editors would also like to thank the reviewers for their meaningful and timely revisions, that allowed to maintain and enhance the high quality of the manuscripts. All of them, authors and reviewers, greatly helped putting together this Special Section during very difficult times, where so many people were affected by COVID-19. We also would like to acknowledge the Editor-in-Chief Prof. R. C. Luo, and the editorial team of these Transactions for their helpful and prompt responses to various queries.

FEDERICO TRAMARIN
Department of Engineering E. Ferrari
University of Modena and Reggio
Emilia
41125 Modena, Italy

MICHELE LUVISOTTO
Hitachi ABB Power Grids Research,
722 26 Västerås, Sweden

ANDREAS WILLIG
University of Canterbury
Christchurch 8140, New Zealand

KAN YU
Department of Computer Science
and Information Technology
La Trobe University
Melbourne, Vic 3086, Australia

Federico Tramarin (Member, IEEE) received the Dr. Eng. degree in electronic engineering and the Ph.D. degree in information engineering from the University of Padova, Padua, Italy, in 2008 and in 2012, respectively.

He is currently an Associate Professor with the "Enzo Ferrari" Engineering Department, University of Modena and Reggio Emilia, Modena, Italy. Previously, he was an Assistant Professor with the Department of Management and Engineering, University of Padova. From 2013 to 2018, he held a Postdoctoral position with the Institute of Electronics and Computer and Telecommunications (IEIIT), National Research Council of Italy (CNR), Rome, Italy. His research interests include performance analysis and measurements on network systems, with particular focus on industrial real-time wired/wireless communications, time sensitive networks (TSN) and on cyber-physical systems.

Dr. Tramarin currently serves in the Editorial Board of several renowned international journals. He contributed to the organization, and also serves in the TPC of several IEEE international conferences, including IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Emerging Technology and Factory Automation (ETFA), International Conference on Industrial Informatics (INDIN), Measurements&Networking (M&N), and MetroAutomotive.

Michele Luvisotto (Member, IEEE) received the Ph.D. degree in information engineering from the University of Padova, Padova, Italy, in 2017.

He is currently a Research Team Manager with Hitachi ABB Power Grids Research, Vsters, Sweden, where he is leading a research team working on the digitalization of power systems. Before he was with ABB Corporate Research, Vsters, Sweden. His research interests include wireless and wired real-time industrial communications, industrial Internet-of-Things, and intelligent industrial systems.

Dr. Luvisotto has served as a Guest Editor for *IEEE Access* and the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, and he contributed to the organization of several IEEE international conferences.

Andreas Willig received the diploma degree in computer science from the University of Bremen, Bremen, Germany in 1994, and the Dr.Ing degree in electrical engineering from the Technical University of Berlin, Berlin, Germany, in 2002.

He is currently a Professor for Computer Networking with the University of Canterbury, Christchurch, New Zealand, having been with Canterbury since 2010. Previously he was a Senior Researcher with the Telecommunication Networks Group (TKN), Technical University of Berlin from 2005 to 2010. From 2002 to 2005, he was a Senior Researcher with the Hasso-Plattner-Institute, University of Potsdam, Potsdam, Germany. His research interests include wireless networks, fieldbus and real-time systems, *ad hoc* and sensor networks, and UAV networks, all with specific focus on protocol design and performance evaluation.

Kan Yu received the Ph.D. degree in computer science from Malardalen University, Vasteras, Sweden, in 2014.

He is currently a Lecturer in Internet of Things with the Department of Computer Science and Information Technology, La Trobe University, Melbourne, Vic, Australia. From 2015 to 2016, he was a Postdoctoral Researcher with Malardalen University. In 2015, he was a Visiting Researcher with the University of Sydney, Sydney, NSW, Australia. His current research interests include industrial Internet-of-Things, reliable and low latency wireless communications, and real-time industrial communications.