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1 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

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2 Abbreviations

Abbreviation	**Explanation**
3D	3-Dimensional
6G	The sixth generation mobile communication systems
AI	Artificial Intelligence
AMP	Amplifier Transistor
ASIC	Application Specific Integrated Circuit
CMOS	Complementary Metal Oxide Semiconductor
CNN	Convolutional Neural Network
CPU	Central Processing Unit
DFOS	Distributed Fiber Optic Sensing
DRAM	Dynamic Random Access Memory
DT	Decision Tree
FPGA	Field Programmable Gate Array
GNN	Graph Neural Network
GPU	Graphics Processing Unit
HDR	High-Dynamic Range
ISP	Image Signal Processor
LDA	Linear Discriminant Analysis
MEMS	Micro-Electro Mechanical System
OFDA	Optical Frequency Domain analysis
OFDR	Optical Frequency Domain Reflectometry
OPTs	Organic Phototransistors
OTDA	Optical Time Domain Analysis
OTDR	Optical Time Domain Reflectometry
PCA	Principal Component Analysis
QKD	Quantum Key Distribution

RFID	Radio Frequency Identification
SVM	Support Vector Machine
TSV	Through Silicon Via

3 Overview

Perception is the process of obtaining target information through various sensing devices [1], including the collection and processing of sensing data and the generation of sensing results. Perception, as the cornerstone of the Internet of Things, provides a data foundation to support intelligent decision-making and control for various businesses, and is a core element in building an "intelligent connection of everything". Sensing technology has been widely used in aerospace, industrial manufacturing, biomedicine, smart transportation, smart energy and environmental monitoring and other fields.

As the informatization of the industry continues to deepen and scenarios continue to be subdivided, various applications have put forward new demands for sensing technology. First, new industry scenarios require further expanding the sensing range, improving sensing accuracy, and increasing sensing targets. Second, the parameters of traditional sensors are fixed, and their accuracy and efficiency decline with time. In the future, they need to be able to dynamically optimize themselves. Third, the intelligent development of vertical industries requires the deep integration of sensing and communication, processing and control and other functions. Fourth, the power lines and data transmission lines of traditional sensors have great constraints on their applications, resulting in high wiring costs and high construction difficulties. In the future, it is necessary to make sensors passive and wireless to achieve "braid-cutting" of sensors. In order to meet the needs of various applications for sensing capabilities, advanced sensing technology continues to develop. Through technological innovation, it improves the accuracy of sensing data and sensing efficiency, expands the sensing range and sensing scale, and continuously realizes networking and intelligence, further opening up the field of sensing. Technology is oriented towards the development space of various application fields.

In recent years, with the continuous development of digital twins and the metaverse, the importance of perception as the underlying data source and technical support has become increasingly prominent. Driven by the continuous demand for applications, perception will promote each other with digital twins and the metaverse, and is bound to welcome Come explosive technological breakthroughs and market growth.

3.1 Trends of advanced sensing technology

The trends of advanced sensing technology cover two aspects: sensing cutting-edge technology and sensing fusion technology. Sensing cutting-edge technology is a comprehensive technology involving sensing principles, sensor device design, sensor development and application, integrating the latest technological advances in multiple disciplines, multiple technologies and multiple fields, involving physics, chemistry, biology, energy, communications and data processing are the core supporting the development, manufacturing and application of sensors. Sensing fusion technology closely integrates the originally independent basic capabilities of single parameter sensing, communication, computing, intelligence and energy supply, which helps to improve sensing efficiency and expand the application scope of sensing technology.

3.2 Cutting-edge sensing technology

With the rapid development of information and communication technologies, cutting-edge sensing technologies continue to emerge. Through technological innovations in five aspects, namely mechanism, materials, process, structure and algorithm, information acquisition with a wider range and higher precision can be achieved.

In terms of new mechanisms, quantum sensing and electroencephalogram (EEG) sensing are typical representatives, and have great application value in aerospace, security monitoring and wearable devices. Quantum sensing improves perception accuracy through quantum effects, and has the advantages of non-destructiveness, real-time, high sensitivity, stability and multi-function. EEG sensing obtains electrical signals generated by brain activity and realizes information exchange between the brain and the outside world through signal analysis. It will play an important role in industries such as medicine, entertainment, military and education.

In terms of new materials, new flexible materials, etc., as sensor sensitive materials, will help expand more business scenarios in the future. Flexible sensing utilizes the good flexibility and ductility of flexible materials to produce wearable devices, which has broad prospects in intelligent robots and medical care for the elderly. Tactile sensing is based on flexible materials and combines cutting-edge advances in device physics and flexible electronics to greatly improve sensing accuracy and mechanical performance.

