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Toward New-Generation Intelligent Manufacturing

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ABSTRACT

Intelligent manufacturing is a general concept that is under continuous development. It can be categorized into three basic paradigms: digital manufacturing, digital-networked manufacturing, and new-generation intelligent manufacturing. New-generation intelligent manufacturing represents an in-depth integration of new-generation artificial intelligence (AI) technology and advanced manufacturing technology. It runs through every link in the full life-cycle of design, production, product, and service. The concept also relates to the optimization and integration of corresponding systems; the continuous improvement of enterprises' product quality, performance, and service levels; and reduction in resources consumption. New-generation intelligent manufacturing acts as the core driving force of the new industrial revolution and will continue to be the main pathway for the transformation and upgrading of the manufacturing industry in the decades to come. Human-cyber-physical systems (HCPSs) reveal the technological mechanisms of new-generation intelligent manufacturing and can effectively guide related theoretical research and engineering practice. Given the sequential development, cross interaction, and iterative upgrading characteristics of the three basic paradigms of intelligent manufacturing, a technology roadmap for "parallel promotion and integrated development" should be developed in order to drive forward the intelligent transformation of the manufacturing industry in China.

1. Introduction

Countries around the world are actively engaging in the new industrial revolution. The United States has launched the Advanced Manufacturing Partnership [1,2], Germany has developed the strategic initiative Industrie 4.0 [3], and the United Kingdom has put forward the UK Industry 2050 strategy [4]. In addition, France has unveiled the New Industrial France program [5], Japan has a Society 5.0 strategy [6], and Korea has started the Manufacturing Innovation 3.0 program [7]. The development of intelligent manufacturing is regarded as a key measure to establish competitive advantages for the manufacturing industry of major countries around the world. The Made in China 2025 plan, formerly known as China Manufacturing 2025, has specifically set the promotion of intelligent manufacturing as its main direction [8], with a focus on the in-depth integration of new-generation information technology within the manufacturing industry.

Since the beginning of the 21st century, new-generation information technology has shown explosive growth. The broad application of digital, networked, and intelligent technologies in the manufacturing industry and the continuous development of integrated manufacturing innovations have been the main driving forces of the new industrial revolution. In particular, new-generation intelligent manufacturing, which serves as the core technology of the current industrial revolution, incorporates major and profound changes in the development philosophy, manufacturing modes, and other aspects of the manufacturing industry. Intelligent manufacturing is now reshaping the development paths, technical systems, and industrial forms of the manufacturing industry, and is thereby pushing the global manufacturing industry into a new stage of development [9–13].

2. Three basic paradigms of intelligent manufacturing

Intelligent manufacturing is a general concept that covers a wide range of specific topics [10,14]. New-generation intelligent manufacturing represents an in-depth integration of new-generation

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artificial intelligence (AI) technology and advanced manufacturing technology. It runs through every link in the full life-cycle of design, production, product, and service. The concept also relates to the optimization and integration of corresponding systems; it aims to continuously raise enterprises' product quality, performance, and service levels while reducing resources consumption, thus promoting the innovative, green, coordinated, open, and shared development of the manufacturing industry.

For decades, intelligentization for manufacturing has involved many different paradigms as it continues to develop in practice. These paradigms include lean production, flexible manufacturing, concurrent engineering, agile manufacturing, digital manufacturing, computer-integrated manufacturing, networked manufacturing, cloud manufacturing, intelligent manufacturing, and more [15–23]. All of these paradigms have played an active role in guiding technology upgrading in the manufacturing industry. However, there are too many paradigms to form a unified intelligent manufacturing technology roadmap; this lack of unity causes enterprises to experience many perplexities in their practice of pushing forward intelligent upgrading. Considering the continuously emerging new technologies, new ideas, and new modes of intelligent manufacturing, we consider it necessary to summarize the basic paradigms of intelligent manufacturing.

Intelligent manufacturing has developed in parallel with the progress of informatization. There are three stages in the development of informatization worldwide [24]:

- From the middle of the 20th century to the mid-1990s, informatization was in a digital stage with computing, communications, and control applications as the main features.
- Starting in the mid-1990s, the Internet came into large-scale popularization and application, and informatization entered a networked stage with the interconnection of all things as its main characteristic.
- At present, on the basis of cluster breakthroughs in and integrated applications of big data, cloud computing, the mobile Internet, and the Industrial Internet, strategic breakthroughs have been made in AI; as a result, informatization has entered an intelligent stage, with new-generation AI technology as its main feature.

Taking the various intelligent manufacturing-related paradigms into account and considering the characteristics of the integration of information technology and the manufacturing industry through different stages, it is possible to generalize three basic paradigms of intelligent manufacturing: digital manufacturing, digital-networked manufacturing, and new-generation intelligent manufacturing (Fig. 1).

