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Review

The Collaborative Development of Sensors and Artificial Intelligence

Shangchun Fan[1,2*], Feiyang Zhang[1], Yufu Qu[1,2]

1 School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing, China

2 Beijing Virtual Teaching and Research Office for Sensor Technology Course Cluster, Beijing, China

* Corresponding author email: fsc@buaa.edu.cn

Abstract: Sensors are the source of information technology and the first unit of intelligent systems, providing real-world "data" for artificial intelligence. They play a crucial role in various aspects of the national economy and the people's livelihood, such as national defense security and the development of new quality productive forces. This paper provides a comprehensive survey of how sensors should adapt to the current upsurge of artificial intelligence, analyzing their technical connotations, application characteristics, and inherent limitations. Furthermore, with a sensor-oriented mindset, it is proposed that sensors will dominate information technology, upgrade connotations, advance ubiquitous bionic intelligence and engage in a "symbiotic dance" with artificial intelligence. This overview provides a promising direction for the higher-level development of sensors and artificial intelligence.

Keywords: sensor; artificial intelligence; information technology; new quality productive forces; collaborative development

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1 Introduction

In recent years, the technology of Artificial Intelligence (AI) has been achieving continuous breakthroughs. From natural language understanding to AI hospitals[1-3], and text-to-video generation to embodied intelligence[4, 5], the application of AI has been increasingly extensive and profound, emerging as a crucial engine promoting the development of new quality productive forces. AI is a technology that simulates, extends, and expands human intelligence through machines[6]. It is required to perceive external data, learn and interpret these data accurately, enhance knowledge, and accomplish specific goals and tasks[7]. Its powerful capabilities are founded on high-quality data, most of which rely on the collection of sensors. For instance, in intelligent driving, cameras and radar sensors provide environmental data to assist the intelligent driving system in making real-time decisions; in smart homes, various sensors measure physical parameters such as environmental temperature and humidity, offering data support for the intelligent control system. Sensors not only drive the realization and improvement of AI algorithms but also endow them with the ability to perceive the real world in real-time, facilitating AI's understanding of the real physical world and playing a significant role in enhancing the intelligence level of AI. Therefore, sensors and AI need to develop in a coordinated manner to achieve the state of "symbiotic dance". This demands a precise understanding and mastery of sensors.

Academician Wang Daheng highlighted that instrumentation serves as the "multiplier" in industrial production, the "vanguard" in scientific research, the "combat force" in military affairs, and the "materialized judge" in modern social activities[8]. Furthermore, "the functionality of instruments is predominantly manifested in sensing elements or sensors"[9]. These assertions indicate the crucial position of sensors in national defense construction and national economic development, as depicted in Figure 1. For example, in 2007, China's civil aviation officially implemented Reduced Vertical Separation Minimum (RVSM), increasing the number of aircraft cruise altitude layers from the previous seven to thirteen, making China the first country in the world to implement RVSM using metric flight altitude layers[10]. The key technology enabling this achievement is the resonant cylinder pressure sensor with a measurands accuracy of two ten-thousandths of the full scale, as shown in Figure 2[11].

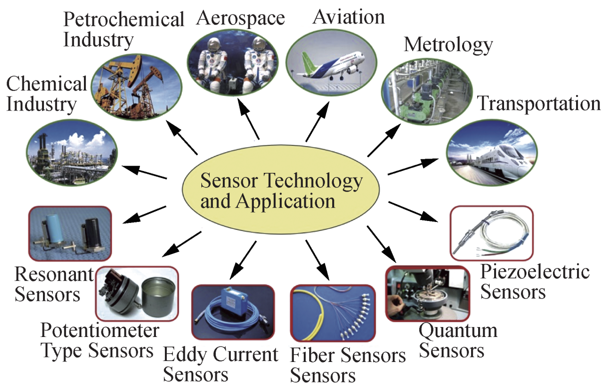


Fig.1 Typical sensor technologies and application fields

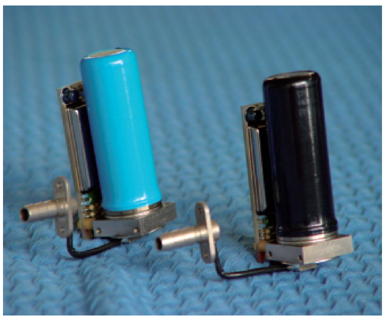


Fig.2 A prototype of a resonant cylinder pressure sensor

What is the technical connotation of sensors? What are the current development trends of sensors? How can sensors achieve better collaborative development with AI? This paper contemplates the above issues, expounding on the technical characteristics, application features and inherent limitations of sensors, predicting that sensors will dominate information technology, upgrade their connotations and advance ubiquitous bionic intelligence, and proposing that sensors should achieve collaborative development with AI through large-range application to create new momentum and advantages for industrial development.

