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Recent advances in Industrial Internet: insights and challenges

Wei Qin, Siqi Chen, Mugen Peng *

State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications, Beijing, 100876, China

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A B S T R A C T

The Industrial Internet is a promising technology combining industrial systems with Internet connectivity to significantly improve the product efficiency and reduce production cost by cooperating with intelligent devices, in which the advanced computing, big data analysis and intelligent perception techniques have been involved. This paper comprehensively surveys the recent advances of the Industrial Internet, including reference architectures, key technologies, relative applications and future challenges. Reference architectures which have been proposed for different application scenarios and their corresponding characteristics are summarized. Key technologies, such as cloud computing, mobile edge computing, fog computing, which are classified according to different layers in the architecture, are presented to support a variety of applications in the Industrial Internet. Meanwhile, future challenges and research trends are discussed as well to promote further research of the Industrial Internet.

1. Introduction

Nowadays, new production and organization methods promote the intelligent transformation of the global industrial system, with the rapid development of new information technologies, such as the Internet, big data, cloud computing, Internet of Things (IoT) and artificial intelligence. As a result, the Industrial Internet comes into being and integrates the advantages of both the Industrial Revolution and the Internet Revolution.

In the recent few years, the Industrial Internet has become the focus of governments, manufacturing enterprises, operators and academic research groups from various fields in different countries. The General Electric (GE) proposed the convergence of industrial equipment and Information Technology (IT) in 2012.

The concept of “Industrial Internet” was defined for the first time, namely, to connect equipment, people and data analysis based on an open, global network [1]. The objective of the concept is to upgrade the intelligence of aviation, medical and other industrial equipments, reduce energy consumption and improve efficiency through the use and analysis of big data. In June 2013, GE proposed the concept of Industrial Internet Revolution, providing operation and maintenance services for a large number of industrial applications, and using key technologies such as the Internet and big data to improve the quality of service. Then, in order to apply the concept of Industrial Internet to practical application scenarios, five leading industrial companies in the United States, including AT&T, Cisco, GE, IBM and Intel, established the Industrial Internet Consortium (IIC). The goal of IIC is to break down technical barriers and promote the integration of the physical world and digital world. As a result, the Industrial Internet will produce innovative industrial products and systems in smart manufacturing, healthcare, transportation, and other fields. IIC published the Industrial Internet Reference Architecture (IIRA) v.1.8 in 2017. The IIRA provides standards-based architectural template and methodology so that the Industrial Internet of Things (IIoT) system architects could design their own systems based on a common framework and concept.

The Industrial Internet has attracted worldwide attention, thus developing the Industrial Internet has become a common choice for most industrial powers for future opportunities and challenges. The German government issued the strategy of Industry 4.0, which is consistent with the essence of the Industrial Internet. The Industry 4.0 is known as the fourth industrial revolution, focusing on the establishment of intelligent products and production processes. The term refers to a large range of different concepts, including smart factory, self-organization, and Cyber Physical Systems (CPSs). A generally accepted viewpoint is that the Industry 4.0 is the technical integration and application of CPSs. CPS is defined as a system integrating physical worlds and computational capabilities that can interact humans through many new information technologies [2]. The CPS focuses on the close integration and coordination of physical resources and computing resources, and is mainly used in some intelligent systems. The underlying concept of the term CPS is that it refers to embedded systems, logistics, coordination and management processes that utilize sensors to directly access physical information and actuators to perform physical processes [3]. The Industry 4.0

* Corresponding author.
E-mail addresses: qinwei75@bupt.edu.cn (W. Qin), pmg@bupt.edu.cn (M. Peng).

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proposes to build a CPS platform based on services and real-time support, and conducts research on technology, business and policy to build a Cyber Physical Production System (CPPS) lab.

The Chinese government has proposed strategies to promote the deep integration of informatization and industrialization, and accelerate the development of advanced manufacturing and economy. In 2016, the Alliance of Industrial Internet (AII) was founded in China, aiming at establishing a public platform for collaborated improvement in administration, industry and academy. The AII redefined the Industrial Internet as the industry and application ecology formed by the deep integration of the Internet, new information technologies and industrial systems. Meanwhile, Japan stresses the Connected Industries as a supplement to the Industrial Internet, creating new added value and solutions to various problems in society through the interconnection of enterprises, people, data and machines.

Recently, the Industrial Internet is considering using the ideas of embedded technology and intelligent objects in the IoT. The term "IoT" is considered as the ultimate global network of interconnected intelligent objects through extended Internet technologies, which are supported by a set of technologies, including Radio Frequency IDentification (RFID), Wireless Sensor Network (WSN), controllers, machine-to-machine communication devices, etc. The Industrial Internet has been drawing on these technologies to involve increasing numbers of smart objects, and then it will provide promising opportunities to build powerful industrial systems and develop various industrial applications. In addition to the IoT, various technologies are needed to support the Industrial Internet, including network communication technology, wireless sensing, cloud computing technology, industrial big data technology and information security. As a kind of interdisciplinary science and integrated technology, the Industrial Internet continues to integrate with emerging technologies, such as edge computing, artificial intelligence, blockchain technology, etc.

The Industrial Internet has rapidly emerged on a global scale with the rapid transformation of manufacturing from digitalization to networking. It has promoted the continuous integration of the cyber world and the physical world. At present, the relevant researches on the IoT, sensor networks and industrial control systems are abundant, but the research of domestic and international industries on the Industrial Internet itself is still in its infancy. The development of the Industrial Internet faces the coexistence of opportunities and challenges. In this paper, we conducted a detailed survey on the research results of the Industrial Internet. The main contributions of this paper are summarized as follows:

1) A comprehensive survey of Industrial Internet architectures is presented, including reference architectures proposed by different alliances applied for the IIoT and the Industry 4.0. In addition, an Industrial Internet architecture supported by wireless technologies is illustrated, which can better meet the requirements of real-time, low delay and high reliability.
2) Key technologies applied to the Industrial Internet are comprehensively surveyed. The principles, technical solutions and recent advances of these technologies are summarized. In particular, emerging technologies, such as, big data, cloud computing, Mobile Edge Computing (MEC), are emphasized to provide a more flexible choice to achieve ultra-dense, large connection, and wide coverage in the Industrial Internet.
3) A comprehensive survey of various applications and use cases of the Industrial Internet in different fields is presented, which are supported by both existing technologies and state-of-the-art communication technologies. Furthermore, advantages compared with traditional applications and recent advances are highlighted.
4) The future challenges and research trends related to the Industrial Internet are identified, especially in wireless networks, such as sensing, communications, computing and security, which are vital for further development of Industrial Internet.

The rest of this paper is organized as follows. In Section 2, several architectures of the Industrial Internet proposed by different countries and academia are presented. In Section 3, a variety of key technologies in the Industrial Internet are summarized, as well as their advantages and application scenarios are included. In Section 4, a survey of various applications supported by emerging wireless technologies is presented. The current challenges and future trends are shown in Section 5. Finally, conclusions are drawn in Section 6. To present the flow of this paper, we provide the structure of the paper in Fig. 1.

2. Architectures

The Industrial Internet contains various processes and elements in the field of information technology and industry, which is complex and diverse. Its emergence and development have been highly valued by governments around the world and actively practiced by the industry. However, domestic and overseas researches on the Industrial Internet itself are still in their infancy, and there is still a lack of uniform standards for the architectures of the Industrial Internet. In this section, several Industrial Internet architectures proposed by different countries and academia are introduced. First, the IIRA for IIoT systems and a reference architecture model proposed by the Industry 4.0 are briefly surveyed, and then an architecture supported by wireless communication technologies is introduced.

2.1. IIRA

IIC proposed the IIRA in order to meet the common technical challenges of the IIoT, and incorporate new IIoT technologies, concepts as well as applications [4]. The reference architecture uses a standard-based framework to describe business, usage, function and implementation viewpoints. IIC also defined its Industrial Internet Architecture Framework (IIAF) that adopts the approach defined by the ISO/IEC/IEEE architecture description standard. IIAF performs as the foundation of the IIRA, which can be applied to present the interests in IIoT systems.

