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Review

Transition of Architecture of Industrial Cyber-Physical Systems (iCPS) from Hierarchy to Cloud-Edge-Device

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Abstract: Industrial cyber-physical systems (iCPS) are central to smart manufacturing and Industry 4.0. By bringing physical processes together with computation, communication, and control, they make it possible for factories and machines to behave more intelligently and in real time. And as the pressure grows for systems that are more scalable, more capable, and faster, iCPS architectures are increasingly shifting toward distributed cloud–edge–device paradigms. In this paper, we provide a systematic survey of that architectural transition. We begin by introducing what iCPS are, along with their key components and a general conceptual model. Then we review and compare traditional hierarchical architectures, focusing on where they tend to break down—openness, interoperability, latency, and system integration. After that, we analyze and compare emerging cloud–edge–device architectures across multiple dimensions, including architectural structure, scalability, latency, and security. Finally, we discuss the main challenges and open research issues, aiming to align with current industrial needs and to offer useful guidance for designing next generation iCPS architectures.

Keywords: industrial cyber-physical systems (iCPS); control architecture; hierarchy; cloud-edge-device; open challenges

1. Introduction

1.1. Definition of iCPS

Industrial cyber-physical systems (iCPS), a form of cyber-physical system used in industrial, are the backbone of today's smart manufacturing and Industry 4.0. They work by tightly combining computation, communication, control, and physical processes. The architecture of iCPS is moving away from rigid, centralized hierarchical models and toward more flexible, distributed cloud–edge–device architectures. This shift is largely driven by the need for greater scalability, smarter capabilities, and better real-time responsiveness. In this paper, we survey the key drivers and mechanisms behind this architectural transition. We also look at the obstacles and practical concerns when deploying cloud-edge-device-based iCPS. The motivation of this study is to provide insights and guidance for the design and implementation of next generation of industrial cyber-physical systems.

iCPS is defined as a complex system that integrates advanced information technologies such as sensing, computing, communication, and control, as well as automatic control technologies. The elements of the complex system such as people, machines, objects, environment, and information in physical space and cyber space are mapped, interact in a timely manner, and coordinate efficiently [1]. iCPS exists in physical space and cyber space. According to first principles, iCPS is naturally divided into physical system, cyber system, and cyber-physical interaction system. On the one hand, iCPS is a complex system composed of physical system and cyber system. On the other hand, there must be transformation and interaction between the systems of the real physical space and the cyber space, that is, cyber-physical interaction system. Therefore, iCPS can be represented by a three-layer conceptual model [2] of physical system, cyber system, and cyber-physical interaction system, as shown in Figure 1. This conceptual model uniformly describes data sensing, control decision-making, and execution behavior in industrial processes, enabling closed-loop control and optimization from the underlying equipment to the upper-level intelligence, and emphasizing the integrity and cyber-physical interaction of iCPS.

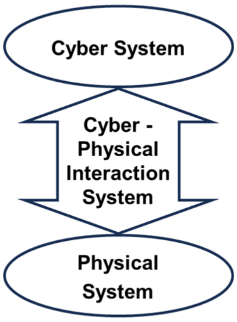

Figure 1. Conceptual model for industrial cyber-physical systems. Reproduced from Ref. [2] with permission of IEEE © 2026.

iCPS includes the following elements:

(1) Physical system: This refers to a system composed of physical components, i.e., physical equipment in the industrial process, including mechanical equipment, sensors, actuators, and local controllers, etc., which constitute the physical infrastructure. Sensors collect data from the production process, and local controllers calculate control signals to activate actuators such as valves and switches to operate the industrial process.

(2) Cyber system: This refers to a system composed of information components, primarily performing data processing and decision-making. For example, a computing platform for data processing and decision-making via a network processes data acquired from the physical system and makes decisions to control or optimize the physical system. This encompasses software, algorithms, and data processing, including cloud computing, artificial intelligence analysis, and digital twins.

(3) Cyber-physical interaction system: This refers to a system composed of cyber-physical components. It's the communication interface layer that links the cyber system to the physical system. For instance, interactive tasks like data conversion, transmission, and reception support two-way real-time communication between the physical and cyber systems. This, in turn, enables reliable data exchange and deeper system interaction. This can be achieved through public networks such as IoT, 5G, or dedicated private industrial networks.

1.2. Evolution of iCPS

The development of general CPS has gone through different stages: embedded systems, intelligent embedded systems, and systems of systems [3]. As the form of CPS in the industrial field, the evolution of iCPS can be divided into three stages: digitalization, networking, and intelligence:

(1) Digitalization stage: The focus is on the conversion between analog and digital quantities, and single-point closed loop control is achieved through embedded systems. Among them, the physical system is the production process mainly composed of physical entities such as mechanical transmission devices and industrial production lines, the cyber system is the control system represented by distributed control systems (DCS) and programmable logic controllers (PLC), and the cyber-physical interaction system is the sensor (physical quantity → electrical signal → digital quantity) and actuator (digital quantity → electrical signal → physical quantity), which constitute bidirectional interaction.

(2) Networking stage: "Data cross-unit and cross-layer connection" is achieved through industrial network protocols, and a horizontal and vertical integrated system is constructed, and the operation technology (OT) and information technology (IT) are initially integrated. Among them, the physical system is expanded into a production system that includes networked equipment such as intelligent instruments and network-enabled devices; the cyber system is the integration of data acquisition and monitoring system, manufacturing execution system, and enterprise resource planning management decision system in the layered architecture; and the cyber-physical interaction system is a real-time data transmission network composed of industrial Ethernet, OPC-UA communication protocol, etc.

(3) In the intelligentisation stage, relying on next-generation data-centric technologies such as artificial intelligence algorithms and digital twins, intelligent optimization of "self-sensing-self-decision-self-execution" is achieved. Taking digital twins as an example, the physical system is the real physical entity,

and the cyber system is a virtual mapping of the physical entity. Its model optimizes and analyzes in real time based on physical parameters, and the cyber-physical interaction system is the communication interaction between physical sampled data and optimized operating parameters. For example, in cloud-edge-device collaboration, edge computing devices (such as smart gateway) in the physical system initially process real-time data, while the cloud computing platform in the cyber system performs big data analysis and model training. The cyber-physical interaction system is the communication network between the two, such as core communication technologies including wireless or wired networks.

Therefore, in the process of "digitalization, networking, and intelligentisation," iCPS simultaneously undergoes the stages of "single-point control → system interconnection → intelligent optimization," from unit-level CPS to complex CPS. It worths to note that humans could be added into CPS to form Human-Cyber-Physical Systems (HCPS), a tri-space integration. For example, a united architecture is employed in [4] to encompass the aspects of cognitive-to-technology integration and human-to-human interaction in HCPS. This article does not take consideration from a human-centric perspective but focusing on technologies involved only.

1.3. Organization of and Contributions Made in the Paper

The aim of this paper is to explore the drivers behind the transition from centralized hierarchical architectures to distributed Cloud–Edge–Device architectures through a systematic and critical overview of architectural patterns for iCPS. The paper is organized as follows. Section 1 gives the definition, components and generic conceptual model of iCPS. The evolution of iCPS is also presented in this section. Section 2 reviews, compares, and analyses traditional hierarchical architectures of iCPS, including CPS5C, ISA-95, RAMI4.0 and IIRA. Section 3 presents Cloud-Edge-Device architecture and its various implementations. Necessities of employing Cloud-Edge-Device architecture and advantages compared to traditional hierarchical architecture are also described. Section 4 extracts challenges and open issues when Cloud-Edge-Device architecture is adopted in real industrial production processes. The paper concludes in Section 5.

