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COMMENTS

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Improve the industrial digital transformation through Industrial Internet platforms

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1 Introduction

1.1 Definition and stakeholders of the Industrial Internet

The Industrial Internet is a novel network technology system that applies the Internet of Things (IoT) to the manufacturing and industrial sectors. It facilitates the connection of various sensors, devices, systems, factories, and enterprises, enabling the sharing and exchange of data to improve production efficiency, reduce costs, enhance product quality, and enable smart manufacturing. The Industrial Internet serves as a crucial cornerstone and essential support for the Fourth Industrial Revolution, offering specific approaches for industrial digital transformation. Through the comprehensive interconnection of people, machines, and things, the Industrial Internet analyzes various data from intelligent feedback, fostering the development of a new manufacturing and service system.

A related concept within the scope of the Industrial Internet is the data platform. Typically, companies establish and employ their proprietary data platforms. In contrast to current data platforms, Industrial Internet platforms involve key stakeholders such as industrial enterprises, application developers, platform service providers, and government regulatory agencies. These stakeholders collaborate within the Industrial Internet platform, as depicted in Fig. 1.

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Let us briefly discuss these stakeholders. Firstly, industrial enterprises are the central users and contributors of application scenarios for Industrial Internet platforms. They link physical devices, including sensors, programmable logic controllers, and equipment, to the platform. They leverage the platform's capabilities for data acquisition, storage, analysis, and optimization to attain production line optimization and intelligence. This, in turn, improves production efficiency and quality while reducing costs and risks. Secondly, application developers play a pivotal role within the Industrial Internet platform by creating diverse applications for industrial enterprises. These applications include data acquisition, monitoring, analysis, prediction, and others, utilizing the application programming interfaces (APIs) and development tools provided by the platform. Effective collaboration with industrial enterprises is crucial, requiring an understanding of their business needs and data sources to develop tailored application programs. Furthermore, close cooperation with platform service providers is essential to stay informed about the latest technologies and functionalities of the platform. This ensures the optimal utilization of development tools and APIs provided by the platform service providers. Additionally, platform service providers act as the operators and managers of Industrial Internet platforms, delivering technical, service, management, security, and other support forms. They shoulder responsibilities for platform development, maintenance, operation, security, and compliance management, ensuring its stability and security. Lastly, government regulatory agencies fulfill a dual role as regulators and promoters of Industrial Internet platforms. They oversee and guide platform compliance, standardization, security, and other aspects while also advancing the development and innovation of Industrial Internet platforms through policies, funding, talent, and various other forms of support.

Furthermore, aside from the expanded participation of stakeholders, the Industrial Internet platform boasts enhanced functionality when compared to conventional data platforms. It places a distinct emphasis on harnessing

