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Development Strategy for the Core Chip Technology of Intelligent Robot in China

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Abstract: Intelligent robots are leading a new round of technological revolution and industrial transformation. Promoting the intelligent robot core chip technology and the relative industry is strategically significant for industrial upgrades and productivity improvement in China. In this paper, we illustrate the strategic significance of the intelligent robot core chip technology in China in promoting technological independence, realizing high-quality economic development, satisfying residents' needs for a better life, and promoting national core competitiveness. Additionally, we review the development status of chips for intelligent robots in terms of policy, technology, and industry and analyze the advantages and disadvantages of developing intelligent robot chips in China. In this study, the development route of the intelligent robot chips was analyzed based on the aforementioned, and strategic development goals of intelligent robot chip technology for 2025, 2030, and 2035 were proposed. Moreover, we proposed key tasks and strategic goals for intelligent robot core chips in China. We suggest that the independent and controllable development of intelligent robot chips should be elevated to a national strategy, major scientific and technological projects should be established for intelligent robot chips, policies should be introduced to encourage intelligent robot chip technology research and industrial applications, and high-level talent training should be implemented.

Keywords: intelligent robot; chip technology; industrial chain; independently controllable; development roadmap

1 Introduction

As an achievement of the new scientific, technological, and industrial revolutions, the research and manufacturing of intelligent robots involves artificial intelligence (AI), mechanical engineering, cybernetics, materials, computers, and other multidisciplinary fields. Its industrial chain presents a comprehensive coverage and strong driving force. It is a strategic industry that promotes the transformation and upgrade of the Chinese industry, agriculture, national defense, and other major industries. It also indicates the strength of national scientific and technological innovations. With the gradual integration of intelligent robots into human life and production, the environments and tasks they engage in have become more diverse and complex. The application requirements of high reliability, dynamics, and intense confrontation has increased. However, China remains relatively weak in terms of high-performance core chips required for robots. This is reflected by the fact that the independent research and development (R&D) and production capacity of the core components significantly differ from those leading internationally, and the performance in computing power, stability, and integration is poor. With the increasingly complicated international situation, Sino-US trade frictions have escalated, and the anti-globalization trend has intensified. It is imperative to strengthen domestic manufacturing capabilities, grasp the dominance of emerging industries, and achieve the autonomous control of intelligent robot chip technology and its industrial chain.

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Current research regarding core chips for intelligent robots in China remains in its nascent stage, and the formulation of a reasonable strategic plan plays a critical role in its development. Existing studies have systematically established the development status of intelligent robots and chip technology and suggested development strategies. Highlighting the current development of core AI software and hardware considering the technology, industry, and policy, relevant studies have summarized the problems faced by China, such as an incomplete ecological system, shortcomings in the fundamental theoretical analysis, and an imperfect innovation environment. In addition, ideas and goals for China's core AI software, hardware technology, and industrial development have been presented [1]. Aiming for a land-air collaborative multimodal intelligent robot, a previous study [2] analyzes its development status, indicating that it lacks a systematic development plan, has not formed a full-chain development model, and has insufficient software and hardware integration. Simultaneously, corresponding developmental suggestions were provided. In another study [3], the concept, classification, and development process of AI chips were introduced and the current situation and trends of their industrial development were investigated. Suggestions for the development of the AI chip industry were also presented. The "Advanced Semiconductor Materials and Auxiliary Materials" writing group proposed a systematic development plan, upstream and downstream coordinated action, and sustainable development of semiconductor and auxiliary materials. Relevant countermeasures and suggestions for the development of integrated circuits have been presented [4]. Fifteen departments, including the Ministry of Industry and Information Technology, National Development and Reform Commission, and Ministry of Science and Technology, jointly issued the *14th Five-Year Plan for the Development of Robot Industry* [5], which guides the development of China's intelligent robot industry.

Robots are the carriers of chip technology research and chips guarantee the achievement of robot functions, the development of which has a profound internal connection and has not been fully explored in current studies. Therefore, the Chinese Academy of Engineering has launched relevant research regarding the general and critical issues of the autonomous and controllable development of the core chips of intelligent robots. It aims to sort strategic planning, demonstrate technical paths, and propose technical solutions. This study analyzes the critical value and international progress of the core chips of intelligent robots, summarizes the primary advantages and problems faced by China, focuses on demonstrating the technological development route, and proposes a development roadmap for 2035. This study is expected to serve as a reference for China's industrial policies, technical planning, and technological research.

2 Strategic significances of the development of core chips of intelligent robots

The core chip of an intelligent robot is a high-performance processor that is specially used to achieve robot computing functions, such as perception, control, navigation, decision-making, and planning. It is critical for robots to complete various tasks in complex environments. Research regarding the development strategy for the core chip technology of intelligent robots promotes the study of related technologies, independent and controllable technologies and industrial chains, and high-quality economic development.

2.1 An important track that promotes autonomous and controllable technology

The Chinese intelligent robot core chip industry is currently facing significant internal and external problems. The internal concern is that the core technology of the robot chip industry chain is insufficient, and the localization rate is limited. The domestic chip packaging test is initially controllable; however, the independent controllability rate of high-end links is insufficient, such as those in design and manufacturing. Considering the international situation of gaining power, foreign issues owing to the blockade of high-end equipment, materials, and technologies by Western countries, as well as the embargo on advanced chips, hinder development in China. Therefore, there is an urgent need to develop a core–chip technology scheme for intelligent robots. Based on the characteristics of the algorithm model, a chip computing architecture is designed, and the computing architecture optimizes the algorithm model and compilation to achieve a high performance, low power consumption, and low latency. The high ground for integrated circuit technological innovation competition should be actively seized, and the independent and controllable capabilities of the core chip technology and industrial chain of intelligent robots should be enhanced.

