Leading Information and Communication Technologies for Smart Manufacturing: Facing the New Challenges and Opportunities of the 4th Industrial Revolution

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The first three industrial revolutions came about as a result of mechanization, electricity, and information technology (IT), respectively. Now, the introduction of the Internet of Things and Services into the manufacturing environment is fostering a 4th industrial revolution (Industry 4.0), where the smart optimization and computerization of all the actors and phases of the manufacturing process, including the conceptualization and design of a product, as well as its production and transaction, are taking a leading role. As highlighted by both the European Roadmap "Factories of the Future" and by the German program "Industrie 4.0," the Smart Manufacturing process can be translated into five important benefits for industry [1].

The articles in this month's special issue cover theoretical concepts and practical case studies highlighting the challenges and opportunities for ICT in the 4th industrial revolution.

1) *Advanced manufacturing processes and rapid prototyping* will make possible to order one-of-a-kind product for each customer without significant cost increase.
2) *Collaborative virtual factory (VF) platforms* will drastically reduce cost and time associated with new product design and engineering of the production process, by exploiting complete simulation and virtual testing throughout the product lifecycle.
3) *Advanced human–machine interaction (HMI) and augmented reality (AR)* devices will help increasing safety in production plants and reducing physical demand to workers.
4) *Machine learning and big data analytics* will be fundamental to optimize the production processes,

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both for reducing lead times and reducing energy consumption.

5) *Cyber–physical systems and machine-to-machine (M2M)* communication will allow to gather and share real-time data from the shop floor in order to reduce down- and idle-times by conducting extremely effective predictive maintenance.

According to a study from the Capgemini Research Institute, these benefits could add at least $1.5 trillion to the global economy in five years' time, through productivity gains, improvements in quality and market share, along with customer services [2].

Given the potentials shown by these numbers, the application of the Smart Manufacturing concepts has been ever-increasing since the first definition of Industry 4.0 in 2011, both in terms of demonstration factories (among the others: Factory 2050—University of Sheffield, U.K., Demonstration Factory—Aachen University, Germany, TRUMPF Group Factory—Chicago, IL, USA, SmartFactoryKL—Kaiserslautern, Germany, etc.) and of "real" factories. In 2017, about 43% of all the countries across the world already had ongoing smart factory initiatives that were fully operational, and 33% planned to have one in the very next future.

As demonstrated by the growing number of initiatives, most organizations fully understand that smart manufacturing is the way of the future. However, about two-thirds of the overall estimated value of $1.5 trillion is still to be realized. The new smart, connected products, along with the massive usage of unstructured information coming from the Internet of Things and Big Data, demand a very deep change of how the industrial processes are managed, and to set up a whole new infrastructure within a company. As a matter of fact, this translates into many challenges for all the information and communication technologies (ICTs) involved. Among the others, the so-called IT and operational technology (OT) convergence, including digital platforms deployment and integration, data readiness and cybersecurity, efficiency by design, and operational excellence through closed-loop operations.

The purpose of this special issue is to showcase the extent to which these challenges and opportunities are disrupting and transforming the ICT sector, providing a broad overview of scenarios across multiple industrial applications.

Proceedings of the IEEE is certainly not new to the topics of Industry 4.0, and this special issue builds upon the past special issues in the areas of industrial cyber–physical systems and smart manufacturing [3], [4]. Nonetheless, given the exponential growth of the smart manufacturing applications in the last couple of years (among the others, in additive manufacturing and robotics), we consider a new issue at this time to be beneficial to the scientific community, as well as to the smart manufacturing practitioners. Unlike previous contributions, the articles in the issue do not focus on a specific topic or technology; instead, they provide a broad perspective of Industry 4.0, covering some of the most current technological advances in the area. Our hope, as Guest Editors of the special issue, is to offer inspiration for further exploration and advancement, for a full realization of the Industry 4.0 concepts and revenue.

I. OVERVIEW OF THE SPECIAL ISSUE

This special issue consists of 13 articles, covering a wide variety of topics and scenarios of smart manufacturing. They are organized into three categories.

