Guest Editorial Special Section on New Frontiers in Smart Factories: Smart Automation and Human–Robot Interaction

I. Introduction

THIS IEEE Transactions on Automation Science and Engineering (T-ASE) Special Section on New Frontiers in Smart Factories: Smart Automation and Human–Robot Interaction focuses on promising, innovative research outcomes and industrial applications of different key technologies for smart automation and human–robot interaction.

In accordance with the Call for Papers, the core topics of this Special Section reflect the key research and development areas of automation and robotics in smart factories, with a focus on enabling and reinforcing technologies for human–robot collaboration, safety and efficiency in industrial settings, eco-sustainability, and circular economy. These topics are highly relevant in the present, amid, and post COVID-19 circumstances and valuable for understanding the global changes in the job market, factory workers' safety, and working conditions. Here, technological advancement is intertwined with ethics, legal, economic, and social (ELES) aspects.

The Guest Editors and Authors of this Special Section are heavily involved in the research communities of automation and robotics focusing on Smart Factories and I4.0 technologies.

All the articles have undergone full peer review by five Guest Editors: Paolo Dario, Scuola Superiore Sant'Anna, Italy; George Q. Huang, The University of Hong Kong, China; Peter Luh, University of Connecticut, USA; Birgit Vogel-Heuser, Technical University of Munich, Germany; and MengChu Zhou, New Jersey Institute of Technology, USA.

II. Special Section Content

This Special Section includes 11 manuscripts that report state-of-the-art research in the field of smart factories.

In [A1], Czimmermann *et al.* propose a novel multi-agent platform able to perform the quality control procedure on a motorcycle autonomously (i.e., defect inspection/correction) on defects that arose from the production process. The platform consists of four agents, three anthropomorphic robots with custom-made end-effectors, and the software. A linear laser scanner is used to reconstruct the 3-D metallic surface with a resolution of $\sim$ 0.1 mm. The system performances are assessed in a real Industry 4.0 scenario. The multi-agent system developed is scalable and can work in a more complex scenario, where the actions of other agents constantly modify the dynamics of the environment. Human intervention is thus promoted to a higher level with tasks concerning supervision and co-working with the robotic platform, with a consecutive reduction of the repetitive manual work.

In [A2], Lu *et al.* present a direct and computationally efficient approach to deadlock detection and recovery in flexible manufacturing systems (FMSs). Deadlocks in those systems cause unnecessary production costs and even catastrophic results. An algorithm is developed to build a new kind of directed graph called resource flow graph of a Petri net. Such graphs can represent the competition for shared resources by different processes, and, according to them, loop graphs can be defined and investigated. In the framework of Petri nets, reachability graph analysis can usually obtain a maximally permissive supervisor of a plant. However, it is relatively inefficient since it suffers from the state explosion problem. In this work, an off-line deadlock detection and recovery policy is built by setting a group of virtual events that are not present in a physical model. This approach guarantees that the resulting system is deadlock-free with all original reachable markings.

In [A3], Dong *et al.* present a multitask deep one-class convolutional neural network (CNN) for defect classification and detection, a fundamental task in industrial production. Automatic inspection systems represent important technologies that help rely less on human inspection, a subjective, biased, and labor-intensive job. To this end, supervised learning algorithms require many annotated data which are hard to collect due to the rarity of the defects and the time it takes to collect them. To solve this issue, the authors propose a CNN architecture which is based on a stacked encoder-decoder autoencoder used as a feature extractor, and train it without annotated data end-to-end along with a deep one-class classifier using a multitask learning scheme, avoiding a two-stage learning process. Defect detection is implemented using a moving-windows scanning method on top of the deep one-class classifier. Overall, the proposed algorithm leads to better performance than its two-stage counterparts and shows promising results compared with

Digital Object Identifier 10.1109/TASE.2022.3185427

its supervised learning ones. This system offers a possible solution to industrial inspection in contexts where abnormal samples are lacking.

In [A4], Chen *et al.* introduce a model that employs machine learning techniques to provide resource configuration recommendations for the heterogenous workloads in a fog computing-based smart factory environment. The increasing number of IoT devices in smart factories generates much data that is handled by data processing workloads with the task of guaranteeing productivity and safety of a smart manufacturing environment. Here, the emerging paradigm of fog computing offers enhanced data processing performance, while introducing some challenges. Indeed, the various workloads in a smart factory often compete for the limited number of resources present, and this requires resource recommendation to optimize system performance. The developed model treats both execution time and operating characteristics of workloads on different configurations, treated as explicit ratings and implicit feedback, and combined into a data matrix used for training the model to capture the relationship between workloads and configurations. The authors explore both linear and nonlinear relationships using matrix factorization and neural networks. The scheme is further optimized using the SARA scheme to improve prediction accuracy. The model is tested on real smart factory workloads, demonstrating its efficacy.

