Frontiers of Information Technology & Electronic Engineering
www.jzus.zju.edu.cn; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Review:

Industrial Internet for intelligent manufacturing: past, present, and future*

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Received Nov. 25, 2023; Revision accepted Dec. 21, 2023; Crosschecked July 23, 2024

Abstract: Industrial Internet, motivated by the deep integration of new-generation information and communication technology (ICT) and advanced manufacturing technology, will open up the production chain, value chain, and industry chain by establishing complete interconnections between humans, machines, and things. This will also help establish novel manufacturing and service modes, where personalized and customized production for differentiated services is a typical paradigm of future intelligent manufacturing. Thus, there is an urgent requirement to break through the existing chimney-like service mode provided by the hierarchical heterogeneous network architecture and establish a transparent channel for manufacturing and services using a flat network architecture. Starting from the basic concepts of process manufacturing and discrete manufacturing, we first analyze the basic requirements of typical manufacturing tasks. Then, with an overview on the developing process of industrial Internet, we systematically compare the current networking technologies and further analyze the problems of the present industrial Internet. On this basis, we propose to establish a novel "thin waist" that integrates sensing, communication, computing, and control for the future industrial Internet. Furthermore, we perform a deep analysis and engage in a discussion on the key challenges and future research issues regarding the multi-dimensional collaborative sensing of task–resource, the end-to-end deterministic communication of heterogeneous networks, and virtual computing and operation control of industrial Internet.

Key words: Intelligent manufacturing; Industrial Internet; Thin waist; Transparent service; Manufacturing as a service
https://doi.org/10.1631/FITEE.2300806 **CLC number:** TP393

1 Introduction

The manufacturing industry, as one of the main pillars of the national economy, is undergoing a major transformation from quantity and scale expansion to quality and efficiency improvement. During this revolution, one of the most important characteristics lies in the evolution from a plain "manufacturing" mode to a "manufacturing + service" comprehensive mode (Kusiak, 2020). Thus, companies are no longer merely manufacturing products; rather, they are undertaking customized production and providing differentiated services. However, there are big gaps in the temporal scale, spatial scale, and value evaluation between manufacturing and services,

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* Project supported by the National Natural Science Foundation of China (Nos. 92267108, 62173322, 62133014, and 61972389) and the Science and Technology Program of Liaoning Province, China (Nos. 2023JH3/10200004, 2022JH25/10100005, and 2023JH3/10200006)

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which impact on and restrict each other. Thus, we should perform full life-cycle product management, which helps open up the value and industry chains. In this way, we can iteratively upgrade the manufacturing industry by service improvements, and in turn, open up the production chain. In summary, the top priority now is to fully open up the production, value, and industry chains and establish transparent channels for manufacturing and services to realize manufacturing as a service (MaaS) (Dutra et al., 2013).

To achieve this goal, industrial Internet (General Electric, 2013; Li et al., 2017; Qin W et al., 2020), as the integration of new-generation information and communication technology (ICT) and industrial operational technology (OT), is regarded as a promising way to completely reshape the entire manufacturing and service modes. Through the comprehensive interconnection of humans, machines, and things, industrial Internet can enable the efficient interaction of all the important elements in the production, value, and industry chains. Obviously, industrial Internet is the core key technology in realizing intelligent manufacturing and is regarded as an important information fundamental cornerstone of the Fourth Industrial Revolution. Hence, developing industrial Internet to establish a transparent channel between manufacturing and services is an inevitable choice, which will help power the manufacturing industry.

From the proposal of industrial Internet, comprehensive research has been performed from the perspective of sensing, communication, computing, or control, separately. Correspondingly, some surveys summarized existing works, where industrial Internet of Things (IIoT) was the most hot topic. For example, Farooq et al. (2023) provided a survey on the role of IIoT in manufacturing for implementation of smart industry. Chi et al. (2023) discussed network automation for IIoT toward Industry 5.0, where fifth-generation mobile communication network (5G) and artificial intelligence (AI) were regarded as the most important technologies. Xu HS et al. (2023) discussed the applications, technologies, and tools of digital twin for IIoT, where AI, blockchain, cloud computing, big data, and edge computing are the most important technologies. However, most existing surveys focus on IIoT, while only a few works specifically survey industrial Internet. Li et al. (2017) surveyed industrial Internet by discussing the architecture, enabling technologies, applications, and existing challenges. Qin W et al. (2020) summarized the reference architectures, key technologies, relative applications, and future challenges of industrial Internet. Jiang et al. (2024) outlined the development and current status of industrial Internet in China and globally.

Different from existing works, in this paper we fully consider the basic networking requirements of intelligent manufacturing and aim to establish a novel architecture integrating sensing, communication, computing, and control. Note that the sensing, communication, computing, and control are jointly considered to enhance the networking capability of industrial Internet, while the single sensing, computing, or control algorithms for specific manufacturing tasks are out of the scope of this paper. Through the multi-disciplinary discussion of communication, computer, and control, we aim to provide a new reference for future industrial Internet. The main contributions of this paper are summarized as follows:

First, we analyze the basic characteristics and requirements of typical intelligent manufacturing scenarios, i.e., process manufacturing and discrete manufacturing, and highlight the importance and urgency of using industrial Internet to achieve MaaS.

Second, we provide an overview on the integrating process of ICT and OT, and systematically analyze and compare the networking capabilities and problems of the current industrial Internet.

Third, we establish a novel industrial Internet's "thin waist" (IITW), which integrates sensing, communication, computing, and control, to establish a transparent channel between manufacturing and services.

Last but not the least, we introduce the key technologies and the challenges in establishing IITW and discuss future research directions.

The remainder of this paper is organized as follows: Section 2 first discusses the basic requirements of intelligent manufacturing. Then, Section 3 introduces the current networking capabilities of industrial Internet. After that, Section 4 analyzes the problems of current industrial Internet while Section 5 proposes the "thin waist" of future industrial Internet. Furthermore, Section 6 summarizes the key technologies and discusses the future research directions. Finally, Section 7 concludes the paper.

2 Basic requirements of intelligent manufacturing

Existing advanced manufacturing systems, both process manufacturing and discrete manufacturing, employ the network-based system to manage and control production (Wang TR et al., 2012). However, the manufacturing requirements for differentiated services are numerous, wide-ranging, and precise. Thus, we first introduce the basic processes of process manufacturing and discrete manufacturing, and then conduct an in-depth analysis on their networking capability requirements in this section.

2.1 Process manufacturing

Process manufacturing is related to the elementary raw material industries such as petroleum, chemicals, metallurgy, and electricity (Qian, 2023). As depicted in Fig. 1a, process manufacturing uses resources such as renewable resources as raw materials, performs continuous complex physiochemical reactions with the multi-state existence of gas, liquid, and solids, and provides raw materials and energy for downstream discrete manufacturing industries. Obviously, the dynamic change or small fluctuation in any step of the manufacturing process will influence the whole manufacturing process and the final products. As a consequence, it is crucial to transform the process industry from partial and extensive manufacturing to full-process, refined manufacturing. To achieve this goal, we must perform ubiquitous sensing and precision control for the entire manufacturing process.

For ubiquitous sensing, there are numerous different types of sensors deployed in the industrial field. On one hand, the sensors must exhibit low power consumption and high precision in sensing and measurement. On the other hand, the sensors must form a large-scale cooperative network and transmit data reliably in real time. The typical networking capability indicators of the process manufacturing system are that the end-to-end transmission latency and reliability should be second-level and above 99%, respectively. Moreover, the network scalability should be up to 1000 nodes, and the effective working time should be at least five years or above (Wollschlaeger et al., 2017; Huang et al., 2018; Yu et al., 2022). Obviously, there are strict networking capability requirements for sensing and communication in process manufacturing.