2.2 Support for achieving high-quality economic development

Intelligent robots are high-end equipment that integrate technologies in various fields and are the products of inter-industry technology integration and innovation. Developing core chip technology can improve the operational capabilities and adaptability of intelligent robots and further alleviate the needs of intelligent robots. Consequently,

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the technological upgrade and product structure optimization of the entire industrial chain has been promoted, which significantly affected the revitalization of the real economy. The vigorous development of intelligent robots and their core chip technologies can drive overall improvements in the manufacturing industry and become a breakthrough in constructing a manufacturing powerhouse. In addition, as an industry of the information revolution, the development of the core chip industry for intelligent robots can further integrate emerging technologies such as big data, cloud computing, the Internet of Things, and 5G communication to build a new industrial system, becoming the "locomotive" to promote the high-quality development of China's economy.

2.3 Guarantee of meeting public needs for a better life

The central contradiction in Chinese society has transformed into that between the ever-growing needs of individuals for a better life and unbalanced and inadequate development. The development of core chip technology of intelligent robots can increase the scope of application of intelligent robots, significantly improve social productivity, free individuals from repetitive mechanical labor, and create high-level and high-quality jobs. Improvements in the adaptability of intelligent robots can also increase the demand for special operations, prevent dangerous tasks, and play essential roles in fire protection, public security, search and rescue, and explosive removal. Large-scale utilization of intelligent robots can effectively improve the production efficiency, thereby reducing consumption and pollution in the production process. Promoting the development of the intelligent robot industry can effectively save resources and reduce emissions and is essential for building a two-oriented society.

2.4 Carrier for enhancing the national core competitiveness

Vigorously promoting the development of core chip technologies and intelligent robots will help ensure national defense security of China, seize the commanding heights of global science and technology, and effectively enhance its core competitiveness. Unmanned warfare is gradually becoming mainstream in modern warfare. Unmanned systems are a class of intelligent robots with autonomous mobility; their situational awareness, planned decision-making, multimachine collaboration, and motion control are inseparable from the computational processing capabilities of the smart robot core chip. This project will help promote the development of military intelligence and modernization of the Chinese national defense. As a typical product of the new scientific and technological revolution, a robot core chip is an important tool for measuring the strength of the national scientific and technical innovations. Currently, China has significant potential for development in this area. Developing core chips for robots can rapidly promote the Chinese high-tech industries and enhance the core competitiveness.

3 International development status of intelligent robot core chips

3.1 Policy planning

The recent global shortage of chips has significantly affected intelligent industries worldwide. Major developed countries and regions formulated policy plans for chip development. We focus on technological innovation, interface standards, financial goals, and other comprehensive layouts to seize the dominance of chip technology development.

In 2020, the United States introduced the *American Foundries Act of 2020*, suggesting that Congress tighten the bottleneck of chip manufacturing technology to prevent China from surpassing the United States in the next few years. Subsequently, the *United States Innovation and Competition Act of 2021* was launched, which advocates strict countermeasures against China and improves the ability of the United States to compete with China in science and technology. In 2020, the European Commission issued the *Declaration: A European Initiative on Processors and semiconductor technologies*, which was expected to invest 145 billion euros in the development of the semiconductor industry. In 2020, Japan released its "Green Growth Strategy," which considers the semiconductor industry a key development area. In 2020, South Korea announced that it would invest 9.5 million USD over the next five years to develop material technologies for semiconductor lithography processes below 5 nm.

Traditional chip powerhouses rely on their rich experience, strong innovation capabilities, and substantial economic strength. Under the guidance of policies and regulations, they rely on national strategies to reach a consensus among all parties and guide valuable resources into the chip field. This will lead to a new round of scientific and technological revolutions and further strengthen the competitive advantage.

3.2 Technical aspects

The application scenarios and operational requirements of robots are becoming increasingly complex considering the new scientific and technological revolutions. Therefore, this requires a higher algorithm computing power

considering the environmental perception, decision planning, navigation and positioning, and motion control. The current computing systems based on general-purpose embedded processors and programmable logic controllers cannot satisfy the requirements of future robots in terms of perception, cognition, and sensitive motion. Therefore, core chips of robots must be urgently developed for new situations, which integrate the latest AI algorithms and improve the intelligent autonomous ability of robots [6].

In terms of intelligent robot algorithms, the empowerment of AI has led to rapid developments [7]. (1) AI improves the efficiency of environmental perception. For target recognition, a series of classic frameworks, such as SSD, YOLO, and R-CNN have been proposed to enable intelligent robots to simulate the computing method of the human brain and rely on multilayer convolutional neural networks to significantly enhance their ability to perceive the environment. (2) AI improves planning and decision-making capabilities. The rapid development of AI technology has dramatically enhanced the autonomy of intelligent robots in planning and decision-making, and they can continue to perform tasks in highly dynamic, complex, and robust confrontation environments. (3) AI strengthens multimachine collaboration. Based on "mobility energy and information interconnection" and considering the core of "model algorithm and data calculation," intelligent robots can achieve autonomous operations, human–machine collaboration, and machine–machine collaboration. This will become the primary method in which intelligent robots will be used in the future. AI technology provides strong technical support for interoperability, autonomous decision-making, and cluster control algorithms.