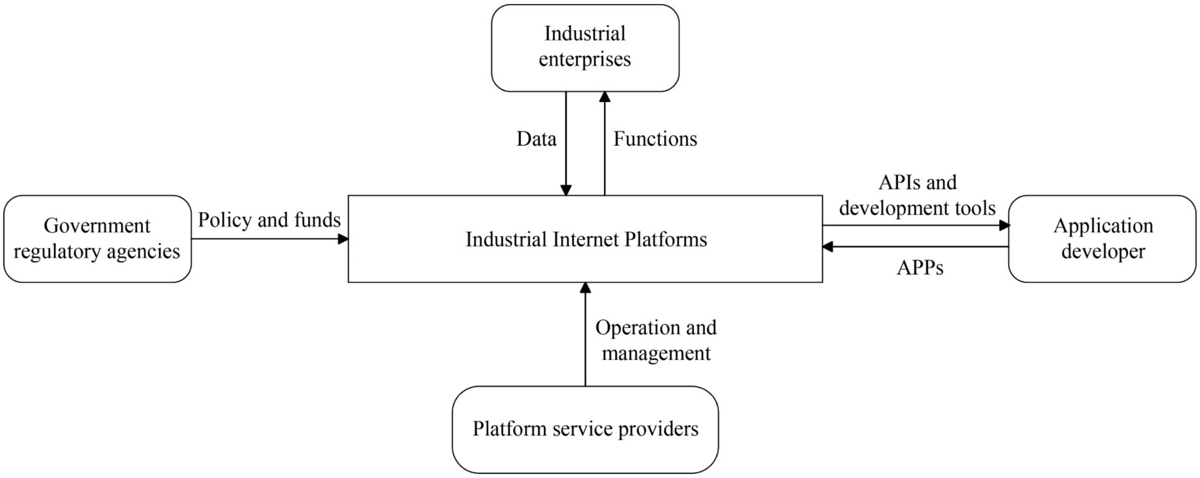

Fig. 1 Stakeholders of the Industrial Internet platform.

big data technologies to optimize data collection, storage, processing, and analysis. Leveraging big data technology empowers enterprises to gather and process vast datasets, including both structured and unstructured data, facilitating precise predictions and real-time decision-making through advanced computing techniques. The integration of artificial intelligence (AI) technology within the Industrial Internet platform further enhances enterprises' ability to discern data patterns and trends, enabling intelligent decision-making, and bolstering business development.

1.2 Digital transformation in China

Presently, the cost advantage that has long characterized the Chinese manufacturing industry is gradually diminishing. It confronts the challenge of advanced manufacturing's "industry hollowing out". For instance, numerous manufacturing enterprises have relocated their processing and assembly operations overseas. China's manufacturing sector has historically occupied the lower rungs of the industrial value chain, necessitating an increase in the production of high-level products. Promoting industrial digital transformation grounded in the Industrial Internet assumes primary significance as it not only facilitates labor reduction but also stimulates the extension of the industrial chain and the expansion of the value chain.

As an illustrative case, a large-scale electronic information manufacturing enterprise in China realized remarkable results following the deployment of a comprehensive Industrial Internet solution to upgrade its factory. This transformation resulted in a 50% reduction in workforce and a 30% improvement in efficiency (Dong, 2019).

Observing recent developments in the digital transformation of the Industrial Internet industry, it becomes evident that the government is accelerating efforts to foster the Industrial Internet and digital transformation. Enterprises, however, are lagging behind in adapting to these changes in the market, talent acquisition, and management dimensions.

Industrial digital transformation in China represents a long-term process influenced by the evolution of digital technologies and the unique characteristics of industrial development in the country. It necessitates a deep integration with industrial technology, knowledge, and expertise, rendering it a complex and formidable undertaking. Furthermore, China's industrial landscape is characterized by its vast scale and relatively low level of digitalization, suggesting that constructing a digital industrial cluster will entail substantial costs and an extended timeframe (Ran, 2022). Nevertheless, enterprises face capital and survival pressures that demand rapid returns and immediate results from industrial digital transformation. Within these constraints, achieving market success for industrial digitalization becomes challenging.

Additionally, data derived from the Industrial Internet is proprietary, contributing to high entry barriers in the big data market. These conditions can lead to market monopolies, impeding the widespread adoption of industrial digitalization.

Simultaneously, the shortage of talent resources poses a significant hurdle for industrial digital transformation. Successful digitalization requires individuals not only skilled in information and communication technology but also possessing digital acumen. In the current talent market, there is a dearth of interdisciplinary professionals who understand industry trends and possess digital expertise, collaborative efficiency, and innovation capabilities (Li and He, 2022). In the digital era, product lifecycles have dramatically shortened, and the window for companies to vie for users has grown increasingly narrow, posing significant challenges to their survival and growth. Talent constitutes the foundational driving force for enterprise development, necessitating the formation of highly skilled digital teams to propel digital transformation.