The constructs of the IIRA and its applications are shown in Fig. 2. The

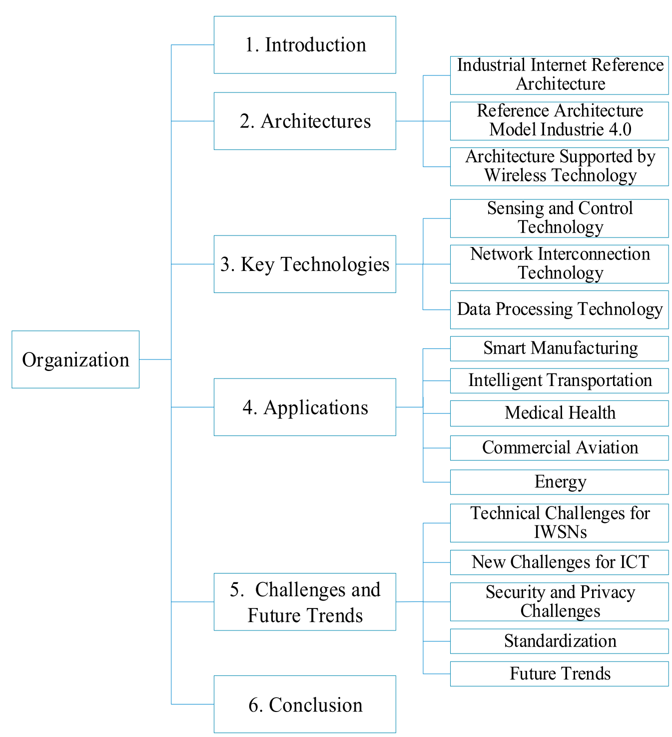

Fig. 1. Structure of the paper.

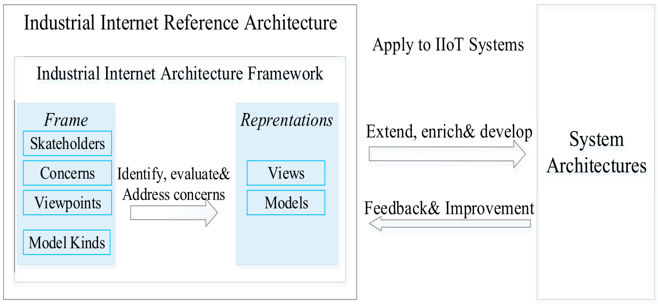

Fig. 2. IIRA constructs and applications.

IIRA has adjusted its models slightly to adapt to the ISO architecture. The models and their representations in the IIRA show the key ideas of the reference architecture, and the establishment of the IIRA provides a common architecture that interconnects smart devices, machines, people, processes and data together.

There are four basic viewpoints that identify the relevant stakeholders of systems and determine the proper framing of concerns, including business viewpoint (requirement model), usage viewpoint (use-case model), functional viewpoint (functional model) and implementation viewpoint (deployment model). Other architectures of the Industrial Internet can expand their viewpoints based on these four viewpoints for specific requirements [4]. These viewpoints are arranged in order as depicted in Fig. 3. The higher-level viewpoint can guide and impose requirements on the lower level of viewpoints. Moreover, there are a number of system concerns related to safety and security that need to be addressed across the viewpoints. According to Ref. [5], there is a set of system characteristics, including safety, security, resilience, reliability and privacy, which emphasize how well the system works. Beside the characteristics about reliability, the IIRA is also provided with interoperability, connectivity, data management, advanced data analysis, intelligent control, dynamic combination and other features.

2.2. Reference architecture model industry 4.0

Germany has officially proposed the Reference Architecture Model Industry 4.0 (RAMI 4.0) in order to provide a uniform architecture as reference for different standardization organizations and associations. The architecture model shown in Fig. 4 describes the Industry 4.0 from three dimensions, including layers, product life cycle & value stream, and hierarchy levels.

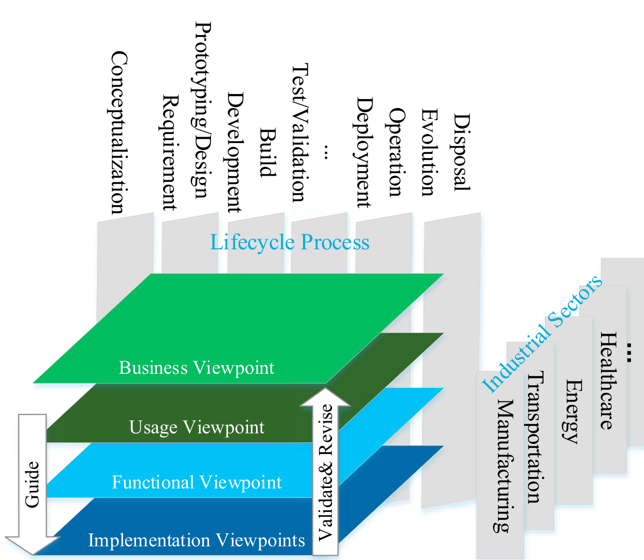

Fig. 3. Relationship among IIRA viewpoints, application scope and system lifecycle process.

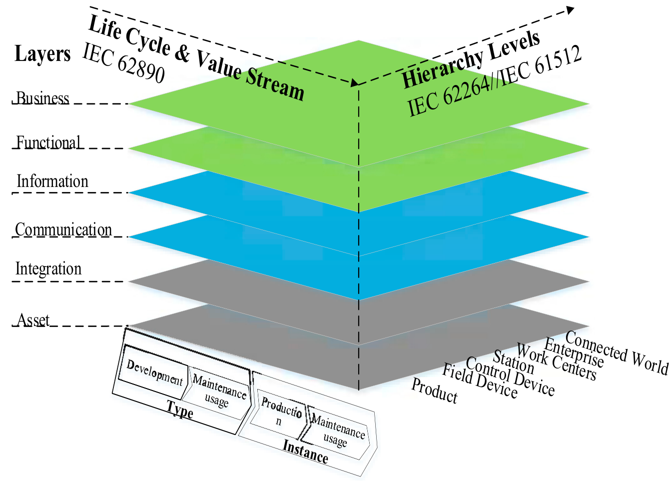

Fig. 4. RAMI 4.0.

The first dimension refers to the common layered concept used in information and communication technologies, which is the core function of CPS. EU Mandate M/490's reference architecture working group proposed the Smart Grid Architecture Model (SGAM) to provide a structured approach for architecture development [6]. The central elements are its five interoperability layers of viewpoints, including business, function, information, communication, and component. Compared with SGAM, the RAMI 4.0 uses the asset layer to replace the component layer, and inserts a new integration layer. These two layers digitally represent various assets of the real world. The communication layer implements a standardized communication protocol and controls the integration layer. The information layer contains relevant data and applies rules in one or more events that initiate processing in the functional layer. The functional layer generates rules and decision-making logic, and it has all necessary functions. The business layer maps the business models and the resulting overall process.

The second dimension represents the associated value streams and the life cycle from planning to design, simulation, manufacturing, then to sales and service. The reference standard for this dimension is IEC 62890 Industrial Process Measurement Control (IPMC) and Automation Systems and Product Lifecycle Management (ASPLM). This dimension is mainly embodied in three aspects. First, it is divided into simulation prototype and physical manufacturing based on IEC 62890 standard. Second, highlighting various parts of industrial production, such as machines and factories, must have both virtual and realistic processes. Third, in the process of value chain construction, industrial production factors are closely linked by digital systems to achieve end-links in industrial production links.

The third dimension describes the functional classification of the Industry 4.0 in different production environments following the IEC 62264 and IEC 61512 standards. Moreover, the product layer is added at the bottom, and the connected world layer is added at the top of the plant.

2.3. Architecture supported by wireless technology

There are many advances in wireless communication technologies, especially in the field of wireless sensor networks. Therefore, wireless technologies have become important parts of researches and innovations in the Industrial Internet, which support application scenarios and demand analysis for it.

Academic and industrial circles all over the world have paid wide attention to the application of wireless communication technologies in the Industrial Internet. Germany plans to provide wide-area network services for the industry by deploying the public 5G network infrastructure, and implement the latest wireless LAN and near-field technologies in the Industry 4.0. There are three major components in the Industry 4.0, including the application layer, network layer and the layer consisting of physical entities. The IIC also attaches great importance to the research of network technologies. The study groups have divided the industrial network into a connection transport layer and a connection frame layer. Wireless technologies, such as Wi-Fi, ZigBee, 2G/3G/4G, become important technologies for connecting the transport layer.

