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Intelligent Manufacturing—Perspective

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).

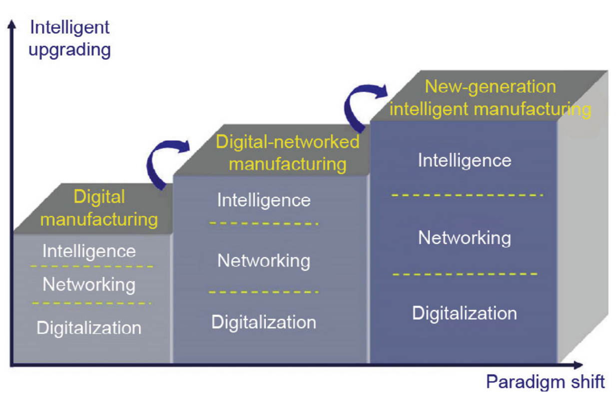

Fig. 1. The evolution of three basic paradigms of intelligent manufacturing.

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

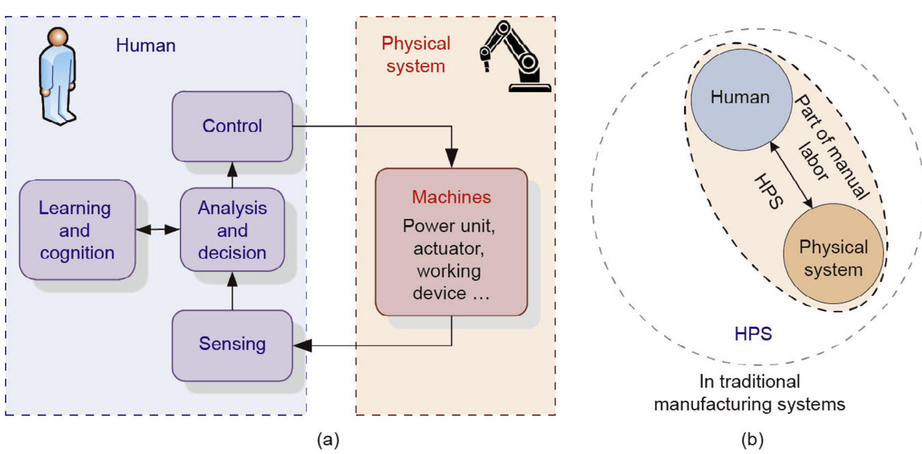

Fig. 2. (a) The technological mechanism of the traditional manufacturing system; (b) schematic of a human-physical system (HPS).

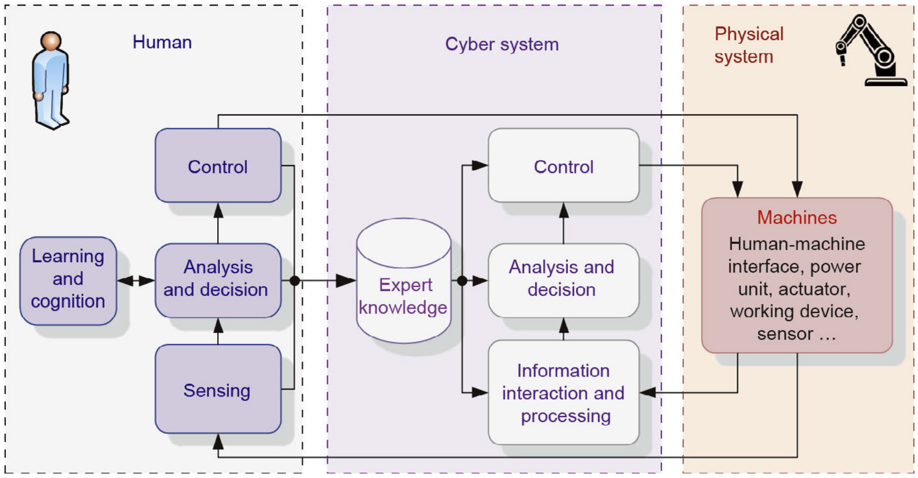

Fig. 3. First- and second-generation intelligent manufacturing systems incorporate cyber systems between humans and physical systems.

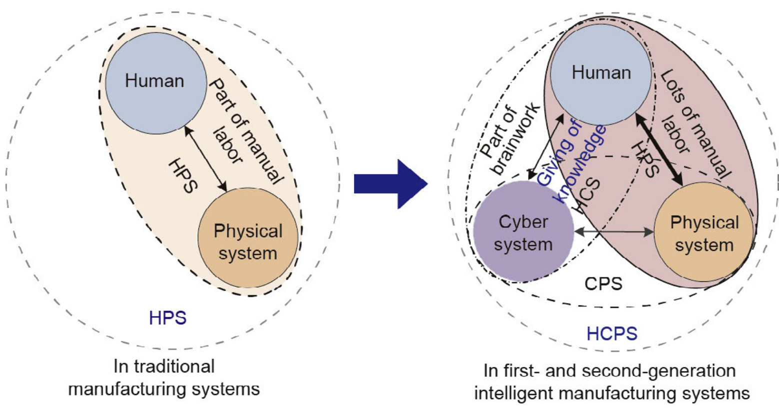

Fig. 4. The evolution of manufacturing systems from traditional HPSs to HCPSs. HCS: human-cyber system; CPS: cyber-physical system; HPS: human-physical system; HCPS: human-cyber-physical system.

