

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

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## I. INTRODUCTION

**I**NDUSTRIAL Cyber-Physical Systems (ICPS) are rapidly evolving to meet the increasing demands and challenges of modern automation, intelligence, and autonomy. In recent years, this evolution has been underpinned by a fundamental paradigm shift in industrial automation architectures – from the well-established hierarchical Industrial Society Automation (ISA)-95 model to an emerging network-centric Cloud-Fog Automation architecture. Cloud-Fog Automation leverages next-generation communication and distributed computing technologies to enable almost-deterministic ultra-reliable low-latency communication (uRLLC) and artificial intelligence (AI)-powered control operations across various industrial sectors. This architecture supports time-sensitive operations that are traditionally performed on specialized hardware in a more open and flexible manner, where low-level hardware-specific functionalities are migrated to fog infrastructures, while high-level functions are executed in the cloud.

This architectural transformation opens up new opportunities for realizing vendor-agnostic and service-oriented industrial applications, which allows flexible and scalable deployments of industrial systems and service provisioning

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models, such as e.g., Control-as-a-Service, Robots-as-a-Service, and Manufacturing-as-a-Service. To fully realize the potential of Cloud-Fog Automation, and accelerate towards a truly autonomous ICPS, a tight synergy and co-design between communications, computing, and control technologies (referred to as “3C co-design”) is required. This synergy implies that design and development efforts must explicitly consider the intricate interplay between the 3C domains, and ensure future ICPS are poised to meet the stringent multi-dimensional requirements of time-critical, safety-sensitive, and goal-oriented industrial operations. Moreover, system-wide cyber-physical security and functional safety must be ensured to protect against cyber threats that could lead to significant financial losses and/or catastrophic failures.

3C co-design introduces several exciting open research avenues which are thematically explored in this Special Issue (SI). These avenues include the development of resource orchestration strategies in *new-generation digital infrastructure*, cross-layer optimization techniques for *goal-oriented communication*, secure and robust system architectures for ensuring *cyber-physical security*, co-design approaches for intelligent *industrial control applications*, and a plethora of novel use cases in *intelligent cyber-physical systems*. New performance metrics and application scenarios, such as AI-empowered digital twins, industrial robotics, and immersive industrial systems using augmented/virtual reality will further drive research efforts toward system integration and performance assurance.

This SI received 155 high-quality submissions from researchers in academia and industry worldwide. Following a rigorous review process, 44 submissions were accepted for publication across two issues. Each submission received at least three reviews, and all accepted papers went through two rounds of review. Parts I and II each contain 22 papers. The accepted papers are categorized 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. In this guest editorial for Part I, we summarize the key contributions from the first three groups, whereas the summary of the remaining contributions will be presented in the guest editorial for Part II.

Part I of this double issue begins with an overview paper [A1] authored by the Guest Editorial team. The article introduces Cloud-Fog Automation as a new paradigm for realizing the vision of a fully autonomous ICPS. It positions the tight synergy between communications, computing, and control as the foundational principle for achieving system-wide autonomy across diverse application domains. The article provides a comprehensive overview of the state-of-the-art, discusses emerging technologies, and identifies key opportunities in goal-oriented communication, virtualization-empowered computing, and quality of service (QoS)-aware control, while also highlighting the critical and cross-cutting importance of cyber-physical security. We hope this forward-looking overview will serve as a valuable resource and bring together researchers and practitioners to accelerate the realization of a fully autonomous ICPS in the near future.

## II. NEW-GENERATION DIGITAL INFRASTRUCTURE

The development of next-generation ICPS is built upon scalable, intelligent, and interoperable digital infrastructure that supports distributed control, learning, and automation. Several papers in this group advance the architectural and algorithmic innovations of such infrastructures.

A key focus is placed on enabling intelligent and distributed decision-making at scale. To this end, Han et al. [A2] propose a transformer-based distributed framework for task offloading and resource management in cloud-edge computing networks for ICPS. The solution integrates a distributed transformer-based actor-critic (DTAC) model with decentralized transfer learning to enable scalable and autonomous decision-making across devices with minimal coordination overhead.