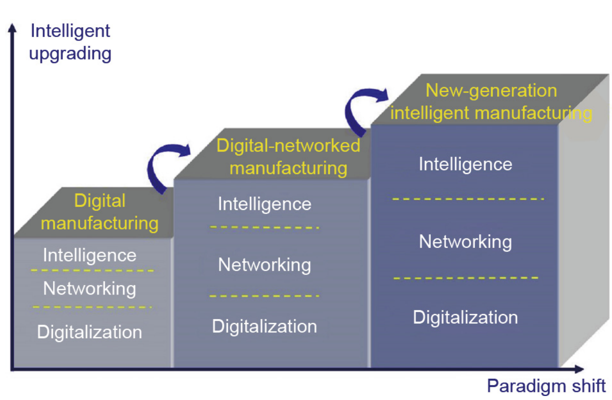

Fig. 1. The evolution of three basic paradigms of intelligent manufacturing.

2.1. Digital manufacturing

Digital manufacturing is the first basic paradigm of intelligent manufacturing; it may also be referred to as first-generation intelligent manufacturing.

The concept of intelligent manufacturing first appeared in the 1980s [10,25–27]. Because the first-generation AI technology that was in application at that time could hardly solve specific engineering problems, first-generation intelligent manufacturing was essentially digital manufacturing.

Starting in the second half of the 20th century, as demand for technological progress in the manufacturing sector became increasingly urgent, digital information technologies were widely applied in the manufacturing industry, driving forward revolutionary changes in the industry. Against a background of the integration of digital technology with manufacturing technology, digital manufacturing undertook the digital description, analysis, decision-making, and control of product information, process information, and resources information; in this way, digital manufacturing remarkably shortened the time required for designing and manufacturing products to meet specific customer requirements [15,16,26,27].

The key features of digital manufacturing are as follows: ① Digital technology is widely used in products, forming a "digital generation" of innovative products; ② digital design, modeling and simulations, and digital equipment information management are widely applied; and ③ production process integration and optimization are achieved.

The point that needs to be clarified here is that digital manufacturing is the foundation of intelligent manufacturing. Digital manufacturing continues to evolve, and runs throughout the three basic paradigms and all the development processes of intelligent manufacturing. The digital manufacturing being defined here is the digital manufacturing of the first basic paradigm, which positions digital manufacturing in a relatively narrow sense. On an international level, several types of positioning and theories on digital manufacturing have also been developed in a broad sense [28].

2.2. Digital-networked manufacturing

Digital-networked manufacturing is the second basic paradigm of intelligent manufacturing; it may also be referred to as "Internet + manufacturing" or as second-generation intelligent manufacturing [29].

In the end of the 20th century, Internet technology started to gain popularity. "Internet +" has continuously pushed forward the integrated development of the Internet and the manufacturing industry. The network connects humans, processes, data, and things. Through intra- and inter-enterprise collaborations and the sharing and integration of all kinds of social resources, "Internet +" reshapes the value chain of the manufacturing industry and drives the transformation from digital manufacturing to digital-networked manufacturing [17,30–33].

The main characteristics of digital-networked manufacturing are as follows [34]:

- At the product level, digital technology and network technology are widely applied. Products are connected through the network, while collaborative and shared design and R&D are achieved.
- At the manufacturing level, horizontal integration, vertical integration, and end-to-end integration are completed, thereby connecting the data flows and information flows of the entire manufacturing system.

- At the service level, enterprises and users connect and interact through the network platforms, while enterprises begin to transform from product-centered production to user-centered production.

Both Germany's Industrie 4.0 report and General Electric's Industrial Internet report present very informative and well-structured descriptions of the digital-networked manufacturing paradigm, and put forward technology roadmaps for digital-networked manufacturing [4,9,31,35–39].

2.3. New-generation intelligent manufacturing

Digital-networked-intelligent manufacturing is the third basic paradigm of intelligent manufacturing; it may also be referred to as new-generation intelligent manufacturing.

Jointly driven by a strong demand for economic and social development, the penetration of the Internet, the emergence of cloud computing and big data, the development of the Internet of Things (IoT), and rapid changes in the information environment, there has been an accelerating development of strategic breakthroughs in new-generation AI technologies; these include big data intelligence, human-machine hybrid-augmented intelligence, crowd intelligence, and cross-media intelligence [24,40,41]. The in-depth integration of new-generation AI technology and advanced manufacturing technology leads to the formation of new-generation intelligent manufacturing. New-generation intelligent manufacturing will reshape all the processes of the full product cycle, including design, manufacture, and services, as well as the integration of these processes. It will promote the emergence of new technologies, new products, new business forms, and new models, and it will profoundly influence and change the production structure, production modes, lifestyles, and thinking models of humankind. It will ultimately result in a great improvement of social productive forces. New-generation intelligent manufacturing will bring revolutionary changes to the manufacturing industry and will become the main driving force for the future development of the industry.

The three basic paradigms of intelligent manufacturing reflect the inherent development pattern of intelligent manufacturing. On the one hand, the three basic paradigms developed in sequence, each with their own characteristics and key problems to solve; in this way, they embody the characteristics of different developmental stages of advanced information technology and advanced manufacturing technology. On the other hand, the three basic paradigms cannot be technologically separated from each other; rather, they are interconnected and iteratively upgraded, thus showing the integrated development characteristics of intelligent manufacturing. China and other emerging industrial countries must leverage their late-mover advantages and adopt a technology roadmap for the "parallel promotion and integrated development" of the three basic paradigms.