Regarding management challenges, the government's coordination of digital transformation requires enhancement. The digital transformation of the Industrial Internet industry calls for collaboration across departments, industries, enterprises, and regions. Additionally, the sheer scale, wide scope, technological complexity, and regulatory challenges associated with digital data circulation make effective supervision a formidable task. The organizational structures of digital management entities vary, impeding their ability to effectively oversee industrial digital transformation (Yu et al., 2020). There is a pressing need for top-level strategic planning for digital transformation at the enterprise level. Most companies require comprehensive strategies, long-term plans, and extensive deliberation to navigate the complexities of digital transformation. Consequently, manufacturing firms often grapple with questions like "what to transform and how to transform" (Wang, 2022). Furthermore, Chinese industrial digitalization efforts encounter technical management issues such as complex data acquisition and application, data security, data management, and data sharing.

2 Role of Industrial Internet platforms in the digital transformation

In China, the Industrial Internet has transitioned from mere concept advocacy to the profound cultivation of practical applications. Chinese Industrial Internet companies have exhibited rapid development, continuously innovating and refining their technologies. According to data from the Ministry of Industry and Information Technology of the People's Republic of China, as of the conclusion of 2022, more than 150 Industrial Internet platforms wielding regional and industrial influence have been established. Chinese Industrial Internet application technology has evolved from singular equipment control to intelligent manufacturing, finding extensive utilization in ten pivotal industries, including electronic equipment manufacturing, steel production, and electric power generation. Notable applications, such as remote equipment control, machine vision quality inspection, and unmanned intelligent patrol, have been conceived (Han, 2021).

As one of the emerging infrastructures, the Industrial Internet bolsters enterprises' digital capabilities and facilitates intelligent manufacturing through digital technology and automation solutions.

In the domain of business model analysis, the Industrial Internet, empowered by big data analysis and machine learning technology, can procure real-time market data and conduct profound data analysis. This aids enterprises in refining their business models and enhancing their value propositions. By establishing enterprise information systems and customer relationship systems, the Industrial Internet attains and assesses customer preferences, enabling enterprises to align with market demands amidst rapid shifts in enterprise and customer information (Wang et al., 2020). For instance, under varying market conditions, a manufacturing enterprise can offer products, predictive maintenance services, and other solutions to forge enduring partnerships with customers while augmenting revenue streams (Jacobson et al., 2017).

Concerning production, the Industrial Internet empowers enterprises to optimize their production processes and reduce waste by scrutinizing copious production data and monitoring real-time production procedures. Through data analysis facilitated by the Industrial Internet, large-scale manufacturing can mitigate the costs associated with misjudgments and production line oversights. For instance, the Bosch factory employs the Industrial Internet platform to scrutinize streaming data, enhancing production efficiency. By dissecting the root causes of production line issues, it achieves complete digital connectivity and transformation (Lade et al., 2017). In the context of industries characterized by small-batch manufacturing, such as aerospace manufacturing, the Industrial Internet mitigates information delays and enables the automatic tracking of equipment information during component assembly (Szymanski, 2016).

Concerning the industrial chain, the Industrial Internet facilitates the coordination and optimization of various segments. Enterprises can achieve optimal resource allocation and collaborative management of production processes through data sharing and coordination links including supply chains, production chains, and sales chains. For example, the Industrial Internet employs deep learning algorithms to realize functions like product maintenance, predictive analysis, product development, and supply chain management. This fosters internal departments' connectivity within enterprises and promotes data collaboration along the industrial chain (Latif et al., 2021). By integrating product production and sales channels through technologies like Digital Twin, the Industrial Internet bridges the virtual network world with the tangible world, enhancing the efficiency and quality of the entire industrial chain and, consequently, elevating the competitiveness of the industry as a whole (Kiel et al., 2017).

