EDITORIAL

Inaugural Editorial: Embracing a New Era of Intelligent and Interconnected Everything

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Abstract

This inaugural editorial aims to provide a comprehensive and in-depth exposition of the profound historical context, core academic value, and long-term vision underlying the establishment of *ICCK Transactions on Intelligent Cyber-Physical Systems* (hereinafter referred to as "the Journal"). We are standing at the forefront of the Fourth Industrial Revolution, driven by the rapid advancement of cyber-physical integration technologies. As the central engine of this transformative wave, intelligent cyber-physical systems—through the deep and organic fusion of computing, communication, control technologies, and artificial intelligence-are fundamentally reshaping industrial infrastructures, urban systems, and even the overarching operational paradigms of human society. The founding of the Journal is by no means accidental; rather, it is an inevitable response to this epoch-making technological revolution. Our foremost objective is to build an international, high-quality, and authoritative academic platform for this highly interdisciplinary frontier field. The Journal seeks to gather leading global expertise, catalyze breakthroughs in fundamental theories, and accelerate innovation in key technologies as well as their translation into practical applications.

Keywords: intelligent cyber-physical systems, artificial intelligence, cyber-physical integration, autonomous systems, system resilience, digital twins.

1 Introduction: The Paradigm Shift from Networking to Intelligence

A review of the history of technological development reveals a clear trajectory of evolution—from mechanization and electrification to automation and informatization. In recent years, cyber-physical systems (CPS), as an integrated framework uniting computation, networking, and physical processes, have emerged as a vital bridge between the digital and physical worlds [1–3]. Early implementations—such as programmable logic controller (PLC) networks in industrial settings and flight control systems in aerospace—primarily addressed fundamental questions of "how to connect" and "how to control." However, as CPS increasingly encounter real-world environments characterized by complexity, dynamism, and uncertainty, their traditional static or rule-based control strategies often prove inadequate. Significant

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gaps remain in system adaptability and cognitive capability [4].

The task of filling this gap has historically fallen to artificial intelligence (AI), particularly data-driven intelligent technologies represented by deep learning and reinforcement learning. The infusion of AI is akin to equipping CPS with a "brain" and a "nervous system," enabling them to evolve from reflex-arc-type automated systems into intelligent cyber-physical systems (ICPS) endowed with a closed-loop capability of "perception–reasoning–action." ICPS not only "see" and "hear" the physical world through sensors, but also "understand" and "predict" environmental states through AI models. Ultimately, they can "autonomously" make optimal or near-optimal decisions that exert influence on the physical world via actuators [5]. This paradigm shift allows manufacturing processes to progress from automation to autonomization, transportation systems to advance from informatization to intelligentization, and energy networks to evolve from being merely interconnected to truly intelligent and interconnected [6, 7].

ICCK Transactions on Intelligent Cyber-Physical Systems emerges precisely against this backdrop. The mission of the Journal goes far beyond merely documenting the trajectory of this technological revolution; it aspires to actively guide and shape its future directions. We recognize that breakthrough progress in ICPS cannot be achieved within the confines of any single discipline. It demands that computer scientists develop a deep understanding of the dynamic characteristics of physical systems and control theory; that control engineers acquire AI tools capable of handling high-dimensional, unstructured data; and that mechanical engineers incorporate considerations of digital twin modeling and simulation into the very design of mechanical structures [8–10]. Accordingly, the Journal places deep interdisciplinary integration at the core of its strategic vision. It is committed to dismantling disciplinary silos and aims to become an "academic switchboard" and a "crucible of ideas" that connects scholars across diverse fields.

The rapid development of ICPS is deeply rooted in the synergistic advancement of a wide range of enabling technologies. Innovations in artificial intelligence algorithms provide unprecedented cognitive capabilities; 5G/6G communication technologies deliver ultra-low-latency and highly reliable data transmission pipelines for massive information flows; edge computing pushes intelligence from the cloud to the device level, meeting stringent real-time requirements; and new generations of sensors and actuators significantly expand the breadth and precision with which systems perceive and manipulate the physical world. The "fusion" of these enabling technologies serves as the inexhaustible driving force behind the continuous evolution of ICPS. Therefore, fostering cross-disciplinary integration, fusion, and collaborative innovation among these technologies within a unified ICPS framework constitutes both the central mission and the historical responsibility of *ICCK Transactions on Intelligent Cyber-Physical Systems*.