The following contributions have been made in this paper:

(1) Traditional hierarchical architectures of iCPS are reviewed and their drawbacks are identified and exploited.
(2) Advancement of Cloud-edge-device architectures of iCPS over traditional hierarchical ones are identified and challenges and open issues in their implementation are pointed out.

2. Traditional Hierarchical Architecture of iCPS

Classic iCPS architectures are typically hierarchical, including key components such as sensors, actuators, embedded controllers, and communication networks. These architectures were widely adopted in early industrial environments, designed to achieve industrial digitization and standardization. Over time, and with the evolution of industrial needs, several mainstream and widely accepted iCPS architectures have emerged. This section introduces some mainstream classic iCPS hierarchical architectures and discusses their characteristics and limitations.

2.1. Industrial Cyber-Physical System 5C Architecture

The iCPS 5C Architecture is one of the earliest CPS architectures to be disseminated in literature. It was proposed by Lee et al. in 2015 and aims to systematically develop and deploy iCPS from data perception to value creation [5]. The 5C architecture is based on real-time data acquisition and processing of industrial equipment and is suitable for CPS deployment in embedded systems and small industrial environments. The 5C architecture defines a five-layer structure to realize the interaction between physical entities and cyber space. The functions of each layer bottom upper are as follows:

- Smart Connection layer: This layer includes sensors, actuators and industrial equipment, and is mainly used to complete data acquisition through sensor networks.
- Data-to-Information Conversion layer: This layer is for intelligent data processing, which processes raw data into structured information and predicts the subsequent behavior of the system.
- Cyber layer: This layer is a central information hub, which centralizes data and information, such as computing infrastructure, cloud servers, etc.
- Cognition layer: This layer enables users to gain a comprehensive understanding of the iCPS, providing accurate information for subsequent decision-making, and conveying information to users through charts when necessary.
- Configuration layer: This layer allows feedback travel from cyber space to physical space and act as a supervisory control, enabling the system to be self-configuring and adaptive.

2.2. ISA-95 Architecture

The ISA-95 architecture is an international standard developed by the International Society of Automation (ISA). It is primarily designed for hierarchical enterprise control and industrial automation, aiming to solve the integration challenges of information technology (IT) and operational technology (OT) in manufacturing, and to promote efficient collaboration between business systems and production control systems. The ISA-95 architecture defines a five-layer hierarchal functional model, bottom upper with the functions of each layer as follows [6,7]:

- Layer 0 Physical Production Process: Actual production equipment and technological flow.
- Layer 1 Sensing and Manipulation: Sensing and manipulating the production process through sensors and actuators.
- Layer 2 Monitoring and Control: Production process monitoring and control. Its functional entities are monitoring and data acquisition systems, distributed control systems, and programmable logic controllers.
- Layer 3 Manufacturing Operations Management: Representing the workflow of product production. Its functional entities are manufacturing execution systems, production information management systems, warehouse management systems, and computerized maintenance management systems.
- Layer 4 Enterprise Business Management: This involves business planning, logistics, production scheduling, operations management, management of business activities, and product development. Functional entities include Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM), Human Resource Management (HRM), Customer Relationship Management (CRM), and Supplier Relationship Management (SRM).

2.3. Industry 4.0 Reference Architecture Model

The Industry 4.0 Reference Architecture Model (RAMI 4.0) [8] is a three-dimensional reference architecture developed by Germany for Industry 4.0. It aims to establish a standardized framework for industrial digitalization. One of its dimensions, referred to as the Factory Dimension, is similar to ISA-95 and consists of six layers: *Asset—Integration—Communication—Information—Functional—Business*.

The two newly introduced dimensions are the Industry Dimension and the Product Lifecycle Dimension. The Industry Dimension focuses on physical entities and describes the overall industrial structure within Industry 4.0. It extends the ISA-95 five-layer architecture (from field devices to the enterprise level) into a seven-layer hierarchical structure: *product—field devices—control devices—station—work center—enterprise—industry ecosystem*.

The third dimension, the Product Lifecycle Dimension, covers the entire lifecycle, including *requirements analysis—prototype design—manufacturing—operation and maintenance services—recycling*. These two additional dimensions embody the core characteristics of Industry 4.0, namely networked entities and full lifecycle management.

2.4. Industrial Internet Reference Architecture

The Industrial Internet Reference Architecture (IIRA), proposed by the Industrial Internet Consortium (IIC), is a global framework that supports the design and implementation of Industrial Internet of Things (IIoT) systems. The IIRA framework organizes IIoT systems into four domains: business, usage, functional, and implementation. Although the IIRA was originally created to describe IIoT systems, we also use it here to capture traditional industrial cyber-physical systems (iCPS). The reason is that iCPS and IIoT are closely related in practice and often overlap, so the same high-level structure still makes sense. As a result, this paper doesn't draw a strict line between iCPS and IIoT, even though they tend to emphasize slightly different things. Particularly, iCPS is mainly concerned with real-time control of physical processes. IIoT, by contrast, focuses more on connecting industrial assets so that value can be extracted from their data—often building on iCPS capabilities.

The four IIRA perspectives are typically described as follows [9]. The business domain identifies the participants in the system and outlines their business views, values, and objectives, with enterprises acting as the main actors. The use domain captures what's expected to achieve the desired business goals. The implementation domain specifies the technologies, communication patterns, and lifecycle processes needed to realize the functional components—down to things like topology, structural organization, and how functions are distributed across technologies. Finally, the function domain concentrates on how functional components interact, both with each other and with the surrounding environment. As with the layered structure in ISA-95, the function domain also includes operation–information–application interactions within the same layer.

2.5. Analysis of Hierarchical Architectures of iCPS

In summary, CPS 5C, ISA-95, RAMI 4.0, and IIRA are all widely used classical iCPS architectures. As shown in Table 1, they mainly rely on function-based hierarchical structures. Together, these frameworks break down enterprise activities into several layers. Typically, the layers run from operational processes up to business management, with the enterprise acting as the core organizational unit. Each layer can also be refined into smaller subsets of work, for example, production activities and industrial control systems.

Table 1. Comparison of Traditional Architectures of Industrial Cyber-Physical Systems.

Dimension	5C Architecture	ISA-95	RAMI 4.0	IIRA
Hierarchy (top-down)	Configuration Cognition Cyber Data-to-information conversion Smart connection	Enterprise business management Manufacturing operations management Monitoring and control Sensing and manipulation Physical production process	Business Function Information Communication Integration Assets	Business Application Information Operation Control
Focus	Data acquisition	Integration of IT and OT	Key CPS functions in industry 4.0	IIoT function
Standardization	Informal and conceptual guide	ANSI international standard Multi-layer interface standard	Industry 4.0 Asset life-cycle management	IIoT standard Function mapping

Traditional hierarchical iCPS architectures focus on how manufacturing and production requirements connect across both production control and business management, along with the associated data acquisition, monitoring, and control functions. This layered approach has helped factories build iCPS implementations that are end-to-end and fully functional, which have been applied successfully across many industries for decades.