Intelligent robot computing hardware encounters Moore's law failure, and is gradually developing considering multiple aspects, such as a high energy efficiency, specialization, and customization. (1) The general AI chip has gradually evolved toward a brain-like and neuromorphic architecture. In 2019, Tsinghua University released the first heterogeneous fusion brain-like chip in the world, "Tianji," which allows bicycles to truly achieve automatic driving and appeared on the journal cover of *Nature* [8]. (2) Chip manufacturing has entered the atomic age. In 2021, the Hunan University and Samsung Advanced Institute of Technology published a review article in *Nature*, which discusses the critical material parameters of two-dimensional semiconductors and traditional three-dimensional semiconductors and summarizes methods to improve the limits of two-dimensional transistors [9]. (3) An AI mechanical design may be achieved in the future. In 2021, Google Brain and the Stanford University published relative studies in the *Nature* journal. The AI-based chip design method was improved and applied to the next-generation tensor processing unit (TPUv4) accelerator, which was officially released at the Google I/O 2021 conference [10].

Regarding the fusion of robot intelligent algorithms and chip hardware, the brain-like chip is a substantiated solution for intelligent algorithms with natural high-energy efficiency advantages. Algorithms, computing power, and data are the three features used to develop AI technology. The introduction of AI technology has enhanced the algorithmic efficiency of robots. Various types of sensors have introduced massive amounts of data into robots, and brain-like chips have emerged as carriers of algorithms and data. The architecture of the information processing unit of the intelligent robot chip has also gradually changed in the direction of the bionic brain structure. The "integrated storage and computing" brain-like chip has become the basis of innovation for AI technology and has the advantage of a high energy efficiency in running intelligent algorithms. Nonvolatile core devices at the bottom are gradually replacing explosive core devices to achieve smart computing functions in unstructured environments and complex tasks.

3.3 Industry

The core chip technology of intelligent robots involves several industries such as semiconductors, robots, and AI. For semiconductors, the market concentration of processing and manufacturing equipment is relatively high, and companies from the Netherlands, United States, and Japan monopolize more than 90% of the global chip manufacturing market [11]. In the chip industry, foreign countries occupy a strong position overall, dominating the three main links of chip design, which are manufacturing, packaging, and testing. Current industrial robot giants are primarily concentrated in industrially developed countries such as Japan, the United States, and Germany.

Therefore, the international intelligent-robot core-chip industry has developed a series of commercial platforms. In November 2017, the Intel China Research Institute officially released the HERO robot platform. It is a set of heterogeneous system platform solutions with a low power consumption, high performance, and is small, which is specially designed for intelligent robots including service robots, medical robots, and self-driving cars. The central processing unit (CPU) acts as the control center in this scheme; it is matched with a field programmable gate array (FPGA) and other specialized accelerator chips that can provide an excellent performance. In December 2018,

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NVIDIA released the world's first chip, the Jetson AGX Xavier, which was designed for robots. As the first computer designed for autonomous machines, the Jetson AGX Xavier is sufficiently powerful to perform visual odometry, sensor fusion, localization and mapping, obstacle detection, and route planning, which are critical for the new generation of robots. In June 2020, Qualcomm launched the iterative product robot RB5 platform, which became the most advanced and highly integrated solution for robots designed by Qualcomm. The RB3 provides a rich combination of hardware, software, and development tools to help developers and manufacturers develop next-generation intelligent robots with a low power consumption and high computing power; it meets the requirements of the consumer, enterprise, industrial, and professional services.

4 Basic advantages and major problems of core chip development in China for intelligent robots

4.1 Basic advantages

4.1.1 China actively creates an environment for the development of core chips for intelligent robots

China considers the development of its basic science, technology, and high-tech industries highly significant. In previous top-level macro-policies of the state, the support for high-tech industries, such as robots and chips, was emphasized. The *14th Five-Year Plan for the National Economic and Social Development of the People's Republic of China and the Outline of Vision 2035*, released in March 2021, were proposed to encounter the critical problems in integrated circuit technology considering science and technology. The innovation and development of industries was promoted, such as those of integrated circuits and robots, to enhance the core competitiveness of the manufacturing industry. Simultaneously, the relevant ministries and commissions of the state presented a series of policy documents regarding special planning, policy support, import and export investment, regional development, and industrial support. Policy and financial support were provided to develop the domestic robot/chip industry to cultivate the market and relative talent. Compared to other countries, the socialist system of Chinese characteristics integrate social resources to the greatest extent, focusing on significant tasks through macro-control, policy planning, and financial and fiscal means, and escorting the development of core chips for intelligent robots.

4.1.2 Large domestic demand market provides a strong impetus for development of core chips for intelligent robots in China

Currently, the scale of the Chinese chip market is expanding, and the output value of chips is annually increasing. Statistics indicate that in the past five years, the annual compound value-added rate of the Chinese chip industry exceeded 21%, reaching nearly five times the global growth rate over the same period. According to the World Semiconductor Industry Association statistics, the Chinese market size has rapidly grown with a market share of 50.7%, ranking first in the world. China is an indispensable component of the global chip market. According to statistics from relevant departments, the compound annual growth rate of the Chinese robotics industry has exceeded 15% in recent years, and the industry scale has surpassed 100 billion yuan. The substantial expansion of integrated applications has increased the density of domestic manufacturing robots to 187 units per 10 000 individuals by 2019, which is significantly higher than the global average. Service robots are proliferating more rapidly. According to relevant data, the compound annual growth rate of global service robot sales from 2013 to 2021 was 19.2%, and its share in the robot market in 2021 reached 36%. This significant domestic demand is the most vital driving force for the development of the core chip industry for intelligent robots [12].

4.1.3 China has the most complete industrial system and a solid industrial foundation

China is the world's largest manufacturing country with a wide range of industries. It has an entire industrial system comprising 39 major, 191 medium, and 525 small industrial categories, according to the United Nations Industrial Classification. Its output ranks first worldwide. A complete industrial system can significantly reduce production costs, improve production efficiency, and support the development of the core chip industry for intelligent robots. The level of chip-related industries, particularly the robotics industry chain, continues to improve. The Chinese robotics industry has grown rapidly, and a relatively complete robotics industry system has been formed. The development of the robotics industry entered the world's first phalanx. With the rapid development of "new infrastructure" such as 5G, AI, and cloud computing in China, the development of the core chip industry for intelligent robots has accelerated further.