For precision control, based on the process data obtained by real-time sensing from the manufacturing process, we should perform comprehensive data exploration, execute knowledge representation and reasoning, establish a precise model of the entire manufacturing process, and clarify the mechanism of material transformation. Then, we can establish a precise control model and conduct precision control and real-time optimization during the manufacturing process. In particular, with the rapid development of big data and AI technologies, data-driven process optimization and control is becoming increasingly important and is the key to realizing the intelligent transformation of process manufacturing (Qian et al., 2017; Yang et al., 2021). Thus, there exist exceedingly high requirements of process manufacturing on computing and control capabilities.

2.2 Discrete manufacturing

Discrete manufacturing is related to industries such as aviation, aerospace, shipping, automobiles, and home appliances. As depicted in Fig. 1b, discrete manufacturing performs a series of physical processes such as non-continuous processing and assembly on multiple parts, and realizes the manufacturing of equipment and products such as rockets, airplanes, ammunition, machinery tools, and electronics equipment. Discrete manufacturing is different from process manufacturing in that it does not change the production materials; nonetheless,

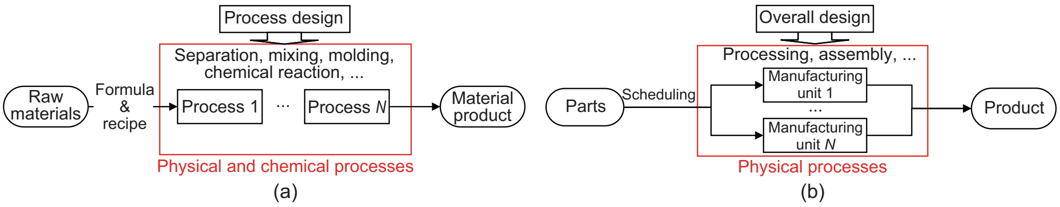

Fig. 1 Basic manufacturing processes: (a) process manufacturing; (b) discrete manufacturing

it changes mainly the shape and combination of the materials. With industrial digitalization, networking, and intelligence, discrete manufacturing is evolving from the traditional single-product, large-scale, and rigid production mode to a multi-product, small-scale, and flexible production mode. Thus, the discrete manufacturing system requires modularized organization that can be customized according to users' requirements and supports real-time dynamic reconfiguration. This is specifically true for advanced equipment manufacturing, which requires precise sensing and robust control for high-precision processing and assembly.

For modularized organization and dynamic reconfiguration, the discrete manufacturing system should be fully modularized from the physical manufacturing system to the information space model. In this way, the production chain can be reconfigured in real time based on the dynamic changes in tasks. Correspondingly, the supply chain can be optimized. The physical manufacturing system, which is primarily based on modular equipment, should support the dynamic interaction and interconnection with external equipment or systems, such as robots and machinery tools. Meanwhile, it should guarantee that the systems' dynamic reconfiguration for product design, processing, and manufacturing is set according to demand, timing, and sequence. Thus, there are strong communication requirements for high reliability and low latency. Moreover, the information space should include the mapping model of the physical equipment, encapsulate the various protocol modules, and support modules' inter-operability. Thus, real-time, efficient modeling and calculations are necessary.

For precision sensing and collaborative control, it is obvious that numerous sensors are required for precise modeling and measurement of the manufacturing process. This will support the precise docking and collaborative control of heterogeneous modular equipment, and realize high-precision network control. To achieve this, we should construct a high-reliability and low-latency network to support the high-concurrency computing of extensive sensing data and the low-jitter and deterministic transmission of control commands. The fundamental networking capabilities of discrete manufacturing systems include a networking scale of 100 nodes, hundreds of microseconds of end-to-end transmission, and 99.99% reliability (Wollschlaeger et al., 2017; Huang et al., 2018; Yu et al., 2022). For high-precision control such as motion control, the latency should be enhanced to the millisecond level, while the reliability should be above 99.9999%. Therefore, the requirements of discrete manufacturing on communication and control capabilities are considerably higher than those of process manufacturing.

2.3 Summary of capability requirements

Obviously, different manufacturing industries have different requirements for sensing, communication, computing, and control. Even for the same type of manufacturing industry, the specific requirements are also substantially different. More importantly, the communication of the manufacturing system is tightly coupled with sensing, computing, and control, which impacts the overall performance of the manufacturing system.

Table 1 summarizes the key networking capability requirements of typical manufacturing tasks (3GPP, 2017, 2018; Kim et al., 2019; Yu et al., 2022). The networking capability requirement of the monitoring task is the lowest, whereas that of the tactile interaction task is the highest. Generally, the latency, jitter, reliability, and rate requirements of process manufacturing (e.g., process monitoring) are considerably lower than those of discrete manufacturing (e.g., controller to controller). However, the network scale and density requirements of process manufacturing are substantially higher than those of discrete manufacturing. Moreover, process manufacturing usually requires the network to operate with low energy consumption and support long-term monitoring. Thus, for the manufacturing process and service requirements of different industry subcategories, we should establish a transparent channel between manufacturing and services by considering the sensing, communication, computing, and control capabilities. This will promote the integration of manufacturing and services, and finally achieve MaaS.

3 Development of industrial Internet

As shown in Fig. 2, the evolution of the Internet can be classified into three stages to date: desktop Internet, mobile Internet, and industrial Internet. During this process, ICT and OT continuously

Table 1 Networking capability requirements of typical manufacturing tasks

Applications	Control features			Communication requirements			
	Packet length (byte)	Cycle time (ms)	Scale	Reliability (%)	E2E latency (ms)	Jitter (ms)	Rate (Mb/s)
Tactile interaction	≤ 20	≤ 1	≤ 10	≥ 99.9999	≤ 0.5	0.001	≤ 10
Individual motion control	≤ 50	≤ 1	≤ 10	≥ 99.9999	≤ 1	0.001	≤ 20
Cooperative motion control	≤ 250	≥ 1	≤ 100	≥ 99.999	≥ 1	0.1	≤ 20
Controller to controller	≤ 100	≤ 10	≤ 10	≥ 99.999	≤ 10	0.1	≤ 20
Visual remote control	$\geq 15\,000$	≥ 10	≤ 100	≥ 99.999	≥ 10	0.1	≥ 100
Automatic guidance	$\geq 15\,000$	≤ 500	≤ 100	≥ 99.99	≥ 10	10	≥ 10
Closed-loop process control	≤ 20	≥ 10	≥ 10	≥ 99.9	≤ 50	20	≤ 1
Process monitoring	≤ 20	≥ 100	≥ 10	≥ 99	≤ 100	20	≤ 1

E2E: end-to-end. The first six applications belong to discrete manufacturing and the last two applications belong to process manufacturing

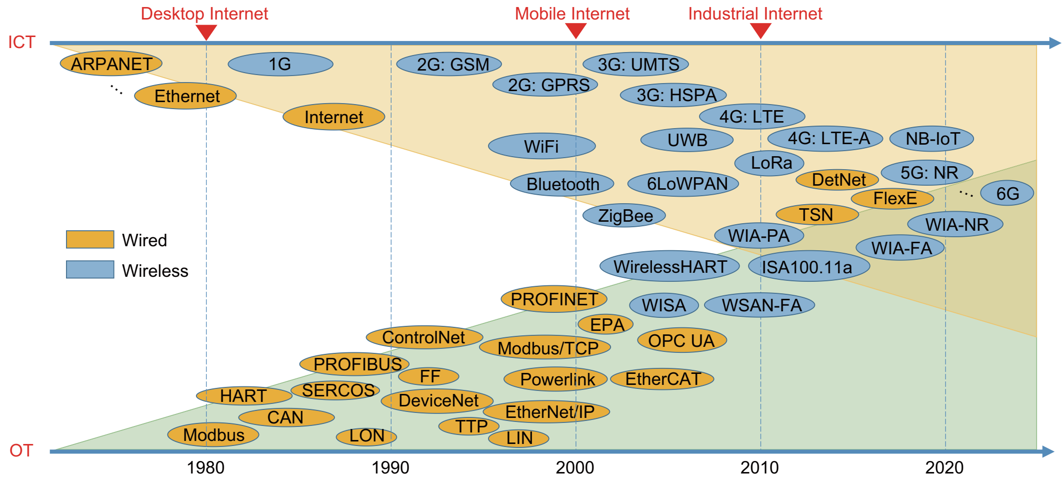

Fig. 2 Information and communication technology (ICT) and operational technology (OT) integrating process of industrial Internet