The key differences among these widely used architectures mainly come down to their core priorities and the standardization frameworks they rely on. The 5C architecture centers on data acquisition and analytics, ISA-95 targets the integration of IT and OT systems, RAMI 4.0 builds on Industry 4.0 concepts, and IIRA focuses on deploying Industrial Internet of Things (IIoT) capabilities. In terms of standardization, the 5C architecture is not formally standardized, whereas ISA-95 follows ANSI international standard and multi-layer interface standards. RAMI 4.0 aligns with Industry 4.0 reference standards, while IIRA provides a framework for mapping IIoT functional standards.

Traditional iCPS architecture relies on a hierarchical structure with functional layers, each layer having a fixed function or responsibility. While this hierarchical architecture was once highly effective for structured, functionally defined industrial environments, its rigidity and rigid hierarchical structure have led to significant limitations as modern industrial development trends have evolved:

(1) Limited Openness and Interoperability

The initial iCPS was designed for specific industries or proprietary systems. Each vendor's dedicated hardware and software systems were tightly coupled, and the upgrade and development of the architecture depended on the specific vendor's ecosystem. Therefore, the maintenance, upgrades, and lifecycle management of dedicated hardware and software were difficult, and integrating emerging technologies was even more challenging [2]. Moreover, the absence of a standardized and flexible iCPS architecture made data sharing difficult. As a result, teams often had to rely on manual work and develop customized middleware to connect different systems. Therefore, building a standardized and interoperable iCPS requires a fundamental architectural redesign—not just incremental improvements. Such a redesign would support flexibility, scalability, and applicability across a wide range of industrial scenarios, while also ensuring openness and interoperability.

(2) Insufficient Real-Time Processing and Intelligent Decision-making Capability

Traditional hierarchical architecture is typically used in centralized industrial production [5]. Even with multiple layers and different communication protocols, the limited communication distance, number of layers, and amount of data still meet the requirements for real-time communication and closed-loop control. With the emergence of large-scale distributed systems, production and control systems are located locally, while data processing occurs on remote servers or control centers. Multiple layers and extended transmission links can lead to high latency, and poor interoperability between different communication protocols can result in information loss during transmission, hindering real-time communication and closed-loop control performance. Therefore, to support low-latency, high-speed industrial automation, ideal iCPS architectures are required to integrate distributed computing architectures (such as cloud computing and edge computing) as much as possible, adopt faster communication protocols (such as 5G communication and industrial Ethernet), and more efficient decision-making (such as artificial intelligence technology).

(3) Insufficient Functional Integration

Because iCPS is designed with a hierarchical structure [6,7], data transmission and access can only be completed between adjacent layers. Direct access to source data from the top layer is complex. Furthermore, there are numerous incompatible communication protocols within and between layers, requiring customized data gateways for communication between devices from different manufacturers, resulting in complex interface devices. In addition, multi-layer transmission under different protocols may lead to information distortion at the lowest level due to the difficulty in fully aligning information differences. Consequently, the conventional top-down hierarchical organization of iCPS hinders the achievement of efficient and flexible management. Addressing this limitation requires a functional rethinking of iCPS architectures, shifting from complex hierarchical structures toward flat, modular frameworks that facilitate integrated data and management operations.

3. Transition to Cloud-Edge-Device Architectures of iCPS

With globalization, digitalization, and automation accelerating—and as a response to the constraints of traditional hierarchical architectures—iCPS architectures are evolving toward distributed cloud-edge-device frameworks. This shift brings together smart manufacturing, cyber-physical systems, the Industrial Internet of Things (IIoT), and artificial intelligence, embedding them into conventional manufacturing and industrial workflows. Overall, the architectural transition reflects several major trends in today's industrial development, which are summarized below.

(1) Increased Scale and Complexity of Industrial Processes

Early industrial processes were typically deployed on a small scale and geographically located in the same area. In those cases, iCPS was mainly used in embedded systems or in specific industrial environments.

However, modern industry is evolving towards large-scale, distributed systems, requiring the integration of numerous devices, sensors, and production units distributed across multiple locations. Simultaneously, manufacturing has shifted from single-product production lines to multi-product, flexible manufacturing systems, and operating points have evolved from single steady-state operating points to dynamic optimization across the entire process. This necessitates iCPS supporting real-time configuration updates and dynamic process optimization.

Therefore, as industrial processes become larger-scale and more distributed, demanding higher levels of interconnectivity, real-time performance, and flexibility, traditional centralized control and monitoring systems struggle to cope with the increasing complexity. This necessitates a more flexible and scalable iCPS architecture.

(2) Flattened and Integrated Industrial Management

Process operators expect to understand production progress and obtain production information in real time, regardless of time or location. However, traditional architecture typically has more than five layers, with communication passing between layers, resulting in poor real-time performance. Furthermore, during cross-layer transmission, differences in communication protocols and encoding/decoding can lead to distortion of complete process information. If industrial processes evolve towards simpler hierarchies and more direct control, operators can obtain information more directly and comprehensively. This also requires the standardization of industrial communication protocols to reduce hardware/software isolation and communication isolation caused by protocol differences.

Therefore, with the increasing demand for flattened and direct management, the existing rigid hierarchical structure and different communication protocols cannot meet the requirements of real-time performance and direct control. This necessitates a streamlined iCPS architecture with standardized and unified process protocols.

(3) Intelligent and Autonomous Decision-Making

Industrial control has undergone several stages of development, from manual control relying entirely on human intervention, to basic automation with human supervision and machine control, then to intelligent decision-making based on artificial intelligence optimization with reduced human involvement, and finally to autonomous systems that achieve self-optimization and adaptability. To meet the demand of increased intelligence and reduced human involvement, the iCPS architecture integrates platforms and applications based on artificial intelligence technology to enhance overall decision-making capabilities and automation levels.

(4) Diversification of Operation Objectives

Industrial systems are typically measured by product quality and economic efficiency. However, modern industry may need to balance multiple objectives beyond product quality and economic efficiency, such as energy efficiency and sustainability, safety and risk management, and supply chain resilience. These additional operation objectives require the collection of more diverse and extensive data, as well as more advanced data processing and analysis and decision-making capabilities, which the traditional hierarchical iCPS architecture struggles to fully support. External high-level computers suffer from low stability and high maintenance costs. Therefore, new iCPS architecture is required to be scalable and compatible, incorporating economic, environmental, and safety objectives into a unified architecture.

3.1. Cloud-Edge-Device Architecture

With the advancement of industrial intelligence and autonomy, iCPS architectures increasingly require the integration of artificial intelligence technologies, such as deep learning and large language models, along with corresponding upgrades to computing and communication infrastructures. Cloud computing, edge computing, and intelligent devices are also enabling technologies to implement distributed cloud-edge-device architectures for iCPS.

As shown in Figure 2, the cloud-edge-device iCPS architecture consists of three main layers that work together. Each layer corresponds to the iCPS conceptual model presented in Figure 1. This architecture is especially suitable for process industries. It allows the system to run stably and efficiently in complex, fast-changing production environments, while also enabling quick responses to external changes. As a result, it improves the overall intelligence, flexibility, and adaptability of industrial systems.

(1) End Devices Layer: This foundational layer sits on the plant floor. It includes sensors, actuators, cameras, and programmable logic controllers (PLCs). Together, these devices produce raw operational data. They're also built to be ruggedized, so they can handle harsh industrial environments.

