Guest Editorial: Co-Design of Communication, Computing, and Control in Industrial Cyber-Physical Systems—Part II

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I. Introduction

THIS is the guest editorial for Part II of the double-part Special Issue (SI) on Co-Design of Communication, Computing, and Control in Industrial Cyber-Physical Systems (ICPS). As presented the guest editorial for Part I [A1], we introduced the scope of this special issue and noted that the 44 accepted papers are organized into five thematic groups: 1) new-generation digital infrastructure; 2) goal-oriented communication; 3) cyber-physical security; 4) co-design for industrial control applications; and 5) co-design for intelligent cyber-physical systems applications.

In [A1], we presented the contributions from the first three groups. This guest editorial highlights the remaining 22 papers featured in Part II, which correspond to the final two groups.

II. Co-Design for Industrial Control Applications

The growing complexity and performance demands of industrial control applications have led to a strong emphasis on control-oriented 3C co-design, particularly in time-critical, wireless, and distributed control systems. The papers in this group explore new architectures and algorithms that drive intelligent control, real-time responsiveness, and system-wide efficiency across diverse industrial environments.

Motivated by the potential of industrial control virtualization, Yang et al. [A2] present control-as-a-service (CaaS), which is a novel architecture that embeds control logic directly into network switches. CaaS enables distributed, flexible, and low-latency control in ICPS through in-network task execution and joint task-traffic scheduling.

Addressing wireless latency in control loops, Chai et al. [A3] introduce an anti-latency intelligent control system for 5G networks based on end-edge-cloud collaboration. Their approach mitigates random latency in industrial control applications by combining deep learning (DL), and reinforcement learning (RL) with data-driven proportional integral derivative (PID) control, and digital twin optimization.

Several contributions target large-scale and complex networked control environments. Pang et al. [A4] develop a deep reinforcement learning (DRL)-based communication and control co-design framework for large-scale wireless networked control systems. The model captures correlated dynamics among distributed agents and addresses hybrid action spaces under time-correlated fading channels.

Similarly, Cao et al. [A5] propose an adaptive time-sensitive networking (TSN) flow scheduling framework for robotic arm teleoperation, called AFS-RT. It integrates control-aware slot allocation and DRL with slot-correlation feature extraction to co-optimize communication and control performance.

Focusing on the role of digital twins and edge intelligence, Fang et al. [A6] present a closed-loop optimization framework for 6G digital twin-empowered autonomous robotic systems. The architecture jointly optimizes sensing, communication, computing, and control resources in edge-based sensing-communication-computing-control (SC3) loops using autonomous aerial vehicles (AAVs) as edge information hubs.

In the context of warehouse automation, Ho et al. [A7] propose an artificial intelligence (AI)-powered digital twin control framework that employs DRL for model adaptation. It uses a game-theoretic approach for resource allocation to optimize energy efficiency and real-time decision-making.

As for hierarchical and heterogeneous systems, Tang et al. [A8] introduce SeCo4, which is a co-design framework integrating sensing, communication, and computing for intelligent ICPS control. Their model incorporates combinatorial auctions for cloud resource competition and mixed-integer programming for joint resource optimization.

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In a similar vein, Wang et al. [A9] address co-design challenges in heterogeneous mobile-agent systems using a logic-based stochastic switched system framework. Their model captures agent movement and wireless link reliability via Markov decision processes and uses a semi-tensor product-based optimization approach to balance communication and control costs.

From a state estimation perspective, Sun et al. [A10] analyze strictly periodic transmission scheduling for remote state estimation with a focus on energy efficiency. They derive the optimal period for scheduling based on packet dropout rate and system dynamics, showing it approximates the performance of complex schemes.

This is followed by the work by Liu et al. [A11], where they present a distributed filtering framework over Gaussian feedback channels. Using an information-theoretic approach, they develop an optimal linear strategy for encoding and decoding and establish connections between Shannon and Fisher information in continuous-time inference.

III. Co-Design for Intelligent Cyber-Physical Systems

As new ICPS applications and use cases continue to grow in complexity and scale, 3C co-design is essential in meeting their performance requirements. This group of papers advances the integration of edge intelligence, digital twins, and reinforcement learning to support distributed decision-making across a wide range of industrial applications and scenarios.

In intelligent logistics, Liu et al. [A12] propose a hierarchical transformer reinforcement learning (HTRL) framework for automated guided vehicle (AGV) scheduling in warehouses. The system integrates packet selection and path planning with model predictive control-based speed regulation to meet delivery deadlines in dynamic logistics environments.

Addressing quality of experience (QoE) fairness in edge AI services, Chen et al. [A13] introduce HARBOR, which is a joint optimization framework for bandwidth, computation, and batch size. The method ensures fair QoE across tasks using long short-term memory-based resource prediction and an efficient mixed-integer non-linear programming approach.

Deployment flexibility and monitoring efficiency are also a key focus. Xia et al. [A14] propose an adaptive edge deployment strategy for smart factories based on improved K-means particle swarm optimization. This scheme supports real-time responsiveness and reliability through dynamic clustering and multi-metric weight adjustment.

The work by Chen et al. [A15] investigates a digital twin-enabled hierarchical monitoring scheme for massive industrial systems under constrained environments. They use a multi-agent reinforcement learning-based approach to optimize compression and region assignment, improving real-time monitoring utility through mask state-assisted scheduling.