2 Sensors' Technical Connotation

2.1 Concept Definition

According to the national standard GB7665-2005, a sensor is a device or apparatus capable of sensing the measurands and converting them into a usable output signal based on a specific principle. It typically consists of a sensing element and a transducing element. The sensing element refers to the portion within the sensor that can directly sense or respond to the measurand; the transducing element refers to the portion within the sensor that can convert the measurand into an electrical signal suitable for transmission or measurement[12].

From the viewpoint of technical realization, the three essential elements of a sensor are "measurand", "sensing element", and "available electrical signal":

(1) Measurand: A sensor is a physical (qualitative) device that measures the characteristic parameters of the measured object.

(2) Sensing element: The part in the sensor that directly interacts with the measured object in terms of energy and information, that is, directly senses the measurement.

(3) Available electrical signal: The sensors utilized in industrial automation ultimately need to output available electrical signals.

Take a resonant cylinder pressure sensor in the Air Data System as an example. As shown in Figure 3, it measures the atmospheric pressure *p*. The sensing element is the resonant cylinder, whose vibration displacement during operation is converted into a periodic electrical signal by the pickup coil. Finally, the measured pressure is obtained by solving the resonant frequency[11].

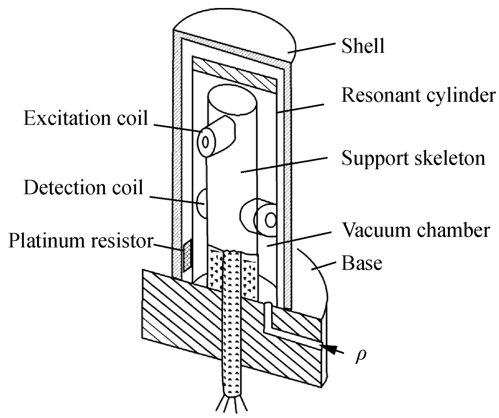


Fig.3 Principle and structure of resonant cylinder pressure sensor

As shown in Figure 4, since the resonant sensor operates in a closed-loop self-excited state and outputs periodic signals (quasi-digital signals), it possesses high sensitivity and resolution.

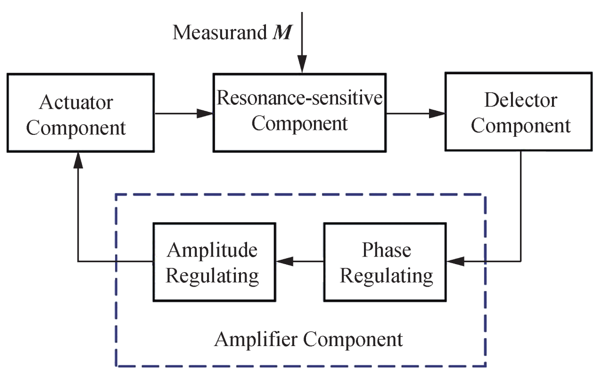


Fig.4 Principle and structure of closed-loop resonant sensor system

2.2 Technical Characteristics

Although sensors are small, their technical characteristics pervade three levels: scientific issues, key technologies, and engineering applications:

2.2.1 Sensitive Mechanisms as the Core; Structural Optimization as the Foundation

The core of a sensor's measurement capability lies in its sensing mechanism and the measurement it detects, while the fundamental aspect is enhancing the structure that transmits and senses the measurement. These two aspects belong to the category of scientific issues. For example, in the fields of petrochemicals and flow measurement, sensing mechanisms of resonant direct mass flow sensors with various structures such as straight-tube and elbow-tube types are all the Coriolis effect. The improved straight-like-tube structure, which combines the high sensitivity of the elbow-tube type with the low-pressure loss of the straight-tube type, has been widely utilized. Further optimization of the sensor structure by adding mass can suppress the multi-frequency nonlinear interference in the detection signal[13, 14]. Figure 5 shows the quasi-straight-tube resonant direct mass flow sensor, independently developed in China during the "11th Five-Year Plan" period, which reached an internationally advanced level of overall performance[13].