(2) Edge Layer: Positioned close to the field devices, edge gateways and servers carry out local data aggregation, filtering, and preprocessing. This layer runs lightweight analytics and AI/ML inference to enable real-time decision-making, including critical actions like emergency shutdowns or immediate quality control adjustments, within milliseconds, without relying on cloud connectivity. By sending only relevant or summarized data to higher layers, the edge layer also helps reduce latency, cut bandwidth usage, and alleviate network congestion. In addition, local processing improves system reliability, allowing industrial operations to continue normally even during network disruptions or cloud connectivity failures.

(3) Cloud Layer: The cloud layer delivers a scalable, flexible, and centralized environment for managing large volumes of data gathered from multiple sites. It also supports advanced analytics and AI/ML model training, using aggregated datasets to build models that enable process optimization and improved forecasting. In addition, the cloud provides centralized governance through continuous monitoring of edge device operational status, application deployment, often via container technologies such as Docker and Kubernetes, and remote software updates. Finally, it serves as a long-term data repository, retaining historical records that support enterprise-wide collaboration, strategic decision-making, and long-range planning.

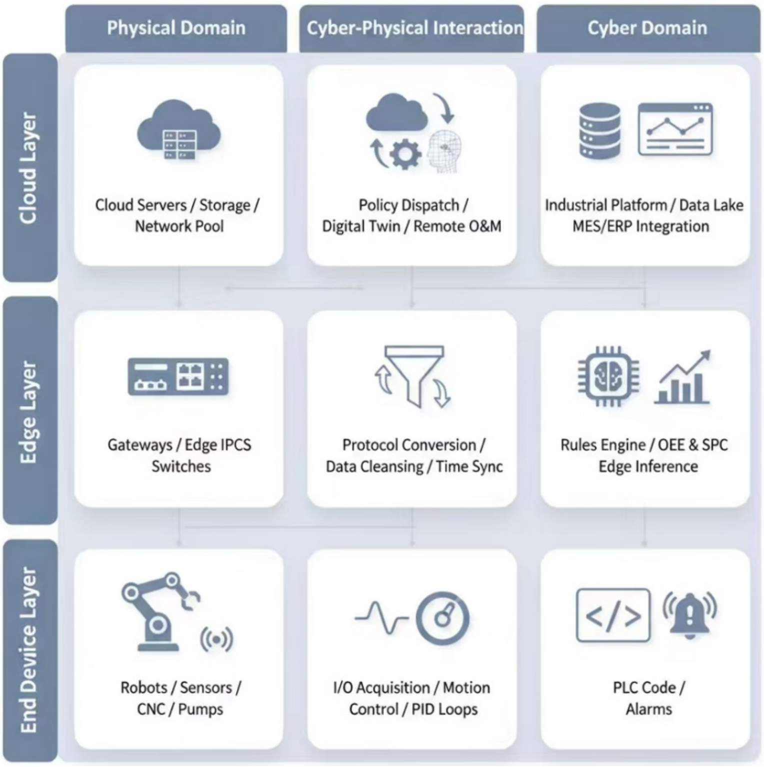

Figure 2. Cloud-Edge-Device architecture for iCPS.

3.2. Related Work in Cloud-Edge-Device Continuums

iCPS depends on low-latency computation, high reliability, scalability, and real-time exchange between physical processes and digital intelligence. These demands strain conventional centralized, hierarchical architectures. As a result, recent work increasingly frames cloud–edge–device continuums as a core architectural basis for next-generation industrial systems.

Early studies examined the shift from centralized infrastructures to distributed computing. Ma et al. [10] investigate cloud-integrated CPS architectures using reliability and performance modeling, showing that shared distributed services can raise system availability while alleviating computational bottlenecks. In a similar direction, Reaño et al. [11] put forward a practical cloud-edge monitoring architecture for industrial settings, arguing that edge-side processing delivers real-time responsiveness, while cloud platforms remain well suited to large-scale analytics and long-term optimization.

Research has also extended to hybrid, heterogeneous computing layers via virtualization and service abstraction. A complementary survey by Andriulo et al. [12] reports that hybrid edge-cloud designs typically outperform purely cloud-based deployments for latency-sensitive CPS applications. Ortiz et al. [13] further addresses workload coordination by proposing a collaborative edge–fog–cloud architecture that adaptively allocates resources based on environmental conditions.

In manufacturing-focused CPS, architectural efforts are increasingly oriented toward Industry 5.0 deployments. Sbaragli et al. [14] propose a cyber-physical architecture that supports human-centric, reconfigurable manufacturing systems aligned with Industry 5.0 principles. Their framework combines sensing, localization, and machine-learning components to help production environments adapt to operator interaction. Digital-twin architectures have also gained momentum. Recent studies show how edge infrastructure paired with private cloud environments can securely keep digital representations of industrial assets synchronized, while enabling predictive monitoring and anomaly detection [15].

A distinct break from traditional automation hierarchies appears in the Cloud–Fog Automation paradigm proposed by Jin et al. [16], which challenges ISA-95-style layered control models. In this paradigm, computation, communication, and control are distributed dynamically across edge and cloud resources, supporting more autonomous industrial decision-making. These ideas align with a broader move toward self-organizing iCPS architectures. Human-centric computing has also driven interest in mist and edge intelligence. Fraga-Lamas et al. [17] show that pushing intelligence down to device-level nodes improves safety and responsiveness in Industry 4.0–5.0 environments. Hu et al.[18] tackle intelligent task scheduling, a foundational problem in cloud-edge-device computing, by determining where, when, and how to execute computational tasks to satisfy application requirements under varying constraints.

Taken together, several contributions synthesize these developments through architectural taxonomies and continuum-based conceptual frameworks. Survey-oriented studies [19–22] classify approaches based on latency requirements, deployment constraints, and autonomy levels, while consistently identifying interoperability, orchestration complexity, and distributed security management as enduring challenges.

Across the reviewed related work, a clear paradigm shift can be observed from rigid hierarchical automation architectures toward flexible computing continuums integrating sensing devices, edge platforms, and cloud services.

3.3. Typical Implementations of Cloud-Edge-Device Architecture

This cloud-edge-device iCPS architecture breaks through the limitations of traditional hierarchical architectures [23], integrating emerging technologies [24] such as the Industrial Internet, edge computing, artificial intelligence, and digital twins, aiming to improve the system's adaptability, flexibility, intelligence, and decision-making capabilities. The following sections summarize five recent implementations of the cloud–edge–device architecture in iCPS. New industrial network architectures, new industrial internet platform reference architectures, and intelligent two-tier structures are well-recognized architectural patterns in Chinese industries, while open process automation architectures and the NAMUR Open Architecture are two typical implementations in the USA and Europe.

3.3.1. New Industrial Network Architecture

In September 2024, the Institute of Technology and Standards of the China Academy of Information and Communications Technology released the "*New Industrial Network Architecture*" [25] and provided an in-depth interpretation of the architecture, as shown in Figure 3. This architecture evolves from the traditional ISA-95 architecture and proposes the concept of "industrial control-network connection-computing power" collaboration, forming a three-layer matrix architecture of "field-edge-center", namely cloud-network-end architecture. The three-layer matrix exactly matches the cloud–edge–device architecture shown in Figure 3. The *New Industrial Network Architecture*, to some extent, represents the current national reference architecture of iCPS in China. Compared with classic hierarchical architecture, this structure is more flattened and enhances the flexibility and scalability of the system.