3. New-generation intelligent manufacturing leads and promotes the new industrial revolution

3.1. Development background

At present, manufacturing enterprises in all countries are faced with an urgent need to improve quality, boost efficiency, lower cost, and have quick responses. There is also a need for enterprises to continuously adapt to the growing personalized consumption demand of users and to address the greater challenges of resources, energy, and environmental constraints. However, existing manufacturing systems and levels can scarcely meet the value appreciation and upgrade requirements of high-end, personalized, and intelligent products and services. The further development of the manufacturing industry faces huge bottlenecks and difficulties. To solve these problems and meet these challenges, there is an urgent need for the manufacturing industry to promote technological innovation and complete intelligent upgrading [14,41].

The new industrial revolution is still emerging; its fundamental driving force lies in a new revolution of science and technology. Since the start of the 21st century, the mobile Internet, supercomputing, big data, cloud computing, IoT, and other new-generation information technologies have developed rapidly [11,12,42–48]; they have achieved swift penetration and applications, resulting in mass breakthroughs. These historical technological advancements are concentrated in strategic breakthroughs in new-generation AI technology, which has taken fundamental strides forward [24]. New-generation AI possesses new features such as deep learning, crossover collaboration, human-machine hybrid-augmented intelligence, and crowd intelligence; with these, new-generation AI provides humankind with new ways of thinking that can help us to understand complex systems and new technologies with the capability to reconstruct both nature and society. Of course, new-generation AI technology is still under development and will continue to develop from "narrow AI" to "general AI"; in doing so, it will expand the "brainpower" of humankind and achieve ubiquitous applications. New-generation AI has become the core technology of a new science and technology revolution. It provides historical opportunities for the revolutionary upgrading of the manufacturing industry into a powerful engine that will boost economic and social development. Most of the major countries in the world have made developing new-generation AI into a top priority [49,50].

The in-depth integration of new-generation AI technology and advanced manufacturing technology is leading to the formation of new-generation intelligent manufacturing technology, and is becoming the major driving force of the new industrial revolution.

3.2. New-generation intelligent manufacturing as a core technology of the new industrial revolution

Science and technology are the first productive force; they are also the fundamental driving force for economic and social development. The first and second industrial revolutions were respectively marked by the invention and application of the steam engine, and by electric power; both innovations greatly improved productive force and helped to usher human society into the modern industrial age. Highlighted by the innovation and application of computing, communications, control, and other information technologies, the third industrial revolution has continuously pushed industrial development to a new height [51].

Since the start of the 21st century, digitalization and networking have made information acquisition, use, control, and sharing extremely rapid and widespread. Furthermore, breakthroughs in and applications of new-generation AI have further raised the levels of digitalization, networking, and intelligence in the manufacturing industry. The most fundamental features of new-generation AI are its cognitive and learning capabilities, which can generate and better use knowledge. In this way, new-generation AI can fundamentally improve the efficiency of industrial knowledge generation and utilization, greatly liberate the physical power and brainpower of humans, enormously speed up the pace of innovation, and make applications more ubiquitous. Thus, it can push the manufacturing industry forward into a new stage of development: new-generation intelligent manufacturing. If digital-networked manufacturing is considered to be the start of the new industrial revolution, then the breakthroughs in and wide application of new-generation intelligent manufacturing will advance the new industrial revolution to its peak; reshape the technological system, production models, and industrial forms of the manufacturing industry; and usher in Industrie 4.0 in its real sense.

3.3. Vision

New-generation intelligent manufacturing systems will acquire increasingly powerful intelligence and, in particular, increasingly powerful cognitive and learning capabilities. The mutually heuristic growth of human intelligence and machine intelligence will shift knowledge-based work in the manufacturing industry toward the direction of autonomous intelligence and then solve the bottlenecks and difficulties that hinder the current development of the manufacturing industry.

In new-generation intelligent manufacturing, products are highly intelligent and human-friendly. At the same time, production processes feature high quality, flexibility, high efficiency, and environmental friendliness. The industrial model will undergo revolutionary changes. The service-oriented manufacturing industry and the production-based service industry will achieve greater development and will then optimize and integrate new manufacturing systems together, thus fully rebuilding the value chain of the manufacturing industry and greatly improving the innovativeness and competitiveness of the manufacturing industry.

New-generation intelligent manufacturing will bring revolutionary changes to human society. On the one hand, the boundary between humans and machines will shift dramatically, with intelligent machines taking over a huge amount of manual labor and a considerable amount of brainwork from humans. This shift will leave humans to be more engaged in creative work. On the other hand, our working and living environments and modes will become more people-centered. Meanwhile, new-generation intelligent manufacturing will effectively reduce the consumption and waste of resources and energy while continuously promoting the green and harmonious development of the manufacturing industry.

