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Research on New-generation Intelligent Manufacturing Based on Human-Cyber-Physical Systems

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Abstract: This paper first discusses development of new-generation intelligent manufacturing from the perspectives of the problems and challenges of the manufacturing industry, major opportunities brought by new-generation artificial intelligence, and core technologies of the new round of industrial revolution. By analyzing the evolution of intelligent manufacturing, this paper points out that the process of developing from traditional manufacturing to intelligent manufacturing is also a process of developing from the original human-physical systems (HPS) to human-cyber-physical systems (HCPS). An HCPS reveals the basic principles of intelligent manufacturing development and is the theoretical basis for supporting the development of new-generation intelligent manufacturing. Based on system integration of HCPS and intelligent manufacturing, the prospect of new-generation intelligent manufacturing is described from the perspective of the revolutionary changes brought to the manufacturing sector and to human society.
Keywords: new-generation intelligent manufacturing; new generation of artificial intelligence; HCPS; system integration; prospect

1 Background of the development of new-generation intelligent manufacturing

1.1 The manufacturing industry urgently needs a revolutionary change

With increasing user demand for personalized consumption and the growing challenges of resources, energy, and environmental constraints, global competition in the manufacturing industry is intensifying. At the same time, there is generally a strong demand from the manufacturing sector for improving quality, increasing efficiency, and reducing costs. Therefore, the manufacturing industry is in urgent need of a revolutionary upgrade [1].

In contrast, manufacturing systems are becoming increasingly complex ubiquitous systems, and the uncertainty of the whole process is growing. To provide manufacturing systems with the ability to quickly respond, reorganize, and make better decisions, it is necessary to explore the new architecture and operating mechanisms of manufacturing systems; further breakthroughs are needed in the acquisition, integration, and fusion of manufacturing information dissemination, processing, and management. The ability to learn and transfer knowledge has become the bottleneck that constrains the development and production of products using modern manufacturing technologies. Consequently, new enabling technologies are urgently needed to resolve the key problems in knowledge generation, efficient utilization, and large-scale application in the manufacturing process and further realize the capability and value in the entire manufacturing system [2].

In general, existing manufacturing systems and manufacturing levels can hardly meet the needs of value-added upgrades

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to high-end, personalized, intelligent products and services; the manufacturing process itself also requires more intelligent tools and computing methods to overcome challenges such as solution optimization and knowledge inheritance. These problems and challenges have raised urgent demands for technological innovation and intelligent upgrading in the manufacturing sector.

1.2 The new generation of artificial intelligence technologies brings major opportunities for transforming the manufacturing industry

In recent years, with the substantial upgrade of computing capability, the Internet has generated big data in a real sense. Based on the integration of various advanced technologies, a new generation of artificial intelligence technology (AI2.0) has emerged. AI2.0 has demonstrated new features such as deep learning, cross-sector integration, human-machine collaboration, and group intelligence. Big-data-based knowledge learning, cross-media collaborative processing, human-machine collaboration enhanced intelligence, and Internet crowd intelligence have become the focus of development, providing new approaches for understanding complex systems, and new technologies for transforming nature and society [3]. The method used by AI2.0 to solve complex problems has transformed from an “emphasis on causality” to an “emphasis on relationship” and then to an advanced model where “relationship” and “causality” are deeply integrated. Thus, the ability to solve complex problems has grown rapidly. Most importantly, artificial intelligence has acquired the ability to learn and to generate and better use knowledge, achieving a qualitative leap. Of course, artificial intelligence technologies will continue to move from artificial narrow intelligence (ANI) to artificial general intelligence (AGI), and the scope of application will be more universal. In short, AI2.0 has become the key technology in the latest scientific and technological revolution and has provided a strong engine for economic and social development [1].