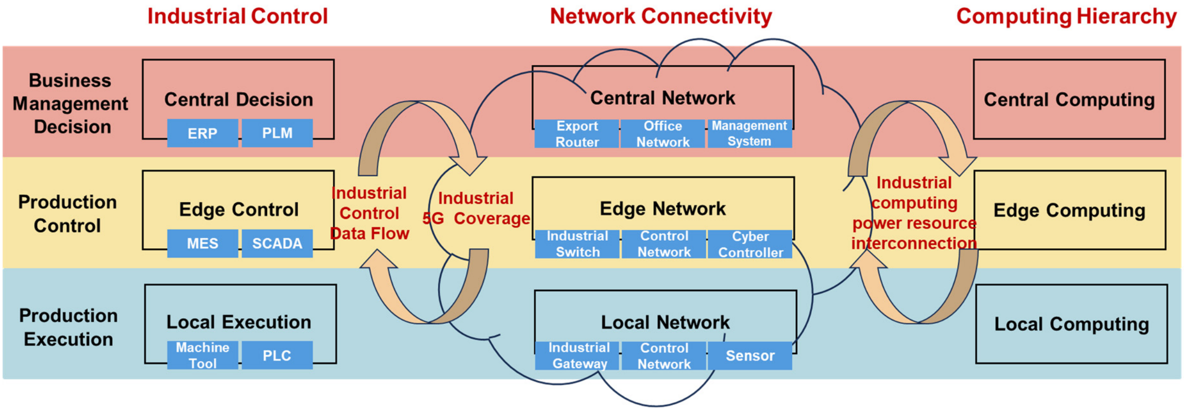

Figure 3. New industrial network system architecture.

3.3.2. Reference Architecture for New Industrial Internet Platforms

As a representative of leading Chinese industries, Huawei Cloud proposed a reference architecture for new industrial internet platforms in its 2024 white paper "Reference Architecture for New Industrial Internet Platforms" [26], as shown in Figure 4. Based on the traditional industrial internet, it integrates the capabilities of large models to enable intelligent empowerment of new industrialization. This architecture is based on a cloud platform and integrates digital resources and capabilities such as networks, platforms, security, industrial intelligence, and applications. Through deep integration with the traditional industrial system architecture, it promotes the all-round upgrade of intelligent manufacturing. The core of the architecture is based on cloud, edge, and terminal device, and serves industrial manufacturing around large models. Through collaborative optimization, it provides five key capabilities, including "industrial cloud-edge collaboration", "industrial intelligent data acquisition", "industrial data fusion", "industrial digital intelligence collaboration", and "industrial application development", to promote the intelligent development of industry. Industrial software positioned above industrial automation systems and industrial equipment represents cloud-based industrial intelligence. This arrangement aligns well with the cloud–edge–device architectural pattern and supports the feasible extension of existing industrial control systems to emerging industrial internet platforms.

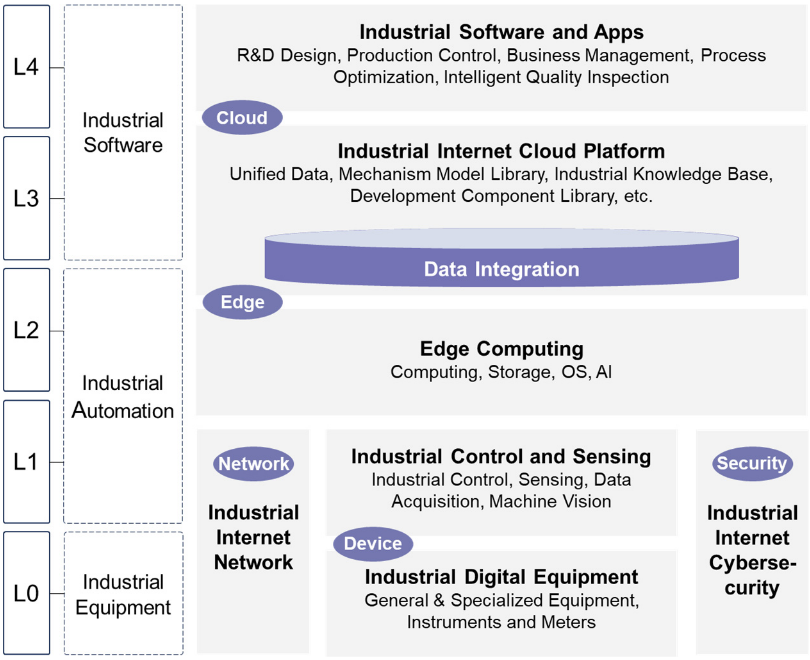

Figure 4. New industrial internet platform reference architecture.

3.3.3. Two-Tier Intelligent Structure for Process Industries

In the ISA-95 hierarchical architecture introduced in Section 2.2, Level 4 (Business Planning and Logistics) corresponds to Enterprise Resource Planning (ERP). Levels 3 (Manufacturing Operations Management) and 2 (Manufacturing Control) can be integrated and collectively regarded as the Manufacturing Execution System (MES), while Level 1 (Production Process Sensing and Manipulation) corresponds to the Process Control System (PCS). Accordingly, the ISA-95 hierarchical architecture can be interpreted as the conventional three-tier structure widely adopted in the process industry, consisting of ERP, MES, and PCS.

This three-tier architecture can be further simplified into a two-tier intelligent structure [27,28] by integrating ERP and MES into an intelligent management and decision-making system based on human–machine collaboration, thereby automating operators' knowledge-intensive tasks. Meanwhile, traditional control systems and processing equipment are transformed into intelligent autonomous control systems. The resulting two-tier intelligent structure is illustrated in Figure 5.

This architecture emphasizes the transformation of human perception and decision-making into an intelligent management and decision-making system, while production control evolves toward intelligent autonomous systems. In this paper, the two-tier structure is regarded as a typical implementation of the cloud–edge–device architecture. The upper layer is centralized and possesses significant decision-making intelligence and computational capability, whereas the lower layer comprises distributed intelligent autonomous systems, each integrating edge computing as a local intelligence center together with production processes governed by the PCS.

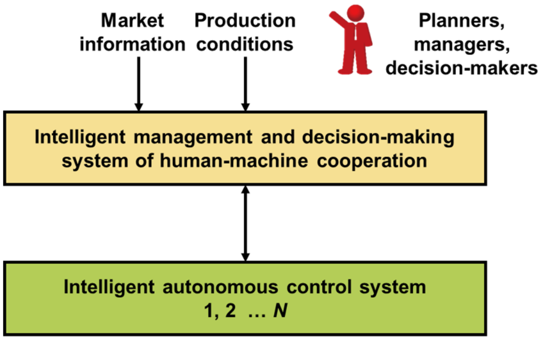

Figure 5. Intelligent Two-Layer Structure for the process industry. Reproduced from Ref. [27] with permission of Acta Automatica Sinica © 2026.

3.3.4. Open Process Automation Reference Architecture

The Open Process Automation (OPA) reference architecture [29] originates from open automation standards promoted by the Open Process Automation Forum in the United States. It aims to enhance the interoperability, modularity, and portability of industrial control systems through open standardization and modular design, as illustrated in Figure 6.