Complementing the need for deterministic low-latency networking, Peng et al. [A3] develop a class-aware mixed-flow scheduling (CAMFS) strategy for hybrid wired-wireless time-sensitive networks (TSN). The framework introduces a time-triggered multiple cyclic-queuing (TTMCQ) shaper and an anti-starvation optimization mechanism to support class-aware flow mapping and efficient resource allocation in 5G-TSN integrated environments.

Similarly, Wang et al. [A4] enhance time synchronization for integrated 5G and TSN systems by addressing interoperability challenges such as multi-gNodeB (gNB) contention, retransmissions, and mobility. The proposed mechanisms improve synchronization precision to support deterministic communications in industrial robotic and mobile scenarios.

Advancing signal processing and learning capabilities at the physical layer, Xiang et al. [A5] present a deep learning-enabled optimization framework for reconfigurable intelligent surface (RIS)-assisted massive multiple-input multiple-output (MIMO) systems in ICPS. The approach jointly tackles channel estimation, symbol detection, and phase shift optimization using transformer-based prediction and co-design of communication, computation, and control.

Infrastructure-level support for adaptive learning is addressed by Shang et al. [A6]. Their work introduces a decentralized deep federated learning (DDFL) architecture and propose a hybrid multi-task deep reinforcement learning (MTDRL) scheme. The method balances computing and network load under diverse delay requirements by optimizing fog server selection and network traffic routing.

To ensure deterministic communication across heterogeneous systems, Wang et al. [A7] propose an inter-domain multiple transmission opportunity mechanism (MTOM) and an asynchronous scheduling model. This approach enables deterministic transmission over converged TSN and Profinet networks, and consequently achieves interoperability using standard devices without requiring hardware or protocol changes.

Finally, in the context of fog radio access networks, Laurinavicius et al. [A8] develop a multi-agent dual deep Q-network (MA-DDQN) algorithm for user association and power allocation. The scheme mitigates coordination overhead by leveraging experience exchange in partially observable environments, while supporting decentralized decision-making.

## III. GOAL-ORIENTED COMMUNICATION

The transition towards autonomous ICPS requires communication architectures to go beyond conventional metrics (e.g., throughput, latency, reliability) and incorporate goal-awareness, semantic relevance, and timeliness to meet application-specific control objectives. Several papers in this group explore novel mechanisms to align communication strategies with control and computing goals in highly dynamic industrial environments.

The integration of 3C co-design principles from the communications perspective is clearly evident in this group, with a particular focus on task-oriented approaches. Diao et al. [A9] propose a task-oriented framework for ICPS that integrates joint source-channel coding (JSCC) based on the information bottleneck principle with a delay-aware trajectory-guided control prediction (DTCP) strategy. This design ensures robust and delay-resilient control for autonomous industrial applications.

Building on the theme of control-aware coding, Chen et al. [A10] develop a progressive goal-oriented communication framework tailored for reinforcement learning (RL)-based control in multi-tier computing systems. The method incorporates variable-rate encoding through hierarchical variational autoencoders and mutual information-based state abstraction to facilitate efficient/adaptive communication.

At the semantic layer, Chen et al. [A11] present a goal-oriented semantic communication (GSC) framework designed for digital twin-based robot arm reconstruction. The approach leverages feature selection and deep reinforcement learning (DRL)-based temporal selection to transmit only task-relevant semantic features, significantly reducing overhead while meeting reconstruction accuracy requirements.

Goal-oriented resource-aware coordination is explored by Abode et al. [A12], where they propose a decentralized interference coordination strategy for dense 6G in-factory subnetworks. This solution aligns power and sub-band allocation with control objectives using a Bayesian optimization

framework, ensuring long-term control stability despite limited spectral resources.

Several new goal-oriented communication metrics are introduced and evaluated in this group. In [A13], Luan et al. focus on end-edge collaboration in short-packet ICPS by embedding a variant of age of information (AoI) into a co-optimization framework. The approach improves control performance by jointly optimizing sampling, computation offloading, and bandwidth allocation under delay constraints.