3 Architecture, key technologies and applications of the Industrial Internet platform

The Industrial Internet platform represents a transformative approach that enhances industrial processes through advanced connectivity and data exchange technologies. Its success hinges upon its innovative architecture and the seamless integration of essential technologies. We present a typical architecture of the Industrial Internet platform, illustrated in Fig. 2. This architecture can be delineated into four distinct layers: The edge layer, the infrastructure-as-a-service (IaaS) layer, the platform-as-a-service (PaaS) layer, and the software-as-a-service (SaaS) layer.

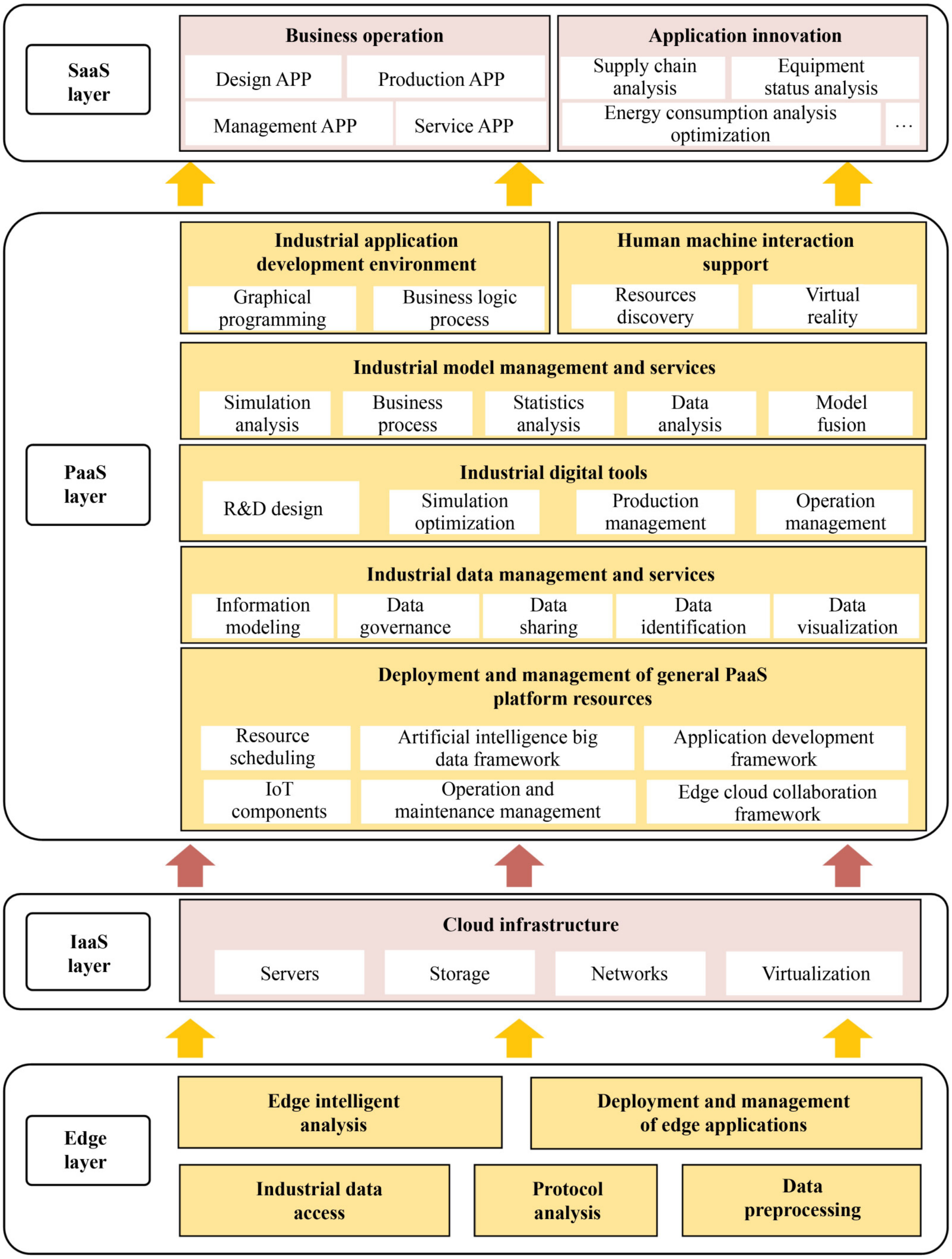

Fig. 2 The architecture of the Industrial Internet platform.

