Guest Editorial Special Issue on Industrial Metaverse for Smart Manufacturing

THE INDUSTRY is undergoing a transformation toward smart manufacturing, fostering intelligent operations, sustainability, and digitalization. However, the current state of the process industry falls short of this future vision. Key areas, such as hybrid modeling, autonomous control, dynamic scheduling, intelligent decision making, security and safety control, and predictive maintenance, still require significant development. Given that the industrial metaverse enables the virtualization and digitization of industrial processes using technologies, such as artificial intelligence, blockchain, cloud computing, and digital twins, it is promising to establish the industrial metaverse for manufacturing, encompassing the entire lifecycle based on the industrial Internet and other modern information technologies.

The aim of this special issue is to provide a collection of the most recent research advances dedicated to the application of the industrial metaverse to the smart manufacturing. After a rigorous and comprehensive review of the submitted manuscripts, we selected 14 articles from the special issue, 11 of which are from the May special issue section and three from the July special issue section. A summary of these articles is provided as follows, focusing on industrial status monitoring, decision making, and overall intelligent management and regulation.

Due to the complexity of industrial manufacturing processes, accurately monitoring and estimating process status and detecting faults and anomalies are vital for ensuring safety, preventing hazards, and reducing the risk of injury or equipment damage. In [A1], a dynamic model interpretation-guided online active learning scheme is proposed for safety assessment. The effectiveness of the method is verified through experiments based on the Jiaolong deep-sea manned submersible data. To ensure the effectiveness of image anomaly detection methods, Xie et al. [A2] proposed a uniform IM benchmark. This benchmark assesses the performance of image anomaly detection algorithms across various levels of supervision, learning paradigms, and efficiency. Ren et al. [A3] proposed a meta-learning-based strategy to improve domain adaptation and generalization for few-shot fault diagnosis. The proposed strategy's performance is validated using two public datasets for bearing fault diagnosis. For early measurements before fault occurrence, Wan et al. [A4] proposed a memory shapelet learning framework for early classification. This framework uses a memory distance matrix, early interpretable shapelets, and an objective function that considers accuracy and earliness. Experiments on benchmark and real-world datasets demonstrate the superior performance of the method in interpretability, accuracy, earliness, and time complexity. Furthermore, Yuan et al. [A5] proposed a multiscale attention-based CNN (MSACNN) to extract spatiotemporal features from soft sensors and predict quality. The superiority of the proposed MSACNN over other state-of-the-art methods is validated through performance evaluations in two real industrial processes.

With the simulation and digitalization of Metaverse platforms, smart manufacturing achieves more efficient optimization, scheduling, decision making, and control. Hou et al. [A6] proposed a hybrid residual multiexpert reinforcement learning approach for interactive learning in the digital industrial metaverse. This approach effectively addresses the high-density parking scheduling problem and is robust to varying parking lot sizes and the accuracy of vehicle exit time estimation. Tan et al. [A7] developed a novel freezing network with a pyramid spatial channel attention mechanism for the large-scale data-driven optimization. Utilizing the "Activate-and-Freeze" block and the Dense-attention module, this network significantly outperforms advanced deep ConvNets methods in large-scale data-driven tasks. Moreover, metaverse technology also provides a simulated-reality platform to verify the superiority performance of the controller performance. Qin et al. [A8] proposed a hybrid controller to overcome the control challenges of musculoskeletal robots. This controller, combining a muscle-synergy-based radial basis function network as a feedforward controller and adaptive dynamic programming in the feedback controller, demonstrates satisfactory performance in lifting tasks. Chen et al. [A9] designed a novel and more challenging multiple peg-in-hole assembly setup by using the advantage of the Industrial Metaverse. Evaluation results demonstrate the effectiveness of the proposed solution, showcasing successful multiple peg-in-hole assembly and generalization across different object shapes in real-world scenarios. Wang et al. [A10] developed a revolutionary context-based deep meta reinforcement learning algorithm to achieve active pantograph control. The proposed algorithm integrates Bayesian optimization with deep reinforcement learning, enabling swift adaptation to changing scenarios and minimizing contact force fluctuations. The results demonstrate the exceptional performance of the algorithm in achieving effective pantograph control.

Digital Object Identifier 10.1109/TCYB.2024.3415688

Metaverse plays a significant role in constructing more visible, intelligent, and efficient production manufacturing frameworks. It guides the management and regulation of industrial development, promoting sustainability, high-value production, and digitalization in the process industry. Zhang et al. [A11] proposed a multicategory aggregated monitoring framework to facilitate production performance monitoring under varying working conditions. This framework improves visualization and interaction, aiding analysts in identifying and perceiving abnormal production performance in heavy-plate production data. To accommodate the complex manipulations with long-horizon steps and high-precision requirements, Sun et al. [A12] proposed a learning-based framework for the acquisition of complex 3C assembly skills assisted by a multimodal digital-twin environment. The experiments are conducted to verify the effectiveness of the proposed framework. For an overarching view on integrating the Metaverse into smart manufacturing, Ren et al. [A13] proposed a conceptual model named IMverse Model, an industrial metaverse architecture involving several key enabling technologies and novel characteristics of the industrial metaverse for smart manufacturing. Moreover, Ren et al. also discussed the challenges and open issues of industrial metaverse and provided the outlook for future research. To incorporate the impact of social factors, such as environment, society, and humans to support the future process industry, Qian et al. [A14] discussed the current status, challenges, opportunities, and future outlook of the process industry through a cyber–physical–social system (CPSS) framework.