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

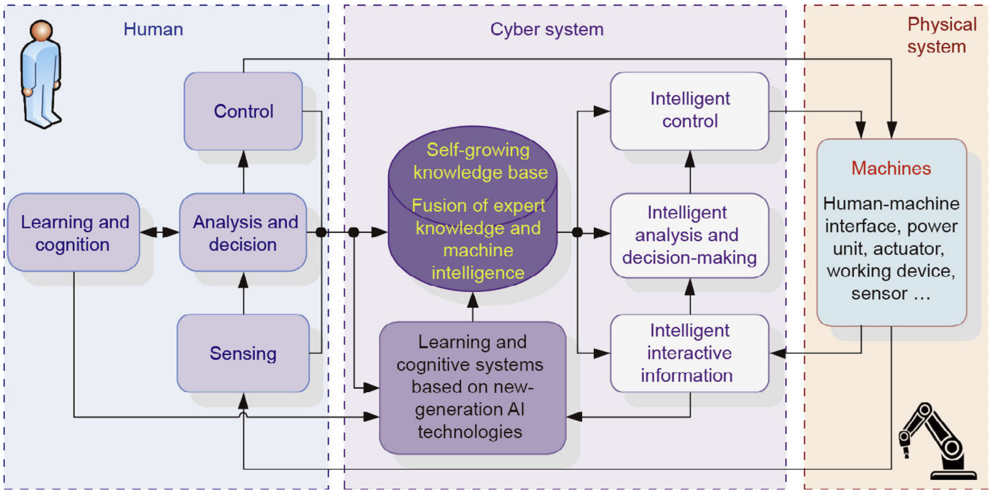

Fig. 5. Basic mechanism of new-generation intelligent manufacturing systems.

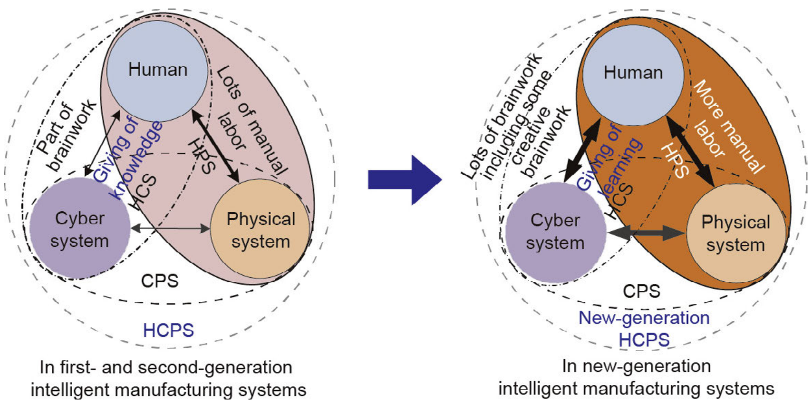

Fig. 6. The new-generation HCPS.

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].

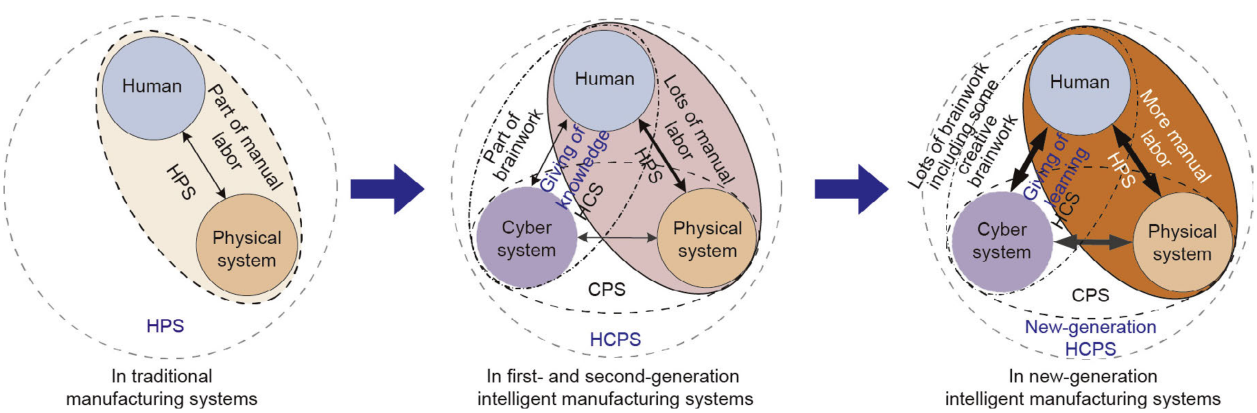

Fig. 7. Evolution from the HPS to the new-generation HCPS.

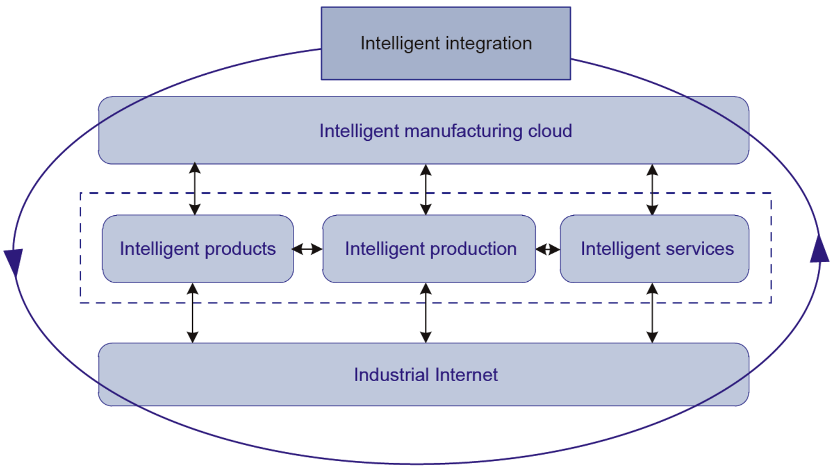

Fig. 8. System integration of new-generation intelligent manufacturing.