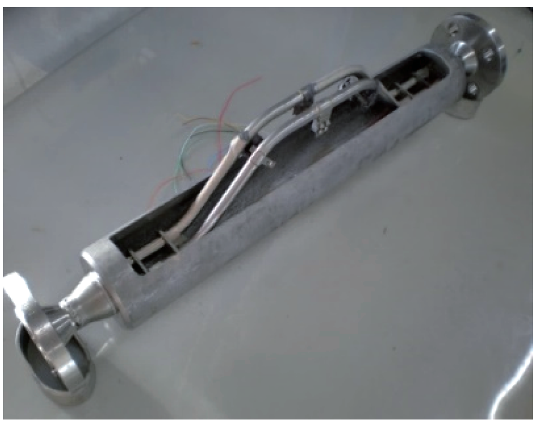
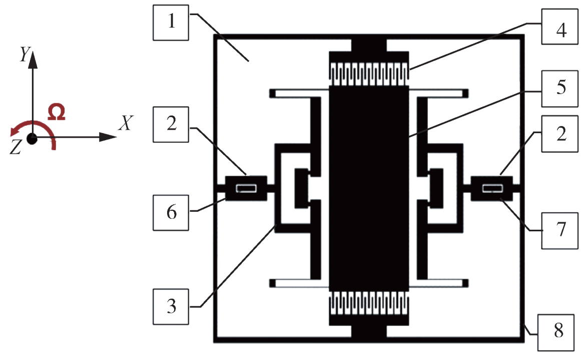


Fig.5 A prototype of a straight-like-tube resonant direct mass flow sensor

2.2.2 Materials and Processes as the Basis; Conditioning Circuits as the Support

The performance of sensors is directly affected by the choice of materials and processing and packaging techniques; the output of usable electrical signals relies on the conditioning circuits at the rear end. These two aspects belong to the category of key technologies. For example, to meet the extremely high sensitivity measurement requirements in complex environments such as deep space and deep sea, graphene-based resonant sensors, which utilize the excellent thermal, mechanical, and electrical properties of graphene and micro-nano electro-mechanical system(MEMS/NEMS) processing techniques, have developed rapidly in recent years. As shown in Figure 6, a differential resonant gyroscope sensor with dual graphene beams has a simulated sensitivity of 22, 990 Hz/°/h, significantly higher than that of existing MEMS resonant angular velocity sensors[15, 16]. As illustrated in Figure 7, a graphene micro-opto-electro-mechanical system (MOEMS) resonant pressure sensor uses vacuum packaging to address the gas permeation issue between the substrate and graphene. Its size is only Φ4mm × 5mm (diameter × length), and the high-pressure sensitivity reaches 1.7 Hz/Pa, which is five times that of similar silicon-based sensors[17, 18].



1- glass substrate
2-transfer beam
3- lever transfer section
4-driving combs
5-gyro mass block
6-first graphene resonant beam
7-second graphene resonant beam
8-frame

Fig.6 Structure of a differential resonant gyroscope sensor with dual graphene beams

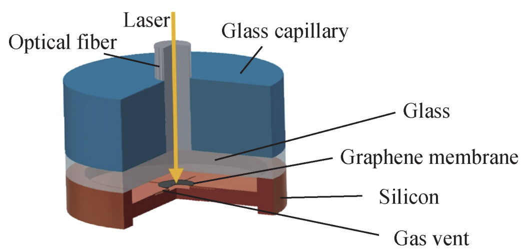


Fig.7 Structure of a graphene MOEMS resonant pressure sensor

2.2.3 Practical Application is the Supreme; Engineering Ethics is the Priority.

The value of a sensor is ultimately reflected in its practical applications in scientific research, production, and daily life. This requires that the sensor be not only functional but also highly operable. Moreover, during its application, it is crucial to meet the relevant requirements of engineering ethics, including ensuring user safety, and environmental friendliness, and promoting fairness. These two aspects belong to the category of engineering application. For example, the first-generation product of the straight-like-tube resonant direct mass flow sensor as depicted in Figure 5, required maintenance on average once every half year when operated in the actual harsh environment of the Karamay Oilfield in Xinjiang. By adopting the innovative vibration coupling suppression method achieved by Beihang University, the sensor's anti-interference ability was significantly improved, thereby extending the repair cycle to over ten years and effectively reducing the maintenance cost.