4. The technological mechanism of new-generation intelligent manufacturing: The human-cyber-physical system

Intelligent manufacturing involves intelligent products, intelligent production, intelligent services, and many other aspects. The optimization and integration of these aspects are also included. Although they differ in terms of technological mechanisms, these aspects are consistent in their essence. Here, we take the production process as an example for analysis.

4.1. Traditional manufacturing and the human-physical system

The traditional manufacturing system includes two major parts: humans and physical systems. Machine operation controls are completely manual in order to complete all kinds of work tasks, as shown in Fig. 2(a). The power revolution greatly improved the production efficiency and quality of physical systems (i.e., machines). From then on, physical systems began to replace humans by taking over the majority of work. The traditional manufacturing system requires humans to complete tasks such as information sensing, analysis, decision-making, operation, control, cognition, and learning. It not only has high requirements for humans but also carries high labor intensity. Moreover, the work efficiency, quality, and capability of the system to perform complex work tasks are still rather limited. The traditional manufacturing system can be abstractly described as a human-physical system (HPS), as shown in Fig. 2(b).

4.2. Digital manufacturing, digital-networked manufacturing, and the human-cyber-physical system (HCPS)

First- and second-generation intelligent manufacturing systems differ from traditional manufacturing systems in their addition of cyber systems between humans and physical systems. A cyber system can replace humans in order to complete some of the brainwork. A considerable portion of humans' sensing, analysis, and decision-making functions are reproduced and migrated to the cyber system. The physical systems are controlled through the cyber system in order to replace humans and complete more manual labor, as shown in Fig. 3.

By integrating the advantages of humans, cyber systems, and physical systems, first- and second-generation intelligent manufacturing systems acquire great capability enhancement, especially in computing analysis, precision control, and sensing capabilities. On the one hand, the work efficiency, quality, and stability of the systems are markedly improved. On the other hand, by transferring humans' relevant manufacturing experience and knowledge to the cyber system, the efficiency of human knowledge management, transfer, and application is effectively improved.

The evolution of manufacturing systems from traditional HPSs to human-cyber-physical systems (HCPSs) is abstractly described in Fig. 4 [11,52,53].

The introduction of the cyber system concurrently adds human-cyber systems (HCSs) and cyber-physical systems (CPSs) to manufacturing systems. In particular, the CPS is a very important part of an intelligent manufacturing system. The United States put

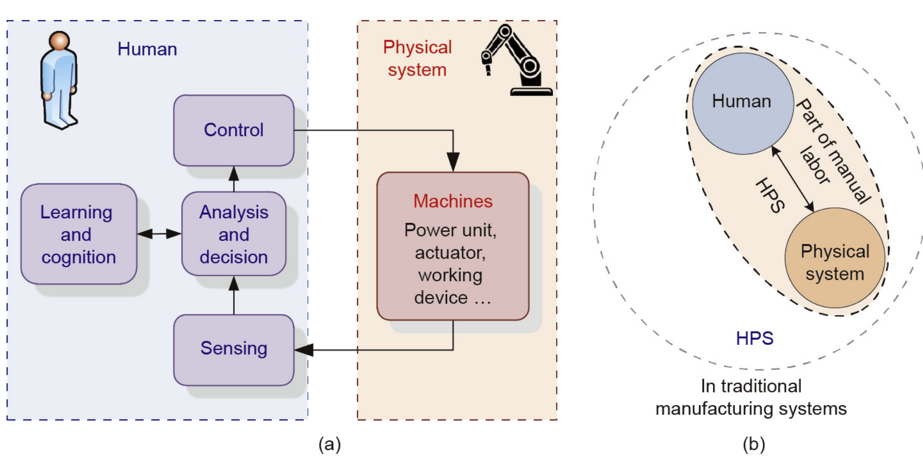

Fig. 2. (a) The technological mechanism of the traditional manufacturing system; (b) schematic of a human-physical system (HPS).

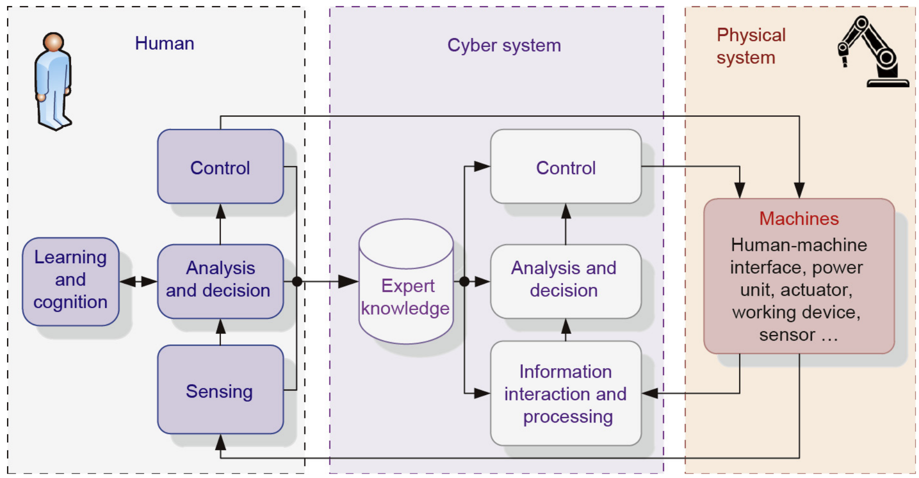

Fig. 3. First- and second-generation intelligent manufacturing systems incorporate cyber systems between humans and physical systems.