To present our discussion in a systematic manner, the remainder of this editorial is organized as follows: Section 2 provides an in-depth deconstruction of the multi-layered technical architecture of ICPS, offering a detailed analysis of its core components and intrinsic interdependencies, while addressing the key challenges faced in current research and practice. Section 3 delivers a comprehensive and nuanced overview of the critical technical domains and research frontiers that fall within the Journal's scope, forming the main body of this article. Finally, Section 4 summarizes the Journal's mission and core values, and extends our most sincere invitation for collaboration to the global academic community.

2 Core Architecture and Critical Challenges of Intelligent Cyber-Physical Systems

2.1 Core Architecture: Building an Intelligent "Perception–Reasoning–Action" Closed Loop

ICPS can be conceptualized as a multi-layered, dynamically evolving complex system [1]. Its core value lies in establishing a continuously optimized intelligent closed loop that transitions from the physical world to the information space and then back to the physical world. This architecture typically comprises the following five key layers:

2.1.1 Intelligent Perception Layer

This layer serves as the "sensory terminal" through which ICPS interact with the physical world. Its technological scope has long surpassed traditional single-sensor data acquisition, evolving instead into a multimodal, collaborative, and intelligent perception framework.

Multimodal Sensor Fusion: The system must integrate a wide range of heterogeneous sensors—including visual (cameras), acoustic (microphones), physical (accelerometers, gyroscopes), environmental (temperature, humidity, gas), and even biosensors—to obtain a comprehensive and redundant representation of physical objects and environmental states. Deep fusion algorithms, ranging from classical Kalman-filter-based methods to end-to-end fusion models powered by deep learning, are essential for ensuring the accuracy and robustness of perception information [2, 3].

Event-Driven and Active Perception: Unlike periodic sampling, event-driven perception reports data only when specific events occur—such as object movement or abnormal vibrations—significantly reducing communication and computational overhead [4]. Going a step further, the system can actively adjust sensor parameters (e.g., camera focal length, scanning angle) based on current task demands and high-level decision guidance, thereby achieving focused "attention" through active perception.

Integrated Perception–Communication Design: On resource-constrained edge devices, the generation of perceptual data and its transmission are no longer independent stages. Jointly optimizing perception accuracy and communication cost, and designing efficient encoding and transmission strategies, has become a frontier direction for enhancing overall system performance [5].

2.1.2 Data–Information Transformation Layer

This layer functions as the "peripheral nervous system" of ICPS. It is responsible for the preliminary processing of the massive, raw, and low-value "data" collected by the perception layer, transforming it into structured, feature-rich "information" that can be effectively utilized by upper-layer intelligent decision-making modules.

Edge Intelligence and Computing: Offloading computational tasks from the cloud to network-edge gateways, devices, and even sensors themselves is an inevitable choice for meeting the real-time requirements of ICPS [6]. At this layer, lightweight AI models—such as pruned or quantized neural networks—are deployed to perform localized intelligent tasks including data cleaning, anomaly detection, feature extraction, and object recognition.

Processing of Temporal Data Streams: Most data in ICPS arrives as continuous temporal streams. Specialized stream-processing engines (e.g., Apache Flink, Apache Storm) are required to support real-time window aggregation, pattern matching, and complex event processing for these data flows [7].

Information Representation and Standardization: The transformed information must be represented in a unified, machine-interpretable form—such as through ontologies or knowledge graphs—and encapsulated into standardized information models (e.g., OPC UA) [8] to enable seamless flow and sharing across different components of the system.

2.1.3 Intelligent Cognition and Decision-Making Layer

This layer serves as the "brain" and "command center" of ICPS, representing the core manifestation of system intelligence. It receives information from lower layers and, through sophisticated computation and reasoning, forms an understanding of the current situation and generates strategies for future actions.

Model-Driven Cognition: Physical and dynamical models constructed using first-principle formulations or system identification techniques can provide precise descriptions and explainable predictions of system behaviors. Such approaches remain highly effective in scenarios where models are accurate and system complexity is manageable [9].

Data-Driven Cognition: Deep-learning-based perception models (e.g., CNNs for image recognition) [10], prediction models (e.g., LSTM and Transformer architectures for time-series forecasting) [11], and diagnostic models can learn complex nonlinear mappings from large volumes of historical data, enabling them to capture phenomena that are difficult to describe through explicit modeling.

Learning-Based Decision-Making and Planning: Reinforcement learning—particularly deep reinforcement learning—allows agents to autonomously acquire optimal policies by interacting with simulators in virtual or real environments and learning through trial and error, even in complex and dynamic settings [12]. Meta-learning aims to equip agents with the capability to "learn how to learn," enabling rapid adaptation to new and previously unseen tasks [13]. Moreover, multi-agent cooperative decision-making, grounded in operations research and game theory, serves as a critical approach for addressing system-level optimization problems [14].