In [A5], Guo *et al.* address the task of end-of-life product disassembling. The dynamic disassembly environment is faced with two main problems, called disassembly sequence planning and disassembly line balancing. The former answers how to find a safe and effective sequence of disassembling operations, while the latter focuses on optimal scheduling of disassembly tasks among all the available workstations to achieve a set of objectives. The article addresses both problems in the context of multiple products disassembling, proposing a multi-product multi-objective disassembly-sequencing-line-balancing problem, which is solved through the combination of multi-objective Discrete Grey Wolf Optimizer and Simulated Annealing with the aim of maximizing disassembly profit while minimizing energy consumption and carbon emission. The article presents real cases to test its efficiency and feasibility.

In [A6], Qiao *et al.* propose a solution for dual-arm cluster tools ensuring the wafer quality in semiconductor manufacturing with operational constraints. As the width of circuits in semiconductor chips shrinks to less than 10nm, time constraints and chamber cleaning requirements on the operations of cluster tools are critical factors for the quality of processed wafers. A virtual wafer-based scheme is proposed to tackle the scheduling problem with these constraints and find a wafer loading sequence with the highest performance in terms of system cycle time. This work establishes an efficient binary integer programming model to search for such a solution, easily implementable and thus making it readily applicable to the semiconductor manufacturing industry.

In [A7], El Makrini *et al.* present a novel ergonomics optimization framework that performs postural optimization based on the virtual element for human workers in hybrid work cells. Thanks to the development of human tracking devices, it is possible to monitor the operator, analyze the postures, and assess the associated musculoskeletal disorders (MSDs) risk. A graphical interfacedisplays users' current pose and proposes to them the improved posture. A controller adapts the pose of the workpiece held by the collaborative robot by computing a displacement vector between the wrist current and optimized positions. The proposed approach improves the human body postures and offers a promising solution to enhance ergonomics by robot assistance.

In [A8], Conti *et al.* present a novel system on human–robot collaboration (HRC) guided by common-sense knowledge (CSK) reasoning for automation in manufacturing tasks and demonstrates the scope of combining HRC and CSK. This fits within the general realm of smart manufacturing. In fact, during HRC where humans and robots work together to handle specific tasks, the robots are required to effectively support human beings. This requires robots to conduct reasoning by using CSK, e.g., fundamental knowledge that humans possess and use subconsciously, to assist humans in challenging and dynamic environments. Currently, there are several effective CSK systems used for organizing information and facts, along with detecting objects and determining their properties. HRC is employed in various manufacturing tasks, such as paint spraying and assembly, to keep humans safe while increasing efficiency. The primary focus is on improving the efficacy of human-robot co-assembly tasks. The evaluations conducted with online simulations and real-world experiments indicate that reasoning using CSK-based robot priorities enhances HRC as compared to simpler robot priorities, e.g., merely handling nearby objects. The system described in this article is modifiable and can be used for larger and more complex real-world tasks, thereby leading to improved automation in manufacturing.

In [A9], Proia *et al.* propose a comprehensive review of the most recent and relevant contributions to the related literature, focusing on the control perspective for human-robot collaboration (HRC) in the digital industry. This work arises from an emerging need for designing suitable decisions and control techniques to ensure a safe and ergonomic HRC while keeping the highest level of productivity. This work aims to provide researchers and practitioners with a reference source in the related field, which can help them design and develop suitable solutions for control problems in safe, ergonomic, and efficient collaborative robotics.

In [A10], Pereira *et al.* first introduce an innovative taxonomy of basic actions that compose the physical tasks of foodservice workers. Following this novel clustering of actions, authors systematically review single action equipment and advanced equipment used in the foodservice industry, from manual utensils to autonomous robots. The article identifies the challenges of automation in the industry and highlights the deep relevance of these technologies to the quality of life of its workers, which constitute a huge section of the workforce in many developed countries. This work contributes intensely to guide future studies toward the design of bio-inspired control models for foodservice robots.

In [A11], Wang *et al.* present a novel and efficient motion-planning algorithm based on rapidly exploring random trees.

While the algorithm focuses on mobile robots, it may be extended to a set of other robots and tasks, such as autonomous driving, medical robots, and service robots. The proposed sampling-based algorithm performs a bidirectional search strategy, growing a forward and backward tree simultaneously, but avoids the two-point boundary value problem, therefore accelerating the extension process. Specifically, the trajectory from the closest node of the backward tree to the goal state is considered as a heuristic to let the forward tree grow continuously. The growing forward tree is biased to this heuristic and nonuniform sampling is performed. This method, called bidirectional–unidirectional RRT (B2U-RRT) is proved to provide probabilistic completeness. Case studies are presented, and the algorithm is further modified to allow for optimization.