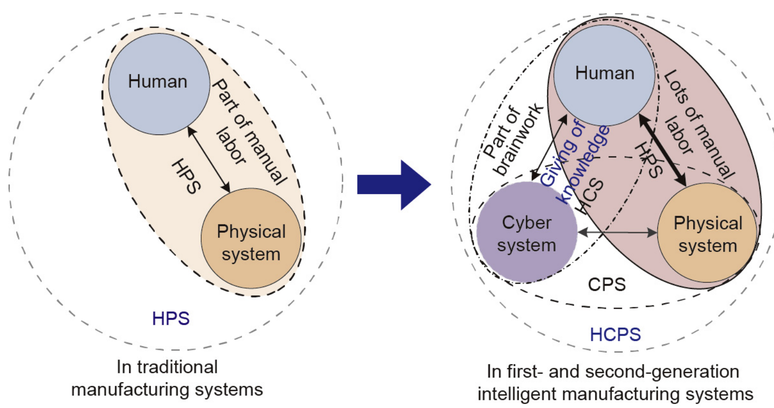

Fig. 4. The evolution of manufacturing systems from traditional HPSs to HCPSs. HCS: human-cyber system; CPS: cyber-physical system; HPS: human-physical system; HCPS: human-cyber-physical system.

forward CPS theory at the beginning of the 21st century [54], and Germany has taken the CPS as a core technology of Industrie 4.0. The application of the CPS in engineering aims to achieve the perfect mapping and in-depth integration of cyber systems with physical systems, with the concept of the digital twin as the most fundamental and essential technology. As a result, the performance and efficiency of manufacturing systems can be improved significantly [13,30,37,55,56].

4.3. New-generation intelligent manufacturing and the new-generation HCPS

The most fundamental feature of new-generation intelligent manufacturing systems is that cognitive and learning functions are added into the cyber systems. Cyber systems not only possess powerful sensing, computing analysis, and control capabilities, but also acquire the capability to improve learning and generate knowledge, as shown in Fig. 5.

At this stage, new-generation AI technology will induce qualitative changes to the HCPS and form a new-generation HCPS, as shown in Fig. 6. The main changes will be as follows.

(1) Humans will transfer some of their cognitive and learning brainwork to the cyber system, enabling the cyber system to "cognize and learn." The relationship between humans and the cyber system will undergo fundamental changes as humans transition from the "giving of fish" (i.e., passing knowledge to the cyber system), to the "giving of fishing" (i.e., having the cyber system cognize, learn, and obtain its own knowledge).

(2) Through the hybrid-augmented intelligence of "humans in the loop," in-depth human-machine integration will fundamentally improve the capability of manufacturing systems to handle complex and uncertain problems, and will greatly optimize the performance of manufacturing systems [52,57].

In the new-generation HCPS, the HCS, HPS, and CPS will all take great strides forward.

New-generation intelligent manufacturing further highlights the central position of humans. It is a grand integrated system that coordinates humans, cyber systems, and physical systems. It will bring quality and efficiency in the manufacturing industry to a higher level, and strengthen the foundation of human civilization. It will free humankind from intensive and tiring manual labor and low-level thinking, thus enabling humans to engage in more creative work. With new-generation intelligent manufacturing, human society will authentically enter the "age of intelligence" [10–12,51].

To sum up, the development of the manufacturing industry from traditional manufacturing to new-generation intelligent manufacturing is a process of evolution: from the former human-physical binary systems to the new-generation human-cyber-physical tertiary systems (Fig. 7). The new-generation HCPS reveals the

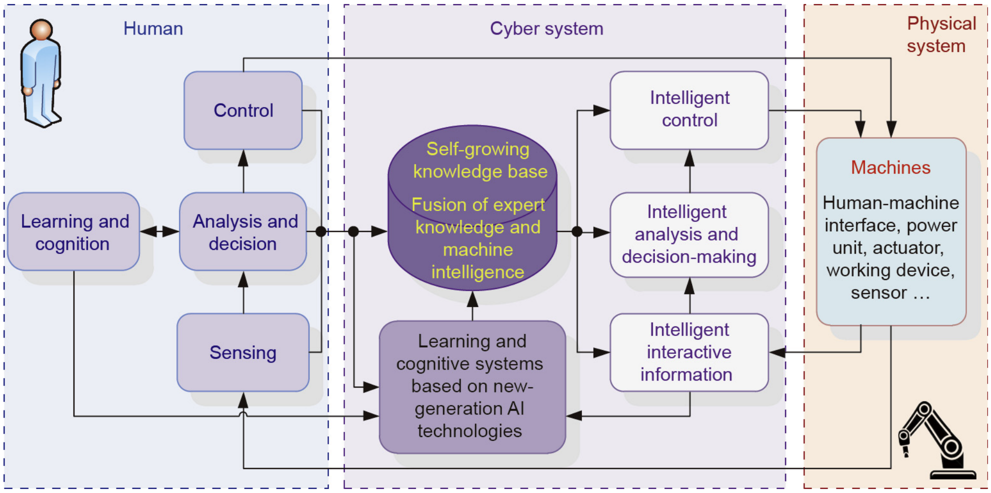

Fig. 5. Basic mechanism of new-generation intelligent manufacturing systems.