As depicted in Fig. 2, the edge layer primarily offers functions such as extensive industrial data acquisition, conversion, data preprocessing, and edge analysis applications. The IaaS layer predominantly includes infrastructures related to hardware servers, data storage, 5G networks, and virtualization technology. These elements furnish the requisite hardware foundation for ensuring the secure and stable operation of Industrial Internet platforms.

The PaaS layer provides an array of functions, including resource management, industrial data and model management, industrial modeling analysis, and support for industrial application innovation. Lastly, the uppermost SaaS layer facilitates business operations and fosters application innovation.

The Industrial Internet platform leverages several pivotal technologies to underpin the aforementioned architecture. These key technologies include sensing, big data analytics, cloud computing, AI, and security. Sensing and data acquisition technologies play a crucial role in gathering and transmitting data from sensors and devices embedded within the industrial infrastructure. Big data analytics is instrumental in extracting valuable insights from the amassed data. Furthermore, security technologies are of primary importance, safeguarding the Industrial Internet platform against cyber threats and ensuring the integrity and privacy of the data. Figure 3 illustrates the key technologies and their application areas. Numerous successful Industrial Internet platforms have emerged both domestically and internationally.

China's pioneering Industrial Internet platform, known as the Industry Intelligent Cloud System (INDICS), was introduced by Chai et al. (2018). Within the INDICS platform's PaaS layer, there are over 200 APIs designed to support application lifecycle management. INDICS offers industrial services, workflow management, and simulation engines, thereby enabling software-defined application manufacturing. This platform has played a pivotal role in facilitating successful digital transformations for small- to medium-sized enterprises. For instance, it connects 1022 fans and processes 200 million pieces of data daily, enabling real-time data monitoring for grid fans. This functionality aids wind power farms in identifying equipment failures and evaluating power generation automatically (Chai et al., 2018). Additionally, INDICS connects 266 robot devices for monitoring robot operation within a Computerized Numerical Control company, reducing unplanned shutdowns and optimizing robot performance through fault data analysis. These solutions rely on two core technologies: The ability to collect diverse production data from sensors and devices and extensive data storage, management, and processing based on cloud computing architecture. These technologies ensure product quality across the product lifecycle.

Li et al. (2017) explored the applications of the Industrial Internet platform within the energy sector. Industrial Internet technologies are revolutionizing traditional energy industries. The platform begins by collecting real-time sensor data, made possible by the pervasive sensing capabilities facilitated by industrial sensing and wireless communication technologies (Luo et al., 2006). Subsequently, this collected data undergoes processing and integration into energy management systems. This aids decision-makers in identifying waste and devising more efficient energy-saving strategies. Moreover, the platform integrates energy data into production management practices to enhance energy efficiency. The platform relies heavily on advanced information and communication technologies such as software-defined machines, smart sensing, and big data analytics. Notably, big data and data analytics contribute predictive analytics insights, minimizing unplanned system downtime and preventing unexpected shutdowns. The adoption of the Industrial Internet platform in the energy industry results in advanced control, remote monitoring, predictive maintenance techniques, and improved safety and efficiency (Zbunjak and Kuzle, 2013).

Outside China, General Electric (GE) pioneered the concept of the Industrial Internet, including the "infrastructure layer" and the "platform layer". The infrastructure layer manages data centers responsible for handling structured and unstructured data, while the platform layer consists of scalable software programming that overlays the infrastructure layer (Agarwal and Brem, 2015). GE introduced the Predix Industrial Internet Cloud Platform for the platform layer, operable on both GE and non-GE devices. Predix is instrumental in developing sector-specific applications, leveraging advanced software technologies and cloud computing paradigms. Several GE business lines utilize Predix as the standard technology platform for big data and analytics-driven software development efforts. For example, it enables predictive maintenance and repair for GE's aero-engines and gas turbines while offering analysis and optimization solutions to customers. However, GE's ambitious strategy of creating a universal platform for all industries did not yield the expected results.