To enhance communication effectiveness in mobile multi-agent settings, Zhao et al. [A14] introduce a novel metric, called loss of information utility (LoIU), to quantify the relevance of shared information in robot teams. They propose a semi-decentralized multi-agent reinforcement learning framework to minimize LoIU by coordinating transmission schedules and resource allocation.

Similarly, Liao et al. [A15] present a timeliness-driven co-optimization framework for sensing, transmission, computing, and control in smart grids. They define a new metric, called age of trustworthy information (AoTI), to guide adaptive voltage regulation and proactive communication-resource decisions for control stability.

Finally, Qiu et al. [A16] introduce the age of result (AoR) as a novel metric for networked control systems to evaluate the freshness of executed control actions. Their random sampling-based approximate algorithms minimize AoR across multi-task environments, which improves real-time system responsiveness under network and computing constraints.

#### IV. CYBER-PHYSICAL SECURITY

Cyber-physical security is paramount as ICPS increasingly depend on distributed architectures and shared computational resources. This group of papers presents innovative approaches for safeguarding data integrity, securing communication channels, and enhancing cross-domain trust across the industrial cloud-edge continuum.

To address the challenge of ensuring trustworthy data across distributed caches, Zhao et al. [A17] propose an over-the-air cloud-fog data integrity verification scheme for ICPS, called AirDIV. This scheme performs aggregated integrity proof transmission directly over the air and introduces an optimization model to minimize aggregation errors while defending against replay and forgery attacks.

Focusing on the reliability within fault-prone industrial networks, Fan et al. [A18] co-design a communication-computation framework to enhance data reliability with the Cloud-Fog Automation paradigm. The solution includes a four-layer communication architecture with a double deep Q-learning-based cluster head algorithm and a hybrid fault detection scheme that combines hard fault protocol-based detection and contrastive learning-based soft fault recognition.

Dynamic security assessment for smart grids is addressed in [A19], where Ren et al. introduce QFEVAL, a quantum federated ensembled variational adaptive learning approach. By combining quantum machine learning and federated learning techniques, QFEVAL enables efficient and privacy-preserving stability prediction of high-dimensional distributed grid data without extensive parameter exchange.

In the context of integrated sensing and communication (ISAC) systems, Li et al. [A20] design a secure communication and sensing scheme for multi-carrier non-orthogonal multiple access (MC-NOMA)-based ISAC under imperfect channel state information (CSI). They meet the hierarchical secrecy and sensing requirements by developing a joint beamforming and subcarrier allocation strategy using a successive convex approximation algorithm within a bounded CSI error model.

To protect industrial control systems from dynamic and unknown threats, Liang et al. [A21] propose a cross-domain security-safety architecture for industrial wireless control systems. The framework integrates cyber, control, and physical domains through a whitelist-based defense mechanism and a closed-loop risk tracking model, forming a comprehensive approach to secure operation in wireless industrial environments.

Finally, Chen et al. [A22] design a blockchain-based cross-domain authentication and data sharing scheme within Cloud-Fog Automation. Their design employs a time-specific plaintext checkable encryption protocol to ensure privacy and integrity in collaborative environments with minimal overheads.

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#### APPENDIX: RELATED ARTICLES