4.1.4 The “demographic dividend” of higher degrees in China forms a unique human resource advantage

China consistently ranks first worldwide for science, technology, engineering, and mathematics graduates. According to the *China Science and Technology Talent Development Report (2020)*, the number of research and experimental development personnel in China has grown rapidly, with an average annual growth rate of more than 7%. As of 2020, this number reached 5.092 million, ranking first worldwide for many consecutive years. Statistics from the *White Paper on Talents in China’s Integrated Circuit Industry (2019–2020 Edition)* demonstrate that by the end of 2019, the number of direct employees in the Chinese integrated circuit industry reached 511 900. According to the current development trends and per capita output value calculations, the demand for talent in this industry will exceed 744 500 individuals by the end of 2022. In 2021, integrated circuit colleges in major domestic universities were rapidly established, including many national “double first-class” construction universities. In the mid- and long-term, based on the continuous engineering dividend and the world’s leading AI technology advantages, China is expected to be comparable to developed countries and lead the development of the future robot and chip industry.

4.1.5 A new step for the upgrade of the Chinese domestic intelligent robot chip industry

Recently, the Chinese robot core chip industry has developed rapidly, driven by policy support and market demand [13]. Several outstanding enterprises have emerged in China for chip design, manufacturing, and robotic applications. The field of chip design is the most mature in China, with the most comprehensive technology, and the area closest to the international first-class level. The main chip design companies include Shenzhen HiSilicon Semiconductor Co., Ltd., Zhongke Cambrian Technology Co., Ltd., and Beijing Horizon Robot Technology Research and Development Co., Ltd. A large gap in the chip manufacturing industry remains between China and the global state of the art; however, China has also gained significant achievements in this field. SMIC Integrated Circuit Manufacturing (Shanghai) Co., Ltd., Shanghai Huahong (Group) Co., Ltd., and Hefei Jinghe Integrated Circuit Co., Ltd. are among the top ten global chip manufacturing foundry companies. China has also made significant progress in robotics. With the further expansion of the market and continuous increase in the policy and r R&D investment, the development of Chinese robots has grown rapidly. Many outstanding enterprises have emerged in this field, including Shenzhen Dajiang Innovation Technology Co., Ltd., Eft Intelligent Equipment Co., Ltd., and Shenyang SIASUN Robot Automation Co., Ltd. The rapid development of these companies demonstrates that the Chinese intelligent robot chip industry has taken new steps.

4.2 Major problems

China has achieved remarkable results in terms of core chips for intelligent robots. However, compared to the development status of the global industry in the same period, a series of problems remain to be overcome to achieve the independent control of the related technologies and industries.

4.2.1 Lack of targeted top-level design and unclear strategic goals

The top-level strategies of the overall nation, such as the “comprehensively deepening reform,” “China Manufacturing 2025,” and “14th Five-Year Plan,” are highly significant for the development of intelligent robot chips. However, owing to the close relationship between robotics and chip technology, smart robot chips exhibit unique developmental rules. As indicated above, it is difficult for the overall national strategy to play a precise strategic guiding role for the development of intelligent robot chips. China has recently successively introduced several policies to support the development of robotics and AI chip industries. After 2009, the government accelerated the speed and intensity of its policy measures. From the top-level design, finance, taxation, demonstration applications, talent training, and other perspectives for supporting the development of the robotics industry, the policy superposition effect has created an excellent development atmosphere for the Chinese robotics industry. However, the robotics and AI industrial policies formulated by Chinese ministries and commissions do not fully match the relevance of current intelligent robots and their core chips; directional policies are lacking for smart-robot chips, and it is challenging to play a leading role in the overall strategy.

4.2.2 The independent controllability rate of multiple technical links is generally low, which is subject to the control of others

The design, manufacturing, testing, and ecological construction of foreign intelligent robot chips has formed significant technical barriers owing to their early development. However, China had a late start and relied heavily on imports. Achieving the independent control of critical core links is challenging, and many technical problems must be overcome, mainly being the lack of core support for the platforms. Platforms and integrated development

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environments that support cross-domain and cross-industry interconnections in intelligent robot chip technology are lacking. The core software and hardware industries have weak foundations and are highly dependent on foreign products. In particular, the industrial foundation of electronic design automation (EDA), intellectual property core, lithography machine, silicon wafer, photoresist, and other links is weak; the independent control rate is low (≤5%), and nearly all rely on imports. The Chinese chip design industry is developing rapidly but is generally small and fragmented. Only three companies had a revenue of over 10 billion CNY. A significant gap in revenue between Chinese companies and world's leading companies Qualcomm and Broadcom remain. Many companies are large-scale but not strong, and their development is rapid but not excellent, restricting the development of intelligent robot system chip technology.

4.2.3. Significant shortage of high-level talent and the development of disciplines is unbalanced

With the continuous development of the chip industry, China urgently requires many leaders. However, there are various internal and external factors, particularly the restrictions imposed by foreign governments and leading international companies. In China, high-level leaders rarely return to work. The significant shortage of high-level talent in China is owing to the lack of experience in the developmental period of the domestic chip industry and the lack of industrial talent in technological innovation, product R&D, and manufacturing management. However, the talent training of chip majors requires a solid academic foundation. There is an insufficient number of teachers with relevant majors, as well as the number of colleges and universities; therefore, it is difficult to effectively meet the enormous demand for talent from rapidly expanding chip manufacturing enterprises.