III. Conclusion

This Special Section confirms the important progress made on the topic of Smart Factories, emphasizing the value of automation and robotics technologies in this evolving domain. We hope this Special Section will bring interesting insights that will encourage and motivate new research and fulfil current technological gaps.

In particular, we hope that this issue will help and motivate researchers and developers to investigate and develop the next-generation smart manufacturing machines, cells, and factories.

Acknowledgment

In closing, we would like to extend our appreciation to all reviewers who played a crucial role in the peer-review process for the manuscripts submitted to this issue for their timely and professional comments.

Most importantly, thanks to all the authors who submitted their manuscripts for consideration of publication.

This Special Section was proposed by the co-Chairs of the IEEE RAS Technical Committee on Digital Manufacturing and Human-Centered Automation.

The submissions to the Special Section were solicited also through the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement 730994, Project TERRINet—The European Robotics Research Infrastructure Network, and through ARTES 4.0, Advanced Robotics and Enabling Digital Technologies and Systems 4.0, the Competence Center on Industry 4.0 co-funded by the Italian Ministry of Economic Development.

Finally, we would like to acknowledge Rossella Raso, Ph.D., Scuola Superiore Sant'Anna, Italy, for her scientific editorial assistance that made this Special Section possible.

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Appendix: Related Articles

[A1] T. Czimmermann *et al.*, "An autonomous robotic platform for manipulation and inspection of metallic surfaces in industry 4.0," *IEEE Trans. Autom. Sci. Eng.*, early access, Nov. 23, 2021, doi: 10.1109/TASE.2021.3122820.

[A2] Y. Lu, Y. Chen, Z. Li, and N. Wu, "An efficient method of deadlock detection and recovery for flexible manufacturing systems by resource flow graphs," *IEEE Trans. Autom. Sci. Eng.*, early access, Oct. 14, 2021, doi: 10.1109/TASE.2021.3114498.

[A3] X. Dong, C. J. Taylor, and T. F. Cootes, "Defect classification and detection using a multitask deep one-class CNN," *IEEE Trans. Autom. Sci. Eng.*, early access, Sep. 14, 2021, doi: 10.1109/TASE.2021.3109353.

[A4] L. Chen, Z. Lu, A. Xiao, Q. Duan, J. Wu, and P. C. K. Hung, "A resource recommendation model for heterogeneous workloads in fog-based smart factory environment," *IEEE Trans. Autom. Sci. Eng.*, early access, Jan. 21, 2022, doi: 10.1109/TASE.2022.3141590.

[A5] X. Guo, Z. Zhang, L. Qi, S. Liu, Y. Tang, and Z. Zhao, "Stochastic hybrid discrete grey wolf optimizer for multi-objective disassembly sequencing and line balancing planning in disassembling multiple products," *IEEE Trans. Autom. Sci. Eng.*, early access, Dec. 27, 2021, doi: 10.1109/TASE.2021.3133601.

[A6] Y. Qiao, Y. Lu, J. Li, S. Zhang, N. Wu, and B. Liu, "An efficient binary integer programming model for residency time-constrained cluster tools with chamber cleaning requirements," *IEEE Trans. Autom. Sci. Eng.*, early access, Dec. 8, 2021, doi: 10.1109/TASE.2021.3122576.

[A7] I. El Makrini, G. Mathijssen, S. Verhaegen, T. Verstraten, and B. Vanderborght, "A virtual element-based postural optimization method for improved ergonomics during human–robot collaboration," *IEEE Trans. Autom. Sci. Eng.*, early access, Feb. 8, 2022, doi: 10.1109/TASE.2022.3147702.

[A8] C. J. Conti, A. S. Varde, and W. Wang, "Human–robot collaboration with commonsense reasoning in smart manufacturing contexts," *IEEE Trans. Autom. Sci. Eng.*, early access, Mar. 25, 2022, doi: 10.1109/TASE.2022.3159595.

[A9] S. Proia, R. Carli, G. Cavone, and M. Dotoli, "Control techniques for safe, ergonomic, and efficient human–robot collaboration in the digital industry: A survey," *IEEE Trans. Autom. Sci. Eng.*, early access, Dec. 6, 2021, doi: 10.1109/TASE.2021.3131011.

[A10] D. Pereira, A. Bozzato, P. Dario, and G. Ciuti, "Towards foodservice robotics: A taxonomy of actions of foodservice workers and a critical review of supportive technology," *IEEE Trans. Autom. Sci. Eng.*, early access, Jan. 21, 2022, doi: 10.1109/TASE.2021.3129077.

[A11] J. Wang, W. Chi, C. Li, and M. Q.-H. Meng, "Efficient robot motion planning using bidirectional-unidirectional RRT extend function," *IEEE Trans. Autom. Sci. Eng.*, early access, Dec. 6, 2021, doi: 10.1109/TASE.2021.3130372.