Realizing that the development of AI2.0 will profoundly change life for human society, as well as change the world, China has released the “New Generation Artificial Intelligence Development Plan” to seize these opportunities and gain the first-mover advantage. The world’s major economies have also placed the development of the new generation of artificial intelligence in the foremost position [1].

1.3 New-generation intelligent manufacturing is the key technology in the new round of the industrial revolution

“Science and technology are equal to productivity” is a basic principle of Marxism. Science and technology are the primary forces behind productivity and scientific and technological innovation is the fundamental driving force for economic and social development [4]. All the previous industrial revolutions had key technologies. The first and second industrial revolutions, which were driven by the invention and application of steam engines and electric power, gave a significant boost to productivity and took humanity into the modern industrial society. The third industrial revolution, which was marked by the innovation and application of computer, communication, control, and other information technologies, brought about a fundamental economic, political, and cultural transformation of human society (as shown in Fig. 1).

The deep integration of the new generation of artificial intelligence technology and advanced manufacturing technology has produced a new generation of intelligent manufacturing technology, which is the key driving force in the latest industrial revolution [1,5]. New-generation intelligent manufacturing will bring revolutionary changes to the manufacturing sector, set the stage for a real fourth industrial revolution, and present historic opportunities for China to make a giant leap forward in the manufacturing sector’s development.

2 Intelligent manufacturing: from human-physical systems (HPSs) to human-cyber-physical systems (HCPSs)

Intelligent manufacturing is a constantly evolving concept, which can be summarized into three basic paradigms: digital manufacturing (first-generation intelligent manufacturing), digital-networked manufacturing (second-generation intelligent manufacturing), and new-generation intelligent manufacturing [1]. Intelligent manufacturing involves many components, such as intelligent products, intelligent manufacturing processes, and intelligent services. The following is an example of the produc-

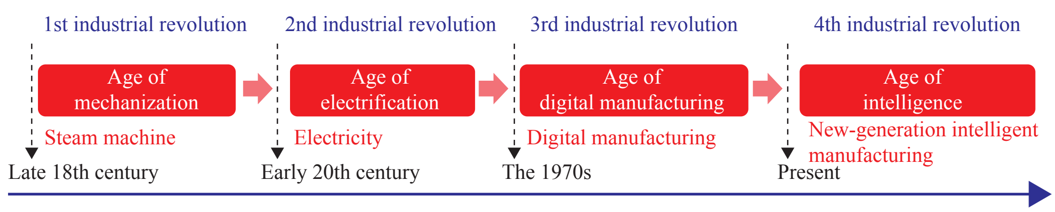

Fig.1. Four industrial revolutions.

tion and manufacturing process, which will serve to analyze the technical principles and evolutionary process of intelligent manufacturing.

In the evolution from traditional manufacturing to intelligent manufacturing, the manufacturing system has gone through a transition from the original human-physical binary system (HPS) to the human-cyber-physical ternary system (HCPS), and then to the new generation human-cyber-physical system (HCPS2.0) (Fig. 2).

2.1 Traditional manufacturing system and HPS

The early stage manufacturing system (traditional manufacturing system) consists of only two parts: human and physical systems. Various tasks are completed entirely through the operation and control of machines by humans. Although physical systems (machines) have assumed a substantial amount of labor from humans, thus greatly reducing the physical labor burden, humans are still required to perform various tasks in a traditional manufacturing system, such as perception, analytical decision-making, operational control, and learning. Therefore, a traditional manufacturing system is essentially an HPS.