1) *Data analytics for optimized industrial processes:* This category covers the latest approaches of artificial intelligence and big data analytics, including their main concepts as well as their applications in product design, optimized production planning and manufacturing, predictive maintenance, etc.
2) *Systems automation, integration, and control in smart factories:* This category covers the latest contributions in industrial automation and networking, including intelligent programming and control of robotic assemblies, heterogeneous systems integration as well as effective and resilient communication in production systems.
3) *Smart virtualization for cyber–physical production systems:* This category covers the latest perspectives of digital twin design and deployment in smart manufacturing and virtual engineering applied to industrial systems.

Each category starts with a paper contributed by the Guest Editors and their collaborators, focused on their respective topics of interest, followed by three to four invited articles by top researchers from academia and industry. In inviting the authors, we specifically solicited contributions including not only theoretical aspects but also practical case studies from industrial applications.

A. Data Analytics for Optimized Industrial Processes

Optimizing Quality Inspection and Control in Powder Bed Metal Additive Manufacturing: Challenges and Research Directions

by S. Di Cataldo, S. Vinco, G. Urgese, F. Calignano, E. Ficarra, A. Macii, and E. Macii

This article deals with the key technological developments of metal additive manufacturing with a special focus on powder bed fusion (PBF). This technology is one of the pillars of Industry 4.0 thanks to its huge potentials for faster, cleaner, and increasingly customizable manufacturing processes. Nonetheless, it is still far from the quality requirements of mass production. After introducing the main quality issues and needs that have to be developed and optimized, the article provides a wide overview of the latest progress of *in situ* monitoring and control in metal PBF, showcasing solutions from both research and industry. Special attention is devoted to *in situ* sensing technologies coupled with data analytics and machine learning to improve the quality of the manufacts and obtain a closed-loop control of the process. Finally, the authors identify the open challenges and discuss the future research directions in this field.

Six-Sigma Quality Management of Additive Manufacturing
by H. Yang, P. Rao, T. Simpson, Y. Lu, P. Witherell, A. R. Nassar, E. Reutzel, and S. Kumara

This article addresses the topic of quality in additive manufacturing (AM) but from a management perspective. In this regard, the breakthrough effect of six sigma (6S) has already been demonstrated in traditional manufacturing industries (e.g., semiconductor and automotive industries) in the context of quality planning, control, and improvement through the intensive use of data, statistics, and optimization. This approach entails a data-driven define, measure, analyze, improve, and control (DMAIC) methodology. In this article, the authors propose to design, develop, and implement the new DMAIC methodology for the 6S quality management of AM, emphasizing the need for analytical methods and tools to characterize and model the interrelationships between engineering design, machine setting, process variability, and final build quality. Finally, they present the methodologies of ontology analytics, design of experiments (DOE), and simulation analysis for AM system improvements.

Artificial-Intelligence-Driven Customized Manufacturing Factory: Key Technologies, Applications, and Challenges
by J. Wan, X. Li, H.-N. Dai, A. Kusiak, M. Martínez-García, and D. Li

This article focuses on the implementation of artificial intelligence (AI) in customized manufacturing (CM), allowing manufacturing systems to perceive the environment, adapt to the external needs, and extract the process knowledge, including business models, such as intelligent production, networked collaboration, and extended service models. The authors present the architecture of an AI-driven customized smart factory, showcasing the details of intelligent manufacturing devices, intelligent information interaction, and construction of a flexible manufacturing line. They survey the state-of-the-art AI technologies of potential use in CM, that is, machine learning, multiagent systems, Internet of Things, Big Data, and cloud-edge computing. Then, they demonstrate the potentials of AI-enabled technologies with a real case study of customized packaging. Challenges and solutions related to AI in CM are also discussed.

Manufacturing as a Data-Driven Practice: Methodologies, Technologies, and Tools
by T. Cerquitelli, D. J. Pagliari, A. Calimera, L. Bottaccioli, E. Patti, A. Acquaviva, and M. Poncino

This article surveys and discusses the latest software technologies needed to collect, manage, and elaborate all data generated through innovative Internet-of-Things (IoT) architectures deployed over a production line, with the aim of extracting useful knowledge for the orchestration of high-level control services that can generate added business value. The survey covers the entire data life cycle in manufacturing environments, discussing key functional and methodological aspects along with a rich and properly classified set of technologies and tools, useful to add intelligence to data-driven services. Therefore, it serves both as a first guided step toward the rich landscape of the literature for readers approaching this field and as a global yet detailed overview of the current state of the art in the Industry 4.0 domain for experts. As a case study, the authors discuss, in detail, the deployment of the proposed solutions for two research project demonstrators, showing their ability to mitigate manufacturing line interruptions and reduce the corresponding impacts and costs.