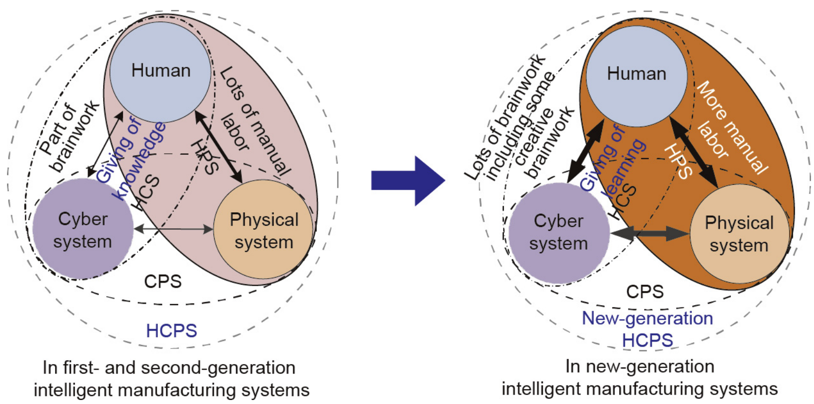

Fig. 6. The new-generation HCPS.

technological mechanism of new-generation intelligent manufacturing and can effectively guide theoretical research and engineering practice in new-generation intelligent manufacturing.

5. System composition and integration of new-generation intelligent manufacturing

New-generation intelligent manufacturing is a giant system that mainly consists of three functional subsystems: intelligent products, intelligent production, and intelligent services. It also includes the supporting systems of the Industrial Internet and the intelligent manufacturing cloud (Fig. 8).

New-generation intelligent manufacturing technology is a core enabling technology that can be widely applied in full-process innovation and optimization across the manufacturing value chain; this includes but is not limited to innovations in products, production, and services in discrete manufacturing and process-based manufacturing.

5.1. Intelligent products

Products and equipment are at the center of intelligent manufacturing. The former is the value carrier of intelligent manufacturing, while the latter is the precondition and foundation for implementing intelligent manufacturing [58].

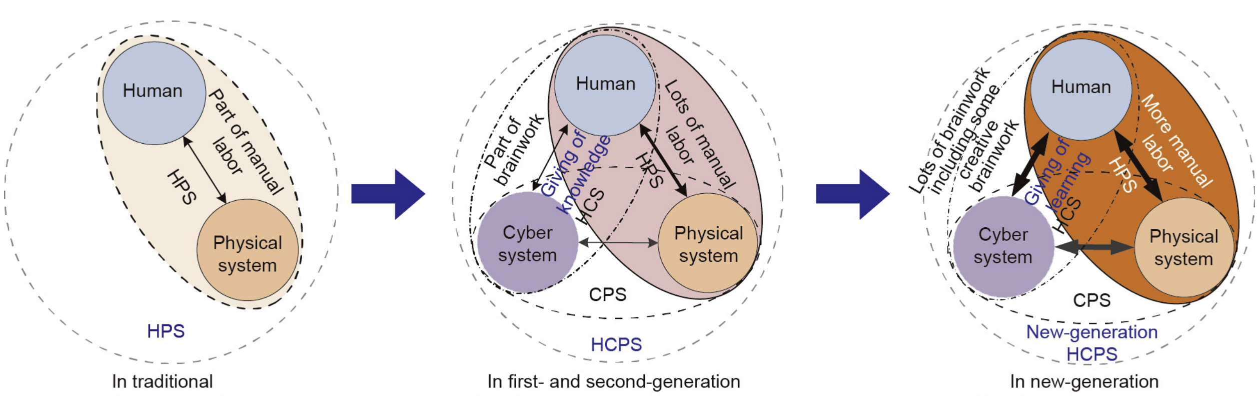

Fig. 7. Evolution from the HPS to the new-generation HCPS.

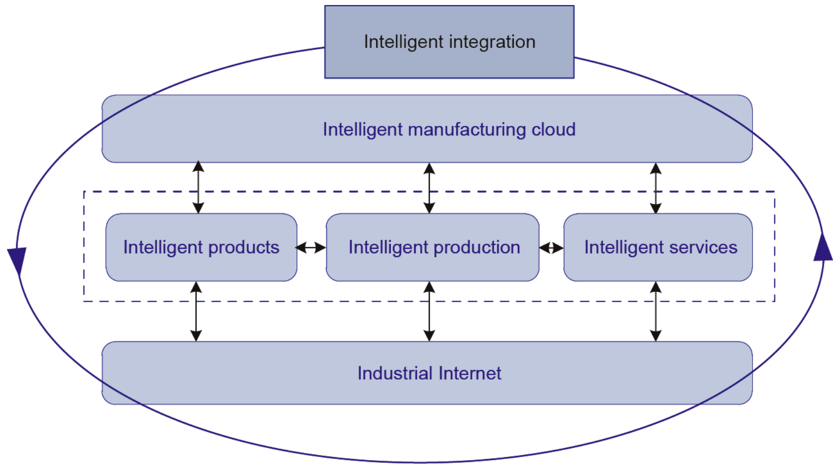

Fig. 8. System integration of new-generation intelligent manufacturing.