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

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Research
Intelligent Manufacturing—Perspective

走向新一代智能制造

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关键词
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并行推进
融合发展

摘要

智能制造是一个不断演进发展的大概念，可归纳为三个基本范式：数字化制造、数字化网络化制造、数字化网络化智能化制造——新一代智能制造。新一代智能制造是新一代人工智能技术与先进制造技术的深度融合，贯穿于产品设计、制造、服务全生命周期的各个环节及相应系统的优化集成，不断提升企业的产品质量、效益、服务水平，减少资源能耗，是新一轮工业革命的核心驱动力，是今后数十年制造业转型升级的主要路径。“人-信息-物理系统”（HCPS）揭示了新一代智能制造的技术机理，能够有效指导新一代智能制造的理论研究和工程实践。基于智能制造三个基本范式次第展开、相互交织、迭代升级的特征，推进制造业智能转型应采取“并行推进、融合发展”的技术路线。

1. 引言

面对新一轮工业革命，《中国制造2025》明确提出，要以新一代信息技术与制造业深度融合为主线，以推进智能制造为主攻方向[1]。世界各国都在积极采取行动，美国提出“先进制造业伙伴计划”[2,3]、德国提出“工业4.0战略计划”[4]、英国提出“英国工业2050战略”[5]、法国提出“新工业法国计划”[6]、日本提出“超智能社会5.0战略”[7]、韩国提出“制造业创新3.0计划”[8]，都将发展智能制造作为本国构建制造业竞争优势的关键举措。

新世纪以来，新一代信息技术呈现爆发式增长，数字化网络化智能化技术在制造业广泛应用，制造系统集成式创新不断发展，形成了新一轮工业革命的主要驱动力。特别是，新一代智能制造作为新一轮工业革命的核心技术，正在引发制造业在发展理念、制造模式等方面重大而深刻的变革，正在重塑制造业的发展路径、技术体系以及产业业态，从而推动全球制造业发展步入新阶段[9–13]。

2. 智能制造的三个基本范式

广义而论，智能制造是一个大概念[10,14]，是先进信息技术与先进制造技术的深度融合，贯穿于产品设

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计、制造、服务等全生命周期的各个环节及相应系统的优化集成，旨在不断提升企业的产品质量、效益、服务水平，减少资源消耗，推动制造业创新、绿色、协调、开放、共享发展。

数十年来，智能制造在实践演化中形成了许多不同的相关范式，包括精益生产、柔性制造、并行工程、敏捷制造、数字化制造、计算机集成制造、网络化制造、云制造、智能化制造等[15–23]，在指导制造业技术升级中发挥了积极作用。但同时，众多的范式不利于形成统一的智能制造技术路线，给企业在推进智能升级的实践中造成了许多困扰。面对智能制造不断涌现的新技术、新理念、新模式，有必要归纳总结提炼出基本范式。

智能制造的发展伴随着信息化的进步。全球信息化发展可分为三个阶段：从20世纪中叶到90年代中期，信息化表现为以计算、通信和控制应用为主要特征的数字化阶段；从20世纪90年代中期开始，互联网大规模普及应用，信息化进入了以万物互联为主要特征的网络化阶段；当前，在大数据、云计算、移动互联网、工业互联网集群突破、融合应用的基础上，人工智能实现战略性突破，信息化进入了以新一代人工智能技术为主要特征的智能化阶段[24]。

综合智能制造相关范式，结合信息化与制造业在不同阶段的融合特征，可以总结、归纳和提升出三个智能制造的基本范式（图1），也就是：数字化制造、数字化网络化制造、数字化网络化智能化制造——新一代智能制造。

2.1. 数字化制造

数字化制造是智能制造的第一个基本范式，也可称为第一代智能制造。

智能制造的概念最早出现于20世纪80年代[25]，但

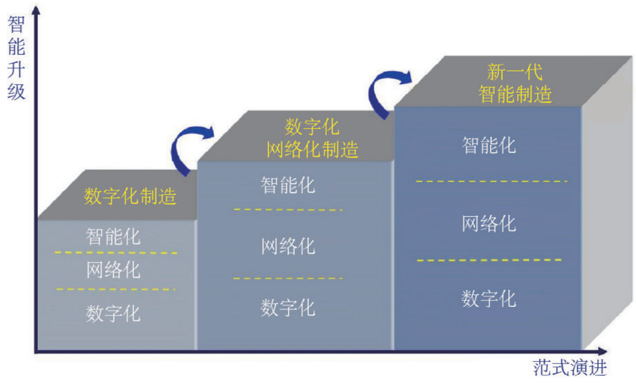

图1. 智能制造三个基本范式演进。

是由于当时应用的第一代人工智能技术还难以解决工程实践问题，因而那一代智能制造主体上是数字化制造。

20世纪下半叶以来，随着制造业对于技术进步的强烈需求，以数字化为主要形式的信息技术广泛应用于制造业，推动制造业发生革命性变化。数字化制造是在数字化技术和制造技术融合的背景下，通过对产品信息、工艺信息和资源信息进行数字化描述、分析、决策和控制，快速生产出满足用户要求的产品[15, 16, 26, 27]。

数字化制造的主要特征表现为：第一，数字技术在产品中得到普遍应用，形成“数字一代”创新产品；第二，广泛应用数字化设计、建模仿真、数字化装备、信息化管理；第三，实现生产过程的集成优化。

需要说明的是，数字化制造是智能制造的基础，其内涵不断发展，贯穿于智能制造的三个基本范式和全部发展历程。这里定义的数字化制造是作为第一种基本范式的数字化制造，是一种相对狭义的定位。国际上也有若干关于数字化制造的比较广义的定义和理论[28]。