In Ref. [7], an Industrial Internet architecture supported by wireless mobile technologies was proposed, which was based on the demand of the existing industrial production business for the wireless mobile Industry Internet. Referring to this architecture model and the hierarchical structure of German Industry 4.0, an architecture oriented to wireless network is shown in Fig. 5. The architecture consists four layers, including the application layer, the platform layer, the network interconnection layer, and the perception and control layer.

2.3.1. Perception and control layer

This layer is responsible for data acquisition from the physical and human world, and for deep perception and precise control. It consists of physical entities, such as machines and intelligent sensing devices controllers, actuators, material, products, etc. The core technologies include RF technology, emerging sensing technology, wireless network networking technology, and Fieldbus Control Technology (FCT).

Wireless sensor network is usually the main way for information acquisition, which can integrate data from sensor nodes over a wireless network. Then large amounts of data are processed through identification and location technologies, embedded intelligence from various actuators deployed in the field.

Industrial control requires real-time, low delay, high reliability and security of network communication. As the data sensed in the physical processes are reflected on the Internet, control strategies need to be taken by the cyber world and transferred into the physical devices. Industrial Control Systems (ICSs) have computing and communication capabilities and they are critical to infrastructure critical systems. And Supervisory Control and Data Acquisition (SCADA) is usually used to control remote ICSs devices with encoded signals, and these ICSs are typical computer-based systems that have access to the Internet. From a communication perspective, monitoring and control require two-way communication: uplink from sensors to applications, and downlink from applications to actuators.

2.3.2. Network interconnection layer

This layer takes care of network interconnection and end-to-end data flow, the network is the foundation to interconnect industrial systems and promote the transmission and seamless integration of industrial data. It divides the communication networks into an enterprise external network and an enterprise internal network according to their ranges of application. The enterprise external network makes connections between different enterprises, enterprises and smart products, enterprises and users, etc. Moreover, the enterprise internal network connects intelligent machines, products, industrial control systems, people and other entities.

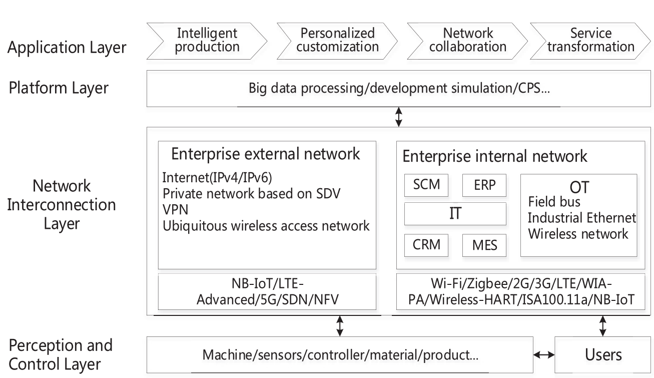

Fig. 5. Architecture of the Industrial Internet.

The enterprise internal network consists of networks based on Information Technology (IT) and Operation Technology (OT). The enterprise IT network connects the information system and terminals. While the OT network performs as an industrial communication gradually infiltrating into the industrial field, which has been used for information collection, non-real-time control, and internal informationization in the factory. Therefore, wireless technologies such as Zigbee, Wi-Fi, 2G/3G/LTE, WIA-PA applied for industrial process automation are already applied in factories. Furthermore, NarrowBand-IoT (NB-IoT) proposed by 3GPP can be applied to industrial information and control scenarios, such as low power consumption and large connections, in the factory.

The enterprise external network under the Industrial Internet scene mainly includes the following four parts: the public Internet based on IPv6, the Industrial Internet private network based on Soft Defined Network (SDN) or VPN, ubiquitous wireless access for massive intelligent products, and support for access and data collection of industrial cloud platforms. The enterprise external network needs to satisfy requirements of high transmission rate, ultra-low latency, safety and reliability, flexible networking, etc. Emerging wireless technologies, such as 5G, SDN [8] and Network Function Virtualization (NFV), can meet these requirements and support the development of the Industrial Internet.

2.3.3. Platform layer

The platform layer executes information fusion, intelligent optimization and decision-making. The essence of the Industrial Internet platform is to apply emerging technologies on the basis of traditional cloud platforms to build a more accurate, real-time and efficient data collection system. This layer is oriented to the digitalization, networking and intelligence of manufacturing industries, and builds an intelligent service system by applying the digital tools, such as big data storage and processing, CPS, resource allocation and optimization. Meanwhile, the platform layer realizes the modeling and software of the industrial technology, and provides various innovative applications for manufacturing enterprises.

2.3.4. Application layer

The application layer analyzes and models the data information stored in the platform layer and forms the required information. This layer provides specific services that solve the problems of information processing and human-machine interface. Typical applications include quality management, energy management, manufacturing execution, equipment operation optimization, etc. Moreover, in Ref. [9], Application Programming Interfaces (APIs) are provided in the application layer for designing a variety of innovative applications (e.g., device failure monitoring, device utilization monitoring, and product processing status monitoring). In addition, developers can accelerate the design of new applications by customizing data collection, transfer and processing, then forms new patterns for intelligent production, personalized customization, network collaboration and service transformation.

3. Key technologies

As a combination of traditional industrial systems and new information technology, the Industrial Internet requires the support of a variety of key technologies, including intelligent sensing and control technology, network interconnection technology, data processing technology, and security technology. The key technologies involved in the Industrial Internet are provided in this section.

3.1. Sensing and control technology

In the Industrial Internet, a large number of sensors for acquiring data and controllers for executing decisions are deployed in the smart factory.

Intelligent sensing and control technologies are important to the interaction between the cyber technologies and the physical world.

3.1.1. Sensing

RFID is an important technology in industrial sensing, which uses radio waves to transmit and automatically identify people or objects [10]. In general, an RFID system consists of a tag, a reader and a middleware. The reader transmits radio frequency signals through the antenna, and the tag obtains energy from the radio wave and sends information to the computer.

Industrial Wireless Sensor Networks (IWSNs) are more adaptable to harsh industrial environments based on WSNs, which integrates embedded computing technology, sensor technology, and distributed information processing technology. It can collaboratively monitor, sense and collect information of different monitoring objects within the Industrial Internet distributed area in real time. IWSNs offers competitive advantages compared with traditional wired industrial monitoring and control system, including self-organization, rapid deployment, flexibility, lower cost and inherent intelligent-processing capability [11].

3.1.2. Control

The ICSs play an important role in infrastructure-critical systems, such as power, water distribution, gas pipelines, etc. The ICSs face new opportunities with the development of Information and Communication Technology (ICT) and the control technology. Reliable methods are needed to collaboratively design control and automation systems in the Industrial Internet. In Ref. [12], hybrid approaches for modeling and implementing distributed controllers in the Industrial Internet were discussed, verifying that hybrid control is suitable for Industrial Internet applications and can be extended appropriately.

3.2. Network interconnection technology

The networking architecture of the Industrial Internet is shown in Fig. 6, which takes smart factory as an application example. The network inside the smart factory mainly includes an OT network and an IT network, which connect sensors, controllers and smart devices from the physical layer. The network outside the smart factory connects the companies, users and other factories. The interconnection of heterogeneous networks in the Industrial Internet is essential for data transmission as well as data processing. Communication technologies in the network interconnection layer can be divided into wired and wireless, depending on ways of transmission. Fieldbus technology and Industrial Ethernet technology are commonly used wired technologies in the industrial field. While wireless technologies, such as Wi-Fi, Zigbee, 2G/3G/4G, have become important for connecting transport layers. The Industrial Internet pays more attention to the application of wireless technologies because the wireless network has obvious advantages compared with the wired network. Firstly, the deployment of wireless networks can significantly reduce the cost of construction and maintenance. In addition, wireless networks can realize the flexible movement of equipment. Finally, wireless technologies can be widely deployed in various industrial environments, which breaks through the limitations of cable.

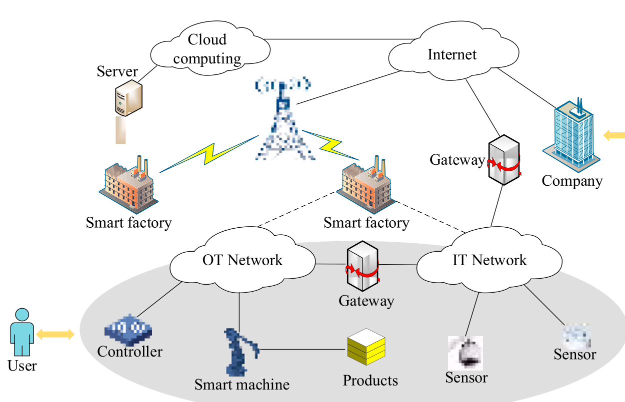

Fig. 6. Components of the Industrial Internet. The Industrial Internet were discussed, verifying that hybrid control is suitable for Industrial Internet applications and can be extended appropriately.