B. Systems Automation, Integration, and Control in Smart Factories

Learning-Based Automation of Robotic Assembly for Smart Manufacturing
by S. Ji, S. Lee, S. Yoo, I. Suh, I. Kwon, F. C. Park, S. Lee, and H. Kim

This article deals with the automation of a sophisticated robotic assembly, which is one of the key enablers for the smart factory of the future. It presents an approach to endowing robots with the capability of autoprogramming of assembly tasks with minimal human assistance that is based on “learning from observation” and “robotic embodiment.” The first involves robots observing human assembly operations to learn a sequence of assembly tasks to be carried out, which is formalized into a human assembly script. The latter transforms a human assembly script into a robot assembly script where a sequence of robot-executable assembly tasks is defined based on action planning supported by workspace modeling and simulated retargeting. Then, pretrained robot skills enable robots to execute difficult tasks that involve inherent uncertainties and variations in assembly. The authors demonstrate the feasibility and viability of their proposed solution in the form of a prototype for the assembly of a power breaker system and an electronic set-top box.

Wireless Control for Smart Manufacturing: Recent Approaches and Open Challenges
by D. Baumann, F. Mager, U. Wetzker, L. Thiele, M. Zimmerling, and S. Trimpe

This article deals with wireless control for smart manufacturing. Sure indeed, the ability to close feedback loops fast and reliably over long distances among mobile robots, remote sensors, and human operators is a key enabler for smart manufacturing. Based on the analysis of real-world use cases, the authors identify the main technical challenges that need to be solved to close the large gap between the current state of the art in industry and the vision of smart manufacturing. They discuss to what extent existing control-over-wireless solutions in the literature address those challenges, including their own approach toward a tight integration of control and wireless communication. In addition to a theoretical analysis of closed-loop stability, they show practical experiments on a cyber–physical testbed to demonstrate their approach in relevant smart manufacturing scenarios.

Wireless Networked Multirobot Systems in Smart Factories
by K.-C. Chen, S.-C. Lin, J.-H. Hsiao, C.-H. Liu, A. F. Molisch, and G. P. Fettweis

This article discusses the challenges of smart manufacturing based on artificial intelligence and information communication technology from a wireless networking perspective. Starting from enabling flexible reconfiguration of a smart factory, the authors discuss existing wireless technology and the trends of wireless networking evolution to facilitate multirobot smart factories. They examine the special sequential decision making of a multirobot manufacturing system, presenting social learning as a way to extend the resilience of precision operation by taking network topology into consideration, which also introduces a new vision for the cybersecurity of smart factories. Finally, they provide a summary of highlights of technological opportunities for holistic facilitation of wireless networked multirobot smart factories.

A Survey of Cybersecurity of Digital Manufacturing
by P. Mahesh, A. Tiwari, C. Jin, P. R. Kumar, A. L. N. Reddy, S. T. S. Bukkapatanam, N. Gupta, and R. Karri

This article presents the cybersecurity risks in the emerging digital manufacturing (DM) context, assesses the impact on manufacturing, and identifies approaches to secure DM. Sure indeed, the Industry 4.0 concept promotes a DM paradigm that can enhance quality and productivity, reduce inventory and lead time for delivering custom, batch-of-one products based on the convergence of additive, subtractive, and hybrid manufacturing machines, automation and robotic systems, sensors, computing, and communication networks, artificial intelligence, and big data. A DM system consists of embedded electronics, sensors, actuators, control software, and interconnectivity to enable the machines and the components within them to exchange data with other machines, components therein, the plant operators, the inventory managers, and customers. This poses a whole new set of security risks, which are reviewed and discussed in this survey-style paper.

A Unified Architectural Approach for Cyberattack-Resilient Industrial Control Systems
by C. Zhou, B. Hu, Y. Shi, Y.-C. Tian, X. Li, and Y. Zhao

This article deals with the cybersecurity issues posed by the Industry 4.0 era, with specific regard to industrial control systems (ICSs). To proactively address these issues, the authors present a unified architectural approach from the perspectives of cyberthreats on ICSs, security-related ICS technologies, and methods for ICSs. It incorporates secure networks, secure control systems, secure physical processes, and their interactions seamlessly into a unified framework. This global and systematic architectural approach is expected to facilitate the design and implementation of cyberattack-resilient ICSs in the networked world. For further development of ICS security technologies, emerging challenges are also identified and discussed to motivate future research efforts.