2.2. 数字化网络化制造

数字化网络化制造是智能制造的第二种基本范式，也可称为“互联网+制造”，或第二代智能制造[29]。

20世纪末互联网技术开始广泛应用，“互联网+”不断推进互联网和制造业融合发展，网络将人、流程、数据和事物连接起来，通过企业内、企业间的协同和各种社会资源的共享与集成，重塑制造业的价值链，推动制造业从数字化制造向数字化网络化制造转变[17, 30–33]。

数字化网络化制造主要特征表现为：第一，在产品方面，数字技术、网络技术得到普遍应用，产品实现网络连接，设计、研发实现协同与共享；第二，在制造方面，实现横向集成、纵向集成和端到端集成，打通整个制造系统的数据流、信息流；第三，在服务方面，企业与用户通过网络平台实现连接和交互，企业生产开始从以产品为中心向以用户为中心转型[34]。

德国“工业4.0战略计划”报告和美国GE公司“工业互联网”报告完整地阐述了数字化网络化制造范式，精辟地提出了实现数字化网络化制造的技术路线[4, 9, 31, 35–39]。

2.3. 新一代智能制造 —— 数字化网络化智能化制造

数字化网络化智能化制造是智能制造的第三种基本范式，也可称为新一代智能制造。

近年来，在经济社会发展的强烈需求以及互联网的普及、云计算和大数据的涌现、物联网的发展等信息环境急速变化的共同驱动下，大数据智能、人机混合增强智能、群体智能、跨媒体智能等新一代人工智能技术加速发展，实现了战略性突破[24, 40, 41]。新一代人工智能技术与先进制造技术深度融合，形成新一代智能制造——数字化网络化智能化制造。新一代智能制造将重塑设计、制造、服务等产品全生命周期的各环节及其集成，催生新技术、新产品、新业态、新模式，深刻影响和改变人类的生产结构、生产方式乃至生活方式和思维模式，实现社会生产力的整体跃升。新一代智能制造将给制造业带来革命性的变化，将成为制造业未来发展的核心驱动力。

智能制造的三个基本范式体现了智能制造发展的内在规律：一方面，三个基本范式次第展开，各有自身阶段的特点和重点解决的问题，体现着先进信息技术与先进制造技术融合发展的阶段性特征；另一方面，三个基本范式在技术上并不是绝然分离的，而是相互交织、迭代升级，体现着智能制造发展的融合性特征。对中国等新兴工业国家而言，应发挥后发优势，采取三个基本范式“并行推进、融合发展”的技术路线。

3. 新一代智能制造引领和推动新一轮工业革命

3.1. 发展背景

当今世界，各国制造企业普遍面临着提高质量、增加效率、降低成本、快速响应的强烈需求，还要不断适应广大用户不断增长的个性化消费需求，应对资源能源环境约束进一步加大的挑战。然而，现有制造体系和制造水平已经难以满足高端化、个性化、智能化产品和服务增值升级的需求，制造业的进一步发展面临巨大瓶颈和困难。解决问题，迎接挑战，迫切需要制造业的技术创新、智能升级[14, 41]。

新一轮工业革命方兴未艾，其根本动力在于新一轮科技革命。新世纪以来，移动互联、超级计算、大数据、云计算、物联网等新一代信息技术日新月异、飞速发展[11, 12, 42–48]，并极其迅速地普及应用，形成了群体性跨越。这些历史性的技术进步，集中汇聚在新一代人工智能技术的战略性突破，实现了质的飞跃[24]。新一代人工智能呈现出深度学习、跨界协同、人机融合、群体智能等新特征，为人类提供认识复杂系统的新思维、改造自然和社会的新技术。当然，新一代人工智能技术还处在极速发展的进程中，将继续从“弱人工智能”迈向“强人工智能”，不断拓展人类“脑力”，应用范围将无所不在。新一代人工智能已经成为新一轮科技革命的核心技术，为制造业革命性的产业升级提供了历史性机遇，正在形成推动经济社会发展的巨大引擎。世界各国都把新一代人工智能的发展摆在了最重要的位置[49, 50]。

新一代人工智能技术与先进制造技术的深度融合，形成了新一代智能制造技术，成为了新一轮工业革命的核心驱动力。

3.2. 新一代智能制造是新一轮工业革命的核心技术

科学技术是第一生产力，科技创新是经济社会发展的根本动力。第一次工业革命和第二次工业革命分别以蒸汽机和电力的发明和应用为根本动力，极大地提高了生产力，人类社会进入了现代工业社会。第三次工业革命以计算、通信、控制等信息技术的创新与应用为标志，持续将工业发展推向新高度[51]。

新世纪以来，数字化和网络化使得信息的获取、使用、控制以及共享变得极其快速和普及，进而，新一代人工智能突破和应用进一步提升了制造业数字化网络化智能化的水平，其最本质的特征是具备认知和学习的能力，具备生成知识和更好地运用知识的能力，这样就从根本上提高工业知识产生和利用的效率，极大地解放人的体力和脑力，使创新速度大大加快，应用范围更加泛在，从而推动制造业发展步入新阶段，即数字化网络化智能化制造——新一代智能制造。如果说数字化网络化制造是新一轮工业革命的开始，那么新一代智能制造的突破和广泛应用将推动形成新工业革命的高潮，将重塑制造业的技术体系、生产模式、产业形态，并将引领真正意义上的“工业4.0”，实现新一轮工业革命。