3.2.1. Wired communication technology

Fieldbus: Fieldbus connects field devices, field controllers and man-machine interfaces, which serves as the basis of digital communication in the factory [13]. Fieldbus is a combination of development automation, computer technology and smart instruments, and it helps the industrial automation control technology develop towards the direction of intelligence and integration. PROFIBUS, WorldFIP, Foundation Fieldbus, DeviceNet, CAN are representative technologies that belong to Fieldbus and they provide abundant solutions to deal with different types of data transmission and applications in industrial networks.

Industrial Ethernet: Industrial Ethernet is the product of extending Ethernet and Internet technologies applied to industrial measurement. The Ethernet used by Internet and common computer network is not suitable to meet the requirements of industrial environments. The technical subject of Industrial Ethernet is formed through improving the real-time communication of Ethernet and adding corresponding control application functions. Industrial Ethernet mainly consists of HSE, Modbus/TCP, PROFINET, Ethernet/IP protocols and provides advantages of high communication rate, good interoperability, and easy connection to the Internet, and abundant hardware and software support.

In contrast to Fieldbus, Industrial Ethernet networks allow the transmission of large amounts of non-time critical data as well as hard real-time process data communication. In general, specific configuration tools are used to set up the network, including integrating the necessary hardware descriptions of the connected devices, setting cycle times and declaring network masters.

TSN: Time-Sensitive Networking (TSN) has the advantages of limited delay variation and low data loss for time or mission critical traffic, making it applicable and economical in industrial automation networks. For example, in an industrial distributed control system, TSN can be used in machine-to-machine communication and motion control application. In addition, faced with the strict requirements of reliability and real-time for industrial applications, a lot of research work have proposed to deploy fog computing as a solution. Thus, it is critical to choose relative technologies to connect fog nodes to the industrial smart devices. In Ref. [14], TSN is advocated as a promising solution that provides related protocol services for fog computing in the Industrial Internet, and a configuration agent architecture is proposed to guarantee requirements of low latency and timely response.

PON: Passive Optical Network (PON) technology has been considered as a key component for high-speed Internet access. Ericsson and other major vendors have used the PON technology in the broadband access portfolios. PONs can support applications, such as human-to-human and machine-to-machine communication, and have different traffic patterns as well as quality of service requirements from classical data users [15].

3.2.2. Short-range communication technology

Wi-Fi: Wi-Fi is widely adopted in industry and enterprises, mainly used for the connection of internal IT networks. The applicability of Wi-Fi can be extended to industrial hard real-time applications due to its ubiquitous coverage in industrial environments. In addition, it has the potential to achieve rapid IT/OT convergence and manufacturing process flexibility. However, Wi-Fi is usually considered as an energy-consuming solution, but due to advances in the implementation technology, some researchers studied the suitability of Wi-Fi as a candidate for low-power industrial demand, then low-power Wi-Fi can easily integrate with existing infrastructures, built-in IP network compatibility with familiar protocols and management tools.

ZigBee: ZigBee is one of the well-known standards for WSNs. As

ZigBee supports plant monitoring and control functions with its adaptive and scalable wireless architecture, it can be used as an advanced metering infrastructure for smart grids, a monitoring system for intelligent buildings and industrial control management systems, etc. Since Wi-Fi and ZigBee share the same frequency in the unlicensed 2.4 GHz industrial science medical band, [16] proposes a solution for the coexistence of the two technologies to resist interference, and to realize optimal wireless resource allocation and reliable transmission communication in the Industrial Internet.

3.2.3. Dedicated industrial wireless communication technology

WirelessHART: WirelessHART is widely used in IWSNs with its simple configuration, flexible installation and easy-to-access instrument data. Besides, WirelessHART also has powerful and reliable communication capabilities, its reliability and real-time performance are essential to industrial production, such as target tracking, industrial control, and remote monitoring. The generally accepted WirelessHART protocol architecture based on the OSI seven-layer protocol is shown in Fig. 7. The scale of a WirelessHART network is limited to 100 sensor/actuator devices due to limited computing power of the network manager [17]. In practical Industrial Internet applications, data flow scheduling and channel resource management are usually required in multiple coexisting WirelessHART networks to achieve reliability and timeliness.

ISA100.11a: ISA100.11a is released as a wireless standard for process control and related applications in the industrial automation. It is based on hybrid channel Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). ISA100.11a aims to realize flexibility, high reliability and integrated security in multiple industrial applications. At present, several works integrate wireless field devices by jointly using WirelessHART and ISA100.11a technologies, aiming to support condition monitoring of instruments or smart devices, and to extend existing plant control networks. The similarities of WirelessHART and ISA100.11a are shown as follows:

- Using the IEEE 802.15.4 standard for Low-Rate Wireless Personal Area Networks (L-R WPAN) to define the radio.
- Similar mechanisms for forming the wireless network and transporting data to and from the gateway.
- Using 2.4 GHz ISM (Instrumentation, Scientific and Medical) radio spectrum band and requiring no licensing.
- Similar graph routing, source routing, security and centralized network management functions.

Besides, the typical differences of two standards are listed in Table 1 [18].

WIA-PA/FA: WIA-PA (Wireless Networks for Industrial Automation-Process Automation) is the standard of industrial wireless communication architecture and specification for process automation developed by the Chinese Industrial Wireless Alliance (CI-WA). It supports routers, gateways, field devices and handheld devices. As illustrated in Fig. 8, WIA-PA networks adopt 2-layered star-mesh network topology [19]. The first layer is a mesh network that consists of gateway devices and routing devices. The second layer is a star structure constituted by router devices and field devices or handheld devices. Field devices, including wireless sensors, actuators and controllers, can be used to realize fields monitoring and control in the production field. Workers use handheld devices to interact with the WIA-PA devices for diagnosis, configuration, maintenance, etc.

Table 1
Comparison between WirelessHART and ISA100.11a.

WirelessHART	ISA100.11a
Every field instrument must be a router (real mesh network)	Field instrument may not be a router (battery life)
Routing at the network layer; 16 bit address	Wireless subnet; Routing at DLL using subnet short address; Backbone: routing at network layer using IPv6
Time slot of 10 ms, a unique channel hopping algorithm	Configurable time slot, 3 types of channel hopping, 5 hop sequences (may cause inter-operability problems)
Complete stack network in wireless technology, but no IP based	IPv6 network in the backbone connecting wireless subnets
Supports unicast and broadcast	Supports unicast, broadcast, duocast and n-cast
Transport layer with acknowledgement(more reliable)	UDP-based transport layer(faster)
Application layer uses HART7	No define application protocol
Command oriented: command-response protocol	Object oriented: virtual modeling of devices

3.2.4. Cellular wireless communication technology

2G/3G/LTE: The rapid development of mobile network technologies has a profound impact on industry fields, such as network connection for intelligent products, large-scale long-distance mobile devices or vehicles, and handheld terminals. [20] also studied the commercial Time Division-Synchronous Code Division Multiple Access (TD-SCDMA), which can provide a relatively cost-effective way to build a full-featured 3G core network. With the wider commercial deployment of TD-SCDMA, a large number of data services and value-added voice services can provide higher transmission rates and better Quality-of-Service (QoS) for the Industrial Internet.

GE Digital collaborated with Nokia and Qualcomm Technologies to successfully demonstrate a private LTE network for the Industrial Internet with their platforms and technologies meshed together.

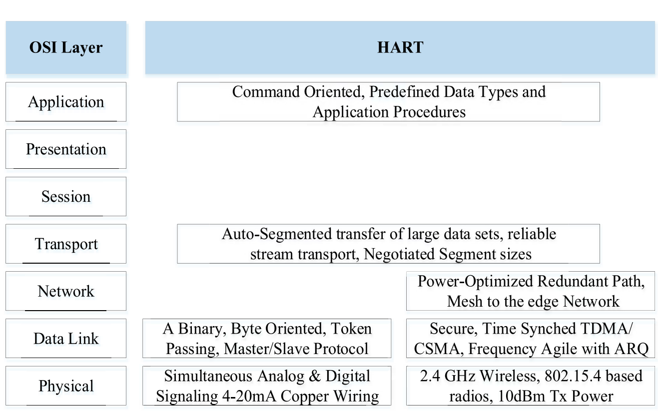

Fig. 7. Architecture of HART communication protocol.