In terms of new processes, MEMS is a cutting-edge research field based on microelectronics technology and an important development trend in sensor technology. On-chip optical sensing uses micro-nano processing technology to achieve sensor miniaturization, low power consumption and low cost, which is an important development direction of optical sensing. Microfluidic biosensing is based on micro-processing technology and can complete all analytical processes required in the laboratory within micron-level flow channels. When used in the medical field, it can significantly reduce the waiting time and pain of patient sampling, and has received widespread attention in the industry.

In terms of new structures, bionic structures and 3D stack structures provide new ideas for technology research and device development in visual sensing and image sensing respectively. Bionic visual sensing simulates the structure and operation of the human retina.

Using the principle of optical fiber to achieve efficient information collection under different lighting conditions is an important direction for future visual sensing. Stacked image sensing improves the efficiency of light reception and processing through structural optimization, thereby reducing noise, improving image quality and expanding dynamic range.

In terms of new algorithms, based on the original infrastructure, through signal detection, analysis and the use of new algorithms, new sensing information can be obtained or sensing accuracy can be further improved. Fiber optic sensing uses the analysis and testing algorithms in fiber optic communication technology to calculate various parameters of light, and can obtain perception results of structural integrity and equipment status. Ultra-sensitive odor sensing achieves performance optimization based on innovative pattern recognition algorithms, bringing new opportunities for applications such as environmental monitoring and auxiliary medical diagnosis.

3.3 Sensor fusion technology

In order to meet the diversified needs of new scenarios and new businesses in life, production and society, future sensing systems also need to have ultimate communication capabilities, powerful computing capabilities, high intelligence capabilities and passive energy supply capabilities. Technologies in communication integration, computing integration, intelligence integration and energy integration have become the development trend of the new generation of mobile information networks, and are also an important direction for the integration and development of 6G Internet of Things technology in the future [2].

In terms of communication integration, wireless communication technologies for wide-area and local-area, as well as micro-area and short-range can support sensors to effectively improve their sensing and transmission capabilities and better meet the needs of differentiated scenarios. Wide-area and local-area communications, represented by cellular networks and passive Internet of Things, can support efficient transmission of sensing information and integration of communication perception in outdoor wide-area coverage scenarios, reduce communication power consumption, and achieve perception of massive targets. A typical representative of micro-domain and short-distance communication is terahertz communication. Terahertz waves have both the volatility of millimeter waves and the particle properties of infrared light. In addition to being used for communications, they also play an important role in medical fields such as genetic testing, realizing the deep integration of communication and perception.

In terms of computing fusion, the research and application of new computing technologies such as data compression, in-sense computing and heterogeneous computing can meet the sensor's requirements for high computing power, low latency and low power consumption. Data compression can reduce the amount of data transmission and extend the life cycle of sensor networks. Combined with AI technologies such as deep learning, it can achieve efficient data compression processing. Intra sensory computing realizes intelligent information preprocessing from the source of information collection by building a new sensory computing module inside the sensor, reducing the scale of data transmission and simplifying the post-processing process. Heterogeneous computing utilizes end-side heterogeneous computing units to work together to achieve joint computing, thereby achieving better performance and lower power consumption.

In terms of intelligent integration, intelligent microsystems, distributed computing and crowd sensing can effectively improve end-to-end comprehensive sensing capabilities through the deep integration of sensing and intelligence. Intelligent microsystems support sensors are improving. While functional density is developing toward integrated capabilities, wireless communications, passive energy supply, and intelligent applications, the future will continue to evolve around autonomous and smart execution and efficient resource utilization. Distributed computing enables sensors to have good scalability and fault tolerance, and task allocation and scheduling algorithms will be further optimized in the future. Crowd sensing uses crowd-generated mobile devices as sensing nodes. It has the advantages of node openness, on-demand deployment and on-demand scheduling, and can meet the requirements of large-scale and fine-grained sensing tasks at the city level.

In terms of energy fusion, technologies such as energy collection and sensing and energy management can improve the problems of traditional active power supply (battery/wiring) and make sensors passive. Energy collection and sensing, on the one hand, collects light energy, wind energy, temperature difference energy, vibration energy or radio frequency energy from the environment, and converts it into electrical energy to ensure the normal operation of the sensor. The research focus is to increase the energy collection density and improve the energy conversion efficiency. On the other hand, the energy supply is used as the sensing object to truly realize the integration of digital energy. Energy management ensures long-term stable operation of sensors, and research focuses include efficient management of energy acquisition, optimal control of energy storage, and on-demand adjustment of energy consumption.