2.3 Application Features

2.3.1 Wide range and Great Variety

Sensors are the source of information technology and the first unit of intelligent systems, and their application scope is extremely broad and almost ubiquitous. As shown in Figure 8, sensors are widely used in land, sea, air and space vehicles. For example, a standard 8-carriage Fuxing high-speed train is equipped with over 2,500 sensors, which can effectively monitor 1, 500 status information of the train and ensure its operation safety.

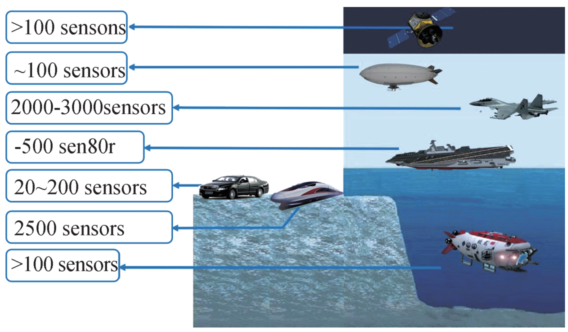


Fig.8 Number of sensors in transport equipment

Simultaneously, the application requirements for sensors vary significantly, characterized by small batch quantities and multiple varieties/specifications. As depicted in Figure 9, in different application scenarios, the measurement range, accuracy, reliability, size, installation, etc. of sensors measuring the same physical quantity might exhibit significant variations. For example, for pressure sensors, on the C919 aircraft at an altitude of 10,000 meters, the pressure to be measured is approximately 30 kPa; on the manned submersible "Striver" in the 10, 000-meter deep sea, it is approximately 110 MPa; and in a car traveling at a speed of 100 km/h, it is approximately 250 kPa.

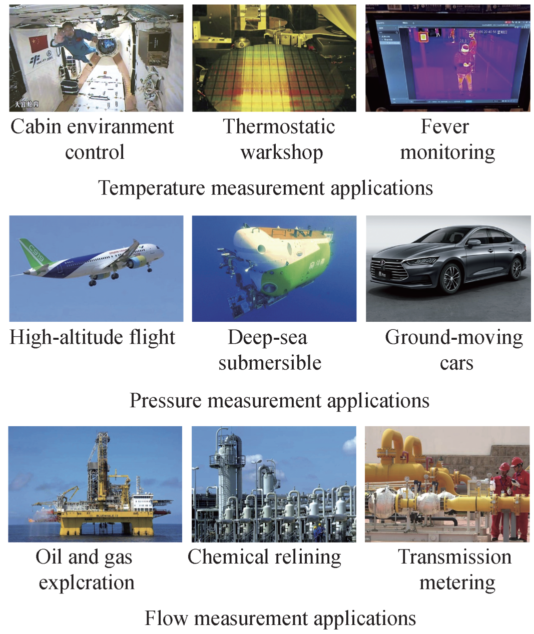


Fig.9 The application requirements of sensors with significant differences

2.3.2 Interdisciplinary Yet Structurally Weak

Sensors are highly comprehensive, encompassing mechanism research and analysis, design and development, performance assessment, and applications. Meanwhile, they involve multiple disciplines including mathematics, physics, chemistry, and biology, as well as various technologies such as materials, mechanics, electrical and electronic engineering, microelectronics, signal processing, computer science, control, and experimental testing.

Nevertheless, the theoretical framework of sensors is weak, with distinct individuality and lack of a clear focus. It is challenging to adopt a unified approach for research or a uniform method for evaluation. Apparently, the threshold for learning about sensors is low and it is relatively easy to get initiated; in fact, to genuinely understand and master a certain type of sensor and be capable of independently designing and developing it, the progress is slow and arduous, which demands the determination and endurance of ten years of dedication and perseverance.

2.3.3 Slow in Development Yet Enduring in Vitality

In comparison with information transmission and information processing in information technology, namely communication and computer technology, the development of sensor technology has been relatively slow, yet it possesses strong vitality. For example, the electronic scale, widely used in the market, is a classic strain sensor. Its sensing mechanism, the "strain effect", was discovered by the British physicist Lord Kelvin in 1856, and its first engineering application occurred between the 1930s and 1940s. To this day, strain sensors still play a crucial role in areas of national economy and national defense such as the health monitoring of bridges and dams, and wind tunnel tests. Additionally, they still exhibit considerable vitality in emerging fields like the metaverse[19-21].