C. Smart Virtualization for Cyber–Physical Production Systems

(Re)deployment of Smart Algorithms in Cyber–Physical Production Systems Using DSL4hDNCS
by B. Vogel-Heuser, E. Trunzer, D. Hujo, and M. Sollfrank

This article focuses on the redeployment of intelligent algorithms and learning as the basis for evolving smart cyber–physical production systems (CPPSs) and Industry 4.0. The authors consider the case of a smart image detection algorithm added in a yogurt-producing plant to reduce downtime due to the extended operation of glass bottles. To do so, they introduce a comprehensive domain-specific language (DSL), DSL4hDNCS, enabling rapid analysis, addressing hardware/software architectures and network-related delays and uncertainties. DSL4hDNCS is defined by a metamodel to avoid ambiguity and enriched by aspects, such as safety, calculation power, and network transmission time. (Re)deployment alternatives are compared using different technologies, such as edge, fog, and cloud, exploiting an acknowledged Industry 4.0 demonstrator plant as a case study.

A Methodology for Digital Twin Modeling and Deployment for Industry 4.0
by G. N. Schroeder, C. Steinmetz, R. N. Rodrigues, R. V. B. Henriques, A. Rettberg, and C. E. Pereira

This article focuses on the digital twin (DT), which is one of the key concepts of Industry 4.0. The DT provides a virtual representation of products along their lifecycle that enables the prediction and optimization of the behavior of a production system and its components. The authors propose a methodology design using model-driven engineering (MDE) that strives toward being both flexible and generic. This approach is presented at two levels: first, a DT is modeled as a composition of basic components that provide basic functionalities, such as identification, storage, communication, security, data management, human–machine interaction (HMI), and simulation; second, an aggregated DT is defined as a hierarchical composition of other DTs. A generic reference architecture based on these concepts and a concrete implementation methodology is proposed using AutomationML. The authors demonstrate their methodology with industrial case studies.

A Connective Framework to Support the Lifecycle of Cyber–Physical Production Systems

by R. Harrison, D. A. Vera, and B. Ahmad

This article deals with the challenges posed by the adoption and lifecycle support of cyber–physical production systems (CPPSs) in smart manufacturing. Such challenges especially arise from the current divide in the information technology (IT) and operational technology (OT) landscape, and from *ad hoc* integration practices that result in inconsistent data and data models at various levels of manufacturing processes. The authors address this problem by envisioning a connective framework to support the engineering of CPPS through the use of a set of digital twins consistent with the real system throughout its lifecycle and not just in the design and deployment phases. After reviewing the latest perspectives on using digital integration frameworks, methods, and solutions for lifecycle engineering of CPPS, they try to demonstrate how a suitable framework can be realized to effectively address the lack of consistent data models throughout the engineering lifecycle.

A Platform Programming Paradigm for Heterogeneous Systems Integration

by K.-B. Gemlau, L. Köhler, and R. Ernst

This article addresses the problem of heterogeneous systems integration in smart manufacturing. To cope with growing computing performance requirements of the Industry 4.0 era, cyber–physical systems architectures are indeed moving toward heterogeneous high-performance computer architectures and networks. Such architectures, however, incur intricate side effects that challenge traditional software design and integration. The programming paradigm can take a key role in mastering software design, as experience in automotive design demonstrates. To cope with the integration challenge, this industry has started introducing a programming paradigm that efficiently preserves application data flow under platform integration and changes with minimum performance loss. This article revisits this paradigm, which is currently used for lock-free multicore programming, and explains its extension to the system level. Then, it explores its application to two important developments in industrial design.

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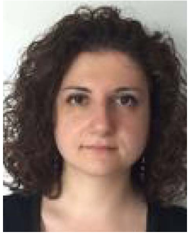

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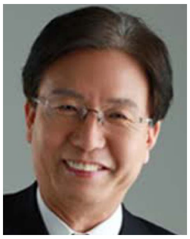

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