4 Cutting-edge sensing technology

4.1 New mechanism

The new sensing mechanism refers to the use of new detection mechanisms based on physical, chemical, and biological effects to improve the sensitivity, accuracy, response speed and other performance indicators of sensing to meet the changing and developing application needs. New mechanisms include quantum sensing, brain electrical sensing, surface acoustic wave sensing, microwave photon sensing and other aspects. Take quantum sensing as an example, which uses quantum mechanics to detect and extract information, breaking through the limits of traditional sensing technology. Quantum sensing technology has a wide range of applications and can be used in important fields such as military, transportation and aerospace. In the future, the continuous development of new mechanisms will continue to promote the upgrading of sensing technology and drive the continued development of new sensing materials, new processes, new structures and new algorithms.

4.1.1 Quantum sensing

At present, the widespread application of electronic, optical, acoustic and other sensing technologies has provided great convenience for production and life. However, important indicators such as detection accuracy, equipment size and response speed of traditional sensing technology are restricted by the basic principles of classical physics, making it difficult to meet the needs of high-precision industries such as next-generation semiconductor R&D and aerospace, demand, and quantum sensing technology based on the principles of quantum mechanics is gradually emerging. Quantum sensing is a technical method that uses quantum mechanics to detect and extract information. It uses quantum objects, quantum coherence effects, or quantum entanglement to measure specific physical properties, thereby providing sensing sensitivity and accuracy beyond classical limits. A quantum sensor is generally a single particle or multi-particle system with discrete energy levels. Such systems will interfere when affected by various fields (such as electromagnetic fields or gravitational fields). That is, when a quantum sensor detects external field interference, it can Convert the initial state of a particle system into another quantum state.

Quantum sensing has many important detection methods, such as Ramsey measurement [3], Rabi detection [4], Bose-Einstein condensation [5], etc. Among them, Ramsey measurement is the most important and basic. It uses two pulses at intervals to control and measure quantum systems. It is mainly used for high-precision measurements such as atomic clocks, nuclear magnetic resonance, inertial navigation and celestial radiation spectrum. Taking an atomic clock as an example, if a pulse (mostly a microwave pulse) is applied to a stable atomic sample (such as rubidium or cesium in the ground state), the atoms will enter a free evolution state, and then a second pulse will be applied to return it to the initial state. By analyzing the probability distribution of the evolution process, the oscillation frequency of atoms can be accurately calculated to achieve time calibration.

Noise is the main reason for reducing the sensitivity and stability of quantum sensing, including quantum projection noise, noise caused by decoherence and relaxation phenomena, etc. The cause of projection noise is the uncertainty principle of quantum mechanics, that is, in the process of quantum state collapse caused by measurement, even the same initial state and evolution process may lead to different results. Decoherence and relaxation noise are both basic phenomena of quantum mechanics. Decoherence represents the weakening of the quantum interference effect of the quantum sensing system under external interference, while relaxation is the process of the quantum system evolving towards thermal equilibrium. Both mean quantum the system gradually degenerates into a classical system. Regarding the noise problem, current research directions include three: first, improving cooling technology, that is, weakening the effects of decoherence and relaxation by lowering temperature; second, studying quantum calibration technology, using quantum interference to improve the sensitivity of phase measurement [6]; thirdly, it is to develop new quantum materials with better quantum states and lower noise levels.

Quantum sensing technology has broad application prospects. Sensors such as quantum gyroscopes [7] and accelerometers can be used to improve the accuracy of navigation systems and can be widely used in fields such as unmanned driving, aerospace and ocean navigation (see Figure 1). At the same time, quantum sensing technology can also be used to measure the structure and interactions of biomolecules, enabling medical research and development or disease detection. Currently, due to limitations in resistance to environmental interference and decoherence effects [8], as well as process difficulties such as stability, coupling, and qubit interaction when integrated into micro-nanoscale devices, there are no commercial products for quantum sensors and they are still in the design stage. or prototype verification phase. For example, relevant companies have already carried out research and development work on quantum gyroscopes [9], which calculate the current angle by measuring changes in the precession frequency of atomic spins. Speed and perception accuracy have been greatly improved. At the same time, many domestic enterprises and scientific research institutions have also successively carried out research and development to promote the continued and rapid development of quantum sensors.