ARPANET: Advanced Research Projects Agency network; GSM: global system for mobile communication; GPRS: general packet radio service; UMTS: universal mobile telecommunications system; HSPA: high-speed packet access; LoRa: long range radio; LTE: long-term evolution; LTE-A: long-term evolution-advance; NB-IoT: narrow band Internet of Things; NR: new radio; WiFi: wireless fidelity; UWB: ultra-wide band; 6LoWPAN: IPv6 over low power wireless personal area network; DetNet: deterministic networking; TSN: time-sensitive networking; FlexE: flex Ethernet; HART: highway addressable remote transducer; CAN: controller area network; SERCOS: serial real-time communication specification; PROFIBUS: process field bus; LON: local operating network; FF: foundation fieldbus; TTP: time-triggered protocol; PROFINET: process field network; LIN: local interconnect network; EPA: Ethernet for plant automation; EtherCAT: Ethernet for control automation technology; OPC UA: open platform communications unified architecture; WISA: wireless interface for sensors and actuators; WSAN-FA: wireless sensor actuator network for factory automation; WIA-PA: wireless networks for industrial automation–process automation; WIA-FA: wireless networks for industrial automation–factory automation; WIA-NR: wireless networks for industrial automation–new radio; TCP: transmission control protocol

collide and integrate to satisfy the escalating service requirements of both process manufacturing and discrete manufacturing, during which numerous networking technologies have been developed for industrial Internet. The major characteristics are mainly reflected in the comprehensive evolution of the network from local-area to wide-area, from fixed to mobile, from wired to wireless, and from human-oriented to human–machine–thing-oriented.

In the ICT field, from Ethernet to Internet and further to the cellular mobile communication network, the network throughput has been improving continuously, which enhances the Internet surfing experience for people. In particular, the rapid development of mobile communication technology by almost every decade has promoted the revolution from desktop Internet to mobile Internet. The development of 5G (Andrews et al., 2014; Hampel et al., 2019) has already completely disrupted the traditional technology path of simply providing broadband communication. Instead, it has adopted scenario-driven technology paths to customize three major application scenarios: enhanced mobile broadband (eMBB), massive machine type communication (mMTC), and ultra-reliable low latency communication (URLLC) (Wollschlaeger et al., 2017; Yousuf et al., 2018; Lei et al., 2021; Ansari et al., 2022). In particular, the millisecond-level latency and 99.999% reliability of end-to-end communication promised by URLLC will be able to fulfill most industrial control applications and provide a suitable foundation for the application of mobile communication in industrial manufacturing. Currently, the commercial deployment of 5G is ongoing for large scale. However, in actual applications, eMBB remains the main application for human-oriented communication, whereas mMTC and URLLC for machine-oriented communication remain under trial and optimization. A major reason is the existence of exceedingly numerous subcategories in industrial manufacturing and substantial differences in communication requirements. In contrast, mobile communication has not penetrated the industrial field as deeply as fieldbus or industrial Ethernet, which is customized according to the industrial demand for dedicated communication. Moreover, there is a lack of knowledge accumulation, and the adaptability for industries must be improved. Thus, both academics and industries have confirmed the need to further develop URLLC and increase its performance including latency and reliability by another order in the sixth-generation (6G) era to better meet and adapt to the massive industrial applications (University of Oulu, 2019; 3GPP, 2020; Dang et al., 2020).

Meanwhile, Institute of Electrical and Electronics Engineers (IEEE) and Internet Engineering Task Force (IETF) have successively formulated standards such as time-sensitive networking (TSN) (Danielis et al., 2014; Pop et al., 2018; Nasrallah et al., 2019; Seol et al., 2021) and deterministic networking (DetNet) (Nasrallah et al., 2019), and attempted to break through the traditional best-effort transmission of Internet from different protocol layers for deterministic communication. This feature is more focused on the field of industrial manufacturing and can fulfill the basic communication requirements of the manufacturing industry, becoming a typical example of deep integration of ICT and OT.

In the OT field, different manufacturing systems have employed different industrial control networks (ICNs). The development of ICNs has undergone four stages, from the analog communication system, distributed control system (DCS), and fieldbus control system (FCS) to industrial wireless networks (IWNs), realizing the transformation from analog to digitalization and networking (Yu et al., 2023). Among these, the timeliness and reliability of ICNs have improved substantially with the continuous boost from ICT technology, from 4–20 mA analog communication to fieldbus and industrial Ethernet, e.g., Modbus, CAN (controller area network), EPA (Ethernet for plant automation), PROFIBUS (process field bus), PROFINET (process field network), Powerlink, and EtherCAT (Ethernet for control automation technology) (Danielis et al., 2014), and further to IWNs, e.g., WirelessHART, ISA100.11a, WIA-PA (wireless networks for industrial automation–process automation), WIA-FA (wireless networks for industrial automation–factory automation), WISA (wireless interface for sensors and actuators), and WSAN-FA (wireless sensor actuator network for factory automation) (Liang W et al., 2011; Vitturi et al., 2013; Holfeld et al., 2016; Verhappen, 2016; Wang Q and Jiang, 2016; Pang et al., 2017; Wollschlaeger et al., 2017; Zheng et al., 2017; Huang et al., 2018; Xu C et al., 2021; Yu et al., 2022). The continuous fusion of ICT and OT drives the cooperative development of both wired and wireless control, supporting from process monitoring to motion control.

Table 2 compares typical networking technologies of industrial Internet and their service capabilities (Liang W et al., 2011; Vitturi et al., 2013; Danielis et al., 2014; Holfeld et al., 2016; Verhappen, 2016; Wang Q and Jiang, 2016; Pang et al., 2017; Wollschlaeger et al., 2017; Zheng et al., 2017; Huang et al., 2018; Pop et al., 2018; Nasrallah et al., 2019; Seol et al., 2021; Xu C et al., 2021, 2023a; Yu et al., 2022). Evidently, they can provide different communication services for different manufacturing tasks, and fulfill different communication requirements inside or outside factories.