The original HPS system was characterized by heavy demands on humans, high labor intensity, yet low system efficiency. The first and second industrial revolutions boosted the performance of physical systems (power machinery, etc.) through

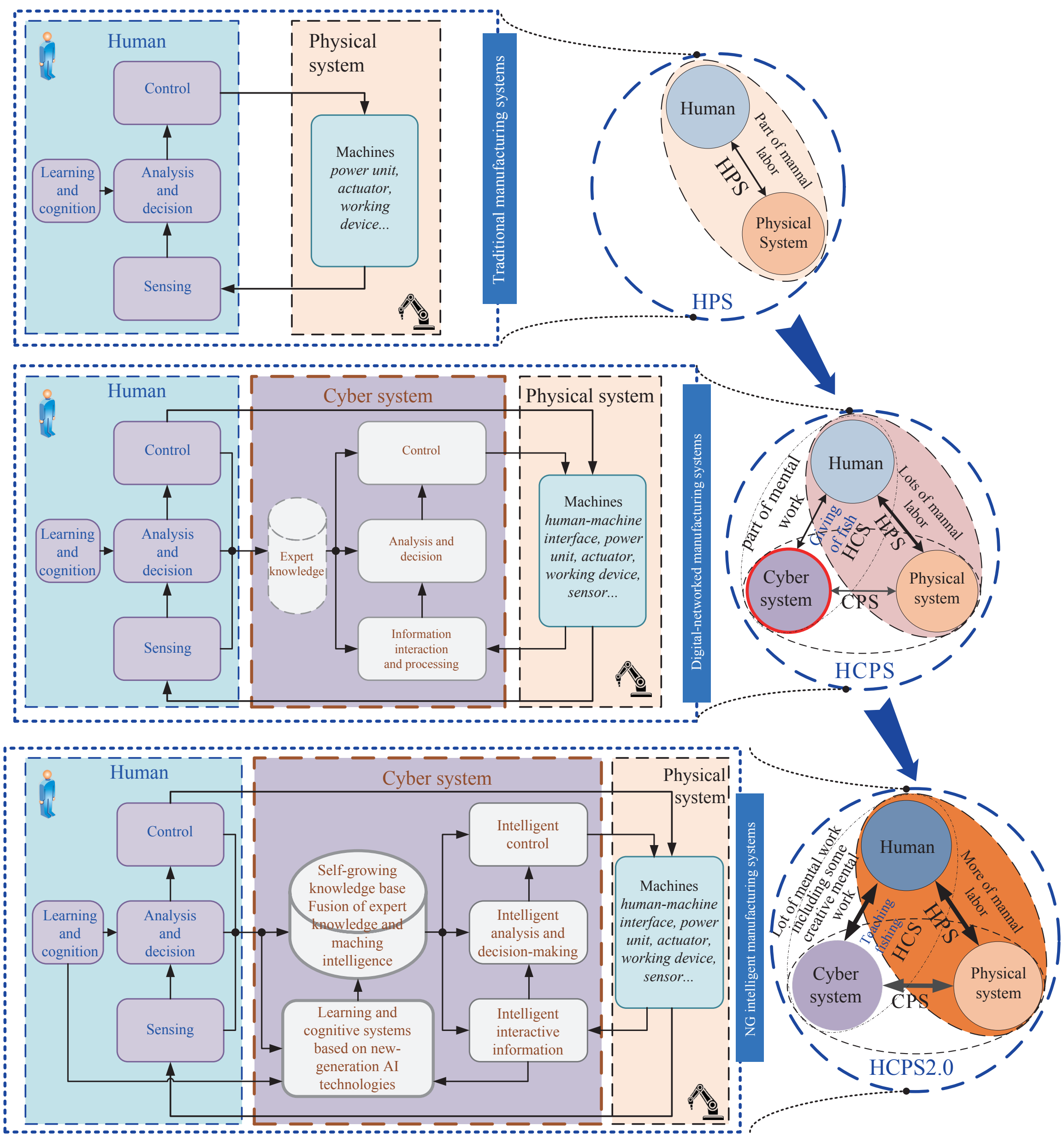

Fig. 2. Intelligent manufacturing: from human-physical systems (HPS) to human-cyber-physical systems (HCPS).

the invention and widespread application of steam engines and electric power, greatly increasing the productivity of the HPS.

