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Guest Editorial: Thematic Section on Applications of Emerging Computing Technologies in Smart Manufacturing and Industry 4.0

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The Smart Manufacturing and Industry 4.0 paradigms are transforming factories into highly complex IT systems, generating massive amounts of data. The modeling and optimization of smart industrial processes, to support decision making, has consequently become a new application domain, with its own unique and peculiar issues, for some of the most prominent emerging technologies across the entire computing stack, from hardware and systems design to application-level software.

The massive data collection which forms the foundation of digital industries is enabled by increasingly complex and heterogeneous Cyber Physical Systems (CPSs). Owing to that, the design of software for CPSs is receiving renewed interest from research and industry in relation to challenges such as managing variability and dependencies with an unprecedented degree of customization.

At a higher level, Digital Twins (DTs) of industrial processes and products, fed with the data collected by CPSs, are widely considered fundamental tools for Smart Manufacturing. Nonetheless, some facets of advanced DTs design are still unexplored, as well as many of their potential applications. The sophistication of DTs with new features, such as the modeling of non-functional aspects (e.g., energy consumption, communication, safety and fault tolerance) require refining or rethinking the underlying computing models. More broadly, fundamental challenges are also brought upon computation models and platforms by the realization of *cognitive* DTs, foreseen as key enablers for realizing the Industry 4.0 vision.

Artificial Intelligence (AI) and in particular Machine Learning (ML) algorithms constitute the core components of cognitive DTs. Moreover, they are at the basis of many other key applications in smart factories, including in-situ quality inspection, product binning, predictive and prescriptive maintenance, and logistics. In recent years, this has spurred a lot of research interest on computational and algorithmic aspects of AI and ML, aimed at eliminating the shortcomings of these algorithms in industrial scenarios, e.g., making them effective despite scarce and imbalanced distributions of labeled data and robust enough to handle complex and variegated inputs, for instance through hybrid conventional/ML solutions.

The *Thematic Section on Applications of Emerging Computing Technologies to Smart Manufacturing and Industry 4.0* covers all the aforementioned aspects, from CPS software design to novel AI pipelines. It includes seven high-quality papers that extend, improve and enrich the contributions presented at the recent 2021 Design, Automation and Test in Europe (DATE) Conference, in the sessions of the Special Day on *Cyber-Physical Systems for I4.0 and Smart Industrial Processes*. Each of the contributions has been thoroughly reviewed by global experts in the field before being accepted for publication.

The first group of four papers describe innovative DT implementations, which deal with largely unexplored yet critical aspects such as the monitoring of the entire life-cycle of an asset, the handling of multiple abstraction granularities, and the enabling of cognitive features. The fifth paper focuses on error-handling as a critical component in Cyber Physical Production Systems (CPPSs). The remaining group of two papers address AI-based flows for the real-time monitoring of innovative manufacturing processes.

In detail, the paper titled *"Machine-Learning-Driven Digital Twin for Lifecycle Management of Complex Equipment"*, by Zijie Ren, Jiafu Wan, and Pan Deng, highlights a limitation of current DT implementations, that lack an holistic management of the entire life-cycle of the monitored assets, and instead tend to focus on single life-cycle phases such as manufacturing or maintenance. Accordingly, the authors propose a three-layer architecture which allows, through the use of sub-modules, the realizations of a unified DT for a complex equipment that encompasses all life-cycle phases, including design, manufacturing, maintenance and recycling/scrapping. An example instance of this architecture is also illustrated, targeting the monitoring of bearing wear-out in a diesel locomotive.

In a similar effort towards generalizing and standardizing DT implementations, *"Key-Components for Digital Twin Modeling With 2 Granularity: Use Case Car-as-a-Service"*, by Harles Steinmetz, Greyce N. Schroeder, Ricardo N. Rodrigues, Achim Rettberg, and Carlos E. Pereira, discusses the characteristics that should be present in a DT in order to support different abstraction granularity levels and model interchangeability. One of the key elements of their approach is the use of AutomationML as a common modeling language, thanks to its ability to describe both individual assets and entire DTs. The authors showcase the characteristics of their solution with a use case in the Car-as-a-Service domain. Lastly, they point at open issues still to be solved for such kind of multi-granularity DTs, such as ambiguity and consistency problems due to integration between models, and limited scalability of current modeling tools.

"Graph Learning for Cognitive Digital Twins in Manufacturing Systems" by Trier Mortlock, Deepan Muthirayan,

Shih-Yuan Yu, Pramod P. Khargonekar, and Mohammad Abdullah Al Faruque promotes so-called cognitive digital twins as the next advancement of DT technology. Cognitive DTs are defined in terms of six core capabilities, i.e., perception, attention, memory, reasoning, problem-solving and learning, all of which enable advanced decision making and autonomy in manufacturing for future Industry 4.0 systems. The authors investigate graph learning as a pathway to enable cognitive DTs, motivated by the pervasiveness of entities and relations that can be naturally represented as graphs within a manufacturing system at all scales, from process fabrication flows to high-level supply chains. Accordingly, they devise a general query-based graph learning framework that can be applied to a broad range of tasks in manufacturing. A specific instance of the framework is then illustrated, targeting the classification of engineering design files for search purposes.