Figure 1. Quantum gyroscope used in automobile yaw rate sensor [10]

In the future, research on quantum sensing will focus on the measurement of important physical parameters, such as quantum gravity measurement and inertial measurement. In addition, the new generation of remote communication based on quantum entanglement can achieve nearly zero-delay communication, and quantum key distribution (QKD) can create a highly secure information channel for both communicating parties. Quantum sensing will also be further combined with technologies such as quantum communication to accelerate mankind's advancement into the era of quantum information technology and promote the digital and intelligent transformation of society.

4.1.2 EEG sensing

For a long time, in order to fully understand human thinking and behavior, scientists have been committed to studying brain structure, function, and signals. However, because the brain is difficult to directly observe and measure, traditional sensing technology has certain challenges in directly acquiring brain signals. The thinking of the human brain involves electrophysiological activities and chemical reactions, which can be captured and recorded using high-sensitivity and high-resolution sensors. EEG sensing technology places sensors on the head to obtain weak electrical signals generated by brain activity. By decoding brain electrical sensing signals through computers and analyzing the information transmitted by neurons, we can understand human brain activities such as cognition, emotion, movement, and further realize the exchange of information between the brain and external devices.

EEG sensing can be divided into invasive and non-invasive. Invasive EEG sensing collects EEG signals through implanted electrodes, but has problems such as high trauma and prone to complications [11]. In recent years, researchers have been exploring minimally invasive surgery to implant EEG sensors into blood vessels and attach them to the walls of cerebral blood vessels, thereby balancing safety and effectiveness to a certain extent. Non-invasive EEG sensing collects EEG signals by placing electrodes on the scalp surface. Although the quality of the collected signals is low, it has the advantages of non-invasiveness and high safety, and is moving towards miniaturization, portability, wearability and simplicity. development in the direction of utilization.

EEG sensing covers both hardware and software. The core of the hardware is the EEG acquisition device. Common EEG collection equipment includes micro-nano electrodes, head-mounted EEG cap electrodes, and brain pacemaker electrodes, which are made of materials that are resistant to high temperatures, chemical etching, and are biocompatible. Flexible electrodes have the advantages of high density, stable signal and low damage. They are the main direction of brain signal sensing electrodes at this stage [12]. In the future, electrodes will tend to be miniaturized, high-throughput and integrated. Software includes signal processing and AI algorithms, etc. Signal processing extracts useful information from brain nerve signals through steps such as signal denoising, signal feature extraction, and signal encoding and decoding. AI algorithm achieves feature classification by establishing the relationship between brain signal feature vectors and brain activity, improving system accuracy [13]. Since the brain is highly complex and there are individual differences in brain activity, the software layer technology needs to have certain adaptability and learnability, and can be optimized and adjusted according to the neural signal characteristics of different individuals. By sharing models and parameters and training on multiple individuals, transfer learning can enable the model to learn a wider range of brain electrical activity characteristics, thereby improving the generalization ability and adaptability of decoding [14].

The main application field of EEG sensing is medical treatment, which is of great value in the diagnosis, treatment and rehabilitation of diseases. It can reduce the pressure on medical personnel and improve medical efficiency. In recent years, EEG sensing has gradually expanded into entertainment, military, education and other fields. It can be used to achieve immersive and personalized human-computer interaction in movies and games. It can be used to develop brain-controlled weapons that enhance combat capabilities. It can also be used to It is used to monitor students' attention and fatigue status to help teachers adjust teaching methods in a timely manner. Restricted by technical, ethical and safety factors, countries' investment in research and development of non-invasive EEG sensing is much higher than that of invasive EEG sensing. Currently, non-invasive EEG sensing already has wearable speech generation devices [15], Mature products such as mind drones [16] and brain-controlled smart bionic hands [17] have been launched. The application of invasive EEG sensing is still concentrated in the medical field. There are products that allow monkeys to control computer cursors through animal tests [18], and human clinical trials will be conducted in the future [19].

With the rapid development of EEG sensing technology and the innovation of micro-domain communication technology of the Internet of Things, micro-sensing devices implanted in the human brain in the future can not only detect brain signals with high precision, but also improve various types and complex human brain activities. With high processing accuracy, it can also form a self-organizing network based on micro-domain communication and interact with the outside world in real time, providing new development opportunities and prospects for brain-computer interaction. It will be widely used in human health monitoring, virtual reality, game control, etc. Achieve a better application experience and bring convenience and well-being to mankind.