Table 2 Capability comparison of typical networks of industrial Internet

Medium	Typical technology	Rate	Latency	Reliability	Scale	Typical applications
Wired	TSN	≥ 100 Mb/s	≥ 10 µs	–	–	In-car communication, controller to controller, motion control
	EtherCAT	≤ 100 Mb/s	≥ 1 ms	–	$\leq 65\,535$	Motion control
	Modbus	≥ 10 Mb/s	≤ 100 ms	–	≤ 256	Process measurement and control
	PROFIBUS	≥ 1 Mb/s	≤ 10 ms	–	≥ 100	Process measurement and control
	PROFINET	≤ 100 Mb/s	≤ 100 ms	–	≥ 100	Process measurement and control, controller to controller, motion control
	CAN	≤ 1 Mb/s	≤ 1 ms	–	≥ 100	In-car communication
	FF	31.25 kb/s	≥ 50 ms	–	≥ 100	Process measurement and control
	EPA	≥ 10 Mb/s	≤ 10 ms	–	≥ 100	Process measurement and control
	Sercos III	≥ 10 Mb/s	≤ 10 ms	–	≤ 256	Motion control
	Powerlink	≤ 100 Mb/s	≤ 10 ms	–	≤ 256	Motion control
	EtherNet/IP	≤ 100 Mb/s	≤ 10 ms	–	–	Process measurement and control
Wireless	WirelessHART	≤ 250 kb/s	≥ 10 ms	$\geq 99\%$	≥ 100	Process measurement and control
	ISA100.11a	≤ 250 kb/s	≥ 10 ms	$\geq 99\%$	≥ 100	Process measurement and control
	WIA-PA	≤ 250 kb/s	≥ 10 ms	$\geq 99.3\%$	≤ 1000	Process measurement and control
	WIA-FA	≤ 54 Mb/s	≤ 10 ms	$\geq 99.99\%$	≥ 100	Video transmission, AGV scheduling
	WIA-NR	≥ 10 Mb/s	≤ 1 ms	$\geq 99.999\%$	–	Process control, controller to controller
	WISA	≤ 3 Mb/s	≤ 10 ms	$\geq 99\%$	≤ 10	Process measurement and control
	WSAN-FA	≤ 3 Mb/s	≤ 10 ms	$\geq 99\%$	≤ 10	Process measurement and control
	Industrial WiFi	≤ 54 Mb/s	≥ 10 ms	$\geq 99\%$	≤ 100	Video transmission, AGV scheduling
	Bluetooth	≤ 1 Mb/s	≥ 10 ms	$\geq 99\%$	≤ 100	Smart home, wearables
	ZigBee	≤ 250 kb/s	≤ 100 ms	$\geq 90\%$	≤ 256	Smart home, wearables
	LoRa	37.5 kb/s	≥ 1 s	$\geq 90\%$	≥ 100	Smart meter, agricultural monitoring
	NB-IoT	≤ 250 kb/s	≤ 10 s	$\geq 90\%$	$\geq 100\,000$	Smart meter, agricultural monitoring
	5G eMBB	≥ 100 Mb/s	≥ 10 ms	–	≥ 1000	HD video transmission, virtual reality, augmented reality
	5G mMTC	–	≤ 10 s	–	$\geq 100\,000$	Smart meter, agricultural monitoring
	5G URLLC	–	≥ 1 ms	$\leq 99.999\%$	–	Controller to controller

− indicates that there is no clear data support. TSN: time-sensitive networking; EtherCAT: Ethernet for control automation technology; PROFIBUS: process field bus; PROFINET: process field network; CAN: controller area network; FF: foundation fieldbus; EPA: Ethernet for plant automation; HART: highway addressable remote transducer; WIA-PA: wireless networks for industrial automation–process automation; WIA-FA: wireless networks for industrial automation–factory automation; WIA-NR: wireless networks for industrial automation–new radio; WISA: wireless interface for sensors and actuators; WSAN-FA: wireless sensor actuator network for factory automation; WiFi: wireless fidelity; LoRa: long range radio; NB-IoT: narrow band Internet of Things; eMBB: enhanced mobile broadband; mMTC: massive machine type communication; URLLC: ultra-reliable low-latency communication; AGV: automated guided vehicle; HD: high definition

4 Problem analysis of the present industrial Internet

As shown in Fig. 3a, through decades of development, the networks inside the factory have gradually formulated a hierarchical heterogeneous "pyramid" architecture. From the bottom to the top, it can be divided into field level (L0), control level (L1), supervisory level (L2), management level (L3), and enterprise level (L4) (IEC, 2013). L0 and L1 adopt fieldbus, industrial Ethernet, and IWNs. The L0 and L1 networks are also known as the factory OT network, which serves mainly the control requirements in the industrial field and requires deterministic communication with millisecond-level or second-level cycles. L2, L3, and L4 all adopt the standard Ethernet. The L2, L3, and L4 networks are collectively known as the factory information technology (IT) network, which serves mainly the transmission of information for factory and enterprise management, with minute-level, hour-level, day-level, or even month-level cycles.

In contrast, the networks outside the factory use the common Internet to complete the factory-level and enterprise-level wide-area interconnection. Obviously, the networks outside the factory are typical IT networks, which provide best-effort transmission services. However, this is insufficient to meet the critical requirements of new manufacturing tasks such as cloud-based robotic control and cross-domain collaborative manufacturing.

Currently, there are numerous network protocols that can be used in manufacturing industries.

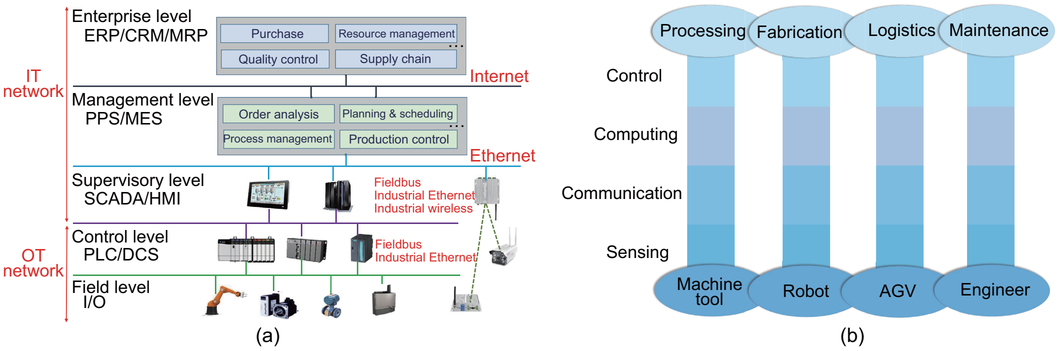

Fig. 3 Network architecture and service mode of present industrial Internet: (a) hierarchical heterogeneous network architecture; (b) chimney-like service mode (IT: information technology; OT: operational technology; ERP: enterprise resource planning; CRM: customer relationship management; MRP: material requirement planning; PPS: production planning and scheduling; MES: manufacturing execution system; SCADA: supervisory control and data acquisition; HMI: human and machine interface; PLC: programmable logic control; DCS: distributed control system; I/O: input/output; AGV: automated guided vehicle)

Specifically, the International Electrotechnical Commission (IEC) alone has defined as many as 20 industrial fieldbus protocol standards (IEC, 2014a). In contrast, there are only four IWN protocol standards, of which WirelessHART (IEC, 2010), ISA100.11a (IEC, 2014b), and WIA-PA (IEC, 2011) are the three major international standards for process manufacturing, while WIA-FA (IEC, 2017) is the only international standard for discrete manufacturing.

However, the flourishing of ICN protocols has also created chaos for communications in the industrial field, where numerous information islets are formulated. This is mainly because different organizations or companies have developed different ICN protocols for specific applications, where each protocol is relatively independent and does not understand with each other (Scanzio et al., 2021). Thus, the interconnection, intercommunication, and interoperation are extremely difficult (Hazra et al., 2023). Moreover, from the perspectives of intellectual property protection, security, and privacy, the ICN protocols developed by different industrial automation companies are less open and even bound with hardware. In this way, it is challenging to achieve "plug and play" during the expansion and integration of equipment from different manufacturers.

As a consequence, the channels between manufacturing and services provided by the current industrial Internet are chimney-like channels as depicted in Fig. 3b. Obviously, each channel is independent, where all the resources and methods for sensing, communication, computing, and control are different. For example, to accomplish processing services, the machinery tool can adopt ICN protocols such as PROFINET for communication to control the motor for high-precision processing. Herein, the computing and control can be locally completed by the industrial controller inside the machinery tool. In contrast, to accomplish assembly and logistics services, mobile equipment such as robots and automated guided vehicles (AGVs) can adopt wireless fidelity (WiFi) or 5G for wireless communication and scheduling. Herein, computing and control can be completed by the cloud or edge servers. Obviously, different manufacturing tasks adopt different computing and control modes and apply heterogeneous ICN protocols. In this way, the different steps of a manufacturing task are independent. More importantly, when there are changes to orders, adjustments to production lines, updates to equipment, or grades to services, the equipment is unable to support "hot-plug" owing to the differences in sensing, communication, computing, and control of heterogeneous networks. As such, the factory and production line must be shut down, causing serious declines in production efficiency and difficulties in ensuring quality. As a consequence, it is very necessary to establish a transparent channel between manufacturing and services through the integrated collaboration of sensing, communication, computing, and control. In this way, we can realize MaaS.