4.2.4 Unbalanced development of various industries and insufficient core technology reserves

Chinese intelligent robot chip companies are generally weak and scattered, with few product lines and low financial strength. The Chinese domestic products remain concentrated mainly in the low-end market, and many high-end chip core technologies require breakthroughs and innovations. In China, the core links of the chip industry chain, such as the intelligent robot chip EDA design tools, chip architecture, chip manufacturing processes, critical raw materials, and software and hardware ecology, cannot be separated from foreign core technologies. In particular, high-end chip EDA design tools and high-tech lithography machines must rely on imports. China has a long way to go before opening the entire intelligent robot chip industry chain.

5 Demonstration and analysis of the development route of intelligent robot core chip technology in China

Intelligent robots have relatively developed "brains," whose primary function is the CPU. Improvements in intelligent robots depend on enhancing the processing power of chips. In reality, the Chinese smart robotic system chips, especially critical components such as processing function chips, have significant problems such as a low self-sufficiency and performance. Therefore, proposing a feasible development route of autonomous and controllable unique chip technology for intelligent robots has a significant industrial value and strategic significance for solving the bottleneck problem of robot development and improving the intelligence and safety of robots in China.

5.1 Technical system framework

This study starts with the pure chip design of an intelligent robot processing function and presents the technical system planning for the chip design algorithm. The technical system recommends starting from the existing technical foundation (scientific research and industrial technology), analyzing the critical algorithms of robots, clarifying the chip technology of key algorithms, and combining the technologies of specific application fields to complete the software and hardware collaborative design of algorithms, circuits, architectures, and system research. Based on the fact that the technology node is not dominant, the system performance can be improved through other levels of transformative innovation, attempting to determine an optimal solution for the autonomous and controllable development of the Chinese intelligent robotic system chip.

5.2 A multi-architecture route comprehensively promotes the development of core chips of intelligent robots

An algorithm is an essential factor for determining the function of a robot. If a robot is compared to a human, the algorithm is equivalent to the wisdom and soul of a human. According to the functional categories, mainstream robotic algorithms can be divided into perception, planning, and control categories. The future development of intelligent robots requires advanced algorithms and should focus on the energy-efficiency ratio of chips. Therefore,

designing chip algorithms by the collaboration of software and hardware is trending. It is also the only means to achieve the autonomous control of the Chinese intelligent robotic system chips in a differentiated manner.

To promote the development of intelligent robot core chips, it is recommended that a parallel development route be adopted for the following processing technology system modes (heterogeneous parallel mode). As a computing system's computing and control core (an intelligent robot also belongs to a computing system), the CPU is the final execution unit for information processing and program operations. It is the core hardware unit that controls and allocates all hardware resources and performs general operations. In this study, from a processing perspective, all technical routes included the CPU. Among these, the graphics processing unit (GPU) and FPGA are relatively mature chip architectures in the early stage and are general-purpose chips. Application-specific integrated circuits (ASICs) are chips customized for specific AI scenarios. ASIC can be divided into all-digital ASIC AI chips, digital-analog hybrid storage, and computing-integrated AI chips [14,15].

Route 1: CPU main processor plus GPU coprocessor

All AI algorithms can be implemented on the CPU; however, the CPU lacks parallelism, which is incompatible with AI algorithms that require many parallel computing methods. GPUs have parallel processing capabilities and are currently the most widely used methods for AI computing.

Route 2: CPU main processor plus FPGA coprocessor

FPGAs can be designed with a non-von Neumann architecture, significantly reducing the amount of information exchanged between computing and storage units. Therefore, it exhibits pipeline processing and rapid response characteristics.

Route 3: CPU main processor plus ASIC coprocessor

After the AI algorithm is stabilized, the AI chip can be fully customized using the ASIC design method. Its performance, power consumption, area, and other indicators are optimized for deep-learning algorithms.

Route 3.1: CPU main processor plus fully digital ASIC AI coprocessor.

Many of the multiple-accumulative operations (MACs) in AI algorithms can be designed as an all-digital ASIC using a "class–memory–computing integration" approach, which will have a higher energy-efficiency performance.

Route 3.2: CPU main processor plus digital–analog hybrid storage–computing integrated AI coprocessor.

The general processing architecture has a von Neumann bottleneck that separates computing and storage, resulting in most of the energy consumed in the communication between the computing and storage units. Mature non-volatile memory devices or emerging non-volatile memory devices combined with the crossbar array architecture have the characteristics of the natural one-step implementation of intensive MAC operations in AI algorithms and thus can achieve a new computing paradigm of storage–computing integration.

5.3 Analysis of technical paths and solutions

The technical route of the intelligent robot system chip analyzes the characteristics of the coprocessor running the AI algorithms on the route and their degree of autonomy. The analysis of the autonomous controllable technology route of an intelligent robot system chip is as follows [16–19].

Route 1: CPU main processor plus GPU coprocessor

This route is currently the most mature and easiest to achieve in a relatively autonomous and controllable manner. In the short term, it can be relatively autonomous and controllable through self-developed algorithms; overall, self-developed chips must be autonomous and controllable. However, there are certain risks because a domestic CPU system does not have an independent instruction set and cannot be a completely autonomous and controllable product. Jingjia Microelectronics Co., Ltd. has significant concentrated competition risks as the only independent GPU manufacturer.

Both CPUs and GPUs are general-purpose processors with advanced technologies. Other countries have a first-mover advantage, whereas China is subject to severe technical restrictions, thus the large gap between domestic and foreign countries. It is easy to be severely restricted on this technical route. However, it is necessary to achieve the autonomous control of intelligent robot chips on this technical route owing to the following: (1) it feeds back and enhances the autonomous controllability of the CPU and GPU, (2) it achieves synergistic optimization combined with specific applications to improve the security and intelligence of intelligent robot chips. This is the most realistic technical route based on the current stage. For particular applications, relying on self-developed algorithms to improve the performance is conducive to enhancing the AI algorithm technology, which breaks through the blockade in the "straight pursuit and differentiated applications."