2.2 First- and second-generation intelligent manufacturing systems and HCPS

Compared with traditional manufacturing systems, there are two major changes in first- and second-generation intelligent manufacturing systems (Fig. 2). First, the most essential change is the addition of cyber systems between humans and physical systems, which can replace humans by automatically performing partial tasks such as perception, analytical decision-making, and control. The second change is the upgrade in physical systems, which includes adding various sensing and testing devices, and replacing traditional power devices with digital ones.

By integrating the respective advantages of humans, cyber systems, and physical systems, the capabilities of the first- and second-generation intelligent manufacturing systems, especially computational analysis, precision control, and perception, have all been greatly improved. As a result, the automation level, work efficiency, system quality and stability, as well as the ability to solve complex problems, have been notably enhanced. At the same time, the operators' labor intensity has been significantly reduced, and human manufacturing experience and knowledge has been transferred to the cyber and physical systems (primarily the cyber system), which makes the transfer and utilization of human knowledge more efficient.

In the evolution of manufacturing systems from the traditional HPS to the HCPS, the introduction of the cyber system has resulted in the addition of both "human-cyber systems" (HCS) and "cyber-physical systems" (CPS) to manufacturing systems. HCS has enabled part of the perception, analytical decision-making, and control functions of humans to be copied and transferred to the cyber systems. At the same time, through CPS, the physical and cyber systems have achieved deep integration in perception, analysis, decision-making, control, and management; together, cyber and physical systems have assumed more physical and mental work from humans, paving the way for the establishment of a new manufacturing system based on HCPS.

2.3 The new-generation intelligent manufacturing system and HCPS2.0

The fundamental goal of intelligent manufacturing is to optimize products and their production and service processes, and to achieve high efficiency, high quality, flexibility, agility, low energy consumption, and user-friendliness. To this end, intelligent manufacturing needs to solve all kinds of problems (product design, process design, process control, production management, health protection, etc.), which have to do with making the best decisions. The resolution of such problems depends on the ability to establish effective decision-making models and rules. However, due to the complexity of manufacturing systems and manufacturing processes, it is often extremely difficult to establish effective decision-making models and rules. It not only requires all kinds of knowledge and laws that humans have already learned, but also involves many types of knowledge and laws that are not yet known or difficult to describe. In the cyber systems of first- and second-generation intelligent manufacturing, models and rules were established by the research and development (R&D) personnel through comprehensive use of relevant theoretical knowledge, expert experience, and experimental data, and were imbedded in the cyber system through programming and other means. The models and rules thus established are limited by the knowledge, capabilities, and R&D conditions of the R&D personnel. On the other hand, they often have a fixed utilization pattern in the system, which makes adaptation to internal and external dynamic changes difficult. Therefore, the first- and second-generation intelligent manufacturing systems remain unable to achieve the fundamental goal of optimized products and production and service processes, hence the need to develop a new generation of intelligent manufacturing systems.

Compared with the first- and second-generation intelligent manufacturing systems, the most essential feature of new-generation intelligent manufacturing systems is the cyber system's learning and cognitive functions, which equip the system with powerful capabilities not only in sensing, computational analysis, and control, but also in learning and knowledge generation (Fig. 2). The "knowledge base" of new-generation intelligent manufacturing systems is jointly established by system developers and intelligent learning and cognitive systems. It contains not only all kinds of knowledge that system developers can acquire, but also knowledge that is difficult for developers to master or describe. More importantly, the system can continue to grow and improve during its operation through self-learning.

The key technology of new-generation intelligent manufacturing systems, that is, new-generation artificial intelligence technology, provides the systems with the ability to learn and discover relevant knowledge and mechanisms and achieve human-machine collaboration through big data intelligence, human-machine hybrid enhancement intelligence, crowd intelligence, and other means. These new-generation intelligent manufacturing systems can build a model that is highly consistent with the actual product and production process, not only to optimize the product and its production process, but also to optimize the service and maintenance of products, effectively optimizing a product's entire life cycle. At present, big data intelligence technology based on big data and deep learning, a typical field of new-generation artificial intelligence technology, has already demonstrated enormous potential in this area.