Siemens, on the other hand, has developed the Industrial Internet platform known as MindSphere. This platform

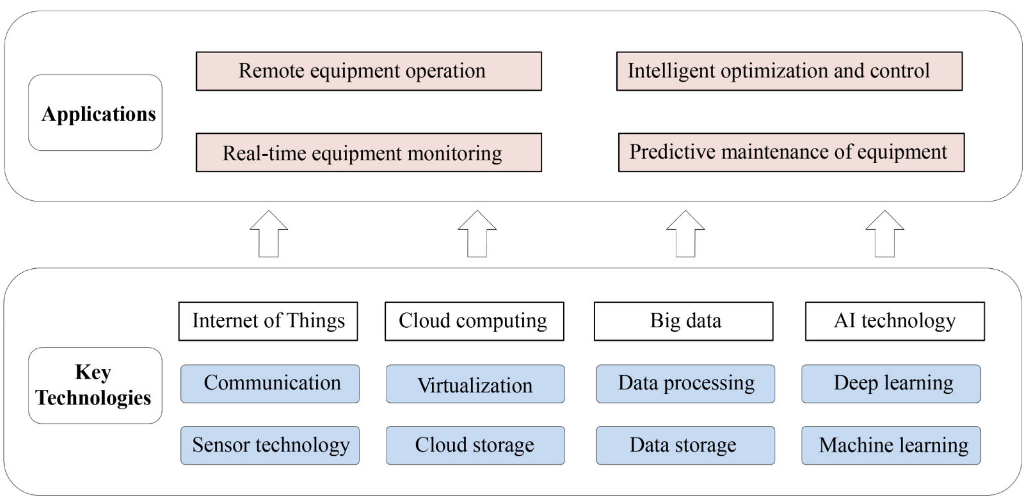

Fig. 3 Key technologies and applications of the Industrial Internet platform.

interconnects approximately 1 million devices and systems while providing predictive maintenance services for these devices (Wang et al., 2020). Many companies have created software applications for specific stages of the product manufacturing process, but integration challenges arise when transferring data between different systems. MindSphere leverages information fusion technology for multi-source heterogeneous data to offer a comprehensive automation solution that spans the entire product lifecycle.

4 Challenges and response strategies of the Industrial Internet platform

Although the Industrial Internet holds substantial promise for transforming manufacturing, it confronts a range of challenges that necessitate resolution. These challenges include mixed-criticality, network latency, security vulnerabilities, and the persistence of legacy long-standing industrial systems (Breivold and Sandström, 2015). In the ensuing section, we provide a concise summary of these obstacles that must be surmounted to facilitate digital transformation via the Industrial Internet platform.

4.1 Mixed-criticality

The Industrial Internet platform necessitates the integration of numerous functions across multiple components, devices, and stages to achieve heightened levels of intelligent control and collaboration. However, the challenge of mixed-criticality arises when functions with differing levels of criticality are amalgamated within a single industrial system. To prevent the interference of low-criticality functions with their high-criticality counterparts, platforms must guarantee the autonomy of software applications. While the availability of multicore processor hardware presents an opportune solution, a significant portion of legacy software is originally designed for single-core execution. In transitioning to multicore processing, the platform must support software partitioning. Virtualization emerges as a valuable technology in this context, facilitating the coexistence of diverse criticality levels within the same system. This is achieved by allowing different operating systems to run concurrently on separate virtual machines, ensuring efficient resource separation and isolation.