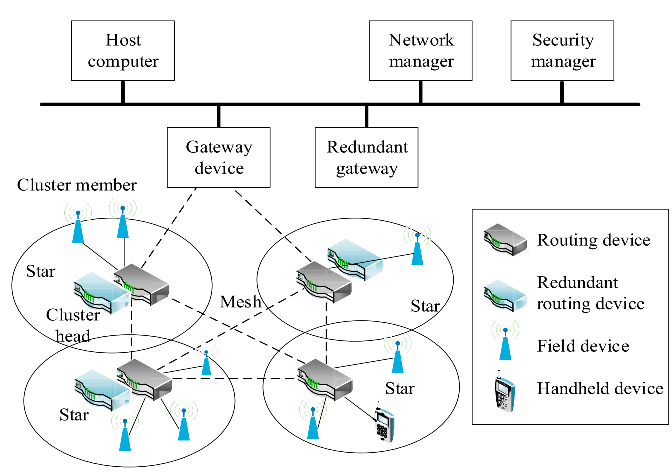

Fig. 8. 2-layered star-mesh network topology of WIA- PA.

Industrial companies usually operate at remote sites, making the connection challenging. Private LTE-based networks utilize LTE-based technologies in shared/unlicensed/dedicated-licensed spectrum, which helps improve performance and reliability for these industrial connections.

NB-IoT: The Narrow-Band Internet of Things is a cellular technology proposed in 3GPP Release 13, which has great potential to meet the huge demand for machine-type communication in the Industrial Internet. The NB-IoT is considered one of the most promising Low Power Wide Area (LPWA) technologies, with advantages of ultra-low power consumption, wide area coverage, long operation life and massive capacity.

The specific application scenes of the NB-IoT include smart cities, smart buildings, intelligent environment monitoring, intelligent user services and smart metering, which can be closely connected with the Industrial Internet. In the process of industrial production, the factory can collect the operation and environmental parameters through the NB-IoT technology and then optimize the production process. For instance, in Ref. [21], the NB-IoT technology is introduced into industrial network to reduce transmission delays, and a path selection algorithm is proposed to improve the schedulability of the industrial system.

5G: Mobile communication technology has developed rapidly over the past few decades. The major requirements of the 5G system include 1–10 Gbps data rates in real networks, 1 ms round trip latency, enormous numbers of connected devices, reduction in energy usage by almost 90%. The Industrial Internet puts a wide range of requirements on the network, such as performance (latency, throughput), security and reliability. The introduction of 5G will solve problems such as low latency, and provides high reliability, high speed and high density deployment in industrial systems [22].

Three scenarios of 5G have been identified by the ITU Radio communication sector (ITU-R), including enhanced Mobile BroadBand (eMBB) scenario, massive Machine Type Communication (mMTC) scenario and Ultra-Reliable and Low Latency Communication (URLLC) scenario. The typical applications of eMBB include 4 K High Definition (HD) video, virtual reality, augmented reality, etc. Augmented reality and virtual reality have potential applications in the field of manufacturing, such as the design, production and maintenance of the products. mMTC supports large-scale IoT devices. The current 3G and 4G transmission networks are not suitable for large-scale machine connections within the factory. Millimeter wave technology can be adopted in 5G, which will meet the needs of a large number of node communication in intelligent manufacturing. URLLC scenario refers to applications that require low latency and high reliability, such as driverless and industrial automation.

In addition, different aspects of the Industrial Internet have different QoS requirements for the network. The 5G network slicing technology can flexibly adjust QoS requirements based on a common network platform. In Ref. [23], a novel 5G-based network slicing framework is proposed, which can support the flexibility expected by the next-generation manufacturing processes and realize the inter-factory cooperation.

3.3. Data processing technology

In the industrial process, a large amount of data will be generated, which needs real-time calculation, analysis, storage and other processing methods. Therefore, data processing technology is a key technology to improve the core competence and efficiency of the Industrial Internet. Big data analysis, cloud computing, edge computing technologies used in the Industrial Internet will be introduced in the following sections.

3.3.1. Big data processing

A large number of industrial data will be generated in the process of Industrial Internet applications. Industrial big data has the characteristics of huge data volume, wide data distribution, complex structure, diverse data processing speed and high confidence requirement for data analysis. Industrial big data includes data preprocessing technology, data storage and management technology, data analysis and mining technology, big data visualization technology and other key technologies [24].

Data preprocessing technology: The II generates massive amounts of data from production equipment, products, information management, factory exteriors and other processes. Data preprocessing technology can realize the preliminary cleaning as well as integration of data, and associate data objects with industrial systems. Thus, it will eliminate redundancy to avoid meaningless industrial data, reduce storage costs and improve analysis accuracy.

Data storage and management technology: Distributed storage, cloud storage and other technologies in the II can be used to achieve the management of data economically, safely and reliably. MEC, cloudlets and fog computing services can be used to perform big data processing and analysis closer to data sources. Current technologies can achieve the goals of remote data storage, fast access to large data and so on.

Data analysis and mining technology: Data analysis and mining technology discovers valuable information and generates knowledge from a large number of noisy and random databases. At present, there are many technological achievements related to big data analysis. Since industrial data has a wide range of application objectives, it is necessary to design feature algorithms in depth with application objectives.

Big data visualization technology: Big data visualization technology is an important method to help big data acquire a complete view of data and discover data values [25]. Seamless integration of big data analysis and visualization enables them to perform better in big data applications in the Industrial Internet.

3.3.2. Cloud computing

Cloud computing is a new universal Internet-based technology through which information is stored on servers and delivered to customers as a service. It was proposed based on various researches of virtualization, distributed computing, utility computing and software services. The currently accepted definition of cloud computing is “a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction”, which was defined by the National Institute Standards and Technology (NIST) [26]. Based on recommendations from NIST, an ideal cloud should have five characteristics, namely, on-demand self-service, broad network access, resource pooling, rapid elasticity, and measured service.

Cloud computing services represent a new business model that provide accessible and available services to users at any time, these services enable multiple users to access service resources while ensuring service reliability. At present, the integration of Mobile Cloud Computing (MCC), cloud computing and mobile services significantly improves data transmission efficiency and processing power in mobile networks [27]. The recognized cloud computing service models mainly include Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS) [26]. With the deepening and continuous development of cloud computing in the field of Industrial Internet, the cloud computing model has a relatively complete technical system, including resource-aware technology, cloud service environment management and construction technology, virtualized cloud service operation technology, and human-machine interactive technology.

The Cloud Radio Access Network (*C*-RAN) has been proposed as an application cloud computing in the radio access network to achieve large-scale cooperative processing gain [28]. The cloud computing-based radio access infrastructure will provide on-demand resource processing, latency-aware storage and high network capacity when needed [29]. Furthermore, Heterogeneous Cloud Radio Access Networks (H-CRAN) were presented to enhance both spectral and energy efficiencies [30]. Applying *C*-RAN and H-CRAN architecture and corresponding resource allocation solutions to the Industrial Internet will significantly improve energy efficiency. The application of cloud computing in the Industrial

Internet involves various fields, such as manufacturing, health care, and transmission. Cloud computing is gaining greater competitiveness through greater flexibility, lower cost and optimal resource utilization.

Cloud manufacturing is researched and promoted as an emerging technology in the Industrial Internet, which is defined as a service-oriented, customer-centered, demand-oriented manufacturing model. It can be applied to the automation of Industrial Internet, ICS, and machine-to-machine cooperation. Besides, cloud manufacturing can use distributed knowledge for intelligent service composition and adaptive resource planning, then realize digital visualization on the cloud [31].

3.3.3. Mobile edge computing

As data is increasingly produced at the edge of the network, cloud computing technology is not efficient to process the data produced at the edge of network. MEC was proposed as an emerging prominent computing paradigm to implement optimization and virtualization locally. ETSI defined MEC as a new technology that provides an IT service environment and cloud-computing capabilities at the edge of the network, within the Radio Access Network (RAN) and in close proximity to mobile subscribers.