3.3. 愿景

制造系统将具备越来越强大的智能，特别是越来越强大的认知和学习能力，人的智慧与机器智能相互启发性地增长，使制造业的知识型工作向自主智能化的方向发生转变，进而突破当今制造业发展所面临的瓶颈和困难。

新一代智能制造中，产品呈现高度智能化、宜人化，生产制造过程呈现高质、柔性、高效、绿色等特征，产业模式发生革命性的变化，服务型制造业与生产型服务业大发展，进而共同优化集成新型制造大系统，全面重塑制造业价值链，极大提高制造业的创新力和竞争力。

新一代智能制造将给人类社会带来革命性变化。人与机器的分工将产生革命性变化，智能机器将替代人类大量体力劳动和相当部分的脑力劳动，人类可更多地从事创造性工作；人类工作生活环境和方式将朝着以人为本的方向迈进。同时，新一代智能制造将有效减少资源与能源的消耗和浪费，持续引领制造业绿色发展、和谐发展。

4. 新一代智能制造的技术机理：“人-信息-物理系统”

智能制造涉及智能产品、智能生产以及智能服务等多个方面及其优化集成。从技术机理角度看，这些不同方面尽管存在差异，但本质上是一致的，下面以生产过程为例进行分析。

4.1. 传统制造与“人-物理系统”

传统制造系统包含人和物理系统两大部分，是完全通过人对机器的操作控制去完成各种工作任务[如图2（a）所示]。动力革命极大地提高了物理系统（机器）的生产效率和质量，物理系统（机器）代替了人类大量体力劳动。传统制造系统中，要求人完成信息感知、分析决策、操作控制以及认知学习等多方面任务，不仅对人的要求高，劳动强度大，而且系统工作效率、质量还不够高，完成复杂工作任务的能力还很有限。传统制造系统可抽象描述为图2（b）所示的“人-物理系统”（human-physical systems, HPS）。

4.2. 数字化制造、数字化网络化制造与“人-信息-物理系统”

与传统制造系统相比，第一代和第二代智能制造系统发生的本质变化是，在人和物理系统之间增加了信息系统，信息系统可以代替人类完成部分脑力劳动，人的相当部分的感知、分析、决策功能向信息系统复制迁移，进而可以通过信息系统来控制物理系统，以代替人类完成更多的体力劳动，如图3所示。

第一代和第二代智能制造系统通过集成人、信息系统和物理系统的各自优势，系统的能力尤其是计算分析、精确控制以及感知能力都得以很大提高。一方面，系统的工作效率、质量和稳定性均得以显著提升；另一方面，人的相关制造经验和知识转移到信息系统，能够有效提高人的知识的传承和利用效率。制造系统从传统的“人-物理系统”向“人-信息-物理系统”（human-cyber-physical systems, HCPS）的演变可进一步用图4进行抽象描述[11, 52, 53]。

信息系统（cyber system）的引入使得制造系统同时增加了“人-信息系统”（human-cyber systems, HCS）和“信息-物理系统”（cyber-physical systems, CPS）。其中，CPS是非常重要的组成部分。美国在21世纪初提出了CPS的理论[54]，德国将其作为“工业4.0”的核心技术。CPS在工程上的应用是实现信息系统和物理系统的完美映射和深度融合，“数字孪生体”（digital twin）即是其最为基本且关键的技术，由此，制造系统的性能和效率可大大提高[13, 30, 37, 55, 56]。

4.3. 新一代智能制造与新一代“人-信息-物理系统”