Route 2: CPU main processor plus FPGA coprocessor

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An FPGA can theoretically implement any ASIC and digital signal processing logic function. In practical applications, instead of replacing and redesigning the chip, developers can modify the chip using the FPGA EDA software. The development process of the FPGA does not involve steps such as masks and tape-outs, thus shortening the development cycle. FPGAs are dominant in current AI enterprise applications.

The cost of FPGA tape-outs is high; the cost of fabricating an FPGA chip may exceed that of an ASIC by more than ten times for achieving the same AI application. To meet the complex and diverse needs and applications of downstream users, the gate circuit integration of FPGA is often significantly high. However, for specific applications, redundant gate circuits increase the power consumption of FPGA. This is a significant problem in power-sensitive fields. However, as a pre-validation route for AI algorithms to ASIC chips, FPGA has a shorter research cycle and lower cost.

Route 3: CPU main processor plus ASIC coprocessor

Route 3.1 is the circuit-level "storage–computing integration" route; that is, the MAC operation is achieved in a digital "class–storage–calculation integration" method. Compared to route 3.2, this route achieves a higher stability but a lower parallelism and energy efficiency ratio. Route 3.2 is a device-level "storage–computing integration" route. For instance, the fixed memory (NVM) used has both storage and computing functions. Combined with the crossbar array architecture, these devices have natural advantages in the MAC operation, and the unit device can have multilevel states with excellent development potential. The two ASIC AI chip technology routes have the potential to perform intelligent robot edge (in the field of robotics, where the edge refers to the near-sensing end) deployment for specific applications, where simple tasks can be managed by themselves, thereby improving the system efficiency. Foreign AI chips do not have an apparent overwhelming advantage thus far and it is not too late to start developing in China. Foreign countries have not yet fully formed a technological monopoly, which is conducive to achieving the transcendence of the system performance based on the fact that the process technology is not dominant.

Overall, considering the maturity: Route 1 > Route 2 > Route 3.1 > Route 3.2 (energy efficiency ratio/autonomous controllability); in terms of the potential: Route 3.2 > Route 3.1 > Route 2 > Route 1 (Table 1). Route 3 is relatively less mature. However, it also implies greater technological autonomy and control opportunities in this field. Representative Chinese companies have also emerged in this field. It is recommended to intensify efforts to deploy the research of cutting-edge technology to achieve breakthroughs. Simultaneously, the general chip field is limited by the slowdown of Moore's Law and the exponential growth of the machine learning scale. The advanced processes and core technologies of high-end chips should be focused on. A comprehensive layout should be promoted to provide a solid foundation for achieving the autonomous controllability of intelligent robot system chips.

Table 1. Technical path characteristics and comparative analysis.

Route	Maturity	Potential (energy efficiency ratio/autonomous controllable)	Coprocessor chip architecture features
1	High	Low	Von Neumann architecture, separation of storage and computing
2	Middle	Medium low	Non-Von Neumann architecture, near memory computing
3.1	Medium low	Middle	Non-Von Neumann architecture, class–storage–computing integration
3.2	Low	High	Non-Von Neumann architecture, storage–computing integration

6 Development ideas, key tasks, and strategic goals of intelligent robot core chips in China

6.1 Basic policy

China needs to closely focus on solving the bottleneck problem of intelligent robot chips and achieve the steady and rapid development of science and technology. Based on analyzing and summarizing the development trend and direction of the chip industry locally and internationally, as well as investigating the advantages and disadvantages of China in the field of robot chips, the following five development ideas are proposed.

China should face the difficulties and be self-reliant. The current international situation is changing, and the national security and development environment is complex. The future is critical for China to achieve a significant rejuvenation, which presents higher requirements for scientific and technological support capabilities in various fields. The Chinese intelligent robot chip development strategy primarily considers the current era and international environment. We should face the bottleneck problem China faces in the chip field and formulate a long-term development strategy.

It is necessary to improve the top-level design and strategic layout. The development of the intelligent robot chip industry is closely related to many industries such as robot technology, robot application technology, chip industry, and chip application industry. This pertains to the Chinese national defense equipment, industrial production, residents' lives, and other aspects. We should propose a programmatic and comprehensive plan for developing robot chips at the national level. The development of this field should not be based on external technical support or the import of equipment but should be regarded as an important pillar industry of national science and technology. The overall planning of the entire chain should be excellent, including from the basic theoretical research and critical technological breakthroughs to the industrial application, and the country's long-term development should be focused on.

China should emphasize the entire process and focus on breakthroughs. The development of the robot chip industry is a system engineering project involving a wide range of significant influences, strong correlations, and complex constraints. If a certain link is insufficient, a barrel effect can easily occur. The development of autonomous and controllable intelligent robot chips must focus on the organic connection of all related aspects to achieve overall progress. Simultaneously, systems engineering should focus on breakthroughs.

It is necessary to consolidate the foundation and expand its advantages. In recent decades, the technologies and applications in the Chinese robotics, chips, and other fields have grown more in quantity. Despite the basic technology and processes of actual robot chips, the design, research, and applications of high-end chips have progressed. However, there remains a large gap between them and advanced levels in foreign countries. To achieve the independent and controllable transformation of critical technologies, it is necessary to take full advantage of the Chinese system of concentrating efforts on significant events and expand its development in terms of market demand, production and processing, talent pool, and infrastructure construction. It should focus on maximizing the strengths and circumventing weaknesses in a globally competitive environment and actively seize the commanding heights of a new round of technology and industry.