4.2 New materials

New sensing materials refer to new materials that are different from traditional metal materials and can be used to respond to environmental changes and transmit electrical signals. They are one of the important development directions of sensing technology in the future. At present, new sensing materials research hot spots mainly include nanomaterials, liquid metal and metal oxide materials, etc. New materials usually have special advantages that are different from traditional materials. For example, nanomaterials have higher sensitivity structures and lower unit weights, and metal oxide materials have better ductility and flexibility. Among new materials, materials with flexible characteristics and tactile-level sensing capabilities can improve the sensitivity of sensors and solve the problem of traditional materials being difficult to deploy in special locations such as curved surfaces and underwater, so they have received widespread attention. New materials will promote the application of sensors in more fields and lay an important foundation for the intelligent connection of all things.

4.2.1 Flexible sensing

Traditional high-performance electronic devices are made of rigid semiconductor materials such as silicon and gallium arsenide. Rigidity limits the compatibility of electronic devices with biological tissue materials [20]. Flexible materials have better flexibility and ductility, and can be deformed arbitrarily according to the requirements of measurement conditions. Therefore, flexible sensors made of flexible materials can be used in a wider range of scenarios due to their flexibility and convenience. Flexible sensors are sensors based on flexible materials that are bendable and deformable [21]. They can be more closely attached to the object to be measured, greatly improving the measurement accuracy of complex signals [22], and it has better biocompatibility [23] and can achieve the same functions as rigid sensing while ensuring performance such as sensitivity and resolution.

Flexible materials can be used to make sensor substrates and sensing media, and can be seamlessly connected with traditional silicon-based electronic systems, allowing sensors to better adhere to object surfaces and interact with biological tissues. Flexible materials can be divided into three categories according to their usage: flexible conductors, flexible semiconductors and flexible media [24]. Flexible conductors mainly include liquid metal, graphene and conductive nano-ink, etc., which are commonly used as base materials such as wires and electrodes in flexible electronic devices. Flexible semiconductors are mainly used to make flexible sensors, mainly including inorganic materials such as zinc oxide and zinc sulfide, small molecule organic materials such as triphenylamine and fullerene, and polymer organic materials such as polyacetylene and polyaromatic rings. Flexible media are flexible materials with insulating properties. They mainly include traditional materials such as polymer substrates and ultra-thin glass substrates, and new materials using biofilm substrates such as pollen, petals or silk. They are mostly used to make flexible substrates attached to the surface of objects. At present, flexible materials still face problems such as high production costs and complex preparation processes. Using materials with good electrical properties such as liquid metal and black phosphorus, mixing inorganic or organic materials or adopting multi-layer structures can effectively improve the performance of flexible materials and reduce the difficulty of preparation.

In addition to flexible materials, manufacturing technology is also the key to ensuring the mass production and application of flexible sensors, which mainly involves three aspects: thinning, flexible structural design and transfer printing [25]. The bottleneck of current manufacturing technology is mainly focused on the difficulty in achieving thinning of small-volume chips, as well as high-resolution and large-scale high-efficiency transfer [26]. Follow with the development of nanotechnology, the industry has proposed methods of using nanodiamond to grind and polish semiconductor chips and wafers, and has initially achieved nanoscale transfer printing in the laboratory.

At present, flexible sensing technology is mainly used in the fields of smart medical care and smart wear. Bedsheets, insoles and bracelets with flexible sensors attached can be used to monitor information such as human body pulse rhythm, exercise status and sleep quality. Flexible sensing technology is also expected to be used in the field of aquaculture to monitor fish activity information and water quality data in real time, improving the level of intelligent farming. However, due to factors such as high material costs, immature preparation processes, and limited integration methods, there is still a gap in the large-scale application of flexible sensing. Currently, many domestic and foreign companies are conducting research on flexible sensing technology and launching products and solutions based on flexible temperature and humidity sensing and pressure sensing. With the investment of more companies, the flexible sensing industry can be further expanded, and more testing instruments and equipment can be made flexible.

In the future, flexible sensing technology will further focus on improving sensitivity, resolution and signal processing capabilities, as well as integrating with wireless transmission and power supply modules. With the development of technology, flexible sensors will be able to get closer to the characteristics of living organisms, support the realization of bionic robots with high sensory capabilities, and become an important foundation for digital twins and metaverses.