The evolution from first- and second-generation intelligent manufacturing systems to the new-generation intelligent manufacturing systems is essentially an evolution from HCPS to HCPS2.0. The most fundamental change is that the HCPS2.0

cyber system is now equipped with cognitive and learning ability, moving from "giving fish" to "teaching how to fish." As a result, the ability of manufacturing systems to deal with complex and uncertain problems has been greatly enhanced, effectively realizing the optimization of products as well as production and service processes.

New-generation intelligent manufacturing has further underlined the central position of humans. In HCPS2.0, the potential of human wisdom will be greatly expanded. By introducing the role of humans or the human cognitive model into the system, new-generation artificial intelligence makes it possible for humans and machines to understand each other and produces an enhanced hybrid intelligence based on the mechanism of human–in-the-loop. Through deep human-machine integration, human brains and machine intelligence can inspire and complement each other. At the same time, the automation of knowledge-based work can help humans escape the heavy burden of labor and mental work and spend more time on valuable creative work.

3 Integration of new-generation intelligent manufacturing systems

New-generation intelligent manufacturing is a general system based on HCPS, which is mainly composed of intelligent products, intelligent production, intelligent services, the industrial Internet of intelligences, and intelligent manufacturing clouds. Among them, intelligent products represent the main body, intelligent production is the main line, and reform of the industrial model centered on intelligent services is the main theme. Together, they make up the three functional systems. Two supporting systems, intelligent manufacturing clouds and the industrial Internet of intelligences, are the cornerstones supporting intelligent manufacturing [1].

The main features of the integration of new-generation intelligent manufacturing systems are as follows. The first is "integration." The two supporting systems enable new-generation intelligent manufacturing systems to function like connection, communication, computing control, and security networks, with the three functional systems highly integrated. Companies in different links can access information sharing, system integration, and optimized resource allocation on the integrated platform. The second is "closed loop." Under the guidance of new-generation artificial intelligence technology, all the intelligent activities of the three functional systems have the features of "perception-analytical decision-execution," which is typical of a closed loop. The third is "intelligence." Based on connectivity, humans, machines, and companies can switch flexibly between centralized intelligence, distributed intelligence, and group intelligence to achieve rapid responses and optimized decision-making [6].

The three new functional systems and two supporting systems are the five key tasks for the development of new-generation intelligent manufacturing. They must all be based on their own advanced technology, with HCPS as the theoretical basis. Therefore, ways should be found to deeply integrate with new-generation artificial intelligence technologies and establish their own development goals and technology routes for the next 20 years.

4 Vision of new-generation intelligent manufacturing

The wide application of the new-generation intelligent manufacturing will push the new round of the industrial revolution to its culmination, bringing revolutionary changes to the manufacturing industry and human society in the direction of people-oriented, intelligent, harmonious, green, and safe development.

4.1 Revolutionary changes to the manufacturing industry

First, the way that manufacturing knowledge is generated, acquired, applied, and inherited, and the efficiency of the process will undergo fundamental changes, and the innovation and service capabilities of the manufacturing industry will be greatly improved. Through integration with the new-generation information technology, especially artificial intelligence technology, the new generation of intelligent manufacturing systems and tools will gain more powerful capabilities, especially machine learning capabilities, leading to fundamental changes in the means and efficiency of generation, acquisition, application, and inheritance of manufacturing knowledge. In the meantime, the intelligence and innovation potential of humans will be greatly unleashed, giving a significant boost to the innovation and service capabilities of the manufacturing sector.

These fundamental changes brought to the manufacturing sector by new-generation intelligent manufacturing are particularly important for developing countries. They will help address a series of problems caused by the late start of industrialization and inadequate accumulation of industrial knowledge, including problems like high-precision basic processes, basic materials, basic components and equipment, and technical quality foundations, and overcome the problems facing the business sector, such as lack of high-skilled professionals and weak innovation capabilities.