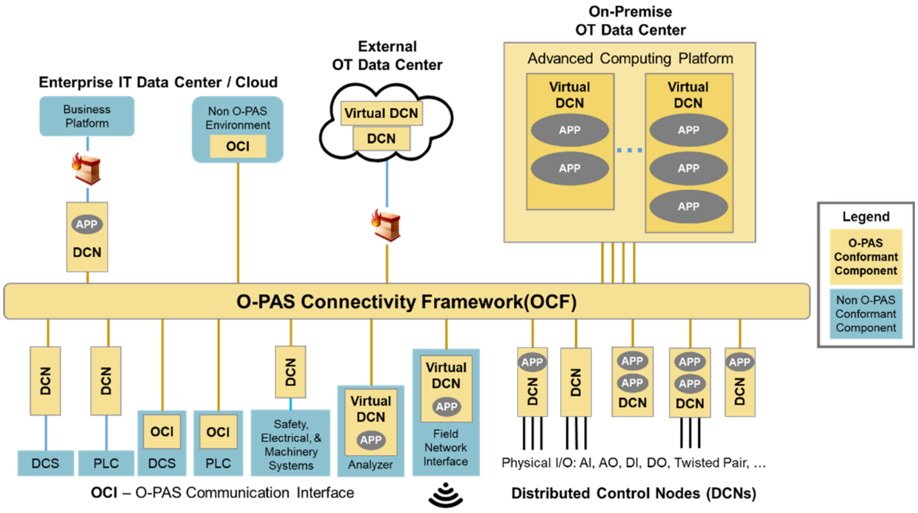

Figure 6. Open process automation reference architecture. Reproduced from Ref. [29] with permission of Elsevier © 2026.

Compared with the distributed control systems defined under ISA-95, the novelty of the OPA architecture lies in the introduction of the Distributed Control Node (DCN), the standards-based control network, namely the Open Process Automation System (O-PAS) and the Open Connectivity Framework (OCF), and the Advanced Computing Platform (ACP). This architecture can also be viewed through a cloud-edge-device paradigm, forming an ACP-OCF-DCN architectural pattern. In this mapping, the ACP represents the cloud-computing layer, the OCF functions as the edge-computing network that supports both vertical and horizontal communications, and the DCN serves as the intelligent device layer.

The OPA architecture mainly standardizes the functions associated with Levels 1 and 2 of ISA-95, including the basic input/output interfaces of field devices and instrumentation, as well as functional blocks for regulation and control. However, it still retains the core characteristics of a hierarchical architecture and, in turn, does not fundamentally address the limitations that come with hierarchical system structures. Moreover, a strong focus on function distribution may add complexity to the overall system and increase integration challenges.

3.3.5. NAMUR Open Architecture

The core objective of the NAMUR Open Architecture (NOA) [30] is to enable data interoperability through open interfaces, especially OPC UA, while preserving the operational stability of existing control systems, as shown in Figure 7. Its basic idea can be summed up as: *"open to the outside, secure to the inside"*.

The principle of *"open to the outside"* is realized by establishing a dedicated data channel that securely transmits equipment data to a remote IT system (denoted as Central M + O in Figure 7) for monitoring, optimization, and advanced analytics applications. This remote IT system can be deployed on a cloud platform. In contrast, *"secure to the inside"* preserves the core automation layer, such as distributed control systems (DCS) and programmable logic controllers (PLC), while connecting them to an upper-level OPC UA Aggregating Server (denoted as Plant-Specific M + O in Figure 7).

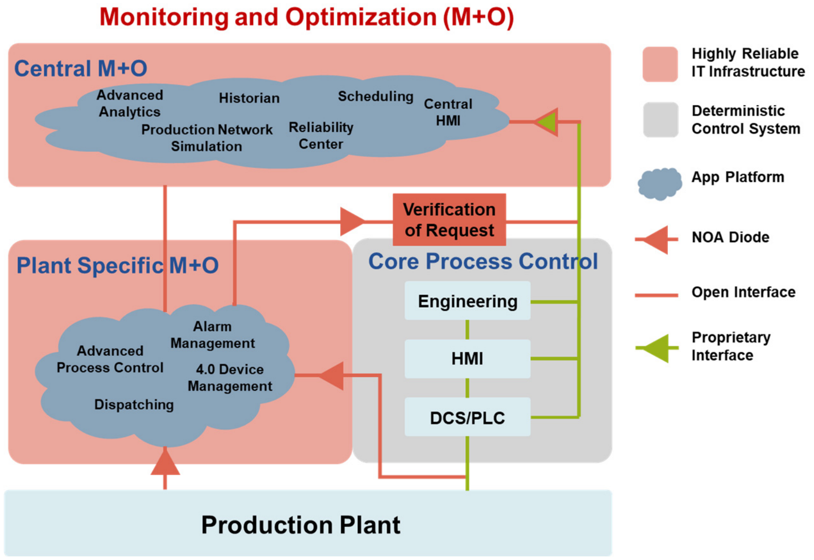

Figure 7. NAMUR open architecture.

The OPC UA Aggregating Server functions as a local edge-computing platform and simultaneously manages NOA devices within the plant area. Consequently, the NOA architecture clearly conforms to the cloud-edge-device architectural pattern.

Specifically, the New Industrial Network Architecture, the New Industrial Internet Platform Reference Architecture, the two-tier Intelligent Structure for Process Industries, and the Open Process Automation Reference Architecture emphasize the application of cloud computing, providing the computing power foundation for intelligent decision-making; the New Industrial Internet Platform Reference Architecture and the Two-Tier Intelligent Structure for Process Industries emphasize the importance of AI technology in industrial analysis and decision-making; the New Industrial Network Architecture and the NAMUR Open Architecture emphasize the importance of real-time and reliable communication; and the New Industrial Network Architecture, the New Industrial Internet Platform Reference Architecture, and the Open Process Automation Architecture emphasize the importance of field data acquisition and standardization. These cloud-edge-device architectures integrate advanced technologies such as distributed computing, artificial intelligence, and advanced communications.

3.4. Advances of Cloud-Edge-Device Architecture

Traditional hierarchical control architectures have been the foundation of industrial automation and control systems for decades. These architectures organize system functions into rigid layers: lower levels handle sensing and actuation, intermediate levels run control logic, and higher levels provide supervision and management. This layered structure does improve determinism and reliability, but it also restricts flexibility, scalability, and adaptability.

The cloud-edge-device architecture marks a shift away from centralized, hierarchical control toward distributed, service-oriented, and data-driven control systems. By spreading intelligence across devices, edge nodes, and cloud platforms, modern systems can execute low-latency control locally while still using cloud resources for large-scale optimization, analytics, and learning. Separating time-critical tasks from computation-heavy workloads improves responsiveness without sacrificing system-wide visibility.

Another major improvement is data utilization. In traditional architectures, limited local storage and computing restrict historical analysis. In contrast, cloud-enabled systems can support long-term data aggregation and advanced analytics, which enables capabilities such as predictive maintenance, adaptive control, and digital twin applications.

From a resilience standpoint, hierarchical systems often depend on centralized components, which can become single points of failure. Cloud–edge–device architectures reduce this risk through decentralized control, redundancy, and automatic failover mechanisms. In addition, using open communication standards and API-based integration lowers vendor dependency and strengthens interoperability.

Finally, the engineering paradigm moves from hardware-centric automation to software-defined control. This enables continuous deployment, remote updates, OTA (Over-The-Aire) updates, and faster iteration, bringing control systems closer to modern DevOps (Development and Operations) practices. As a result, lifecycle costs can drop while system agility improves.

In summary, as shown in Table 2, cloud–edge–device architectures extend traditional control systems by enabling distributed intelligence, scalable analytics, better resilience, and global optimization, making them a strong fit for complex, dynamic, and data-intensive applications.

Table 2. Comparison of hierarchical architecture and Cloud-Edge-Device architecture of iCPS.