2.4 Innate Insufficiency

2.4.1 Long Development Cycle

As the research and development of sensors encompasses multiple links including the design of sensing elements, the improvement of materials and processes, and the adaptation to application environments, it typically takes a minimum of three years, and often five years or even longer for the technology to mature[22].

2.4.2 Weak Outcome Effects

The function of sensors is measurement. They have to rely on the systems in which they are used to be transformed into productive forces. Technological breakthroughs of sensors are hardly perceived by end users, and thus the degree of social attention to sensors is relatively low.

2.4.3 Low Visibility

Sensors are typically concealed within systems and, as technological processes advance, their size is decreasing continuously. They are hardly directly observable by the general public, and the importance of their existence is often disregarded.

2.5 Sensor-Oriented Mindset

Scientists and engineers in the field of sensors should strive to become high-performance "sensors", namely, develop a sensor-oriented consciousness and cultivate a sensor-oriented mindset.

The sensor-oriented mindset means closely focusing on the core key technologies and cutting-edge scientific issues of sensor technology, which is manifested in both national demands and academic frontiers. On one hand, they should continuously assess how their research and achievements can address major national needs. On the other hand, they should strive to reach the academic summits and make original breakthroughs.

To cultivate students' sensor-oriented mindset, the course "Sensor Technology and Application" at Beihang University has implemented a teaching reform exploration for predicting the Nobel Prize in natural sciences since 2020. It encourages interested students to confidently predict the winning projects of the Nobel Prize in natural sciences of the year providing rationales, prediction methods, and references. As of October 2024, eight third-year undergraduate students from the School of Instrumentation and Optoelectronic Engineering have made successful predictions for a total of nine times. Notably, student Li Shangru has successfully predicted all Nobel Prizes in natural sciences in two years including Physiology or Medicine, Physics, and Chemistry. This exploration has effectively enhanced students' ability to acquire information accurately and maintain an open, sensitive, and enterprising mindset.

3 Trends in Sensor Development

3.1 Dominating Information Technology

3.1.1 Insights From the Three Industrial Revolutions

During the three Industrial Revolutions, the emergence of the steam engine, the harnessing of electricity, and the explosion of information technology have respectively realized the in-situ amplification of energy, the long-distance transmission and distributed utilization of energy, and the highly efficient application of energy. All of these are centered around the critical goal of delaying entropy increase, allowing humans to utilize energy more efficiently. In the future, the mainstream in the energy structure will be stable, clean, and controllable nuclear energy[23], which requires a large number of sensors to ensure the safe, green, and efficient process of usage.

3.1.2 The Development Characteristics of Information Technology

Moore's Law, proposed by Gordon Moore, one of the founders of Intelstates that the number of transistors on an integrated circuit doubles every 18 to 24 months, along with a doubling of performance. Introduced in 1965, it has driven the rapid development of the semiconductor industry, but has currently approached the physical limit, representing the first stage of the information and communications technology (ICT) industry, known as ICT 1.0. The "Internet Plus" represents the advent of the ICT 2.0 era and has become a new development engine. Currently, with the development of new technologies such as AI, the Internet of Things, and edge computing, information technology is entering the intelligent ICT 3.0 era.

In the ICT 3.0 era, whether in industry, agriculture, or daily life, the realization of intelligence requires the creation of intelligent systems that can autonomously sense, analyze, make decisions, and control like humans, and this is inseparable from a vast amount of high-quality and multi-modal measured data. Hence, as the source of information technology, sensors will dominate information technology and become its new development impetus and advantage.

3.2 Upgrading connotations

3.2.1 The Bridge Leading From the Physical World to the Digital World

Sensors are capable of converting various measurands in the real environment into data recognizable by digital systems. They are typically considered as the "bridges" from the physical world to the digital world[24] and also the basis of intelligent systems, as illustrated in Figure 10.