4.2.2 Tactile sensing

In recent years, robots have been widely used in various scenarios in production and life, such as industrial robots and home service robots. When operating fragile or soft objects, it is difficult for traditional computer vision to obtain the hardness, texture, material and other attributes of the object, making the robot prone to damage or even destruction of the object due to excessive grasping force, or too small grasping force. causing slipping. Therefore, in precise operation scenarios, tactile sensing has gradually become an important method for robots to sense and grasp objects, greatly improving the robot's flexibility and scene adaptability. Tactile sensing can be used to detect physical characteristics such as contact, pressure and sliding, and extract the stiffness, shape and size information of the contact object by simulating human skin, and convert it into corresponding electrical signals [27] (Figure 2).

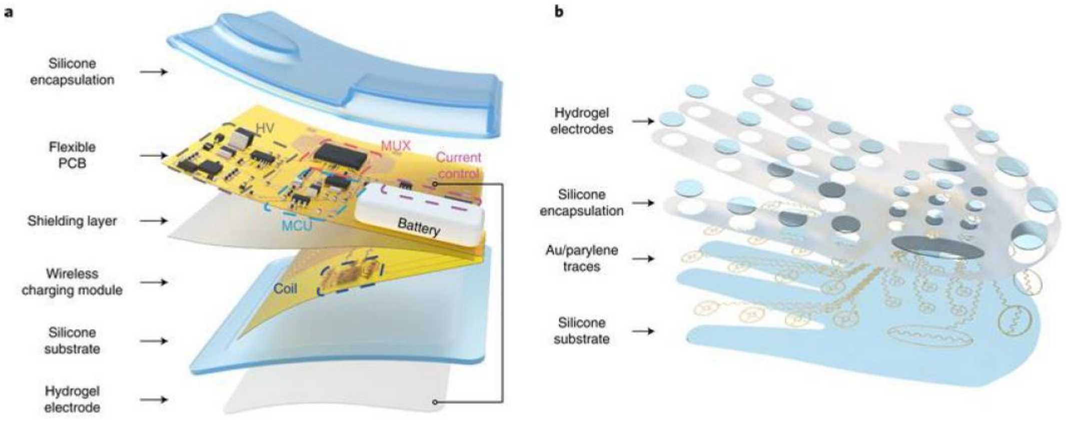

Figure 2. Tactile sensor example [28]

The principles and goals of tactile sensing are similar to pressure sensing, but the requirements are higher. The key lies in the device's accurate perception of force and force direction. In terms of strength, it is usually necessary to sense forces on the order of micro-Newton or nano-Newton, and upward force needs to sense normal force and shear force [29]. Tactile sensors can be roughly divided into three types according to their principles: piezoresistive, capacitive and piezoelectric [30]. The piezoresistive tactile sensor uses the principle that the deformation of the force-sensitive material causes its resistance to change, and obtains force change information by covering the electrode with a thin film of force-sensitive material. Capacitive tactile sensors usually use a "sandwich" structure composed of two plates and electrodes. When an external force affects the plate spacing or overlapping area, a linear change curve of capacitance with external force is obtained. Piezoelectric tactile sensors work based on the piezoelectric conversion effect, that is, when the force-sensitive material is deformed by force, the force and force direction are judged based on the charges accumulated at different positions [31].

According to the above principles, force-sensitive materials and structural processes are the key to determining the performance of tactile sensors. Force-sensitive materials usually require both high electrical conductivity and minimal impact on mechanical properties. Although most current carbon-based materials are low-cost, they are difficult to process and cannot guarantee yield. In recent years, carbon-based nanomaterials such as carbon nanotubes [32], graphene, and hollow carbon spheres [33] have gradually become a research hotspot due to their good stretchability, high sensitivity, and obvious directional conductivity. In terms of structural technology, since tactile sensors must be made of materials with elastic modulus, elastic coupling between components is unavoidable, resulting in inaccurate mapping of the spatial distribution of force in the sensing array, making it difficult to effectively distinguish forces in various directions. Therefore, most tactile sensors are still in the research or prototype stage.

Tactile sensing is a cutting-edge sensing technology that accompanies the concept of smart robots. It can be used in application scenarios such as the operation of fragile objects such as smart robot arms and industrial smart robot arms, or in the production of automated minimally invasive surgical tools, environmental detection and Automated screening of fruits, etc. As a key basic technology for the future metaverse, intelligent robots and bionic skin, many domestic and foreign companies have carried out tactile sensing technology layout and released multiple prototype products, but it is still far from practical application.

In the future, tactile sensors will continue to develop toward materials with better conductive directionality, finer processes, and more sensitive structures to achieve miniaturization, high integration, and flexibility of sensors. In addition, the integration of multiple abilities such as vision and bionic tactile sensors are also the focus of the industry. By imitating biological structures such as mole whiskers [34] or primate finger structures [35], tactile sensors are gradually achieving micro-Newton or nano-Newton quantities. The goal of high-level perception is to further broaden its application scope, giving it broader application prospects in aerospace, industrial manufacturing, wearable devices, human-computer interaction and other fields.