5 “Thin waist” for future industrial Internet

To realize the transparency of manufacturing and services, this section explores breakthroughs in the hierarchical heterogeneous network architecture as shown in Fig. 3a, simplifies the network coupling and superposition relationships, and proposes to establish a flat network architecture as shown in Fig. 4a, like a service bus for manufacturing. In this way, the existing chimney-like service mode is no longer applicable, which motivates us to establish a transparent service mode.

The existing Internet employs Internet protocol (IP) communication as its core and establishes transparent channels between different types of users and the underlying protocols, forming an hourglass-like “thin waist” (Trammell and Hildebrand, 2014; Beck, 2019). On one hand, the application types corresponding to the upper portion of the “thin waist” can be expanded, and various services are provided. On the other hand, multi-protocol compatibility at the bottom portion of the “thin waist” is also guaranteed, and the wide-area interconnection of massive computers can be realized.

However, in the era of Internet of Everything, it is difficult for the IP-based “thin waist” to fulfill the interconnection and interoperability requirements of all manufacturing elements including humans, machines, and things, for customized manufacturing and differentiated services. Thus, it is unable to efficiently support a suitable and orderly interaction of the entire production chain, value chain, and industry chain.

As shown in Fig. 4b, following the core idea of Internet’s “thin waist” but not exclusively restricted to IP communication, in this paper we propose to establish a novel “thin waist” for industrial Internet, namely IITW. IITW fully considers the coupling characteristics among sensing, communication, computing, and control in industrial Internet. Through their integration and coordination, all aspects from equipment, data, and network to platform will be fully interconnected to activate industrial Internet’s capabilities such as self-sensing, self-computing, self-optimization, and self-decision-making. In this way, for different manufacturing requirements such as single/multiple-variety, small/large-batch, and rigid/flexible, IITW will establish a transparent channel between manufacturing and services for different manufacturing steps including manufacturing process monitoring, process control, machining, cutting and welding, robot assembly, AGV logistics, and product testing.

In the following, we introduce the basic functions of IITW.

5.1 Sensing

Sensing is the neuron of industrial Internet and the basics for communication, computing, and control of industrial Internet. Thus, sensing is an important prerequisite for establishing IITW. By sensing various communication and computing resources as well as control services, we can obtain massive multi-dimensional sensing data to establish a digital twin model and conduct dynamic configuration and management of industrial Internet. In this way, we can realize self-sensing, supporting self-computing, self-decision-making, and self-optimization of industrial

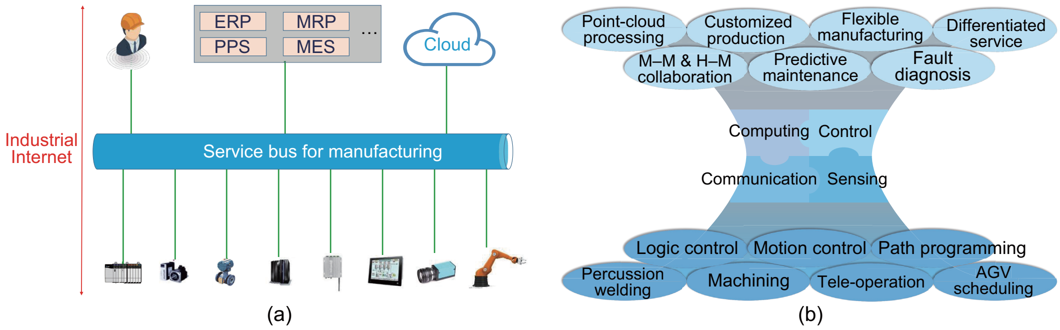

Fig. 4 Network architecture and service mode of future industrial Internet: (a) flat network architecture; (b) transparent service mode (ERP: enterprise resource planning; MRP: material requirement planning; PPS: production planning and scheduling; MES: manufacturing execution system; M–M: machine–machine; H–M: human–machine; AGV: automated guided vehicle)

Internet and further enable the control and optimization of the entire manufacturing process. Note that the sensing stated here is not limited to specific services such as sensing the manufacturing process or monitoring the production process. In contrast, it is oriented toward sensing the resources and operating status of industrial Internet.

5.2 Communication

Communication, which depends on sensing, serves for computing, and supports control, is the central nervous system of the industrial Internet. Obviously, communication is the key to establishing IITW and opening up the channel between manufacturing and services. Considering the requirements of stability, robustness, and security along manufacturing, IITW must provide deterministic communication. That is to say, it must meet the communication requirements such as being strong real-time, high reliability, and low jitter, before the given deadline of all types of manufacturing tasks. Note that determinism represents the lower bound of bandwidth, upper bound of delay, upper bound of jitter, and upper bound of packet loss. As such, IITW should establish mechanisms such as time synchronization, bandwidth reservation, data packet filtering, and traffic shaping to fulfill the on-demand quality of service (QoS) requirements from heterogeneous and high-concurrent manufacturing tasks.

5.3 Computing

Computing is the brain of the industrial Internet and provides computing power for the operation and optimization of industrial Internet. Based on the massive data obtained by the deep sensing of industrial Internet, we can visualize industrial equipment, network elements, users, and services, establish a digital twin model for industrial Internet, and further complete the calculation for the communication and control processes. This will provide decision-making services for the overall operation and optimization of industrial Internet. Herein, to satisfy different requirements of control tasks, IITW will collaboratively use the computation resources distributed at the cloud, edge, and end. This will provide differentiated services for the manufacturing tasks on one hand, and also provide self-computing, self-decision-making, and self-optimization services for sensing, communication, and control of industrial Internet on the other hand.

5.4 Control

Control is the execution backbone of industrial Internet, and it conducts system configuration based on multi-dimensional sensing, real-time communication, and computing decision results. In this way, the operation of industrial Internet can be dynamically optimized, and the QoS requirements of various manufacturing tasks can be well satisfied. To realize high-precision control such as robotic motion control, we should execute joint optimization combined with sensing, communication, and computing. In this way, we can fulfill the control precision requirements from the perspective of timeliness and reliability and ensure the stability, robustness, and security of control.

In summary, sensing, communication, computing, and control coupling with each other not only restrict but also promote one another. The lack of any single step can easily cause the failure or even collapse of the entire industrial Internet, thus affecting the efficiency and safety of industrial manufacturing. Thus, we should realize collaborative integration of sensing, communication, computing, and control to achieve self-sensing, self-computing, self-optimization, and self-decision-making for industrial Internet and guarantee the stable and safe operation of the manufacturing system.

6 Key technologies and future research directions

In this paper, we aim to reform the hierarchical heterogeneous network architecture and chimney-like service mode of the traditional industrial Internet, and establish a flat network architecture and transparent service mode by proposing IITW to provide transparent channels for manufacturing and services. Motivated by this, in this section we further propose the key technologies from the perspectives of multi-dimensional sensing, deterministic communication, virtual computing, and operation control, as shown in Fig. 5. This will support the establishment of IITW and ensure the collaborative integration of sensing, communication, computing, and control.