3.2.2 The "hub" Between the Physical World and the Digital World

In the future, sensors might break through the constraint of unidirectional information acquisition, and their connotations will undergo a fundamental transformation from passive sensing devices to active intelligent systems: On the one hand, while maintaining the core function of "information acquisition", they will

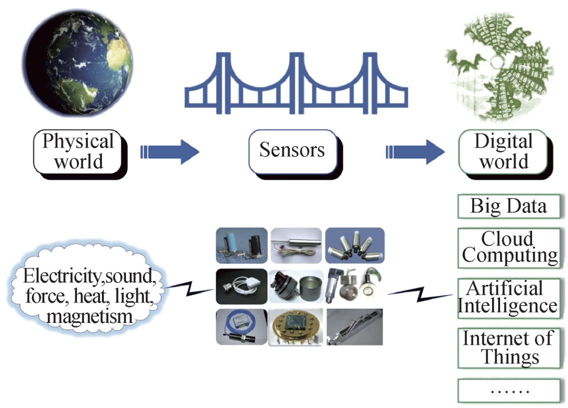


Fig.10 Sensors bridge the physical and digital worlds

expand the "information execution" ability; on the other hand, autonomous decision-making and dynamic response will be achieved through embedded intelligent algorithms; ultimately, they will evolve into a "hub" with bidirectional interaction capabilities between the physical world and the digital world.

3.3 Advancing Ubiquitous Bionic Intelligence

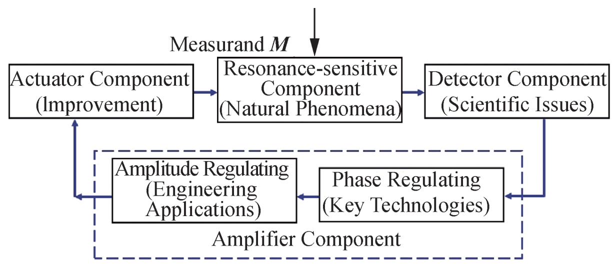
3.3.1 The Five Phases of Scientific Research

From the closed-loop system of the resonant sensor depicted in Figure 4, a scientific research path of "five phases " can be analogically distilled, as shown in Figure 11.

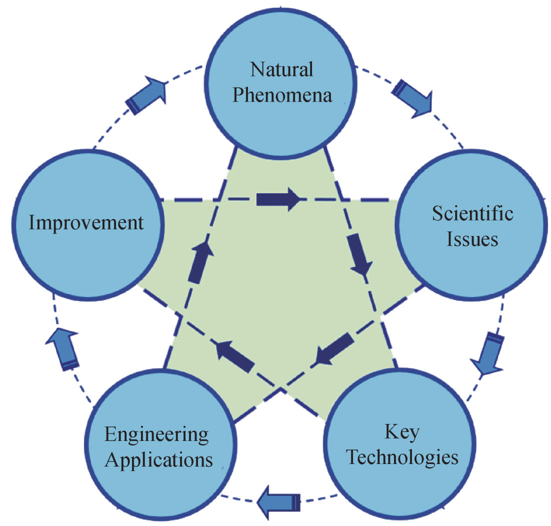
Scientific research originates from nature. The first phase is to observe nature, apprehend its subtleties, recognize natural phenomena and discover laws in the correct direction. The second phase is to summarize the laws, condense scientific issues, reveal natural phenomena, and establish models by universal principles. The third phase is to break through key points, propose implementation approaches, master core technologies, lay the theoretical foundation for leaps, and develop prototypes. The fourth phase is practical application, form specific achievements, achieve mass production for engineering practice, and focus on serving major national demands. The fifth phase is continuous improvement, identifying deficiencies in practical applications making amendments, and pursuing betterment. The five phases are not simply a unidirectional serial relationship but rather a mutually coupled, cyclical, continuously optimized, and ever-approaching-optimal perpetuating process.

3.3.2 The Inspiration for Bionic Sensing

The working principles of nearly all sensors stem from natural phenomena. In the past, sensors were dubbed "electronic five senses", namely imitating the traditional sensory functions such as human vision, hearing, and touch to acquire external information. However, apart from humans, there are more diverse "intelligent entities" in nature. All of them need to obtain information from nature for survival and possess unique wisdom, which serves as an inexhaustible source of



(a) The five essential elements of resonant sensors



(b) The five phases of scientific research

Fig.11 From five essential elements of resonant sensors to five phases of scientific research

inspiration for sensor technology research. For instance, inspired by the compound eye structure of insects like bees, scientists have carried out research on bionic polarization navigation. By real-time measurement of the information of the polarized light field, a pair of "compound eyes" can be installed on unmanned aircraft, which can not only fulfill navigation functions but also resist electromagnetic interference and effectively prevent signal deception and shielding[25, 26].