Dimension	Hierarchy	Cloud-Edge-Device	Key Advancement
Architectural Structure	Rigid, layered hierarchy with predefined functional levels (sensors, actuators, control, supervision, management)	Loosely coupled, distributed architecture with cloud, edge, and device layers	Transition from rigid vertical integration to flexible distributed coordination
Control Intelligence	Centralized in PLCs/DCS and supervisory controllers	Distributed across devices, edge nodes, and cloud platforms	Enables local autonomy and global intelligence
Latency Handling	Deterministic local control but slow system-wide response	Time-critical control at edge; non-critical optimization in cloud	Hybrid latency model balances real-time and optimization needs
Scalability	Limited scalability; expansion requires redesign of hierarchy	Horizontal and elastic scaling via cloud-native services	Dynamic and cost-efficient system growth
Data Management	Limited data storage and historical analysis	Large-scale data aggregation and long-term storage	Supports big data analytics and learning-based control
Analytics Capability	Rule-based and static control algorithms	AI/ML-based predictive and prescriptive analytics	Shift from reactive to intelligent control
System Resilience	Vulnerable to single points of failure	Distributed fault tolerance and redundancy	Improved robustness and availability
Interoperability	Vendor-specific protocols and tight coupling	Open standards and API-driven integration	Reduced vendor lock-in and enhanced interoperability
Maintenance & Updates	Manual, on-site configuration and updates	Remote updates, OTA deployment, DevOps workflows	Shorter maintenance cycles and reduced downtime
Security Model	Perimeter-based and static access control	Zero-trust, identity-based, continuous monitoring	Adaptive and fine-grained cybersecurity posture
Optimization Scope	Local loop or plant-level optimization	Cross-system optimization	Global performance enhancement
Engineering Paradigm	Hardware- and automation-centric	Software-defined and data-centric	Supports rapid innovation and continuous improvement

4. Challenges and Future Research in the Adoption of Cloud-Edge-Device Architecture

Despite their significant advantages, cloud–edge–device architectures introduce non-trivial challenges that slow adoption in industrial production systems. One of the most critical concerns is real-time determinism. Industrial control often requires strict timing guarantees, yet control functions that rely on networked or cloud-based components face latency variations and packet loss. Therefore, safety-critical and fast control loops must stay at the device or edge level.

Another major challenge is system complexity. Because cloud–edge–device architectures are inherently distributed, they involve more interacting components, more communication interfaces, and more possible failure modes. As a result, designing, integrating, testing, and maintaining these systems demands advanced engineering methods and tooling, often beyond what traditional automation practices can support.

Reliability and availability are also central issues. Industrial environments require near-continuous operation, but cloud services and wide-area networks cannot always match the availability of local control systems. Connectivity disruptions may reduce performance or even lead to production downtime.

From a security perspective, connecting isolated industrial networks to cloud infrastructures expands the attack surface considerably. Achieving end-to-end cybersecurity, covering secure device authentication, encrypted communications, and continuous monitoring, becomes both technically difficult and operationally expensive.

In addition, industries face organizational and economic barriers. Integrating legacy control systems with cloud-native platforms is often costly and technically challenging. At the same time, ongoing cloud subscription fees, data transfer charges, and edge hardware investments can make total cost of ownership harder to predict. Many industrial organizations also lack staff with combined expertise in control engineering, cloud computing, and data science.

Finally, regulatory compliance and certification remain unresolved. Many safety standards and certification processes were developed for deterministic, locally controlled systems and have not yet fully adapted to cloud-assisted architectures. This creates uncertainty in highly regulated areas such as energy, manufacturing, and process automation.

At the same time, cloud–edge–device architectures are converging with emerging technologies—including 6G networks, digital twins, and blockchain, which opens new research directions. For example, 6G is expected to support ultra-reliable low-latency communication (URLLC) and integrated sensing capabilities, potentially reshaping cloud–edge coordination mechanisms. Digital twins provide real-time virtual representations of physical systems, improving predictive maintenance and overall optimization. Blockchain can enable decentralized trust management, but practical deployment still needs improvements in scalability and energy efficiency.

In summary (as shown in Table 3), although cloud–edge–device architectures offer transformative capabilities, deploying them in real industrial settings requires careful architectural partitioning, strong security frameworks, workforce upskilling, and continued evolution of standards and certification processes. Consequently, most industrial deployments today use hybrid architectures, keeping critical control locally while gradually introducing intelligence from edge and cloud layers.

Table 3. Challenges and future research in the adoption of Cloud–Edge–Device architecture in real industrial production processes.

Challenge Category	Description	Industrial Concern
Real-Time Determinism	Cloud-based components introduce variable latency and jitter	Risk of violating hard real-time control constraints
System Complexity	Increased number of distributed components and interactions	Higher design, integration, and validation complexity
Reliability and Availability	Dependence on network connectivity and cloud services	Production disruption due to connectivity or service outages
Cybersecurity Risks	Expanded attack surface across devices, edge, and cloud	Increased vulnerability to cyberattacks
Data Privacy and Ownership	Operational data stored off-site	Compliance, IP protection, and confidentiality concerns
Integration with Legacy Systems	Existing PLC/DCS systems not cloud-native	High migration cost and interoperability issues
Standardization Gaps	Lack of universally accepted industrial cloud standards	Vendor lock-in and fragmented ecosystems
Cost Uncertainty	Ongoing cloud service and data transmission costs	Difficulty in predicting total cost of ownership
Skills and Workforce Readiness	Need for IT, cloud, and AI expertise	Skills gap in traditional automation teams
Validation and Certification	Cloud-based control logic difficult to certify	Challenges in meeting safety and regulatory requirements
Edge Resource Constraints	Limited compute, memory, and power at edge devices	Trade-offs between performance and hardware cost
Data Quality and Management	High data volume, heterogeneity, and noise	Reduced effectiveness of analytics and AI models

5. Conclusions

In conclusion, the transition of iCPS from traditional hierarchical architectures to cloud–edge–device architectures is both inevitable and necessary. While hierarchical iCPS architectures have worked well in earlier, relatively isolated industrial settings, their rigid structure, limited interoperability, insufficient real-time processing capability, and weak overall system integration make it difficult to support today’s industrial requirements.

Modern industrial development is marked by larger and more complex systems, flatter and more integrated management approaches, diversified performance goals, and increasing reliance on intelligent, often autonomous, decision-making. Moving from localized, single-product operations to large-scale, multi-product, globally distributed systems require architectures that can deliver scalability, flexibility, real-time responsiveness, and seamless interoperability.

Recent advances in enabling technologies—such as high-speed communication networks, distributed and edge computing, artificial intelligence, and standardized hardware and cloud platforms, have made distributed intelligence and real-time autonomous control feasible. In this context, cloud–edge–device architectures provide a flexible and resilient foundation for distributing computation, control, and intelligence across complex industrial processes.

Overall, the cloud–edge–device paradigm is not a small upgrade to iCPS architecture, it calls for a fundamental redesign. Its successful adoption will depend on striking the right balance between real-time control at the edge and large-scale data analytics in the cloud. Future research should focus on key challenges such as cybersecurity, edge resource constraints, and system reliability to fully unlock the potential of next generation iCPS.

Author Contributions

Y.W.: data curation, writing—original draft preparation; Y.D.: visualization, writing—original draft preparation, editing, and applying for copyright; S.Y.: conceptualization, methodology, reviewing and supervision. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used ChatGPT to check the grammar. After using this tool, the author reviewed and edited the content as needed and take full responsibility for the content of the published article.