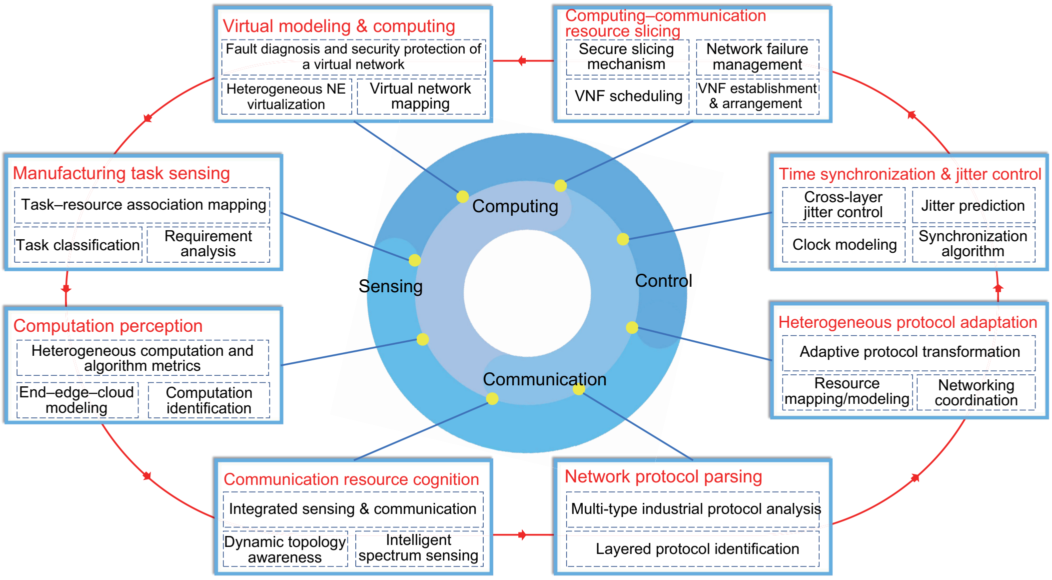

Fig. 5 Key technology architecture (NE: network element; VNF: virtual network function)

6.1 Multi-dimensional collaborative sensing of task–resource

6.1.1 Sensing for manufacturing tasks

The manufacturing industry is diverse. However, different manufacturing tasks have different communication, computing, and control requirements, and correspondingly require different resources. Thus, we must first be aware of the types of manufacturing tasks and subsequently determine their execution requirements along with their resource requirements. In this way, there will be guidance for the scheduling of communication and computation resources, thereby satisfying the differentiated QoS requirements of diverse manufacturing tasks.

First, we need to determine the type of manufacturing tasks, establish a classification model for diverse manufacturing tasks, and clarify their QoS requirements. For example, manufacturing tasks can be simply divided into three types: control, video, and monitoring. Control tasks require strong real-time, high-reliable, and deterministic communication and thus require extensive communication and computation resources (Jin et al., 2023). Video tasks require high-rate communication and thus large communication resources, but with lower timeliness and reliability requirements than those of control tasks. Monitoring tasks require large-scale, high-concurrent, and low-power communication, and thus require fewer communication and computation resources compared with other tasks. To summarize, there are significant differences in the requirements for communication, computing, and control owing to the differentiated QoS requirements of diverse manufacturing tasks. Thus, a task classification model is urgently required.

Furthermore, we need to perceive the demands pertaining to communication and computation resources according to the detailed execution requirements of manufacturing tasks. Specifically, we can add information such as task types and resource requirements into the packets of different protocol layers. The indicators can include task identification, task priority, communication performance requirements with respect to bandwidth, delay jitter, packet loss rate, and security, and computing performance requirements with respect to computation resource type and volume.

Finally, we need to construct the mapping relationships between the requirements of manufacturing tasks and the actual network resource supply. Specifically, according to the task execution requirements, we should analyze and determine resource requirements such as end-to-end communication delay and jitter, computation type, and volume. In this way, we can obtain the boundary relationships such as the lower bound of task resource requirements and upper bound of network resource supply. Furthermore, we can construct the measurement system of industrial Internet for task and resource requirements. Accordingly, it can support the dynamic adjustment of network resources on one hand and promote the interaction of tasks and resources on the other hand, thereby improving the efficiency of service sensing.

6.1.2 Sensing for network protocols

The industry has developed extensive ICN protocols to satisfy different manufacturing tasks, and this has caused the current chaotic status of ICN protocols in the industrial field. As industrial Internet continues to develop further, many pieces of industrial equipment are connected to the open Internet. However, there are still many private or unknown protocols in operation, of which a few include extensive amounts of malicious code traffic. This will significantly influence industrial information security and directly threaten industrial production. Thus, in the mixed-communication environment with the coexistence of the private ICN and the open Internet, we should perceive the network protocols, identify the features of different protocols, and guarantee the security of heterogeneous networks.

First, protocol identification should be performed based on different protocol layers, from the physical layer, data link layer, and network layer to the application layer. The protocol type can be identified by analyzing the protocol port, content, and even the intent according to the characteristics of network topology, traffic, and data packet. Available methods include regular expressions, clustering, Markov modeling, and machine learning (de Donato et al., 2014).

Next, protocol classification and analysis should be executed for various known and unknown ICN protocols. Despite the in-depth research and extensive results on Internet-oriented protocol analysis, there is still a requirement for improvements with respect to accuracy and timeliness, as there are strong real-time and high-security requirements for manufacturing tasks. In particular, the openness of ICN protocols is inferior and similar to that of private protocols, which are difficult to analyze. Existing analysis methods are mainly based on transport layer ports, network traffic behaviors, link frame segmentation, and packet format inference (Shao et al., 2014; He et al., 2020). In the future, data-driven methods such as pattern mining, association rule mining, and deep reinforcement learning can be used to improve the accuracy of protocol classification and analysis.

6.1.3 Sensing for communication resources

The communication resources of industrial Internet are distributed in different dimensions such as temporal, spatial, and frequency. Through precise resource allocation such as time slot, channel, carrier, transmission path, and transmit power, the communication requirements for different manufacturing tasks can be fulfilled. By sensing communication resources, we can deconstruct the best-effort transmission strategy and realize the deterministic communication of industrial Internet.

First, the equipment moves dynamically according to the changes of manufacturing tasks and processes, and frequent login or logout of the network during industrial production. Thus, the network topology is dynamic. This is particularly evident in the industrial field, where the environment is harsh with significant electromagnetic interference and the communication reliability is difficult to guarantee. The instabilities in the communication links may cause key equipment to transition into standby mode or be disrupted, thus affecting the entire production chain and supply chain, causing production paralysis. Hence, we should clarify the complex connection relationships among equipment, determine the network topology, and fully guarantee the redundancy of communication links and the robustness of networks. Topology sensing is important in determining the connection relationship among equipment, maintaining network stability, and ensuring the reliability of tasks' communications. Real-time and accurate topology sensing is also beneficial for the expansion of spatial-domain resources, realizing network traffic balance, supporting the establishment of elastic and reconfigurable networks, and ensuring the smooth execution of manufacturing tasks. This is of immense significance to the flexibility in production.

Next, technologies such as 5G are driving industrial Internet to become wireless and flat, where wireless networks are penetrating the production process layer by layer and fulfilling control applications. However, the electromagnetic space in the industrial field is extensively complex and dynamically changing, where problems such as vibration and random movement of large mechanical equipment cause random mutations in the channel state. In particular, existing IWNs are generally operating in the unlicensed band and are easily affected by other networks working in the same band such as ZigBee, Bluetooth, and WiFi. Hence, performing accurate spectrum sensing and ascertaining available channels before accessing unlicensed bands are necessary.

Cognitive radio (Haykin, 2005; Chiwewe et al., 2015) technologies have been proposed for nearly 20 years, during which extensive theoretical research results are accumulated, and focused on solving the spectrum scarcity problem and improving spectrum utilization. However, for different manufacturing tasks, it is still necessary to optimize and upgrade the equipment cost, power consumption, and timeliness. Recently, the proposal of intelligent radio (Qin ZJ et al., 2020) and symbiotic radio (Liang YC et al., 2020) has provided new ideas for improving the accuracy and energy efficiency of spectrum sensing. However, breakthroughs are necessary for their practical application and deployment in the industrial field.