2.1.4 Precision Execution and Control Layer

This layer serves as the "limbs" of ICPS, responsible for applying decision commands generated in the information space to physical entities with precision, reliability, and safety.

Networked Control Systems: When control loops are closed through communication networks, new challenges arise—including communication delays, packet loss, and timing jitter. Robust and adaptive networked control algorithms must be designed to ensure system stability and performance under such conditions [15].

Learning-Enabled Control: By integrating learning techniques with classical control theory, controllers can better handle model uncertainties and complex nonlinearities. Examples include embedding neural networks as approximators for unknown dynamics within model predictive control frameworks, or employing reinforcement learning to directly acquire control policies [16].

Safety-Prioritized Execution: Actuator behaviors must strictly comply with physical constraints and safety regulations. Theoretical tools such as control barrier functions and reachability analysis are applied to design safety-guaranteed controllers that ensure the system never enters hazardous states under any circumstances [17].

2.1.5 *Closed-Loop Feedback and Evolution Layer*

This layer represents the ultimate distinction between ICPS and traditional automated systems, endowing ICPS with the characteristics of self-evolution and continuous optimization—akin to a living organism.

Digital Twins: As virtual replicas of physical entities, digital twins achieve synchronized mapping and interaction with their physical counterparts through real-time data streams. Beyond serving as tools for monitoring and diagnosis, they act as sandboxes for predicting future states, testing control strategies, and performing what-if analyses [18]. Simulation data generated by digital twins can also be used to augment the training of AI models.

Online Learning and Adaptation: During system operation, ICPS can continuously fine-tune—or even restructure—their AI models and control parameters based on feedback regarding execution outcomes and performance metrics. This enables the system to adapt to gradual environmental variations or equipment degradation.

Lifelong Learning and Knowledge Transfer: The system can transfer knowledge learned from one task or environment to new yet related tasks or contexts, significantly accelerating learning and mitigating the problem of catastrophic forgetting [13].

2.2 Major Challenges

Behind the promising vision of ICPS lies a host of formidable challenges faced by researchers and engineers. Overcoming these challenges constitutes the primary direction in which future contributions to this Journal are expected to drive progress.

2.2.1 *The "Curse of Dimensionality" in Model Complexity*

ICPS are quintessential hybrid dynamical systems whose states encompass both continuous physical variables (e.g., velocity, temperature) and discrete logical modes (e.g., device on/off, operational states). Constructing precise and unified hybrid models is exceedingly difficult [19]. Moreover, the scale of the system (number of interconnected nodes) and the complexity of intelligent algorithms (e.g., deep neural network parameters) lead to extremely high-dimensional state spaces. This results in the "curse of dimensionality," which severely hinders system analysis, verification, and control design.

2.2.2 *Harsh Trade-offs Between Real-Time Performance and Reliability*

In safety-critical scenarios—such as autonomous driving and industrial robotics—decision making and control must be completed within milliseconds or even microseconds. This must be achieved under constrained computational resources, communication bandwidth, and energy availability, while still executing sophisticated intelligent algorithms. However, pursuing extreme real-time performance often requires sacrificing algorithmic complexity and accuracy, whereas high-precision algorithms may fail to meet real-time deadlines. Striking the optimal balance between the two poses a perpetual engineering challenge [20]. In addition, both software and hardware systems must exhibit extremely high reliability, with mean time between failures far exceeding that of consumer-grade devices.

2.2.3 *The Intertwined "Pandora's Box" of Safety and Cybersecurity*

The deeply integrated nature of ICPS means that cybersecurity threats can directly escalate into physical safety catastrophes. Attackers may forge sensor data (spoofing attacks), disrupt communication channels (denial-of-service attacks), or inject malicious control commands—potentially causing equipment damage, production shutdowns, or even loss of life [21]. Unlike traditional IT security, ICPS security must simultaneously address informational properties (confidentiality, integrity) and physical properties (safety, reliability)—that is, the fusion of functional safety and information security.

2.2.4 *The Trust Crisis of Intelligent "Black Boxes" and Lack of Explainability*

Although deep neural network–based intelligent models exhibit strong performance, their decision-making processes remain opaque "black boxes." When the system makes an erroneous decision, engineers often lack effective means to trace the root cause and implement corrective measures. In high-stakes domains such as healthcare and aviation, this lack of transparency severely impedes technology deployment and regulatory approval. Therefore, advancing explainable AI—through methods such as attention mechanisms, counterfactual explanations, and Shapley values—is essential for building trust between humans and intelligent systems, and constitutes a crucial step toward the maturity of ICPS [22].