4.3 New process

Technology is an important step in making physical sensing devices. The development of technology can make technological innovation not only stay at the idea level, but also complete engineering implementation. Currently, the industry is mainly focusing on the optimization and evolution of MEMS manufacturing technology. MEMS manufacturing processes include silicon micromachining, deep reactive ion etching, photolithography, molecular deposition,

Surface micromachining, laser micromachining and micro-encapsulation, etc. Each subdivision process has unique advantages. For example, some laser micromachining supports printing base electrodes directly on ultra-thin gel films to achieve flexible sensing; surface micromachining supports traditional springs, valves, switches, lenses and shafts. By reducing the size of devices to the micron or nanoscale, we can further enhance the functional density of on-chip systems and the physical properties of devices at the micron and nanoscale, and expand the application fields of sensors. Sensors constructed by MEMS manufacturing processes have the advantages of small size, light weight, low power consumption, good reliability, low cost and stable performance, and have good industrial prospects.

4.3.1 On-chip optical sensing

In the field of target detection, optical technology does not have electromagnetic interference and self-interference between optical signals [36], and has the characteristics of being able to image and obtain spectral information, so it has the advantages of high precision, speed, real-time and non-contact. However, traditional optical sensing technology often relies on complex coupling optical paths and external precision detection equipment. It has problems such as large size, heavy weight, high power consumption, high cost, and complex operation, making it difficult to meet the needs of portable applications. On-chip optical sensing integrates optical devices such as lenses, light sources, waveguide structures and coupling arrays on a chip to achieve miniaturization, low power consumption and low cost of the sensor, and uses nano-optical technology to achieve high-precision detection of objects. It is an important direction for the future development of optical sensing.

On-chip optical sensing can be divided into two types of device technology architecture: waveguide type and free space type. The former uses a planar optical waveguide as the control unit for in-plane light transmission, and couples the light source, light detector and optical sensing unit in the plane to form a monolithic integrated detection system. The latter utilizes a free-space optical path that can be integrated on-chip, in the vertical plane The directionally coupled light source, photodetector and optical sensing unit form a monolithically integrated detection system. Nano-optical technology and micro-nano processing technology are the core of realizing on-chip optical sensing. Nanoscale resonance structures can enhance the interaction between light and matter, provide multi-dimensional light field control capabilities in the spatial domain and frequency domain, and enhance the sensitivity of the sensor and the quality factor of the sensor spectrum. Micro-nano processing technology is a key technology to achieve nanoscale structures and has become a research hotspot for on-chip optical systems. Optical devices completed by micro-nano processing technology have the advantages of high sensitivity, high integration and low noise. Taking the efficient optical ultrasonic sensor microcavity light particle system as an example [37], it is difficult to achieve high sensitivity in an air environment due to problems such as ultrasonic absorption loss. The industry uses micro-nano processing processes such as photolithography, hydrofluoric acid etching, xenon fluoride etching, and carbon dioxide laser reflow to obtain microcore toroidal cavities with high mechanical quality factors and high optical quality factors, reducing mechanical movement from the substrate. The constraints make the sensitivity of the microcavity light particle system no longer affected by the impedance mismatch at the air-sound source interface. In addition, in response to the problem that nanomaterials are sensitive to waveguide surface roughness, the industry has proposed a method based on inductively coupled plasma etching, using CF_4/Ar. The mixed gas is used to smooth the surface, achieve an etching depth of 4 microns and maintain smooth side walls and ideal waveguide steepness, which can reduce waveguide loss and improve sensitivity and detection range [38].

Currently, on-chip optical sensing is used in smart factories, smart buildings, hazardous gas detection, on-site rapid inspection and other fields. Miniaturized optical sensors do not take up space and have the characteristics of low cost, low power consumption, small size, and ease of use. It can be integrated into various smart terminals and deployed in various scenarios. However, limited by issues such as high-quality light source integration, processing cost, and difficulty in heterogeneous integration with other modules, on-chip optical sensing technology has not yet achieved spectral resolution and performance similar to traditional optical detection technology at a low cost. Extraction efficiency, etc. At present, some foreign companies have launched passive and miniaturized optical sensing equipment, and many traditional optical sensor industries such as spectrometers have realized chip-based technology. At the same time, on-chip optical sensing has also received widespread attention and research in China, but related products are still in their infancy, and there is still a certain gap compared with advanced foreign products.