In the future, sensors should progress from "human-like perception" to "ubiquitous intelligence", learning how more life forms (natural phenomena) in nature adapt to nature and obtain the information they require, achieving sensing in a broader spectral range and more dimensions, and conducting research and development of sensors. Simultaneously, the "intelligent" data of sensors will also enable the back-end AI to acquire higher-level " intelligence ".

4 The Collaborative Development of Sensors and Artificial Intelligence

4.1 Development Status

Although sensors can provide measured data for AI, their slow development and distinct characteristics within information technology significantly constrain the advancement of AI. This is mainly reflected in the following aspects:

4.1.1 Data quality and Reliability

The quality of data acquired by sensors directly determines the performance ceiling of AI models. However, sensors can be affected by environmental factors such as temperature, humidity, and interference, leading to inaccurate or unstable data.

For example, smart locks that use biometric features to control door access have experienced sustained market growth in recent years. In 2023, national production and sales volumes reached approximately 22.3 million units, with the total industrial output value reaching approximately 20 billion yuan[27]. However, many consumers have reported that smart locks malfunction during "Hui Nan Tian" (a humid weather phenomenon) and the plum rain season[28]. This occurs because excessive environmental humidity can hinder sensors from obtaining accurate fingerprint signals or clear images.

4.1.2 Data Diversity and Complexity

With the widespread adoption of the Internet of Things, sensor types have become increasingly diverse. However, sensors of different types exhibit varying data formats and characteristics, and their manufacturing lacks uniform standards. Sensors from different manufacturers present discrepancies in aspects such as interfaces and data formats. These factors increase the complexity of data fusion and system integration.

For example, the smart home industry is undergoing rapid development. The national market scale exceeded 710 billion yuan in 2023 and is expected to reach one trillion yuan by 2029. However, smart products of various brands are relatively independent, and achieving interoperability across brands and ecosystems remains challenging[29]. One significant reason for this is the lack of uniformity in communication protocols among devices.

4.1.3 Real-time Performance and Compatibility

In numerous application scenarios, AI is required to process sensor data in real-time to make rapid decisions. However, when the volume of data generated by sensors is substantial or the demand for response speed is high, traditional centralized computing architectures may struggle to meet real-time processing demands. Hence, it is necessary to deploy AI models on edge devices. This raises higher demands regarding computability and energy consumption, among others.

For instance, plant protection unmanned aerial vehicles, equipped with remote sensing sensors and supported by back-end recognition algorithms, can conduct operations such as weed mapping and disease detection. They have been extensively applied and have developed rapidly in the field of smart agriculture in recent years. As of 2023, the national possession exceeded 200, 000 units, and the operation area reached 2.13 billion mu[30]. However, due to the high computing, memory and network requirements during the training and inference phases, deploying AI models on the platform of unmanned aerial vehicles with limited computing, storage, power consumption, and bandwidth resources poses a challenge. For example, a classic convolutional neural network VGG-16 contains approximately 140 million parameters, occupies more than 500MB of memory and has 15 billion floating-point operations[31].

4.2 Solution Approaches

To overcome the restrictive factors of sensors in the development of artificial intelligence, it is essential to commence with large-range applications and facilitate the enhancement of sensor reliability, low-cost manufacturing, and batch production.

4.2.1 The Large-range Application of Sensors Promotes the Widespread Implementation of AI

With the large-range application of sensors, the large-range production will reduce the manufacturing cost per unit. Simultaneously, the huge market demand will attract more manufacturers to enter the competition and promote the research and development of products with higher performance and lower costs, thereby providing fundamental support for the popularization of AI.

For example, under the global market demand of billions of units for sensors such as gyroscopes and optical sensors in smartphones, the cost has decreased significantly, enabling the rapid and mature application of facial recognition.

4.2.2 The Large-range Application of Sensors Improves the Processing Capacity of AI

With the large-range application of sensors, greater data consistency reduces the adaptation costs of AI deployment, the accumulation of vast amounts of data enhances the generalization capability of AI models, and distributed sensor networks increase the response speed of AI systems, thereby providing superior conditions for the optimization of AI.

For example, sensors such as LiDAR, millimeter-wave radar, and cameras in intelligent driving vehicles have been deployed on tens of millions of vehicles globally. The model capabilities have been continuously upgraded. Currently, L2-level assisted driving has become the mainstream in the market, while L3/L4-level advanced autonomous driving is also gradually being implemented and promoted.