We hope that these 14 articles in this special issue are beneficial for promoting the further development and application of Industrial Metaverses for Smart Manufacturing. We would like to thank all the authors who submitted their work to this special issue, and all the reviewers for their great efforts in assessing the submissions. Finally, we also extend our gratitude to the Editor-in-Chief and the editorial office for their timely guidance and consistent support.

FENG QIAN, *Guest Editor*
Key Laboratory of Smart Manufacturing in Energy Chemical Process
Ministry of Education
East China University of Science and Technology
Shanghai 200237, China
E-mail: fqian@ecust.edu.cn

HONG QIAO, *Guest Editor*
State Key Laboratory of Multimodal Artificial Intelligence Systems
Institute of Automation
Chinese Academy of Sciences
Beijing 100864, China
E-mail: hong.qiao@ia.ac.cn

BIAO HUANG, *Guest Editor*
Department of Chemical and Materials Engineering
University of Alberta
Edmonton, AB 510632, Canada
E-mail: biao.huang@ualberta.ca

YANG TANG, *Guest Editor*
Key Laboratory of Smart Manufacturing in Energy Chemical Process
Ministry of Education
East China University of Science and Technology
Shanghai 200237, China
E-mail: yangtang@ecust.edu.cn

DAVID BOGLE, *Guest Editor*
Department of Chemical Engineering
Centre for Process Systems Engineering
University College London
WC1E 6BT London, U.K.
E-mail: d.bogle@ucl.ac.uk

AIBING YU, *Guest Editor*
RC Research Hub for Smart Process Design and Control
Department of Chemical and Biological Engineering
Monash University
Melbourne, VIC 3800, Australia
E-mail: aibing.yu@monash.edu

APPENDIX: RELATED ARTICLES

[A1] X. He and Z. Liu, "Dynamic model interpretation-guided online active learning scheme for real-time safety assessment," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2734–2745, May 2024, doi: 10.1109/TCYB.2023.3339242.

[A2] G. Xie et al., "IM-IAD: Industrial image anomaly detection benchmark in manufacturing," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2720–2733, May 2024, doi: 10.1109/TCYB.2024.3357213.

[A3] C. Ren, B. Jiang, N. Lu, S. Simani, and F. Gao, "Meta-learning with distributional similarity preference for few-shot fault diagnosis under varying working conditions," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2746–2756, May 2024, doi: 10.1109/TCYB.2023.3338768.

[A4] X. Wan, L. Cen, X. Chen, Y. Xie, and W. Gui, "Memory shapelet learning for early classification of streaming time series," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2757–2770, May 2024, doi: 10.1109/TCYB.2023.3337550.

[A5] X. Yuan et al., "Quality prediction modeling for industrial processes using multiscale attention-based convolutional neural network," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2696–2707, May 2024, doi: 10.1109/TCYB.2024.3365068.

[A6] J. Hou, G. Chen, Z. Li, W. He, S. G, A. Knoll, and C. Jiang, "Hybrid residual multiexpert reinforcement learning for spatial scheduling of high-density parking lots," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2771–2783, May 2024, doi: 10.1109/TCYB.2023.3312647.

[A7] D. Tan et al., "Large-scale data-driven optimization in deep modeling with an intelligent decision-making mechanism," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2798–2810, May 2024, doi: 10.1109/TCYB.2023.3278110.

[A8] S. Qin, H. Li, and L. Cheng, "A hybrid controller for musculoskeletal robots targeting lifting tasks in industrial metaverse," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2708–2719, May 2024, doi: 10.1109/TCYB.2024.3358739.

[A9] W. Chen, C. Zeng, H. Liang, F. Sun, and J. Zhang, "Multimodality driven impedance-based Sim2Real transfer learning for robotic multiple peg-in-hole assembly," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2784–2797, May 2024, doi: 10.1109/TCYB.2023.3310505.

[A10] H. Wang, Z. Liu, Z. Han, Y. Wu, and D. Liu, "Rapid adaptation for active pantograph control in high-speed railway via deep meta reinforcement learning," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2811–2823, May 2024, doi: 10.1109/TCYB.2023.3271900.

[A11] T. Zhang et al., "iHPPPVis: Interactive visual analytics approach for production performance monitoring of heavy-plate production process," *IEEE Trans. Cybern.*, early access, May 7, 2024, doi: 10.1109/TCYB.2024.3387129.

[A12] F. Sun et al., "Digital-twin-assisted skill learning for 3C assembly tasks," *IEEE Trans. Cybern.*, early access, Apr. 5, 2024, doi: 10.1109/TCYB.2024.3368148.

[A13] L. Ren et al., "Industrial metaverse for smart manufacturing: Model, architecture, and applications," *IEEE Trans. Cybern.*, vol. 54, no. 5, pp. 2683–2695, May 2024, doi: 10.1109/TCYB.2024.3372591.

[A14] F. Qian, Y. Tang, and X. Yu, "The future of process industry: A cyber–physical–social system perspective," *IEEE Trans. Cybern.*, early access, Aug. 22, 2023, doi: 10.1109/TCYB.2023.3298838.