The last paper of this group, titled *"Digital Transformation of a Production Line: Network Design, Online Data Collection and Energy Monitoring"*, by Nicola Dall'Ora, Khaled Alamin, Enrico Fraccaroli, Massimo Poncino, Davide Quaglia, and Sara Vinco, also targets the realization of DTs, but concentrates more on infrastructural aspects, illustrating a complete flow for the digitalization of a production line. The flow is applicable either to new lines or for the transformation of pre-existing low-technology ones, and covers several aspects of the digitalization process. In particular, automated synthesis techniques are employed to design and optimize the plant's communication network, mapping data flows to physical network channels based on bandwidth and latency requirements, as well as spatial constraints given by the plant layout. Then, a system architecture for the collection of data and the creation of digital twins is described. The entire flow is demonstrated on an academic Industry 4.0 line prototype, for the creation of DTs modeling the power/energy production of several pieces of equipment, such as conveyors, pick-and-place robots, and quality inspection stations.

The fifth contribution of the section, titled *"Boosting Extra-functional Code Reusability in Cyber-physical Production Systems: The Error Handling Case Study"*, by Birgit Vogel-Heuser, Juliane Fischer, Dieter Hess, Eva-Maria Neumann, and Marcus Würr, addresses the problem of extra-functional code variability and reusability in Programmable Logic Controllers (PLCs) that manage industrial equipment. Focusing in particular on error-handling, a critical extra-functional software component in Cyber Physical Production Systems (CPPSs) both in terms of code size and importance, the authors describe the limitations of the current state-of-the-practice, based on procedural software and templates, in relation to the handling of dependencies, hardware and software variability, and reuse. They then highlight the potential advantages deriving from an Object-Oriented (OO) approach to error handling, such as better modularity and separation of concerns, which ease code reusability and reduce the risk of incomplete or incorrect error handling. With an interview study, they shown that, while OO features are provided by the latest PLC control software standard (IEC 61131-3), their widespread adoption in industry finds resistance, mainly due to the incompatibility with legacy systems and to engineers habits.

Last but not least, the sixth and seventh papers illustrate two AI-based flows for the real-time monitoring of innovative manufacturing processes, respectively in metal additive manufacturing and modular chemical production.

In the contribution titled *"In-Situ Defect Detection of Metal Additive Manufacturing: An Integrated Framework"* by Davide Cannizzaro, Antonio Giuseppe Varrella, Stefano Paradiso, Roberta Sampieri, Yukai Chen, Alberto Macii, Edoardo Patti and Santa Di Cataldo, the authors use AI to address one of the key issues in Additive Manufacturing (AM) technologies, i.e., the variation of a product's mechanical and geometric properties due to defects generated during the layering process. Targeting in particular metal AM based on powder bed fusion, they propose a real-time quality monitoring framework based on an off-axis camera mounted on the machine, and a distributed software architecture composed of microservices for collecting, integrating and storing data. On top of this framework, they implement multiple image processing pipelines, using both classical computer vision and deep learning techniques, for the detection of different categories of defects in powder bed layers, and for the quality monitoring of the object's profile. Furthermore, they introduce a novel method based on generative adversarial networks to produce synthetic defective images, thus coping with the scarcity of labelled data.

The difficulties associated with obtaining sufficient data for AI models are also addressed in the paper titled *"Artificial Intelligence for Mass Spectrometry and Nuclear Magnetic Resonance Spectroscopy Using a Novel Data Augmentation Method"*, by Florian Fricke , Marcelo Brandalero, Sascha Liehr, Simon Kern, Klas Meyer, Stefan Kowarik, Robin Hierzegger, Stephan Westerdick, Michael Maiwald, and Michael Hübner. In this case, the application domain is Modular Chemical Production (MCP), an emerging methodology for the fast generation of new chemicals by combining standardized production modules. Mass Spectrometry (MS) and Magnetic Resonance Spectroscopy (NMR) are two of the best methods for monitoring the quality of MCP, but time-consuming and manual data analysis has limited their application in real-time, closed-loop process control. The paper uses deep learning to automate and speed-up MS- and NMR-based monitoring, dealing with the limited amount of data available for training with augmentation techniques based on simulated spectra.

In conclusion, we believe that the contributions included in this thematic section touch upon some of the most relevant emerging computing technologies for the future of Smart Manufacturing and Industry 4.0, and we sincerely hope that you will enjoy reading it. We would like to thank the authors for submitting their high-quality contributions, and the reviewers for providing their expertise and constructive feedback. We would also like to thank the IEEE Transactions on Emerging Topics in Computing Editorial Board for providing the opportunity of organizing this thematic section, as well as the entire editorial staff for their continuous support.

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