新一代智能制造系统最本质的特征是其信息系统增加了认知和学习的功能，信息系统不仅具有强大的感知、计算分析与控制能力，更具有学习提升、产生知识的能力，如图5所示。

在这一阶段，新一代人工智能技术将使“人-信息-

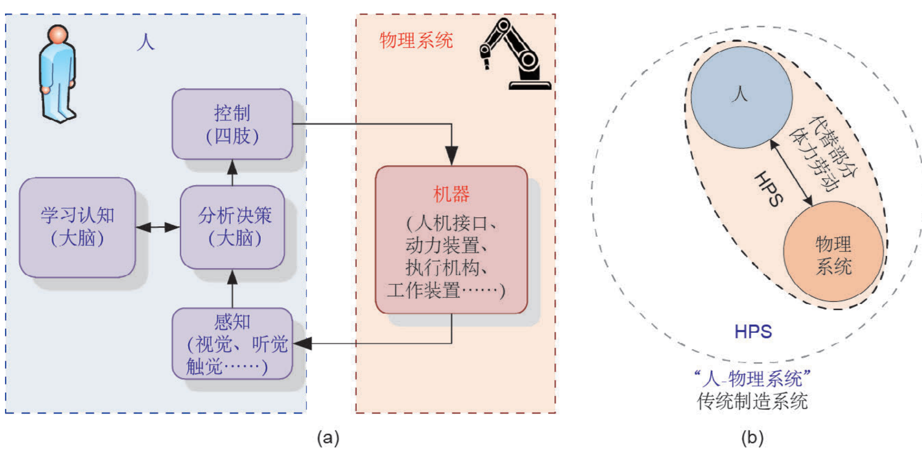

图2. 传统制造系统与“人-物理系统”。

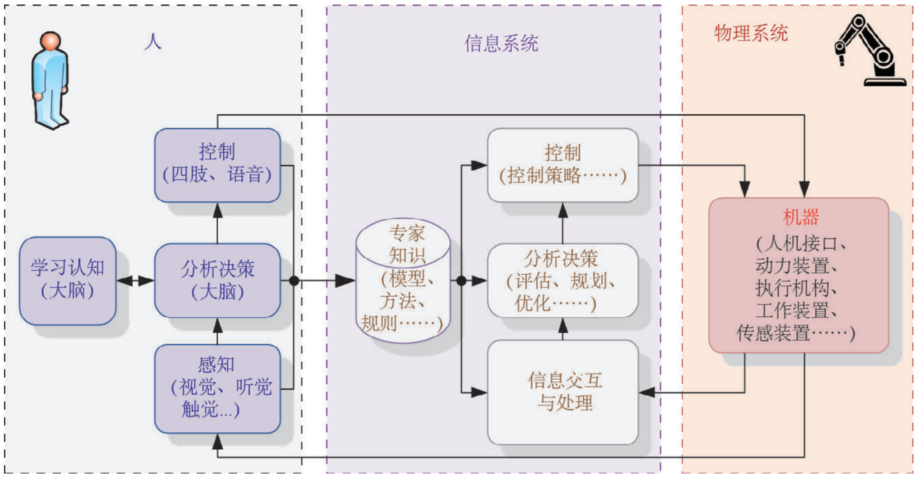

图3. 第一代和第二代智能制造系统。

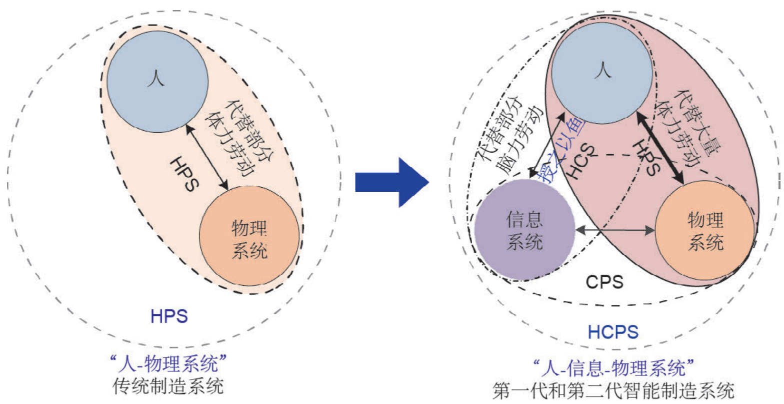

图4. 从“人-物理系统”到“人-信息-物理系统”。

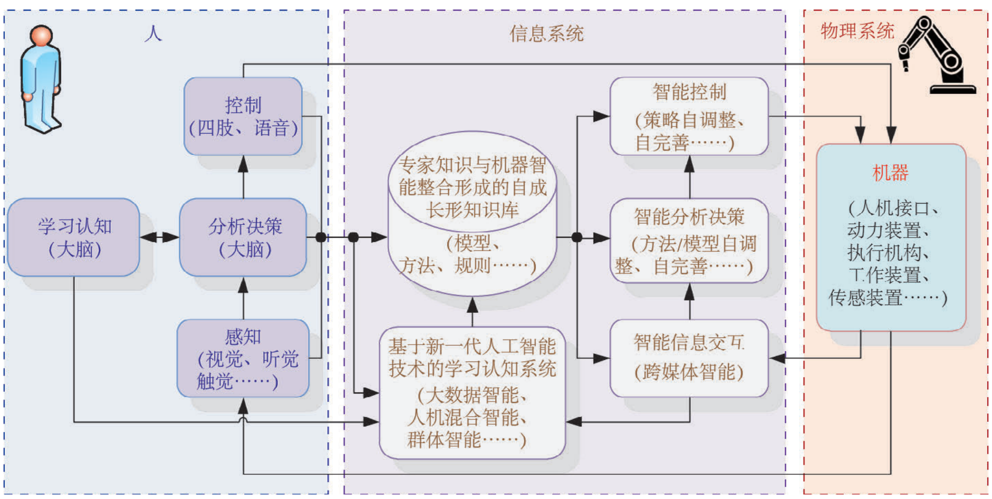

图5. 新一代智能制造系统的基本机理。

物理系统”发生质的变化，形成新一代“人-信息-物理系统”（图6）。主要变化在于：第一，人将部分认知与学习型的脑力劳动转移给信息系统，因而信息系统具有了“认知和学习”的能力，人和信息系统的关系发生了根本性的变化，即从“授之以鱼”发展到“授之以渔”；第二，通过“人在回路”的混合增强智能，人机深度融合将从本质上提高制造系统处理复杂性、不确定性问题的能力，极大地优化制造系统的性能[52, 57]。

新一代“人-信息-物理系统”中，HCS、HPS和CPS都将实现质的飞跃。

新一代智能制造进一步突出了人的中心地位，是统筹协调“人”“信息系统”和“物理系统”的综合集成大系统；将使制造业的质量和效率跃升到新的水平，为人民的美好生活奠定更好的物质基础；将使人类从更多体力劳动和大量脑力劳动中解放出来，使得人类可以从事更有意义的创造性工作，人类社会开始真正进入“智能时代”[10–12, 51]。

总之，制造业从传统制造向新一代智能制造发展的过程是从原来的“人-物理”二元系统向新一代“人-信息-物理”三元系统进化的过程（图7）。新一代“人-信息-物理系统”揭示了新一代智能制造的技术机理，能够有效指导新一代智能制造的理论研究和工程实践。

5. 新一代智能制造的系统组成与系统集成

新一代智能制造是一个大系统，主要由智能产品、智能生产和智能服务三大功能系统以及工业智联网和智能制造云两大支撑系统集合而成（图8）。

新一代智能制造技术是一种核心使能技术，可广泛应用于离散型制造和流程型制造的产品创新、生产创新、服务创新等制造价值链全过程的创新与优化。

5.1. 智能产品与制造装备

产品和制造装备是智能制造的主体，其中，产品是智能制造的价值载体，制造装备是实施智能制造的前提和基础[58]。

新一代人工智能和新一代智能制造将给产品与制造装备创新带来无限空间，使产品与制造装备产生革命性变化，从“数字一代”整体跃升至“智能一代”。从技术机理看，“智能一代”产品和制造装备也就是具有新一代HCPS特征的、高度智能化、宜人化、高质量、高性价比的产品与制造装备。