The combination of the Industrial Internet and MEC has attracted attention. The Industrial Internet requires a high demand for computing and data processing capabilities, while MEC provides close-range cloud computing services for smart devices in the Industrial Internet through edge servers. The edge server is a mobility-enhanced and resource-rich data center that provides fast access to Internet and users, and it reduces the computational burden of devices through proximity-based services. MEC can save the response time, and reduce overall traffic load and energy consumption. Thus, the introduction of this technology can effectively optimize real-time network transmission performance.

Although MEC shows outstanding advantages in the Industrial Internet, it faces unprecedented challenges, such as energy delay that has constrained MEC offloading and the resource allocation for various edge devices. Besides, the MEC system must handle rigorous latency constraints while processing massive amounts of data. In the meanwhile, resources and running applications of individual edge servers for their tight connections are of great importance. Thus, novel virtualization technologies are required to enhance flexibility of hardware, isolation and scalability as a solution.

The existing MEC resource allocation works mainly focus on MEC offloading, while future research will emphasize more specific MEC attributes, such as communication, compute offloading [32], security and virtualization. [33] illustrates an example of MEC in the application of IIoT, in which devices, such as mechanic hands, industrial camera, offload computing-intensive tasks to nearby edge servers to save energy and reduce processing delays. In the Industrial Internet application scenario, MEC services can be extended to various types of smart objects from sensors [34] and actuators to smart vehicles.

4. Applications

Under the dual promotion of information technology and industrial technology, the Industrial Internet has been continuously applied in various fields and has begun to change our lives subtly. Driven by emerging wireless communication technologies, the Industrial Internet can achieve end-to-end integration in interconnection, improve industrial efficiency and meet the needs of industrial intelligence and digitization. Considering these advantages, industrial powers attach great importance to applications of the Industrial Internet. As a result, the Industrial Internet is currently used in several vertical industries: smart manufacturing, intelligent transportation, medical health, commercial aviation, and power production.

4.1. Smart manufacturing

Smart manufacturing is a key application of the Industrial Internet. The rapid development of information technology has promoted the transformation and upgrading from traditional manufacturing to intelligent manufacturing. Smart manufacturing can achieve the access of industrial devices, the scheduling and coordination of resources through the application of integrated information technology, such as intelligent sensing, emerging industrial networks and industrial big data platforms in the Industrial Internet.

The manufacturing powers of industry have proposed different strategic plans to improve the core competitiveness in the industrial field, and the CPS plays an important role in the field of intelligent manufacturing. The United States advocates the Industrial Internet, and in report [35], it proposes to integrate the CPS, the IoT, automation, big data and cloud computing together to achieve data synergy and sustainable production. Germany has proposed Industry 4.0, the core of which is to achieve smart manufacturing through CPS. China also has proposed China Manufacturing 2025, and intelligent manufacturing, such as intelligent equipment and smart factory, is leading the change of manufacturing mode.

A 5C architecture of the CPS for Industry4.0-based manufacturing systems is proposed in Ref. [36], which provides guidance for the development of intelligent manufacturing. Therefore, in smart manufacturing, it will transform traditional factory management to a self-aware, self-predicting and self-configuring factory with CPS technologies. The framework shown in Fig. 9 illustrates that the deployment of smart manufacturing systems follow a bottom-up approach in terms of the 5C architecture of the CPS, and the information gathered from various machines provides the plant with self-configuration and self-maintenance capabilities. Factories can achieve better product quality and system reliability by implementing the CPS through smarter and more flexible manufacturing equipment. [37] provides four representative examples of the CPS in smart manufacturing, including service oriented architecture, cloud manufacturing, adaptive manufacturing systems and model-driven manufacturing systems.

A smart factory is an intelligent manufacturing solution that provides flexible and adaptive production processes to solve problems in production facilities. This solution can be related to automation and considered as a combination of software, hardware and mechanical. The deployment of smart factories can effectively lead to manufacturing optimization, thereby reducing unnecessary labor and resource waste. At present, a smart factory of Industry 4.0 can be realized by widely applying existing technologies while actively coping with technical challenges. Some studies combine industrial wireless networks, cloud, fixed or mobile terminals with intelligent artifacts (such as machines, products and conveyors) to propose a smart factory framework. The reference architecture of smart factory generally consists of smart devices, smart machines, smart engineering, smart logistics, smart grid,

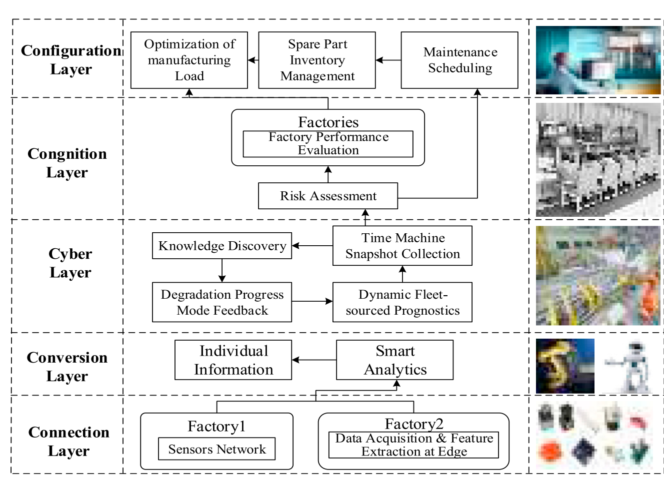

Fig. 9. Smart manufacturing systems based on 5C CPS architecture.

smart suppliers, etc.

Emerging information technologies and wireless communication technologies are driving multiple processes of smart manufacturing transformation, including automated and programmable product line, process automation, supply-chain optimization, remote human assistance, remote control of equipment, etc.

The Industrial Internet is a key comprehensive information infrastructure supporting intelligent manufacturing. Based on real-time network transmission and efficient data analysis, the Industrial Internet supports the intelligence of individual machines to production lines, workshops, factories and even industrial systems under the premise of security and credibility.

4.2. Intelligent transportation

Researches on Intelligent Transportation Systems (ITS) were introduced more than twenty years ago and the ITS has been continuously improved and applied with the development of technology. Then with the rise of the IoT, the ITS has been gradually developed to improve transportation efficiency, reduce traffic load and ensure traffic safety. [38] integrates IoT technology and ITS technology, and discusses the setting of a new generation of ITS. With the application of the Internet, wireless communication networks and sensor technologies, ITS has great potential for development in the next few years.

Technologies of the Industrial Internet such as CPS, MEC and fog computing applied in the field of transportation, have received extensive attention. The ITS based on CPS can process real-time processing and transmission of signals, analyze and predict traffic behaviors and conditions through various intelligent sensing devices, then the ITS will achieve autonomous coordination between people and vehicles, vehicles and vehicles, vehicles and equipment. By integrating CPS into infrastructures, vehicles and roads, the ITS can achieve driver assistance, avoid collisions, improve travel time, reduce congestion and provide advanced energy-saving control.

Several architectures of Transportation Cyber Physical Systems (T-CPS) are proposed, a framework of which is shown in Fig. 10. The T-CPS aims to solve the traffic problem by using the CPS method based on the integration of 3C (computing, communication, and control) technologies [39]. Then, it can achieve information exchange, system coordination and optimization decisions in the transportation system. The rapid development of mobile Internet provides new technical support and development opportunities for intelligent transportation.

In addition, the wireless sensing and the monitors can monitor the vehicle condition, driving environment and external conditions. Vehicle Communication System (VCS) is one of the network platforms of the ITS, which supports message exchanges between vehicles and between vehicles and infrastructure. However, security is one of the main problems in the VCS, thus the Industrial Internet can provide technologies and methods to improve transportation safety. [40] proposed a framework based on the concept of blockchain to provide secure management in the ITS.

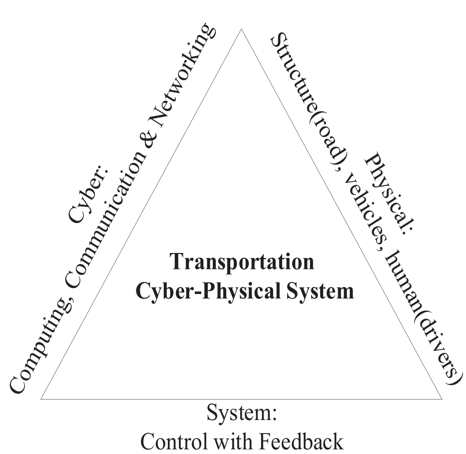

Fig. 10. Transportation cyber physical system.