China should focus both the domestic and international markets. China has the world's largest market and a potential market for intelligent robot chips, which has become an inexhaustible driving force for chip development in China. The Chinese chip industry should base itself entirely on the domestic market, tap into the domestic needs, and fully exploit local advantages to enter the global market. Meanwhile, the Chinese technological and social development has an urgent demand for robot chips. Learning from the experiences of developed countries and regions such as Europe, the United States, and Japan is also necessary. Based on the Chinese national conditions, the government should properly address the relationships between product imports, technology introduction, and independent R&D. We should bravely explore the development path for robot-specific chips suitable for the Chinese national conditions.

Overall, it is necessary to conscientiously summarize the experiences and lessons in the development of robot chips and accurately grasp the global development trends, needs, and directions in the new era. Based on its basic national conditions in the new era, the China should fully exploit the various advantages of robot chip and explore a development path for intelligent robot chips with Chinese characteristics.

6.2 Key tasks and development roadmap

The development of intelligent robot chips in China must accurately capture the significant opportunities presented by the development of global information technology, robotics, AI, and other fields. The China should consider the integrated development of the robot and chip industries, fully summarize the experiences and lessons of historical development, aim for strategic future scientific and technological development, and focus on the following critical tasks: (1) conducting the top-level design of the development of smart robot chips, (2) formulating the development route of intelligent robot chips, (3) carrying out industrial layout of intelligent robot chips, (4) building an industrial structure for the collaborative optimization of the smart robot chip industry, (5) creating a collaborative innovation mechanism to release the innovative vitalities of market and talent, (6) clarifying the boundary between self-dependence and international collaboration, and (7) promoting the application of intelligent robot chips.

The development of the Chinese intelligent robot chips will resolve the bottlenecks of robot-specific chips and serve the steady and rapid development of science and technology in China as the general goal. It will strive to become a powerhouse for intelligent robot chips by approximately 2035. The robot chip industry will become autonomous, controllable, coordinated, and efficient, and its role in supporting China's economic and social

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development will be significantly enhanced. The development roadmap for the Chinese intelligent robot core chip industry is shown in Fig 1. Achieving the overall goal can be divided into “three steps”.

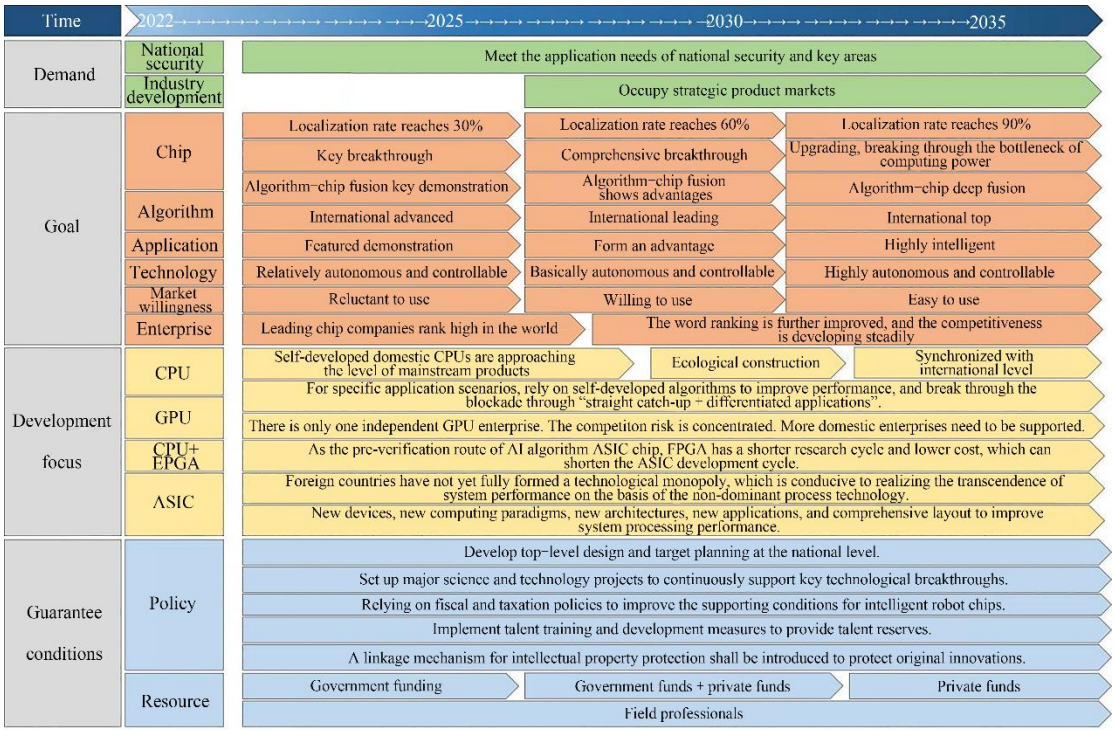

Fig. 1. Development roadmap of intelligent robot core chips in China.

In the first step, there will be a strong consensus on the autonomous and controllable development of robot chips across the country by 2025, which will significantly enhance independent innovation. China will master several key core technologies and its competitiveness in advantageous fields will be improved. In particular, progress will be made in the areas of chip design, processing of mid- to low-end chips, and the industrial integration of chips. The role of robotic chips in improving the quality and efficiency of the robotics industry will gradually become more prominent. The gap between self-controllable intelligent robot chips and the chip industry in developed countries will be narrowed.

Second, China is expected to build an independent innovative robot chip R&D system by 2030. The key core technologies and applications in China are likely to reach the world’s leading level, and the entire industry chain will be safe and controllable. Its position in the global value chain will be significantly improved. The new Chinese robot chip industry ecology will be established. A complete industrial cluster covering chip design, processing, manufacturing, and applications will be emerged. The role of robot chips in supporting the development of the robotics industry, national economy, and society will continue to increase. The autonomous controllable intelligent robot chip industry of China will be on a par with that of developed countries.