New-generation AI and intelligent manufacturing will bring unlimited space for expansion in product and manufacturing equipment innovation, and will induce revolutionary changes, causing a transformation from the "digital generation" to the "intelligent generation." In terms of technological mechanisms, the products and manufacturing equipment of the "intelligent generation" are highly intelligent, user-friendly, high quality, and cost effective, and feature the new-generation HCPS.

Design is the most important link to various product innovations. Intelligently optimized design, intelligently collaborated design, user-interactive intelligent customization, and mass creation based on crowd intelligence are all major components of intelligent design. Developing intelligent design systems with the characteristics of the new-generation HCPS is a key step in developing new-generation intelligent manufacturing.

5.2. Intelligent production

Intelligent production is the main activity of new-generation intelligent manufacturing [40,59,60], and intelligent production lines, intelligent workshops, and intelligent plants are the main carriers of intelligent production [61–63]. New-generation intelligent manufacturing achieves precision modeling and the real-time optimization and decision-making of complex systems; it forms self-learning, self-sensing, self-adaptive, and self-controlling intelligent production lines, intelligent workshops, and intelligent plants; and it achieves high-quality, flexible, efficient, safe, and green product manufacturing.

5.3. Intelligent services

Intelligent service-centered industrial model change is the theme of new-generation intelligent manufacturing [64,65]. In the intelligence era, all product life-cycle services, including marketing, sales, supply, operation, and maintenance, will take on entirely new content as enabled by the IoT, big data, AI, and other new technologies. The application of new-generation AI technology will give birth to new models and new business forms in the manufacturing industry: ① Large-scale streamlined production will be changed to small-scale customized production, and ② production-based manufacturing will be changed to service-oriented manufacturing. These changes will push forward the integrated development of the service-oriented manufacturing industry with the production-based service industry, and will create new business forms of universal manufacturing. Industrial models in the manufacturing industry will undergo fundamental changes from product-centered to user-centered models, and will provide remarkable support to the ongoing supply-side structural reforms in China.

5.4. The intelligent manufacturing cloud and the Industrial Internet

The intelligent manufacturing cloud and the Industrial Internet are the foundation that support new-generation intelligent manufacturing [9,20,31,44,66,67].

With the development and application of new-generation communications technology, network technology, cloud technology, and AI technology, the intelligent manufacturing cloud and the Industrial Internet will take great strides forward. Being comprised of intelligent network systems, intelligent platform systems, and intelligent safety systems, the intelligent manufacturing cloud and the Industrial Internet will provide space for growth and the requirements for change in production forces and modes for new-generation intelligent manufacturing [68].

5.5. System integration

New-generation intelligent manufacturing systems present the unprecedented feature of ubiquitous integration, both internally and externally. On the one hand, in internal ubiquitous integration, dynamic integration in an enterprise is achieved among intelligent design, production, sales, services, and management processes—resulting in vertical integration. With the intelligent manufacturing cloud and the Industrial Internet, integration, sharing, collaboration, and optimization can be achieved among enterprises—resulting in horizontal integration [69–72].

On the other hand, in external ubiquitous integration, deep integration exists among the manufacturing industry, the financial industry, and upstream and downstream industries; this results in a new commercial co-development of service-oriented manufacturing and production-based services. In addition, intelligent manufacturing is integrated with intelligent cities, intelligent agriculture, intelligent healthcare, and intelligent society to form an ecosystem of intelligent manufacturing.

The system integration of new-generation intelligent manufacturing also carries the significant and promising characteristic of openness—that is, concentration and distribution, coordination and precision, and tolerance and sharing.

6. Parallel promotion and integrated development: A technology roadmap for promoting intelligent manufacturing in China

In Western developed countries, intelligent manufacturing has followed a sequential development process: These countries spent decades fully developing digital manufacturing before developing digital-networked manufacturing and then entering a period of more advanced intelligent manufacturing [16]. In China, there is an extremely strong demand in the manufacturing industry for intelligent upgrading. Although recent years have seen rapid technological progress in the manufacturing industry, intelligent manufacturing in China has a very weak foundation in general. Most enterprises, and many small and medium-sized enterprises (SMEs), have not completed the transformation to digital manufacturing. How should China push forward the technological restructuring and intelligent upgrading of its manufacturing industry?

First, it is necessary to be realistic. In the process of pushing forward intelligent upgrading, Chinese enterprises must be down-to-earth, solidly establishing a digital foundation and then consolidating this foundation for intelligent manufacturing. Meanwhile, they may not necessarily take the same path of sequential development that was followed by Western developed countries. Rather, Chinese enterprises should strive to explore a new road of "leapfrog development" in intelligent manufacturing.