- [A1] J. Jin et al., "Cloud-fog automation: The new paradigm towards autonomous industrial cyber-physical systems," *IEEE J. Sel. Areas Commun.*, 2025.
- [A2] M. Han, X. Sun, X. Wang, W. Zhan, and X. Chen, "Transformer-based distributed task offloading and resource management in cloud-edge computing networks," *IEEE J. Sel. Areas Commun.*, 2025.
- [A3] G. Peng, S. Wang, T. Huang, K. Zhao, and G. Li, "Achieving class-aware mixed-flow scheduling in hybrid wired-wireless time-sensitive networks," *IEEE J. Sel. Areas Commun.*, 2025.
- [A4] Z. Wang, Z. Li, C. Long, Y. Zheng, B. Ai, and X. Song, "Time synchronization for 5G and TSN Integrated Networking," *IEEE J. Sel. Areas Commun.*, 2025.
- [A5] W. Xiang, M. U. Zia, J. Ahmad, P. Cheng, K. Yu, and T. Huang, "Deep learning-enabled RIS massive MIMO systems for industrial IoT: A joint communication and computation approach," *IEEE J. Sel. Areas Commun.*, 2025.
- [A6] X. Shang et al., "Computing and network load balancing for decentralized deep federated learning in industrial cyber-physical systems: A multi-task approach," *IEEE J. Sel. Areas Commun.*, 2025.
- [A7] J. Wang, C. Li, Y. Zhao, and Z. Li, "Deterministic transmission for the asynchronous converged networks of profinet and TSN," *IEEE J. Sel. Areas Commun.*, 2025.
- [A8] I. Laurinavicius, H. Zhu, Y. Pan, C. Chen, and J. Wang, "Novel deep reinforcement learning for user association in fog radio access networks," *IEEE J. Sel. Areas Commun.*, 2025.
- [A9] Y. Diao, Y. Zhang, D. D. Martini, P. G. Zhao, and E. L. Li, "Task-oriented co-design of communication, computing, and control for edge-enabled industrial cyber-physical systems," *IEEE J. Sel. Areas Commun.*, 2025.

- [A10] D. Chen, T. Huang, J. Shi, X. Hong, and Y. Yang, "Progressive goal-oriented communications for reinforcement learning control over multi-tier computing systems," *IEEE J. Sel. Areas Commun.*, 2025.
- [A11] S. Chen, E. Spyros-Papastavridis, Y. Jin, and Y. Deng, "Goal-oriented semantic communication for robot arm reconstruction in digital twin: Feature and temporal selections," *IEEE J. Sel. Areas Commun.*, 2025.
- [A12] D. Abode, P. M. de Sant Ana, R. Adeogun, A. Artemenko, and G. Berardinelli, "Goal-oriented interference coordination in 6G in-factory subnetworks," *IEEE J. Sel. Areas Commun.*, 2025.
- [A13] M. Luan, Z. Chang, S. Mumtaz, G. Min, and T. Hämmäläinen, "End-edge collaborative control for AoI-aware short-packet industrial cyber-physical system," *IEEE J. Sel. Areas Commun.*, 2025.
- [A14] X. Zhao et al., "A novel indicator for quantifying and minimizing information utility loss of robot teams," *IEEE J. Sel. Areas Commun.*, 2025.
- [A15] H. Liao et al., "Timeliness-driven integrated sensing, transmission, computing and control for power-communication coupling smart grid," *IEEE J. Sel. Areas Commun.*, 2025.
- [A16] X. Qiu et al., "Minimizing age of result in multi-task networked control systems," *IEEE J. Sel. Areas Commun.*, 2025.
- [A17] Y. Zhao et al., "AirDIV: Over-the-air cloud-fog data integrity verification scheme for industrial cyber-physical systems," *IEEE J. Sel. Areas Commun.*, 2025.
- [A18] X. Fan et al., "Co-designed communication and computing for data reliability in industrial cyber-physical systems with cloud-fog automation," *IEEE J. Sel. Areas Commun.*, 2025.
- [A19] C. Ren et al., "QFEVAL: Quantum federated ensembled variational adaptive learning for dynamic security assessment in cyber-physical systems," *IEEE J. Sel. Areas Commun.*, 2025.
- [A20] X. Li, Z. Wu, Y. Cai, S. Hu, Y. Liao, and W. Yuan, "Win-win of communication and sensing security for MC-NOMA ISAC systems," *IEEE J. Sel. Areas Commun.*, 2025.
- [A21] W. Liang, S. Zhang, Y. Zhang, J. Zhang, and X. Yuan, "An integrated security-safety architecture for industrial wireless control system based on cyber-control-physical cross-domain collaboration," *IEEE J. Sel. Areas Commun.*, 2025.
- [A22] X. Chen, C. Hu, B. Cai, P. Hu, and J. Yu, "Secure cross-domain authentication and data sharing scheme for IIoT in cloud-fog automation architecture," *IEEE J. Sel. Areas Commun.*, 2025.



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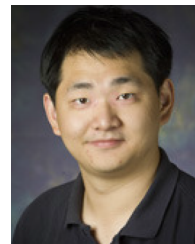


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