Federated learning (FL) under constrained settings is addressed by Sun et al. [A16], who design a socially optimal incentive mechanism for relay-assisted asynchronous FL. The framework uses dual-based Lagrangian optimization to ensure fairness, incentive compatibility, and robust training under infrastructure constraints.

Similarly, Wang et al. [A17] propose F^{2}NAS, an energy-friendly federated neural architecture search framework for ICPS. The system incorporates fine-grained aggregation, bi-directional knowledge transfer, and adaptive communication strategies to improve accuracy and reduce energy consumption on heterogeneous edge devices.

Following this work, Fresa et al. [A18] present a profiling and learning-based co-design method for communication and computing in scalable robotics. A dual-phase strategy integrates static optimization and reinforcement learning-based dynamic tuning to improve offloading decisions and network performance in edge-cloud robotic systems.

For immersive media systems and applications, Gao and Braun [A19] present a dual-engine intelligent caching framework for 360° mobile virtual reality (VR) video delivery. Combining operations research with DRL, the system employs a hierarchical architecture and cache boundary pruning to enhance placement efficiency under stringent latency constraints.

Complementing these efforts, Li et al. [A20] develop RIVA, an adaptive streaming framework for real-time industrial video analytics in ICPS. Leveraging online learning and hierarchical reinforcement learning, RIVA jointly schedules model retraining and bitrate allocation to balance communication efficiency and quality of service under highly dynamic network conditions.

Knowledge distillation and ensemble learning techniques are featured by Wu et al. [A21], where they introduce an adaptive ensemble knowledge distillation framework (AEKDF) to support collaborative inference on heterogeneous edge devices. The system combines cloud-trained diverse models with edge-side ensemble techniques to enhance generalization and maintain low-latency performance in dynamic conditions.

In energy-constrained integrated sensing, communication, and computation (ISCC) network, Yao et al. [A22] develop a co-optimization framework that jointly performs inference splitting, model pruning, and feature quantization. The approach applies an alternating optimization method to minimize energy usage while preserving accuracy.

Finally, Yuan et al. [A23] propose a digital twin-driven multi-agent deep reinforcement learning (MADRL) framework for communication-computation-control co-optimization in ICPS, particularly for medical applications. The system integrates self-attention-enhanced QMIX and multi-task deep Q-networks to support distributed execution and centralized training under dynamic and resource-constrained environments.

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APPENDIX: RELATED ARTICLES

[A1] J. Jin et al., "Guest editorial: Co-design of communication, computing, and control in industrial cyber-physical systems—Part 1," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 9, pp. 2912–2916, Sep. 2025, doi: 10.1109/JSAC.2025.3572638.

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[A3] T. Chai, F. Xing, R. Zheng, Y. Jia, and Y. Song, "An anti-latency intelligent control for 5G wireless networks based on end-edge-cloud collaboration," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 10, pp. 3281–3294, Oct. 2025, doi: 10.1109/JSAC.2025.3574593.

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[A8] Q. Tang et al., "SeCo4: Co-design of sensing, communication, and computing for intelligent control in industrial cyber-physical systems," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 10, pp. 3362–3378, Oct. 2025, doi: 10.1109/JSAC.2025.3574623.

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[A10] B. Sun, X. Cao, W. X. Zheng, and Y. Cheng, "On optimal energy-efficient transmission scheduling for remote state estimation," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 10, pp. 3394–3409, Oct. 2025, doi: 10.1109/JSAC.2025.3574608.

[A11] Z. Liu, A. Conti, S. K. Mitter, and M. Z. Win, "Continuous-time distributed filtering via a Gaussian feedback channel," *IEEE Sel. Areas Commun.*, vol. 43, no. 10, pp. 3410–3425, Oct. 2025, doi: 10.1109/JSAC.2025.3574610.

[A12] B. Liu et al., "Efficient AGV scheduling in warehouses via hierarchical transformer reinforcement learning," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 10, pp. 3426–3439, Oct. 2025, doi: 10.1109/JSAC.2025.3574621.

[A13] L. Chen, S. Zheng, J. Wu, and H.-N. Dai, "HARBOR: Harnessing bandwidth, computation, and batch for fair QoE having collaborative edge-AI services in industrial CPS," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 10, pp. 3440–3455, Oct. 2025, doi: 10.1109/JSAC.2025.3574583.

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[A21] S. Wu et al., "Enhancing collaborative inference on heterogeneous edge devices via adaptive ensemble knowledge distillation," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 10, pp. 3564–3579, Oct. 2025, doi: 10.1109/JSAC.2025.3574594.

[A22] J. Yao, W. Xu, G. Zhu, K. Huang, and S. Cui, "Energy-efficient edge inference in integrated sensing, communication, and computation networks," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 10, pp. 3580–3595, Oct. 2025, doi: 10.1109/JSAC.2025.3574612.

[A23] X. Yuan et al., "Digital twin-driven MADRL approaches for communication-computing-control co-optimization," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 10, pp. 3596–3611, Oct. 2025, doi: 10.1109/JSAC.2025.3574616.

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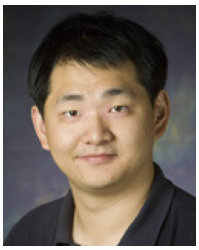

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