In recent years, China's industrial circles have vigorously promoted the concept of "Internet + manufacturing." On the one hand, a number of enterprises with a good digital manufacturing foundation have successfully transformed and achieved digital-networked manufacturing. On the other hand, some enterprises that have not realized digital manufacturing have adopted a technology roadmap of parallel promotion for digital manufacturing and digital-networked manufacturing. While "catching up" in digital manufacturing, they simultaneously and successfully take a great stride toward digital-networked manufacturing. These situations provide us with successful experiences.

To promote intelligent manufacturing, China should undertake a "coexistence" development approach and a technology roadmap of "parallel promotion and integrated development"; that is, China should promote digital manufacturing, digital-networked manufacturing, and new-generation intelligent manufacturing concurrently, while making prompt and full use of the fast-developing advanced information technology and advanced manufacturing technology of integrated innovation. Such a process will initiate and impel an intelligent transformation in China's manufacturing industry.

At present, new-generation intelligent manufacturing is emerging and is not yet mature. Therefore, in the coming years, efforts in upgrading China's manufacturing industry should focus on the large-scale promotion and comprehensive application of "Internet + manufacturing." During the process of vigorously popularizing "Internet + manufacturing," particular attention should be paid to the integrated application of various advanced technologies in order to upgrade low-end technology to high-end technology, and thus achieve integrated development. On the one hand, the majority of enterprises can correct problematic systems by installing new, high-quality technologies. On the other hand, it is necessary to apply new-generation intelligent manufacturing technology as quickly and as well as possible. As a result, the speed of manufacturing upgrading can be accelerated to a great extent.

It can be expected that in several years, new-generation intelligent manufacturing will be basically mature. At that time, China's manufacturing industry will enter into a new phase that features the comprehensive promotion and application of new-generation intelligent manufacturing.

While promoting the integrated development of the three basic paradigms of intelligent manufacturing, it is necessary to establish uniform standards [72]. In the coming decades, enterprises in China will face several rounds of paradigm shifts and technological upgrading during the process of intelligent transformation. Therefore, we must pay great attention to the establishment and implementation of relevant standards for intelligent manufacturing, so as to prepare for follow-up development and avoid low-level redundant construction in enterprises. This will allow us to successfully promote phased implementation and the continuous upgrading of China's intelligent manufacturing.

In carrying out a technology roadmap of "parallel promotion and integrated development," we should emphasize the principle of the "five adherences":

(1) Adherence to innovation-driven development. We should firmly seize the historical opportunities generated by new-generation intelligent manufacturing; fully leverage the Internet, big data, AI, and other advanced technologies; target high-end directions; step up the research, development, demonstration, promotion, and application of new-generation intelligent manufacturing technology; and initiate and promote production quality, efficiency, and performance improvement in the manufacturing industry through innovation. This will enable China's manufacturing industry to transition from "big" to "competitive."

(2) Adherence to enterprise-specific policies. To push forward intelligent manufacturing, it is essential to fully motivate enterprises' internal impetus. Chinese enterprises vary greatly, and it is impossible for one particular model of intelligent transformation to suit them all. Enterprises, and SMEs in particular, must start from their specific development situation, maintain a balance between technological advancement and technological economy, and realistically explore a technology pathway that suits their transformation and upgrading.

(3) Adherence to industrial upgrading. Pushing forward intelligent manufacturing must not be confined to models, demonstrations, and certain manufacturing links or manufacturing fields. Rather, attention must be paid to enterprises at large, to various industries, and to the whole manufacturing industry; this will advance quality, efficiency, and power changes in the development of the industry, and will achieve the intelligent transformation and upgrading of China's manufacturing industry.

(4) Adherence to establishing a better ecological system. All levels of government, academia, financial sectors, and other sectors should jointly establish a better ecological system in order to help and support the intelligent upgrading of enterprises, especially for the large number of SMEs; this will form an environment of mass entrepreneurship and innovation. The innovation system of intelligent manufacturing should be established with an integration of efforts from industry, universities, research, finance, and public administrations. Meanwhile, it is also urgent to form a cluster of emerging enterprises that are engaged in the promotion and application of various enabling technologies and system solutions.

The key to advancing intelligent manufacturing lies with talents. This advancement should be talent oriented; we need to cultivate a generation of talents for intelligent manufacturing.

(5) Adherence to "opening up" and collaboration. China's manufacturing sector should continuously enlarge its international communication and implement a higher level of "opening up." China's market is open, and China's innovation system is also open. Therefore, we must work together with colleagues in manufacturing sectors across the world to jointly push forward new-generation intelligent manufacturing, promote the new industrial revolution, and make the manufacturing industry serve humankind in a manner that is better than ever before.

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Compliance with ethics guidelines

ZHOU Ji, LI Peigen, ZHOU Yanhong, WANG Baicun, ZANG Jiyuan, and MENG Liu declare that they have no conflict of interest or financial conflicts to disclose.

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