设计是产品创新的最重要环节，智能优化设计、智能协同设计、与用户交互的智能定制、基于群体智能的“众创”等都是智能设计的重要内容。研发具有新一代HCPS特征的智能设计系统也是发展新一代智能制造的核心内容之一。

5.2. 智能生产

智能生产是新一代智能制造的主线[40, 59, 60]。

智能产线、智能车间、智能工厂是智能生产的主要载体[61–63]。新一代智能制造将解决复杂系统的精确建模、实时优化决策等关键问题，形成自学习、自感知、

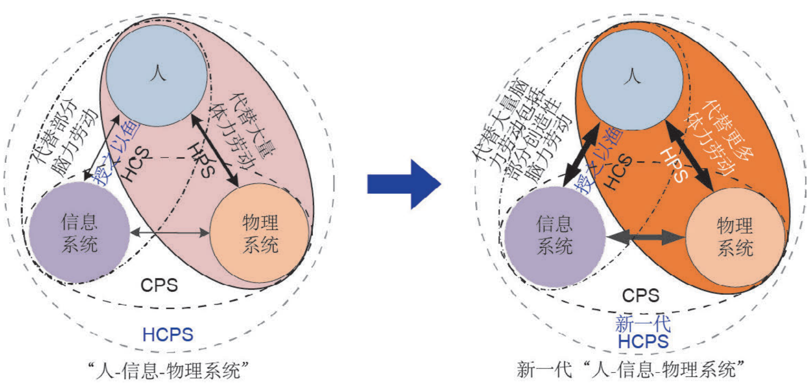

图6. 新一代“人-信息-物理系统”。

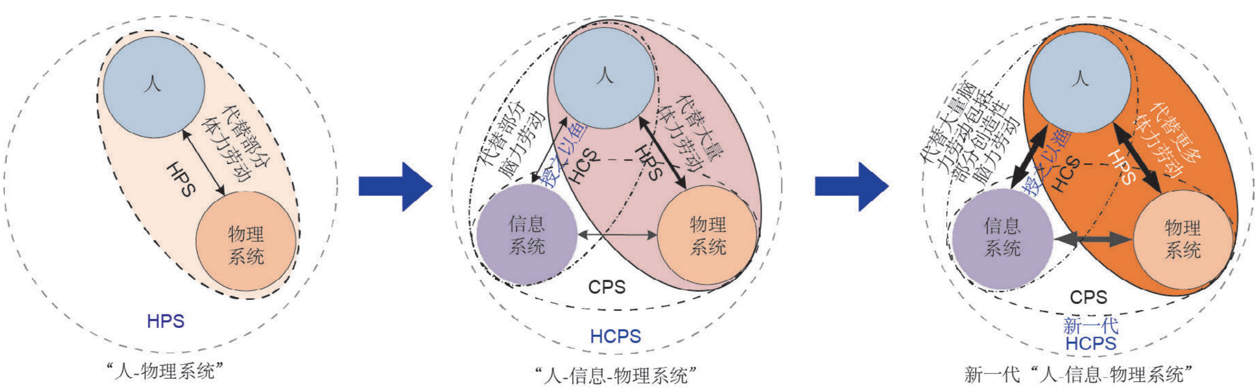

图7. 从“人-物理系统”到新一代“人-信息-物理系统”。

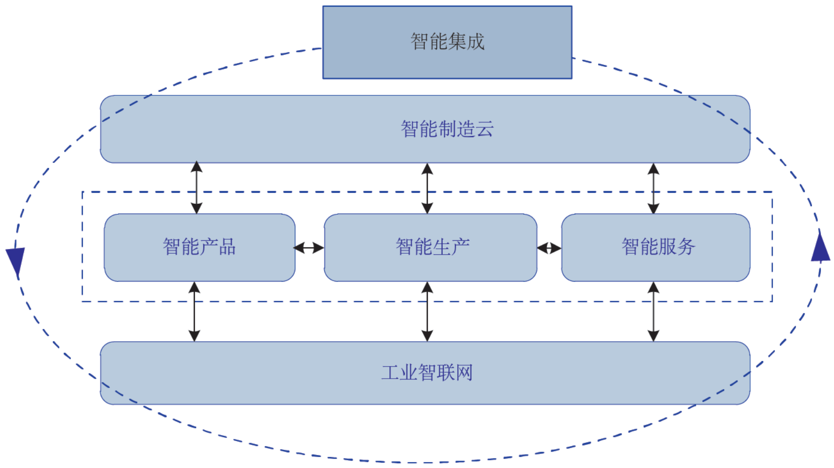

图8. 新一代智能制造的系统集成。

自适应、自控制的智能产线、智能车间和智能工厂，实现产品制造的高质、柔性、高效、安全与绿色。

5.3. 智能服务

以智能服务为核心的产业模式变革是新一代智能制造的主题[64, 65]。

在智能时代，市场、销售、供应、运营维护等产品全生命周期服务，均因物联网、大数据、人工智能等新技术而赋予其全新的内容。

新一代人工智能技术的应用将催生制造业新模式、新业态：一是，从大规模流水线生产转向规模化定制生产；二是，从生产型制造向服务型制造转变，推动服务型制造业与生产性服务业大发展，共同形成大制造新业态。制造业产业模式将实现从以产品为中心向以用户为中心的根本性转变，完成深刻的供给侧结构性改革。