2.2.5 *The "Tower of Babel" Problem in Interdisciplinary Co-Design*

The design of ICPS spans multiple disciplines, each equipped with distinct terminology, methodologies, and toolchains. Mechanical engineers rely on CAD/CAE software, control engineers on MATLAB/Simulink, and computer scientists on Python/TensorFlow. Ensuring effective collaboration among experts with such diverse backgrounds—while avoiding fragmented "siloed" workflows—is essential for project success. This requires the development of unified modeling languages (e.g., SysML), model integration platforms, and interdisciplinary educational frameworks [1].

3 Key Technical Domains and Research Frontiers of the Journal

To systematically address the aforementioned challenges and to steer the development of the field, *ICCK Transactions on Intelligent Cyber-Physical Systems* will focus on research advancements in four major directions, each further divided into multiple specific subdomains.

3.1 AI-Enabled ICPS Design and Optimization

This direction represents the core embodiment of intelligence within ICPS, concentrating on cutting-edge explorations of how AI technologies enhance system cognition, decision-making, and adaptive capabilities.

3.1.1 *Learning-Driven Control and Optimization*

Applications of Deep Reinforcement Learning in Complex Dynamic Environments: Investigating sample-efficient offline reinforcement learning, inverse reinforcement learning, and multi-agent reinforcement learning in scenarios such as robotic control and smart grid scheduling [12, 14].

Meta-Learning and Adaptive Control: Exploring how control systems can rapidly adapt to new dynamic characteristics or task requirements using only a small number of samples [13].

Integration of AI with Model Predictive Control (MPC): Employing neural networks as approximators of system dynamics or for learning MPC cost functions and constraints, enabling the handling of high nonlinearity and uncertainty [16].

3.1.2 *Perceptual Intelligence in ICPS*

Multimodal 3D Environmental Perception: Fusing vision, LiDAR, and millimeter-wave radar to achieve all-weather, high-precision object detection, tracking, and semantic scene segmentation [3].

Event-Camera-Based Vision Processing: Exploring the advantages of event cameras—such as ultra-high temporal resolution and high dynamic range—in fast-changing environments, along with their associated processing algorithms [4].

Anomaly Detection and Predictive Maintenance: Utilizing temporal AI models (e.g., LSTM-Autoencoder, Transformer) to analyze vibration, acoustic, electrical, and other signals for early fault diagnosis and remaining useful life prediction [11].

3.1.3 *Explainable AI and Safety Verification*

XAI Methods and Tools for ICPS: Developing explainability techniques specifically tailored to time-series data, dynamical systems, and control policies [22].

Formal Verification and Robustness Assurance: Investigating formal verification methods for learning-enabled systems to ensure compliance with safety properties under all possible inputs [23].

3.2 ICPS Architecture and Middleware

This research direction focuses on the software and system-level infrastructures that support efficient, reliable, and flexible operation of ICPS.

3.2.1 Edge–Cloud Collaborative Computing Architectures

Dynamic Task Offloading and Resource Management: Investigating how computational tasks can be intelligently distributed among devices, edge nodes, and cloud servers based on network conditions, computational load, and real-time task requirements [6, 24].

3.2.2 Real-Time Intelligent Systems

Deterministic and Time-Sensitive Networking: Studying technologies such as TSN and DetNet for guaranteeing deterministic communication latency within ICPS and analyzing their performance in real deployments [25].

3.2.3 Digital Twins for ICPS

High-Fidelity Multi-Physics Modeling and Simulation: Exploring the construction of accurate equipment models that incorporate mechanical, thermal, electromagnetic, and other multi-physics effects [18].

Hybrid Data–Model-Driven Twins: Investigating methods for online calibration of simulation parameters using real-time sensor data to maintain alignment between the digital twin and its physical counterpart [26].

3.3 Security, Privacy, and Resilience of ICPS

This direction aims to build intrinsically secure, trustworthy, resilient, and recoverable ICPS.

3.3.1 ICPS Security Defense

Intrusion Detection and Security Monitoring: Developing AI-based anomaly detection algorithms for identifying stealthy attacks targeting sensors, actuators, and control networks [27].

3.3.2 Privacy-Preserving Computation

Federated Learning in ICPS: Enabling collaborative training of AI models across multiple factories or devices without sharing sensitive local data [28].

3.3.3 System Resilience

Resilient Control and Self-Healing Systems: Studying algorithms that allow systems to reconfigure control laws and maintain essential functionality—or degrade safely—after component failures or cyberattacks [29].