Finally, as the demand for bandwidth increases, the communication spectrum is gradually moving toward the millimeter wave and terahertz frequency bands. Thus, sensing and communication will be overlapping in both temporal and spatial domains. In other words, sensing and communication interact with each other, causing a high degree of coupling. As such, the integration of sensing and communication (ISAC) was proposed and listed as one of the key technologies of 6G (Cui et al., 2021). ISAC can sufficiently use radio signals for target positioning, detection, imaging, and recognition by sharing software and hardware resources and information. Accordingly, it can realize deep sensing of the physical environment and assist and guide wireless communication to realize intelligent wireless communication. Through two-way enhancement, namely communication-enhanced sensing and sensing-assisted communication, we can improve the sensing accuracy and spectrum utilization simultaneously. In this way, the network performance can be improved, and the power consumption can be reduced. Furthermore, it gets through the physical domain and the information domain, which can help guarantee the QoS requirements of manufacturing tasks. Nevertheless, as ISAC is still in its initial research stage, there is a pressing requirement for breakthroughs in the software and hardware design of equipment, temporal–spatial–frequency resource multiplexing, and joint optimization of wireless air-interfaces.

6.1.4 Sensing for computation resources

Industrial Internet provides ubiquitous distributed access, realizes the interconnection of extensive industrial equipment, and introduces extensive heterogeneous computation resources simultaneously. These heterogeneous computation resources centralized and/or distributed at cloud, edge, or end have jointly constructed the computation power pool of industrial Internet (Liu et al., 2022). However, the distribution, scale, quantity, and core types of the computation resources of cloud, edge, and end are significantly different. They are also coupled and restricted by one another, and provide different computation power for manufacturing tasks. Thus, there is a need for accurate sensing of the heterogeneous computation resources and establishing a complete computation power model to support the collaborative scheduling of computation resources and provide differentiated services for different manufacturing tasks.

First, the computation resources should be accurately modeled, where the coupling relationship and temporal–spatial distribution of computation resources around cloud, edge, and end should be clarified. In this way, we can analyze the load status and real-time usage status of computation resources. To achieve this, we should fully use the network resources of industrial Internet to collect, notify, and report the computing power information and formulate the computation power distribution map. Here, computing and communication integrated sensing and modeling in real time is the basis for realizing computation power sensing.

Next, computation resources distributed at the cloud, edge, and end of industrial Internet adopt heterogeneous chip architectures such as X86, ARM, and RISC-V, which can provide general or specialized computing power such as central processing unit (CPU), graphics processing unit (GPU), data processing unit (DPU), and field programmable gate array (FPGA). Standardized measurements for hardware at all levels are required to provide consistent computing services for specific manufacturing tasks. This will require the measurement of the computation power of different chips or modules with different forms as well as their combinations. Furthermore, abstracting and mapping out the computation power of different hardware are required to establish a standardized computing power measurement system.

Meanwhile, the cloud, edge, and end platforms of industrial Internet adopt different algorithms, including different neural networks, deep learning, reinforcement learning, migration learning, and federated learning (Arulkumaran et al., 2017; Aledhari et al., 2020; Zhuang et al., 2021), which are suited for different manufacturing tasks and require different computation power support. Thus, measuring the computation power of different algorithms and determining the cloud–edge–end computation power support according to the requirements of manufacturing tasks are also crucial.

Finally, based on the computation power measurement of hardware and algorithms, computation power identification for different levels is also required. Here, a globally standardized and secure identification mechanism must be established. This will provide information such as the temporal–spatial distribution of computation power and the status of resource usage. In this way, we can realize computation power scheduling and routing, providing on-demand computation resources for different manufacturing tasks.

6.2 End-to-end deterministic communication of heterogeneous networks

Manufacturing tasks demand end-to-end deterministic communication, which is a key requirement differentiating industrial Internet from common Internet. However, the current Internet with IP-based "thin waist" can provide only best-effort transmission services. Thus, it is difficult to fulfill the differentiated QoS requirements of different types of manufacturing tasks. Particularly, manufacturing tasks often perform end-to-end communication across multiple work domains and may compete for network resources. This imposes high transmission requirements on industrial Internet. However, industrial Internet is not a single network; rather, it consists of heterogeneous networks across media, protocols, and domains, forming a complicated multi-modal system. Hence, in a complicated industrial environment, different types of manufacturing tasks will be affected by the coupled superpositioned effect of many factors when conducting end-to-end communication. Thus, it is extremely challenging to ensure end-to-end deterministic communication.

6.2.1 Convergence of heterogeneous network protocols

The independence and competition of industrial equipment manufacturers and the current chaotic situation of ICNs have determined that IITW should support multi-protocol fusion communication. This includes IT/OT networks across different levels and OT networks at the same level, which all have cross-media and cross-protocol interconnection requirements.

First, cross-media communication involves the integration of wired and wireless networks, where cables, optical fibers, and electromagnetic waves in different frequency bands can be used. Typically, the convergence of 5G and TSN can realize wide-area end-to-end deterministic communication and is regarded as one of the typical structures for future industrial Internet (Prados-Garzon and Taleb, 2021). However, 5G air-interface wireless resources cover at least the temporal, spatial, frequency, and code domains, which include time slots, channels, power, antennas, beams, and coding. In contrast, the TSN wired resources usually cover only the temporal and spatial domains, including time slots and transmission paths. Obviously, there are substantial differences in the type, quantity, and characteristics of the available network resources. Thus, there is a high degree of loose coupling of end-to-end resources in heterogeneous converged networks. To address this challenge, we should establish a standardized mapping and management mechanism for cross-media network resources to build end-to-end resource integration models, balance the usage of resources, and realize the collaborative scheduling of diverse network resources, thereby realizing deterministic communication.

Next, different types of industrial equipment at the industrial field require frequent cross-protocol communications during interconnection. However, problems such as unequal protocol stacks, inconsistent syntax, inconsistent data formats, and mismatched communication rates exist in heterogeneous networks, causing issues such as inferior information interconnection and low real-time performance.

Thus, the relationships should be deeply investigated from the perspectives of protocol stack structure, syntax mechanism, data format, transmission strategy, network topology, and traffic changes. Then, quantitative analysis on characteristic indicators such as delay bounds, throughput, and cache occupancy should be performed to establish virtual associations and the mapping relationship. This will enable clarification of the dynamic characteristics and the collaboration mechanism when heterogeneous networks interconnect and intercommunicate.

Lastly, using the protocol identification and analysis as a basis, it is expedient to investigate task prediction, resource reservation, and traffic shaping in heterogeneous networks and propose the caching/rate matching technology. In this way, we can establish a transparent channel for heterogeneous protocols, where they are adaptively conversed and adapted (Xu C et al., 2023c). Furthermore, we can realize rapid protocol adaptation at the chip level and solve the problems of high-rate, strong real-time, and high-reliable interconnection and intercommunication in the industrial field.

6.2.2 High-precision time synchronization and jitter control

Time synchronization is a prerequisite for the end-to-end scheduling of heterogeneous networks to realize deterministic communication. Thus, it is the basis for supporting the collaborative work of manufacturing tasks. Meanwhile, by the precise control of network delay jitter and the establishment of a precise clock system, we can realize high-precision manufacturing tasks such as robotic tactile teleoperation (Xu C et al., 2023a). Thus, it is crucial to establish a high-precision time synchronization mechanism to complete delay and jitter control.

First, all existing networks have defined their own clock systems and synchronization mechanisms, and they can independently realize time synchronization with different precision according to different network scales. However, we should align the clocks to establish a unified clock system when heterogeneous networks interconnect. Existing methods usually perform simple clock adaptation at the interface of heterogeneous networks, namely relative time synchronization. The advantages of this method are that it is flexible and simple. However, the low synchronization precision renders it difficult to support high-precision cooperative control tasks. Thus, we should study methods such as timestamp handover, delay measurement, error compensation, and clock matching among heterogeneous networks and attempt to establish a globally standardized clock system to realize absolute time synchronization.