4.2 Network latency

Within the Industrial Internet system, the interconnection of thousands of sensors, devices, and programmable logic controllers occurs via industrial field buses and communication protocols such as IoT and 5G. To enable real-time monitoring, the Industrial Internet platform must ensure dependable and low-latency data transfer. However, as modern factories witness a rapid proliferation of sensors and distributed devices, network latency has emerged as a formidable challenge. Research by Hegazy and Hefeeda (2015) indicates that roundtrip delays over the Internet typically range from tens to several hundred milliseconds, a range that can significantly affect latency-sensitive industrial applications.

To address this challenge, the concept of fog computing or edge computing has been introduced in the literature (Hegazy and Hefeeda, 2015). In fog computing, applications or services with real-time performance requirements are shifted to the network edge or end devices to mitigate response time and latency. Edge computing, on the other hand, involves relocating services that are ill-suited for execution in the cloud to end devices, thereby reducing response times. To enable the digital transformation of the industry through the Industrial Internet platform, researchers must achieve substantial advancements in the domain of fog computing or edge computing.

4.3 Security challenges

There is often an assumption that the network housing industrial control systems is secure and insulated from external interference. However, the Industrial Internet platform interconnects sensors, actuators, machinery, and industrial networks, thereby posing challenges for system designers concerning data privacy. Secure storage of data collected from multiple devices is crucial to thwart malicious attacks.

Within existing platforms, signature-based security technology prevails as the norm. Nonetheless, attackers can readily manipulate the syntactical representation of these signatures to launch attacks. Consequently, a pivotal challenge confronting the Industrial Internet platform is to represent attacks with a balanced abstraction that can accommodate variations of a specific attack (Li et al., 2017). Additionally, platforms necessitate periodic security upgrades. However, even a millisecond of downtime is unacceptable for machinery. Hence, ensuring seamless security upgrades that neither compromise functional safety nor disrupt provided services within a control process represents another formidable challenge for Industrial Internet platforms (Breivold and Sandström, 2015).

4.4 Legacy long-lived industrial systems

Presently, the industrial landscape predominantly relies on legacy software systems, typically possessing lifespans ranging from ten to thirty years. These systems exhibit certain characteristics, such as escalating complexity, inadequate documentation, and limited comprehension by contemporary developers (Breivold and Sandström, 2015). Regrettably, legacy systems struggle to adapt to the swiftly evolving market demands and customer prerequisites. Consequently, effectively harnessing and retrofitting these legacy systems represents a substantial challenge for Industrial Internet platforms. These platforms are expected to continually deploy new features and services to meet unpredictable market dynamics.

In China, numerous factories are situated in the Industrial 2.0 phase, signifying relatively low levels of automation. The digital transformation and intelligent upgrade of equipment entail significant costs and complexities, giving rise to additional challenges. For instance, data collected from these factories may be incomplete, inaccurate, or even unattainable. Addressing the current needs of small- and medium-sized manufacturing enterprises while mitigating industry-specific challenges to enhance the depth of platform application constitutes a formidable undertaking.

5 The prospect of industrial digital transformation using Industrial Internet platforms

With the emergence of technologies such as AI, information transmission, and blockchain, Industrial Internet platforms have demonstrated significant developmental potential. Simultaneously, the evolution and expansion of industrial digital transformation through these platforms are anticipated to continue in the foreseeable future. Here are some potential future directions for this field.

First and foremost, a pivotal future direction involves the fusion of IoT and AI technologies. Industrial Internet platforms will increasingly harness the integration of IoT devices and AI technologies. IoT devices will amass vast volumes of data from diverse industrial processes, with AI assuming a critical role in the analysis and extraction of valuable insights from this data. The utilization of AI within the Industrial Internet platform will progressively expand, enhancing the intelligence of industrial production platforms. Through data analysis and machine learning, machinery can autonomously execute tasks, enabling efficient production and elevating product quality. Moreover, AI can facilitate companies in achieving personalized product customization. Through intelligent production and streamlined supply chain management, companies can swiftly respond to consumer demands, providing products and services tailored to meet consumer needs.