3.4 Domain-Specific Applications and Validation of ICPS

This direction encourages research that drives deep adoption of ICPS in vertical industries, emphasizing system-level integration and empirical validation with significant engineering value [30].

3.4.1 Industry 4.0 and Smart Manufacturing

Scheduling and Coordination of Autonomous Mobile Robot (AMR) Fleets: Investigating task allocation, path planning, and collision avoidance for large-scale AMR systems in dynamic warehouse environments.

Adaptive Manufacturing and Mass Personalization: Using real-time sensing and AI decision-making to dynamically reconfigure production lines, supporting "batch-size-one" personalized manufacturing.

Enhanced Human–Robot Collaborative Assembly: Studying how vision- and force-based robotic systems can safely and efficiently collaborate with human workers to accomplish complex assembly tasks.

3.4.2 Intelligent Transportation and Autonomous Driving

Vehicle–Road–Cloud Integrated Intelligence: Investigating how vehicular networks and roadside intelligent units can extend the perception range and situational awareness of individual vehicles, enabling global traffic optimization.

Decision-Making and Planning for High-Level Autonomous Driving: Generating safe, comfortable, and socially compliant driving decisions in highly uncertain urban environments. Drone Logistics and Urban Air Mobility: Studying autonomous navigation, fleet formation management, and airspace traffic control for unmanned aerial vehicles.

3.4.3 Smart Energy Systems

Stability and Control of Renewable-Energy-Dominated Grids: Leveraging AI and distributed control to handle the intermittency and uncertainty of solar and wind power.

Optimization of Integrated Energy Systems: Coordinating electricity, heating, cooling, and gas networks for synergistic scheduling and cross-energy-domain complementarity.

Virtual Power Plants and Demand-Response Management: Aggregating large-scale distributed energy resources and flexible loads to participate in grid regulation as a unified entity.

3.4.4 Intelligent Healthcare Devices and Systems

Surgical Robots and Intelligent Operating Rooms: Studying precise control, intraoperative navigation, and AI-assisted decision support for surgical robotic systems.

Telemedicine and Continuous Health Monitoring: Utilizing wearable devices and home sensor networks to enable long-term, unobtrusive monitoring and early warning for chronic disease patients.

Intelligent Prosthetics and Rehabilitation Robots: Developing rehabilitation and assistive devices capable of understanding user intent and providing adaptive physical support.

4 Conclusion: Toward a New Era of Intelligent Systems—A Collective Endeavor

The launch of *ICCK Transactions on Intelligent Cyber-Physical Systems* is a solemn declaration to the global research community: we are committed to establishing a dedicated academic venue—one grounded in deep intellectual inquiry, rigorous validation, and open scholarly exchange—for this vibrant and rapidly expanding field. We fully recognize that the challenges facing ICPS are formidable, and its evolution will be a long-term endeavor, a "Long March" requiring sustained effort over decades. Yet the potential societal benefits—from enhancing industrial productivity to safeguarding human life, from addressing resource and environmental constraints to extending the boundaries of human capability—render every step of this journey profoundly meaningful.

The Journal will steadfastly uphold the principles of quality first, innovation driven, interdisciplinary integration, and service to society. We will assemble a globally representative editorial board composed of distinguished scholars with deep expertise and strong academic responsibility. Through a peer-review process that is rigorous, fair, transparent, and efficient, we will ensure that every article published in the Journal stands the test of time and truly reflects the state-of-the-art in the field.

With openness and sincere anticipation, we extend our most heartfelt invitation to colleagues across computer science, artificial intelligence, electronic engineering, control science, mechanical engineering, biomedical engineering, and all related disciplines. We invite you to submit your most insightful theoretical discoveries, your most ingenious technological innovations, and your most exemplary system-level implementations. In addition to mature and comprehensive research studies, we also welcome forward-looking perspectives, in-depth analyses of grand challenges, as well as high-quality open datasets and benchmark studies.

Let *ICCK Transactions on Intelligent Cyber-Physical Systems* serve as a new starting point—a platform where we join forces, integrate collective wisdom, transcend disciplinary boundaries, and collaboratively confront the scientific challenges of intelligent cyber-physical systems while unlocking their immense potential. We firmly believe that through the collective efforts of the global academic community, we will successfully navigate this sweeping technological revolution and jointly compose a magnificent chapter in humanity's journey toward an intelligent future. Together, we will lay a solid scientific and technological foundation for building a safer, more efficient, more inclusive, and more sustainable world.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Ethical Approval and Consent to Participate

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