4.2.3 The large-range Application of Sensors Facilitates the Upgrading of Domestic Industries

With the large-range application of sensors, the motivation for domestic enterprises to conduct independent research and development increases. Domestic sensors gradually substitute for high-cost imported products, reducing dependence on foreign supply chains. Simultaneously, after the expansion of the industrial scale, AI can be employed to optimize sensor design, manufacturing, and application, promoting technological innovation of domestic sensors. Consequently, the autonomous controllability of information technologies such as sensors and AI is enhanced.

4.3 Key Fields

In the future, the potential of the collaborative development of sensors and AI will be further released in the following extensive key fields:

4.3.1 Smart Learning

For the 290 million students currently enrolled in academic education nationwide[32], the combination of visual, motion, and physiological sensors with AI can optimize teaching approaches through real-time monitoring of learners' states such as sitting posture, attention, expressions, and mental fatigue, leading to individualized education.

For example, an intelligent desk lamp integrated with a 3D camera and an AI chip can capture the 3D skeletal joint points of the human body to identify the sitting posture of young students, assisting parents in providing targeted correction and guidance; simultaneously, it can detect learners' concentration, eye fatigue values, etc., enabling parents to have a comprehensive understanding of their children's learning status[33].

4.3.2 Smart Senior Care

For the 310 million individuals aged 60 and above throughout the country[34], robots integrating visual, tactile, and posture sensors with AI can offer life assistance and mental companionship to the elderly through environmental perception and voice interaction.

For example, wearable exoskeleton robots can utilize inertial or pressure sensors to detect the movement data of the users' hip and knee joints, analyze and predict the intention of the movements, and provide driving forces. This assists elderly individuals with limb dysfunction in conducting rehabilitation training[35].

4.3.3 Smart Home

For the 490 million households nationwide[34], the integration of sensors such as light, radar, temperature and humidity with AI is capable of fulfilling functions like environmental perception, security monitoring, automatic control, and health management, rendering family life safer, more comfortable, and more convenient.

For example, millimeter-wave radar can be utilized to detect whether there are any individuals in the room, their precise locations, and behaviors, to achieve intelligent power conservation; and through modeling and learning, it can conduct posture recognition, sleep detection, fall alarm, etc., offering intelligent guardianship[36].

4.3.4 Smart healthcare

For a population of 1.4 billion in the country[37], the integration of imaging, physiological, and biological sensors with AI enables big data analysis and diagnosis and will be extensively applied in early disease screening and health management.

For example, zero-magnetic medical equipment based on zero-magnetic space and zero-magnetic sensors can detect extremely weak magnetic signals produced by human organs and conduct imaging, thereby obtaining functional information about human organs such as the heart, brain, and nerves, and facilitating the diagnosis of diseases such as myocardial infarction, cerebral infarction, and tumors[38].

4 Conclusion

Sensors are the source of information technology, the first unit of intelligent systems, and the crucial element for propelling AI to a higher level. Sensors will dominate information technology, transforming from a unidirectional "bridge" between the physical and digital world into a bidirectional "hub", and upgrading connotations from "human-like perception" to "ubiquitous intelligence".

The collaborative development of sensors and AI will enable AI to evolve from a data analysis tool into an intelligent system capable of real-time perception, feedback, and optimization. To rapidly establish the intelligent foundation of the intelligent society, advancements should focus on the large-range application of sensors, with particular emphasis on extensive fields such as people's clothing, food, housing, transportation, quality of life, and daily consumption (including green recycling).

In the future, the collaborative development of sensors and AI will further drive information technology into a new stage driven by data acquisition, facilitating the evolution of artificial intelligence into augmented intelligence, and achieving an advanced stage from the "symbiotic dance" of sensors and artificial intelligence to the "symbiotic dance" of sensors and augmented intelligence.

Author Contribution:

Conceptualization - Shangchun Fan; Data curation - Shangchun Fan, Feiyang Zhang; Funding acquisition - Shangchun Fan, Yufu Qu; Investigation - Shangchun Fan, Feiyang Zhang; Supervision - Shangchun Fan; Visualization - Shangchun Fan, Feiyang Zhang; Roles/

Writing - Feiyang Zhang; and Writing - review & editing- Shangchun Fan, Yufu Qu.

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Data Availability:

The authors declare that the main data supporting the findings of this study are available within the paper and its Supplementary Information files.

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The authors declare no competing interests.

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