Secondly, the integration of autonomous systems and robotics into industrial processes is another notable direction. Industrial Internet platforms will facilitate the incorporation of autonomous systems and robotics, which may include autonomous vehicles, robotic assembly lines, and drones for monitoring and inspection. These technologies are poised to augment efficiency, precision, and safety within industrial operations.

Thirdly, the foundation of industrial digital transformation on Industrial Internet platforms necessitates blockchain technology. Given the abundance of sensitive data on the Industrial Internet platform, the compromise or tampering of such data could lead to risks such as production interruptions and quality issues. The decentralized and encrypted attributes of blockchain technology offer assurance against data tampering and leaks, thereby enhancing data security. Furthermore, blockchain technology can enhance data transparency. The Industrial Internet platform involves data exchange and sharing among multiple enterprises, yet inconsistencies in data formats and standards between different enterprises can lead to information asymmetry. The distributed ledger mechanism inherent to blockchain technology ensures data consistency and transparency, thus mitigating information asymmetry and elevating data accuracy and reliability.

Furthermore, future advancements in information transmission technologies will play a pivotal role in industrial digital transformation and the operation of Industrial Internet platforms. These technologies will continue to evolve and improve, including higher data transmission speeds, reduced latency, broader coverage, enhanced security, and more intelligent interaction modes. For instance, the 5G network supports network slicing technology, which enhances the adaptability of Industrial Internet platform applications to cater to diverse industry requirements.

Lastly, it is crucial to acknowledge that Industrial Internet platforms and the digital transformation within these platforms constitute crucial technological foundations underpinning Industry 5.0. As a novel paradigm, Industry 5.0 underscores the integration and synergy between humans and machines to address personalized and highly customized production demands. It underscores the active participation and creativity of employees, transforming them from mere operators on the production line into primary agents propelling process optimization and technological advancement. Industrial Internet platforms play a pivotal role in advancing Industry 5.0. Firstly, they facilitate human–machine collaboration within Industry 5.0. Through the interconnection of various devices and systems, the Industrial Internet enables real-time connectivity and information exchange across distinct stages of the industrial production process, fostering seamless cooperation between humans and machines. Secondly, Industrial Internet platforms facilitate real-time interaction in Industry 5.0. Through these platforms, various stakeholders, including manufacturing enterprises, customers, and suppliers, can engage in real-time information exchange and collaboration, better catering to customized requirements and enhancing production efficiency and product quality. Lastly, Industrial Internet platforms provide secure support for Industry 5.0. They enable secure storage and transmission of data, ensuring the safeguarding of manufacturing enterprises' information and bolstering the protection of their intellectual property and trade secrets.

6 Conclusions

Digital transformation through Industrial Internet platforms plays a pivotal role in fostering rapid economic growth, ensuring the stable development of the manufacturing sector, and promoting innovation and entrepreneurship. Specifically, achieving industrial digital transformation requires the indispensable support of Industrial Internet platforms across domains like business model analysis, production, and the industrial chain. This paper conducts an analysis of exemplary Industrial Internet platforms such as INDICS and the Predix Industrial Internet Cloud Platform. It explores the examination of key technologies while scrutinizing the pivotal role played by the Industrial Internet. Notably, Industrial Internet platforms have instigated revolutionary changes in sectors such as energy and manufacturing. However, the continued progression of the Industrial Internet is hampered by certain nascent technologies. Consequently, prospective studies should accord priority to research in areas such as mixed criticality, network latency, and security management. Moreover, grappling with legacy long-standing industrial systems presents a formidable challenge for Industrial Internet platforms. Finally, a critical facet of investigation pertains to addressing physical-cyber errors, a vital consideration for propelling industries from automation towards unmanned operations.

Competing Interests The authors declare that they have no competing interests.

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