4.3. Medical health

Smart health uses the advanced technologies of Industrial Internet to create interaction between patients and medical staff, medical institutions and medical devices by creating a health record regional medical information platform. The intelligent management of the Industrial Internet supports digital collection, processing, transmission and control in hospitals, and promotes the development of medical service systems in the direction of intelligence and modernization.

Some relevant use cases in the medical health where the Industrial Internet could play a role are discussed below.

4.3.1. Health and wellness monitoring

Healthcare monitoring involves the use of various types of sensors and wearable devices to track health-relevant indicators. At present, such devices use short-range communication technologies, then applications (e.g., smartphones) use the data detected by these devices to help individuals monitor and manage health or disease (e.g., blood glucose level management). There has been a wide range of emerging applications based on the cloud, the IoT or other wireless communication networks currently used in health management and monitoring. From these studies, it can be seen that healthcare monitoring is one of the most revolutionary potential applications. The Industrial Internet based on cloud computing and big data will play an important role in health monitoring applications. Healthcare Industrial IoT (HealthIIoT) has significant potential in these applications. A conceptual illustration and scenario for HealthIIoT ecosystem is shown in Fig. 11. HealthIIoT seamlessly collects data from patients by using a large number of interconnected machines, wearable devices (devices and sensors) and cloud computing technologies [41].

Modern wearable devices, such as Fitbit health monitors, Pebble smart watches and Google glasses, have inspired new ways to promote self-management and self-monitoring in the Industrial Internet.

4.3.2. Remote healthcare

When the health monitoring, treatment or consultation of the patients need to be carried out outside the traditional medical institution (hospital or clinic, etc.), doctors and the patients can communicate and complete the treatment process through telepresence facilities and video conferencing. Sensors, smart devices and wireless transmission technologies in the Industrial Internet can supplement these processes. Some works established remote healthcare systems based on WSNs. Family and friends can achieve remote care by inferring the condition of patients at home through WSNs, and the information can help to detect early symptoms of the disease and prevent its progression. The remote healthcare system can be used in a home or hospital to form a telehealth

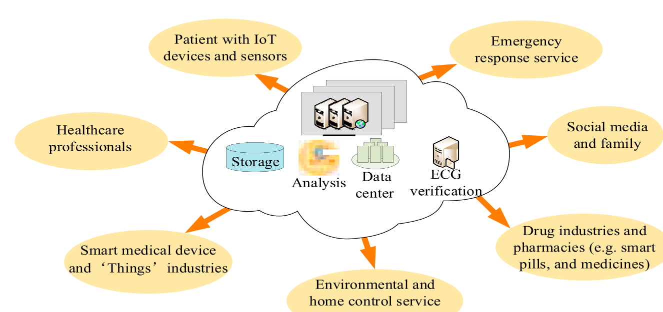

Fig. 11. HealthIIoT ecosystem.

system between the home, the community, and the hospital by wireless communication between the wireless physiological sensor nodes and the care base station [42].

4.3.3. Assisted surgery and remote surgery

A specialist can remotely assist another doctor in the operation through the transmission of remote data and video presentation. For instance, a doctor could watch a live 3D video feed and provide real-time guidance so that another doctor from another place can locally perform a surgery on a patient. The surgeon is allowed to remotely operate the surgical robot to perform surgery on the patient. Wireless communication technology is required to enable reliable transmission of video and audio feeds and data between surgeons and remote surgical robots in real time [43].

4.4. Commercial aviation

Aviation is a typical high-tech manufacturing enterprise. With a complete research and development system, aviation itself is a large-scale collaborative supporting industrial system, which has an inherent demand for digital development and flexible, intelligent production. The Industrial Internet with digital virtualization can achieve product design, manufacturing and testing in a cyber space, all of which can be accomplished virtually. Problems of design, processing, manufacturing and testing will be found constantly in this process. Then the virtual model can be adjusted directly, which is mapped to the production process and the test process later.

The integration of a cloud-based analysis with industrial machinery is driving the development of the Industrial Internet, which enables predictive maintenance of aviation through continuous data collection, monitoring and advanced analysis applications when aircraft components need to be repaired or replaced [44]. Staff can control the machine-engine through big data analysis and complex algorithms. GE provides advanced technologies critical to superior aircraft performance and brings a future for the commercial aircraft.

4.5. Energy

Manufacturing and development sectors consume more energy than other industries. In the industrial sectors, there are still some gaps in intelligent operation and maintenance services, life cycle management, performance monitoring and fault warning of complex equipment, which lead to low utilization rate, frequent failure and long maintenance cycle of the equipment. The level of equipment management is generally difficult to meet the requirements of low energy consumption and green economic development. Since operating costs will have a significant impact on major decisions in the production and maintenance processes, the Industrial Internet connects devices to smart sensors, uses electricity only when needed, and consumes less energy in dormant mode to realize energy conservation.

At present, all countries are striving to solve the problem of energy consumption in manufacturing. There are many possibilities to reduce energy costs and pollution emissions in manufacturing plants. [45] discusses issues related to the combination of production systems, process energy and facility energy to improve manufacturing sustainability. Factories can adjust their production processes to a desired efficiency level by measuring the energy usage of each manufacturing process in real time. Real-time monitoring of production systems and collection of performance data have a positive impact on improving proactive maintenance. Industrial Unmanned Aerial Vehicles (UAVs) are capable of automatic detection and measurement at anytime and anywhere, which is a promising solution for power line detection. And it is essential for realizing the future Industrial Internet ecosystem framework. An energy-saving Industrial Internet of UAVs (IIoUAVs) architecture is analyzed in Ref. [46], which takes advantages of multiple benefits while minimizing energy consumption. [47] has studied on the UAV access selection and BS bandwidth allocation in UAV-assisted IoT communication networks, which aims to balance available communication resources and service costs.

Emerging autonomous technologies (such as loT, Industrial Internet) and new market demands are promoting the manufacturing transformation. Based on the implementation of Industry 4.0, [48] proposes a smart factory energy management method based on the IoT paradigm, which integrates energy data into production management. At present, many industries put green manufacturing and energy efficient production processes as their prime concern. Data acquisition in the Industrial Internet relies heavily on a large number of sensor nodes and smart devices, and WSNs are one of the main sources of energy consumption. [49] proposes a three-layer framework, which applies a new sleep scheduling protocol to improve energy efficiency, balance the flow load, and extend the life of the entire system. In the meanwhile, due to the openness of the wireless channel, it is necessary to jointly consider reducing the power consumption of the sensor nodes and improving the security performance when designing models or protocols.

5. Research challenges and future trends

The Industrial Internet pays close attention to the value brought by the deep integration of the industrial field and the information field, which is the key foundation for building modern industrial systems and realizing intelligent manufacturing. It can fully utilize the potential of physical equipment and process materials, improve production efficiency and optimize resource allocation. It is an important way to realize intelligent, digital and networked manufacturing. The Industrial Internet involves interdisciplinary fields, and there are differences in the standard definitions of Industrial Internet between industry and academia. With the continuous evolution of Industrial Internet, there exist various research challenges and open issues for future research work in the Industrial Internet. In this section, several research challenges and future research trends of the Industrial Internet are introduced.

5.1. Technical challenges for IWSNs

IWSNs are provided with self-organizing, rapid deployment, flexibility and inherent intelligent processing capabilities. IWSNs can be applied to industrial automation and improve system efficiency and productivity. However, complex Industrial Internet environments put forward higher technical requirements on IWSNs. The main technical challenges faced by IWSNs are discussed as follows.

5.1.1. Harsh environments and interference avoidance

Harsh industrial environments (such as corrosive environment, high humidity, vibration, dust, RF interference, etc.) are likely to lead to failure of industrial sensor nodes, thus affecting the connection and data transmission of the Industrial Internet. At the same time, there are many different wireless communication technologies in the Industrial Internet. Efficient solutions need to be proposed to avoid interference. Innovative techniques such as radio resource management with complex algorithms can help IWSNs avoid interference [50].

5.1.2. QoS requirements

Various applications of the IWSN need to meet different QoS requirements and specifications. First, wireless links exhibit widely varying characteristics in time and space, and their capacity is constantly changing due to environmental changes and interference, thus failing to meet QoS requirements. In addition, the IWSN also has different QoS requirements for transmission delay, system reliability and network throughput. The data collected by the sensor is usually time-sensitive, so it is necessary to ensure end-to-end data delivery in real time. [51] proposed some error control techniques to decrease the number of retransmissions, but innovative techniques that save energy with lower complexity need to be put forward as improvements.