Third, by 2035, China is expected to have a leading innovation advantage and a world’s leading robot chip system will be built. Thus, the ecology of the new robot chip industry will be gradually improved. The development of chip technologies, robotics, and other fields will be coordinated. The role of chips in supporting the economic and social development will be dramatically improved. The controllable intelligent robot chip will achieve a global lead.

7 Countermeasures

7.1 Incorporating the autonomous and controllable development of intelligent robot chips into national strategies

It is suggested that a strategy for the autonomous and controllable development of intelligent robot chips be formulated to clarify the prominent position of the autonomous and controllable development of intelligent robot chips in the overall national strategic plan. A leading group for developing intelligent robot chips should be established to be responsible for the unified planning and implementation of the development of the robot and chip industries. Top experts in technology, economy, energy, environment, transportation, communications, urban

planning, and other fields should be organized to establish an advisory committee for the autonomous and controllable development of intelligent robot chips. It provides decisional support for the development of smart robot chips, and promotes the coordinated development of robotic and chip technologies and industries. A top-level design with clear goals, directions, and practical measures should be formulated around critical tasks, such as systemic and mechanism reform, construction of a characteristic market environment, construction of an independent innovation system, intelligent robot industry ecology, and dedicated smart chip industry and clusters.

7.2 Setting up a major scientific and technological project for intelligent robot chips

Faced with an urgent need for robots and robot chips in various application fields, we seize significant transformation opportunities for the continuous in-depth integration and development of robots and chips. A major scientific and technological project for intelligent robot chips needs to be established to achieve fully autonomous and controllable core and critical technologies in the field of smart robot chips. Major scientific and technological projects for intelligent robot chips should be guided by strategic, forward-looking, and critical technological requirements. Platforms such as national laboratories and engineering research centers should be fully utilized. Therefore, it is necessary to focus on the technologies that create technical reserves for intelligent robot chips. It is essential to focus on the chip design, manufacturing, packaging and testing technologies as well as intellectual perception, cognition, interaction, planning, control, and collaborative robot technologies based on basic chip science and technology. The focus should be on model compression, algorithm fusion, and new architectural design technologies for algorithm chip fusion. It is necessary to simultaneously focus on the application technology of intelligent robot chips for industrial robots, service robots, autonomous unmanned systems, unique robots, and intelligent transportation systems. The field of robotics should be promoted in China to catch up with the world's advanced core theories and key technologies. Sources of significant scientific and technological funding for intelligent robot chips can be obtained from the application market. It relies mainly on the tax dividends generated by industries related to robot applications. A diversified investment mechanism should be established based on ensuring a certain amount of government capital investment.

7.3 Introducing policies to stimulate intelligent robot chip technology research and industrial application

In 2020, the State Council issued the *Several Policies for Promoting the High-Quality Development of the Integrated Circuit Industry and Software Industry in the New Era* (hereafter referred to as "Several Policies") [20]. "Several Policies" emphasize that the integrated circuit and software industries are the core of the information industry and the fundamental forces leading a new round of scientific and technological revolution and industrial transformation. Since the "Several Policies" was issued, the proposed integrated circuit and software industries have rapidly developed, strongly supporting the national informatization construction and promoting the sustainable and healthy development of the national economy and society. The overall guiding ideology of "independent and controllable" should be highlighted within this framework, emphasizing basic and applied research. Simultaneously, a detailed implementation policy for developing the chip industry for intelligent robots is issued. It elucidates the special measures for robot-specific chips in finance and taxation, investment and financing, R&D, imports and exports, talent, intellectual property rights, market applications, and international cooperation. The leading group for the development of intelligent robot chips will encourage various departments and localities to formulate specific supporting policies the soonest possible. The government should simultaneously accelerate the implementation of policies to ensure effective results and promote the high-quality development of intelligent robot chips in China.

7.4 Strengthening talent training for the development of intelligent robot chips

Talent is the key for supporting and determining the development of the intelligent robot chip industry. China is suggested to introduce policies and measures that promote the multi-party collaborative R&D mechanism involving government, industry, universities, and research institutes. We should continue to strengthen the cultivation of talent in the chip industry, improve industrial R&D capabilities, and narrow the skills gap in the industry. First, an in-depth industry–university–research cooperation and cultivation of industrial talent needs to be promoted. Highlighting and accelerating the training and development of robotics, semiconductors, and integrated circuit skills is necessary. All types of R&D institutions, universities, scientific research institutes, high-tech zone enterprises, base carriers, and other organizations should be encouraged to cooperate various forms of high-level, shortage, and backbone professional and technical personnel training. Furthermore, talent evaluation and incentive mechanisms, in addition to the distribution incentive mechanism that encourages innovation and creation, should be improved; effective

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positive incentives should be formed to enable talent to fully exploit their innovative potential. They should fully mobilize their enthusiasm of skills and provide an entire space for their creative potential and vitality. Furthermore, China should actively introduce high-end talent, improve the talent-gathering mechanism, and increase the attraction to high-end skills in the global chip industry. The government should conduct matching activities between talented individuals and enterprises, as well as projects according to the needs of the industrial development and expand the opportunities for global technology R&D, manufacturing, and other science and engineering talent to the domestic chip industry. Finally, it is recommended that China build a professional talent service system to provide in-depth value-added services for high-level talent in the chip industry for scientific and technological R&D, achievement transformation, and market expansion. The government is advised to support the creation of a sound ecology suitable for the long-term development of talent, gathering talent and retaining skills.

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