References

1. Plakhotnikov, D.P.; Kotova, E. Design and Analysis of Cyber-Physical Systems. In Proceedings of the 2021 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus), Moscow, Russia, 26–29 January 2021.
2. Wang, Y.; Cao, Y.; Yang, S.H. Unified Industrial Cyber-Physical Systems Modelling and Performance Analysis under Cyber-to-Physical Attacks. In Proceedings of the 2024 IEEE International Conference on Systems, Man, and Cybernetics (SMC), Kuching, Malaysia, 6–10 October 2024.

3. Sendler, U. Beherrschung der Industriellen Komplexität mit SysLM (Systems Lifecycle Management). In *Industrie 4.0*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 1–19.
4. Lou, S.; Hu, Z.; Zhang, Y.; et al. Human-Cyber-Physical System for Industry 5.0: A Review from a Human-Centric Perspective. *IEEE Trans. Autom. Sci. Eng.* **2025**, *22*, 494–511.
5. Lee, J.; Bagheri, B.; Kao, H. A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems. *Manuf. Lett.* **2015**, *3*, 18–23.
6. ISA. *Enterprise-Control System Integration—Part 1: Models and Terminology*; ANSI/ISA-95.00.01-2025; International Society of Automation: Research Triangle Park, NC, USA, 2025.
7. Jiang, J.R. An Improved Cyber-Physical Systems Architecture for Industry 4.0 Smart Factories. *Adv. Mech. Eng.* **2018**, *10*, 1687814018784192.
8. Zezulka, F.; Marcon, P.; Vesely, I.; et al. Industry 4.0—An Introduction in the Phenomenon. *IFAC-PapersOnLine* **2016**, *49*, 8–12.
9. Pivoto, D.G.; De Almeida, L.; da Rosa Righi, R.; et al. Cyber-Physical Systems Architectures for Industrial Internet of Things Applications in Industry 4.0: A Literature Review. *J. Manuf. Syst.* **2021**, *58*, 176–192.
10. Ma, S.; Li, J.; Li, J.P.; et al. Cloud-integrated Cyber–physical Systems: Reliability, Performance and Power Consumption with Shared Servers and Parallelized Services. *Front. Eng. Manage.* **2025**, *12*, 272–290.
11. Reano, C.; Riera, J.V.; Romero, V.; et al. A Cloud–edge Computing Architecture for Monitoring Protective Equipment. *J. Cloud Comput.* **2024**, *13*, 82. https://doi.org/10.1186/s13677-024-00649-1.
12. Andriulo, F.C.; Fiore, M.; Mongiello, M.; et al. Edge Computing and Cloud Computing for Internet of Things: A Review. *Informatics* **2024**, *11*, 71. https://doi.org/10.3390/informatics11040071.
13. Ortiz, G.; Zouai, M.; Kazar, O.; et al. Atmosphere: Context and Situational-aware Collaborative IoT Architecture for Edge–Fog–Cloud Computing. *Comput. Stand. Interfaces* **2022**, *79*, 103550. https://doi.org/10.1016/j.csi.2021.103550.
14. Sbaragli, A.; Ghafoorpoor, P.Y.; Thiede, S.; et al. A Cyber-Physical Architecture to Monitor Human-centric Reconfigurable Manufacturing Systems. *J. Intell. Manuf.* **2026**, *37*, 549–571.
15. Al-Hawawreh, M.; Hossain, M.S. Digital Twin-driven Secured Edge–private Cloud IIoT Framework. *J. Netw. Comput. Appl.* **2024**, *226*, 103888. https://doi.org/10.1016/j.jnca.2024.103888.
16. Jin, J.; Pang, Z.; Kua, J.; et al. Cloud–Fog Automation: The New Paradigm Towards Autonomous Industrial Cyber-Physical Systems. *IEEE J. Sel. Areas Commun.* **2025**, *43*, 2917–2937.
17. Fraga-Lamas, P.; Barros, D.; Lopes, S.I.; et al. Mist and Edge Computing Cyber-Physical Human-centred Systems for Industry 5.0: A Cost-Effective IoT Thermal Imaging Safety System. *Sensors* **2022**, *22*, 8500. https://doi.org/10.3390/s22218500.
18. Hu, B.; Zhao, M.; Cao, Z.; et al. *Intelligent Scheduling of Tasks for Cloud-Edge-Device Computing Systems*; IEEE Press/Wiley: Piscataway, NJ, USA, 2025.
19. Kuchuk, H.; Malokhvii, E. Integration of IoT with Cloud, Fog, and Computing: A Review. *Adv. Inf. Syst.* **2024**, *8*, 65–78. https://doi.org/10.20998/2522-9052.2024.2.08.
20. Surabhi, P.K. Distributed Edge-Cloud Healthcare Architecture: A Technical Overview. *J. Comput. Sci. Technol. Stud.* **2025**, *7*, 701–711. https://doi.org/10.32996/jcsts.2025.7.4.83.
21. Fernando, N.; Shrestha, S.; Loke, S.W.; et al. On Edge-Fog-Cloud Collaboration and Reaping Its Benefits: A Heterogeneous Multi-Tier Edge Computing Architecture. *Future Internet* **2025**, *17*, 22. https://doi.org/10.3390/fi17010022.
22. Carvalho, G.; Cabral, B.; Pereira, V.; et al. Edge Computing: Current Trends, Research Challenges and Future Directions. *Computing* **2021**, *103*, 993–1023. https://doi.org/10.1007/s00607-020-00896-5.
23. White, D. Edge to Cloud: Understanding New Industrial Architectures. Control Engineering. Available online: https://controleng.com/edge-to-cloud-understanding-new-industrial-architectures/ (accessed on 1 January 2026).
24. Tong, Y.; Jia, X.; Qiao, H.; et al. Cloud-Edge-Device Integration Based on Edge Computing. In Proceedings of the 2022 3rd International Conference on Computer Science and Management Technology (ICCSMT), Shanghai, China, 18–20 November 2022.
25. Industrial Internet Industry Alliance. AI Achieves "New Industrial Network Architecture" Officially Released. Available online: https://www.aii-alliance.org/index/c189/n5224.html (accessed on 1 January 2026).
26. Huawei Cloud Computing Technology Co., Ltd. New Industrial Internet Platform Reference Architecture. Available online: https://res-static.hc-cdn.cn/cloudbu-site/china/zh-cn/HuaweiCloudStack/HCS_IIPlat.pdf (accessed on 1 January 2026).
27. Chai, T.-Y. Development Directions of Industrial Artificial Intelligence. *Acta Autom. Sin.* **2020**, *46*, 2005–2012. https://doi.org/10.16383/j.aas.c200796.
28. Yang, T.; Yi, X.; Lu, S.; et al. Intelligent Manufacturing for the Process Industry Driven by Industrial Artificial Intelligence. *Engineering* **2021**, *7*, 1224–1230.
29. Bartusiak, R.D.; Bitar, S.; DeBari, D.; et al. Open Process Automation: A Standards-Based, Open, Secure, Interoperable Process Control Architecture. *Control Eng. Pract.* **2022**, *121*, 105034.
30. Klettner, C.; Tauchnitz, T.; Epple, U.; et al. Namur Open Architecture: Die Namur-Pyramide Wird Geöffnet für Industrie 4.0. *Atp Mag.* **2017**, *59*, 20–37.