5.1.3. Resource constraints

Sensor nodes have limited battery energy supply, memory storage and computational processing due to their physical conditions. Therefore, the design and implementation of the IWSN are subject to several constraints. Due to the refresh rate required in process automation, it is difficult to save a lot of energy by minimizing the duty cycle of wireless field devices. The maintenance period of wireless devices is shorter than that of wired devices, and the regular maintenance of massive nodes causes great cost [52].

5.1.4. Security

The IWSN may encounter many new security attacks and intrusions, including eavesdropping transmission, modification, interruption and malicious modification of sensor data because of its own characteristics. How to integrate security mechanism into the whole automation system in an effective way is a key issue. More detailed challenges about communication safety and security in the II are discussed in the following section.

5.2. New challenges of ICT

The Industrial Internet integrates Internet-based ICT into a complete industrial chain to make industrial production process more efficient and adaptable. Various intelligent ICT technologies, such as the Internet, cloud computing, embedded hardware and software can realize personalized products and services, adaptability, flexible processes of production chain and supply chain.

At present, a large number of researches on the Industrial Internet are not mature enough to be applied to actual industries, and the development process is relatively slow. There are many reasons involved. From the perspective of the ICT technology, the Industrial Internet is based on the development of the ICT environment and has strict requirements of high security, ultra-reliable, low-latency, and large connections, therefore the ICT technology needs to adopt adaptive optimization.

Due to various data transmission requirements of the Industrial Internet, the rapid increase in data rate and processing power of the ICT systems require many researches to improve the energy efficiency, and thus new challenges have arisen. The application of ICT in the Industrial Internet involves many technologies such as the IoT, industrial automation, connectivity and ubiquitous information, network security, intelligent robotics, product lifecycle management, semantic technology and industrial big data. [53] analyzes many challenges and trends related to the visual computing technology mentioned in the vision of Industry 4.0.

5.3. Security and privacy challenges

Under the trends of the open, interconnected and intelligent development in the industrial field, the Industrial Internet is facing severe security challenges. The integration and innovation of the Internet and industry continuously promote to connect a large number of industrial equipment and infrastructures to the public internet. If the network is attacked unfortunately, it will cause huge losses and even endanger public life. The openness of the control environment makes it possible for the threat of the external Internet to penetrate into the factory control environment. The intellectualization of equipment also makes the devices and products directly exposed to network attacks, then viruses and hackers have chances to attack the enterprise network. With the development of information technology, the protection of data and privacy is facing unprecedented challenges. Exhibition, network IP, wireless and flexible information networking will also bring greater security risks to the factory network. In the future, the Industrial Internet will mainly face the following security problems.

5.3.1. Equipment security issues

In future intelligent manufacturing, equipment and products will integrate with general embedded operating system and application software, which will directly lead to a large number of devices exposed to network attacks and virus threats. The main security challenges faced by intelligent devices and products include chip security, application software/hardware security, embedded operating system and functional security.

5.3.2. Network security issues

The existing TCP/IP protocol attack methods are mature enough to attack the factory network directly. Smart grids are promising applications in the Industrial Internet, but increased interconnection and integration will also introduce network vulnerabilities into the grid. In the meanwhile, communication systems are vulnerable to attacks such as illegal intrusion, information leakage and denial of service.

5.3.3. Control security issues

Due to the high requirement of real-time and reliability of industrial control, additional information security functions, such as authentication, authorization and encryption, will be reduced, resulting in insufficient information security protection capability. The integration of the IT and the OT makes it possible for network attacks to penetrate from the IT layer to the OT layer and from outside to inside of the factory.

5.3.4. Application security issues

Complex industrial applications put forward requirements to improve network security isolation and security assurance capabilities. Application software and industrial cloud platforms will face traditional security challenges such as Trojan horse virus and vulnerabilities.

5.3.5. Data security issues

Industrial big data is numerous, complex, and openly shared inside and outside the factory. As a result, there will be many security threats such as data loss, leakage and tampering.

5.4. Standardization

Standardization of the Industrial Internet can improve the interoperability of different applications or systems. Serious standardization processes and extensive coordination are required to ensure that devices and applications from different countries can exchange information with each other. Different companies and alliances in various countries have proposed numerous Industrial Internet standards, yet there is not a recognized uniform Industry Internet standard.

Standardization plays a key role in the Industrial Internet because it helps resolve inter-operability, compatibility, reliability, security and efficient operation between heterogeneous solutions. [54] studies the status of Industrial Internet standardization, and the results show that standardization in the field of Industrial Internet has just emerged. At present, all walks of life need to speed up the strategic layout, accelerate the technical standardization process related to the Industrial Internet, and complete the standard setting for domestic and international cooperation.

5.5. Future trends

With the continuous development of emerging science and technologies such as fog computing, blockchain [55] and a new generation of artificial intelligence, the technical system of the Industrial Internet is constantly improved. Though the Industrial Internet faces many challenges, in the meanwhile, it has broad prospects for development. We discuss some future research trends of the Industrial Internet as follows.

5.5.1. Integration of fog computing and Industrial Internet

Fog computing extends powerful capabilities of cloud computing to the edge of the network. Cloud-based computing may encounter latency issues due to limited capacity of the fronthaul, and fog/edge computing solves real-time applications that are not suitable for the cloud at the edge of the network and distributed control [56]. In fog computing, edge access points can directly perform Collaboration Radio Signal Processing (CRSP) and Cooperative Radio Resource Management (CRRM) locally, thus the heavy burden of fronthaul and the BBU pool is alleviated, and the delay is significantly reduced [57]. Meanwhile, Fog computing-based Radio Access Network (F-RAN) has been proposed as an advanced socially aware mobile network architecture. As a result, F-RAN can achieve high SE/EE, low latency and excellent reliability for different Industrial Internet applications such as industrial automation, transportation and mobile vehicle connectivity [58,59]. In the future, there will be tens of billions of terminal devices connected to each other. The requirements for massive data processing, low latency and high reliability for Industrial Internet applications need the integration and development of fog computing and Industrial Internet.

5.5.2. Blockchain enhances the security of the Industrial Internet

At present, the blockchain has relatively mature applications in the fields of finance, health care, etc. Many studies have focused on the security, privacy and scalability of blockchains [60]. Transforming the Industrial Internet platform through blockchain technology can avoid data loss and tampering caused by attacks on a single data center, and improve data security of the platform. [61] proposes a distributed peer-to-peer platform based on blockchain technology. The platform enables peers in a decentralized, untrusted peer-to-peer network to interact with each other without a trusted intermediary by using blockchain technology. At the same time, the application of blockchain technology will predict and prevent the failure of manufacturing plant equipment, which ensures the reliability of the equipment. With the technological innovations in the Industrial Internet field, blockchains can integrate with the Industrial Internet platforms and cloud computing more quickly to improve the security and intelligence of the Industrial Internet.

5.5.3. Development of new generation artificial intelligence

The information environment developed by artificial intelligence has undergone profound changes with the popularity of the Internet. The development of big data, and the interconnection and integration of physical space and cyber space have led to a new evolutionary phase: AI 2.0. In the future, the Industrial Internet needs to be developed toward the direction of intelligence. Driven by the recent development of artificial intelligence, [62] proposed a joint model selection and resource management method based on Deep Reinforcement Learning (DRL) to support IoT services. The deep integration of the new generation of artificial intelligence technology and the Industrial Internet is conducive to the rapid development of the application technology in the manufacturing industry chain, especially intelligent production and intelligent services.

6. Conclusion

The Industrial Internet is a deep integration of advanced computing, analysis, and sensing technologies into global industrial systems. This paper surveys the recent research works in the Industrial Internet, including the system architecture, key techniques, and open issues. To further understand the intricacies of the Industrial Internet, three reference architectures of the Industrial Internet in different scenarios have been presented. As the stringent requirements of the Industrial Internet for transmission rate, low delay and high reliability require emerging technical support such as cloud computing, MEC, fog computing and intelligent artificial. Key technologies especially wireless communication technologies and emerging technologies are emphasized as well. Moreover, emerging applications of Industrial Internet used in different fields are presented. Nevertheless, there are still a large number of challenges and open issues that need to be solved.

Conflict of interest

The authors declared that they have no conflicts of interest to this work.

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted。

Authors: Wei Qin, Siqi Chen, Mugen Peng.

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Appendix A. Supplementary data

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