Next, many rounds of interaction will be performed among the different protocol layers of different equipment during the end-to-end data transmission for the manufacturing task. However, considerable differences exist in the software and hardware processing capabilities of different equipment, and the functions and performance of each protocol layer. This causes the nonlinear coupling and superposition of various delays, making jitter control difficult. To address this challenge, we can use network calculus and other methods to analyze the boundary characteristics of delay jitter, clarify the mechanism of delay jitter, and propose a protocol-sensitive jitter decoupling and prediction method. Furthermore, we can propose a cross-layer jitter control method to realize high-precision jitter control.

6.3 Virtual computing and operation control of industrial Internet

The flexible manufacturing tasks require dynamic re-configurability and on-demand customized services from industrial Internet. However, "users and networks," "control and data," and "resources and locations" are bound with each other in the existing Internet (Zhang and Quan, 2022). These render a static, rigid, and fixed system which is unable to provide differentiated services for multiple manufacturing tasks. Hence, according to the control requirements for specific manufacturing tasks, we should conduct a precise digital twin model of industrial Internet based on multi-dimensional collaborative sensing and build a complete information space of manufacturing equipment and network infrastructure. In this way, we can realize multi-dimensional decoupling of network elements including tasks, data, resources, and locations. Furthermore, we should establish a task–resource virtual model for the entire network and perform coarse-grained slicing and fine-grained scheduling of multi-dimensional communication and computation resources. As such, we can realize operation control and dynamic optimization for industrial Internet.

6.3.1 Virtual computing for digital twin

To establish a digital twin model for industrial Internet, we can employ virtual computing (Posada et al., 2015) to virtualize all network elements. Network virtualization (Garg et al., 2021) can create many isolated parallel virtual networks through the abstraction and pooling of network infrastructure such as routers, switches, and base stations, realizing the decoupling of logical services from physical equipment. This allows for more flexible sharing and scheduling of physical resources and provides on-demand customized services for manufacturing tasks. Research on network virtualization has encompassed multiple development stages such as the virtual local area network, virtual private network, active programmable network, and overlay network. It is continuously integrating with new technologies such as software-defined network and cloud computing to achieve efficient network management. Nevertheless, some challenges are still prevalent in the cross-media integration of multiple heterogeneous networks, the large volume of concurrent access of massive industrial equipment, and the dynamic changes of complex manufacturing tasks.

First, the large-scale industrial applications of novel networks such as optical and wireless networks have completely broken the practice of single-medium networking by fieldbus or industrial Ethernet. Hence, virtualizing the cross-media heterogeneous converged networks is required. As the wired network includes fixed physical network elements, relatively stable topology and links, and abundant resources, the virtualization considers mainly the availability of physical resources, network response methods, dynamic adaptability of network mapping, and global optimality of resource allocation. In contrast, wireless networks are often mobile, whose topology and link are dynamically changing, and have limited bandwidth resources. Thus, we need to consider the diverse wireless network protocols, dynamic topology, limited spectrum, time-varying channels, and randomness of interference for network virtualization. As such, research is needed to establish heterogeneous virtual network elements, design standard interfaces, optimize virtual network commands, build homogeneous or heterogeneous virtual clusters, establish isolation mechanisms for heterogeneous virtual networks, and improve the mobility and spectrum management.

Next, existing virtualization methods simply conduct the abstraction of various physical network elements and do not consider the complex coupling relationship between the various manufacturing tasks and the physical network elements. Thus, we need to comprehensively consider the constraints of manufacturing tasks on virtual network elements from various aspects such as timeliness and reliability. On this basis, we establish the mapping mechanism to match resources and tasks, and design containers or virtual machines for different types of manufacturing tasks. Furthermore, basic problems such as virtual network function (VNF) creation and configuration and monitoring for manufacturing tasks should be systematically investigated. Thereafter, we can propose new virtual network mapping methods to support the on-demand dynamic scheduling and superimposed networking of virtual resources.

Finally, the application of network virtualization will make the networks' superimposed layers and topological relationships more complex. Should any one network element fail, large-scale faults may occur owing to the polymorphism and conductivity of the fault. This may further influence the normal operation of the system and thus substantially threaten production safety for enormous losses. Thus, with full consideration of different scales' faults in nodes, links, and regions, we should establish an accurate fault model of virtual networks, study the detection, location, recovery, and protection methods of virtual network faults, and establish the multi-reliable and collaborative security protection mechanism.

6.3.2 Operation control by communication–computation collaborative scheduling

With virtual computing as the basis, we can construct different virtual networks using the same physical infrastructure, namely network slicing (Afolabi et al., 2018; Ksentini and Frangoudis, 2020). Furthermore, we can establish a virtual computing-aware network through the collaborative scheduling of communication–computation resources at different levels. In this way, differentiated network services are provided for different manufacturing tasks, where different QoS requirements are fulfilled. For example, machine vision requires large bandwidth, industrial process measurement and control requires high-concurrent communication, and robotic motion control requires strong real-time communication. All of these require different communication and computation resources. That is to say, IITW should configure VNFs according to the specific task requirements, create programmable network slices for multi-dimensional collaborative resource scheduling, and provide customized end-to-end services for different manufacturing tasks.

First, different network slices will construct different service function chains (SFCs). Herein, the homogeneous or heterogeneous VNFs of one SFC will be deployed on the same physical resource to improve resource utilization efficiency through resource recycling and sharing. However, excessive resource allocation will result in over-competition for physical resources at the bottom layer for different types of manufacturing tasks. This may cause sharp declines in QoS and the inability to fulfill the requirements of high-concurrent manufacturing tasks. In particular, the dynamic changes in the number, type, and QoS requirements of the manufacturing tasks render it difficult for current quasi-static network slicing methods to handle such changes. Therefore, based on multi-dimensional collaborative sensing, we should study the dynamic scheduling and offloading methods of VNFs and construct an end-to-end SFC for cloud–edge–end collaboration and communication–computation integration (Xu C et al., 2023b). Accordingly, we should arrange, manage, and optimize SFCs for on-demand and reliable deployment and realize the dynamic and scalable network slices. On this basis, by fully considering the dynamic changes of manufacturing tasks, we should propose novel algorithms for SFC reconstruction, forwarding graph re-mapping and VNF re-scheduling. In this way, we can establish robust SFCs from different levels, i.e., node level and link level.

Next, network slicing is an end-to-end arrangement of global resources, where the life cycle generally includes slice request, configuration, operation, and release. Once a certain link in the network slice is attacked, it will result in a chain reaction, where at least one network slice or even all network slices will fail, significantly threatening production security. Thus, we should consider the failure of VNFs and security issues in the entire life cycle of network slices and investigate the detection, location, recovery, and protection methods of network slicing security. By locating the attack point of a network slice, we can construct an accurate network slice failure model and remove potential slice security risks in time. This will help establish the security mechanism of network slicing and guarantee the robustness and security of network slices.

7 Conclusions

In this paper, we first analyzed in detail the basic networking capability requirements of process manufacturing and discrete manufacturing. Then, by reviewing the developing process of industrial Internet, we made a systematic comparison of the current networking capabilities of industrial Internet. For future industrial Internet, we proposed IITW by integrating sensing, communication, computing, and control to establish a flat network. To achieve this goal, we summarized the key technologies in three areas requiring urgent breakthroughs, including the multi-dimensional collaborative sensing of task–resource, the end-to-end deterministic communication of heterogeneous networks, and the virtual computing and operation control of industrial Internet. Particularly, we also explored in depth the key challenges and future research directions. In summary, this paper focused on interdisciplinary fields of communication, computer, and control. By constructing the novel IITW, we attempted to achieve transparency in manufacturing and services for personalized customization and differentiated services, thus fulfilling the future demands of major revolutions in intelligent manufacturing.

Contributors

Chi XU summarized the literature and drafted the paper. Xi JIN, Changqing XIA, and Dong LI helped organize the paper. Chi XU, Peng ZENG, and Haibin YU finalized the paper.

Conflict of interest

All the authors declare that they have no conflict of interest.

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