Second, products are highly intelligent and user-friendly. Product innovation is fundamentally important. The new-generation intelligent manufacturing will bring unlimited space and possibilities for product innovation to the manufacturing industry. High intelligence and user-friendliness will become the most important features of future products. For example, products will have no difficulty fully understanding human intentions, and even reach a state of "get what you think;" if necessary, the products can also monitor their own state and the external environment and confirm their own loss level at any point over the entire life cycle. They can also offer a dynamic response to environment changes and keep improving their performance by learning to ensure the best effect in the utilization process.

Third, the product manufacturing process is high quality, flexible, efficient, and low in consumption. In the environment of new-generation intelligent manufacturing, various highly intelligent systems and tools will support all the functions of manufacturing enterprises, leading to a notable increase in quality, cost-effectiveness, efficiency, and other factors of competition.

In terms of product design, the new-generation intelligent design system of the future will be supported by a powerful knowledge base, which can be constantly improved through self-learning. It will be able to conduct accurate modelling and simulation of product performance, reliability, life cycle, cost, and other factors, not only boosting the efficiency and quality of product designs to quickly respond to market demand, but also reducing the burden on product designers, and making it easier for users to participate in the design process, even independently designing their own preferred products. All these can greatly improve the efficiency of product innovation.

In terms of product production, information connectivity will extend from within the enterprise to the entire supply chain and the entire industry chain. In the meantime, with the support of new-generation artificial intelligence technologies, the difficulties acquiring critical technologies for complex systems (manufacturing equipment, workshops, enterprises, full supply chains), such as precise modeling and real-time optimized decision-making, can be overcome. This will help solve problems through the full life cycle of manufacturing systems, including high reliability, high accuracy, and high adaptability; build intelligent factories and smart enterprises that are driven by knowledge and self-learning; and achieve high quality, flexible, efficient, and green product manufacturing.

Fourth, the industrial model and industrial form of the manufacturing sector will undergo revolutionary changes. The first will be rapid development of service-oriented manufacturing, while the second will be extensive application of large-scale, customized production, especially in the field of consumer goods. Third will be the development of the production service industry, which will generate a new form of manufacturing in combination with the manufacturing industry.

4.2 Revolutionary changes to human society

First, the working and living environment of human beings will go through fundamental changes. On the one hand, changes in the division of labor between humans and machines will bring about revolutionary transformations. Humans will now be able to spend more time doing creative work and working in a user-friendly environment, and leave work that is dangerous, boring, heavy, with little added value, or work they simply do not like doing to machines. On the other hand, various kinds of intelligent and user-friendly products produced by the manufacturing industry will penetrate all aspects of human life and economic and social development, making the working and living environment friendlier to humans.

Second, problems with resources and the environment will be significantly alleviated. The new-generation intelligent manufacturing will effectively reduce the consumption and waste of resources and energy. At the same time, it will play an important role in China's efforts to promote industrial restructuring and address overcapacity, while sustaining the momentum of healthy and stable economic growth.

5 Conclusions

The transition from traditional manufacturing to intelligent manufacturing is characterized by an evolution from the original HPS to the new HCPS. HCPS speaks to the basic principles of intelligent manufacturing, provides the theoretical basis for the development of new-generation intelligent manufacturing, and points the way forward for intelligent manufacturing. In the next 20 years, we must strive to promote technological progress and industrialization of the functional and supporting systems of intelligent manufacturing in a phase-by-phase manner. In particular, we must expedite the process of exploration, research, and pilot demonstration, and strive to achieve key breakthroughs in several directions within three to five years, come up with a number of exemplary achievements with symbolic significance in the development of new-generation intelligent manufacturing, and truly lead and promote the new industrial revolution.

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