5.4. 智能制造云与工业智联网

智能制造云和工业智联网是支撑新一代智能制造的基础[9, 20, 31, 44, 66, 67]。

随着新一代通信技术、网络技术、云技术和人工智能技术的发展和应用，智能制造云和工业智联网将实现质的飞跃。智能制造云和工业智联网将由智能网络体系、智能平台体系和智能安全体系组成，为新一代智能制造生产力和生产方式变革提供发展的空间和可靠的保障[68]。

5.5. 系统集成

新一代智能制造内部和外部均呈现出前所未有的系统“大集成”特征：

一方面是制造系统内部的“大集成”。企业内部设计、生产、销售、服务、管理过程等实现动态智能集成，即纵向集成；企业与企业之间基于工业智联网与智能云平台，实现集成、共享、协作和优化，即横向集成[69–72]。

另一方面是制造系统外部的“大集成”。制造业与金融业、上下游产业的深度融合形成服务型制造业和生产性服务业共同发展的新业态。智能制造与智能城市、智能农业、智能医疗等交融集成，共同形成智能生态大系统——智能社会。

新一代智能制造系统大集成具有大开放的显著特征，具有集中与分布、统筹与精准、包容与共享的特性，具有广阔的发展前景。

6. 并行推进、融合发展——中国推进智能制造的技术路线

在西方发达国家，智能制造是一个“串联式”的发展过程，他们是用几十年时间充分发展数字化制造之后，再发展数字化网络化制造，进而迈向更高级的智能制造阶段[16]。在中国，制造业对于智能升级有着极为强烈的需求，近年来技术进步也很快，但是总体而言，中国智能制造的基础非常薄弱，大多数企业，特别是广大中小企业，还没有完成数字化制造转型。面对这样的现实，中国如何推进制造业的技术改造、智能升级？

首先，必须实事求是，中国企业在推进智能升级的过程中要踏踏实实地完成数字化“补课”，夯实智能制造发展的基础；同时，不必走西方发达国家“顺序发展”的路径，努力探索一条智能制造跨越式发展的新路。

近几年，中国制造业界大力推进“互联网+制造”。一方面，一批数字化制造基础较好的企业成功转型，实现了数字化网络化制造；另一方面，部分原来还未实现

数字化制造的企业，则采用并行推进数字化制造和数字化网络化制造的技术路线，在完成数字化制造“补课”的同时，成功实现向数字化网络化制造的跨越。这给我们提供了成功的经验。

中国推进智能制造应采取“并联式”的发展方式，采用“并行推进、融合发展”的技术路线：并行推进数字化制造、数字化网络化制造、新一代智能制造，以及时充分应用高速发展的先进信息技术和先进制造技术的融合式技术创新，引领和推进中国制造业的智能转型。

未来若干年，考虑到中国智能制造发展的现状，也考虑到新一代智能制造技术还不成熟，中国制造业转型升级的工作重点要放在大规模推广和全面应用“互联网+制造”；同时，在大力普及“互联网+制造”的过程中，要特别重视各种先进技术的融合应用，“以高打低、融合发展”。一方面，使得广大企业都能高质量完成“数字化补课”；另一方面，尽快尽好应用新一代智能制造技术，大大加速制造业转型升级的速度。

再过若干年，在新一代智能制造技术基本成熟之后，中国制造业将进入全面推广应用普及新一代智能制造的新阶段。

我国在推动三个基本范式“融合发展”时，必须制定统一的标准。未来数十年，我国企业在智能升级过程中，将普遍面临多次范式转化和技术升级，必须高度重视制定和实行智能制造的相关标准，为后续发展做好准备，避免企业的低水平重复建设，有利于我国推进智能制造的分阶段实施和不断升级。

在实施“并行推进、融合发展”这一技术路线的过程中，要强调“五个坚持”的方针。

一是坚持“创新引领”。紧紧抓住新一代智能制造带来的历史性机遇，充分利用互联网、大数据、人工智能等先进技术，瞄准高端方向，加快研究、开发、示范、推广和应用新一代智能制造技术，用创新引领和推动制造业生产质量和效率提升，实现中国制造业由大变强。

二是坚持“因企制宜”。推动智能制造，要充分激发企业的内生动力。中国的企业参差不齐，实现智能转型不能搞“一刀切”，各个企业特别是广大中小企业，要结合企业发展实情，充分考虑技术先进性和技术经济性的平衡，实事求是地应用适合自己转型升级的技术路径。

三是坚持“产业升级”。推动智能制造不能仅仅停留在典型、示范、部分制造环节或者部分制造领域，而是要着眼于广大企业、各个行业和整个制造产业，推动中国制造业质量变革、效率变革、动力变革，实现中国制造业全方位的智能化转型升级。

四是坚持建设良好的发展生态。各级政府、科技界、学界、金融界等社会各界要共同营造良好的生态环境，帮助和支持企业特别是广大中小企业的智能升级。营造“大众创业、万众创新”的良好环境；建设“用产学研金政”紧密结合的智能制造技术创新体系；形成从事推广应用各种共性使能技术和提供系统解决方案的新兴企业集群。

推进智能制造成败的关键在于人才，要以人为本，动员各方力量，努力培养一代智能制造优秀人才。

五是坚持开放与协同创新。中国制造业界要不断扩大与世界各国制造业界的交流，实行更高水平的开放。中国的市场是开放的市场，中国的创新体系是开放的创新体系。我们要和世界制造业的同行们共同努力，共同推进新一代智能制造，共同推进新一轮工业革命，使制造业更好地为人类造福。

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Compliance with ethics guidelines

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