In the future, on-chip optical sensing technology is expected to achieve further breakthroughs in performance, achieve accuracy, recognition speed and light source quality similar to traditional optical sensors, improve the big data processing capabilities of integrated optical devices, and further realize the application of optical sensing in more fields. Its application and promotion has become an important foundation for the implementation of metaverse and virtual reality technology.

4.3.2 Microfluidic biosensing

In the medical field, traditional biological sample testing often has problems such as high consumption of samples and reagents and long testing time. In recent years, with the gradual maturity of MEMS and polymer material technologies, as well as the rise of in vitro non-invasive detection and on-site instant detection, microfluidic biosensing technology is characterized by its low sample consumption and high sensitivity. Advantages such as high speed and fast analysis have received widespread attention. Microfluidic biosensing technology, or Lab on a Chip (Lab on a Chip), can use microfabrication technology to create a network of tiny channels for solution flow on a glass or plastic substrate and integrate it into the chip. Thus, several laboratory testing items can be concentrated and reduced to a chip of several square centimeters [39] (Figure 3).

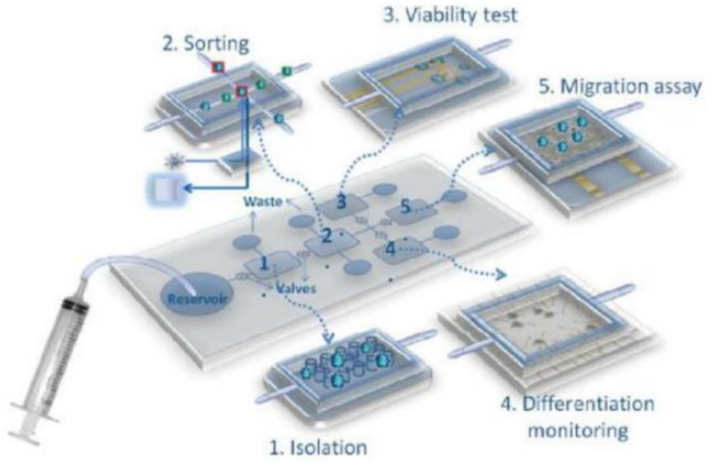

Figure 3. Schematic diagram of microfluidic technology principle [40]

Microfluidic chip is the core of microfluidic biosensing. It is generally composed of multiple sets of microfluidic channels, micropumps and microvalves. It uses phenomena such as laminar flow, diffusion and surface tension to operate and control the sample to be measured, including the Processes such as sample transportation, mixing, reaction and separation [41]. First, the sample is transported into the microfluidic channel through external thrust such as air pressure and piezoelectric drive, or natural force such as capillary force [42]. The flow direction and flow rate of the sample are controlled by microvalves. After that, the sample enters the mixing zone and enters the separation zone after a thorough mixing reaction. The separation of the analyte from the non-analyte is achieved based on characteristics such as particle inertia, size and specific affinity [43] .

Currently, research on microfluidic chips mainly focuses on aspects such as fluid control, materials, and biochemical specificity. In terms of fluid control, current microfluidic channels are usually micron-scale [44], but for single-molecule or single-cell samples, or ultra-micro samples with volumes of aL~fL, the operation requires nano-scale flow channels (10~10^3nm). However, too small a size will lead to enhanced interaction between the fluid and the flow channel wall, resulting in negative effects such as vortex, surface adhesion or clogging, making sample mixing and analysis more difficult [45]. At the same time, micron-level flow channels require different fluid control methods to be designed for different biochemical analyses, which greatly increases the design difficulty. In terms of materials, traditional silicon materials, glass and quartz materials have problems such as poor compatibility with biochemical particles, difficulty in photolithography and etching, and complex manufacturing processes. Polymer materials are easy to process and form, and have outstanding performance in insulation, high voltage resistance, thermal stability, biocompatibility and gas permeability. Organic polymers represented by polydimethylsiloxane [46], and new materials such as hydrogel [47] and paper-based [48] have gradually become a hot spot in industry research. In terms of biochemical specificity,

The binding ability and screening ability of probe molecules to the molecules to be measured determine the reaction rate and analysis accuracy of microfluidic biosensing. Therefore, during the microfluidic chip design process, probe molecules need to be selected or targeted surface decoration, or probe molecules must be artificially synthesized to further improve sensitivity and accuracy.

Microfluidic biosensing is mainly used in the medical and biochemical fields, and is currently widely used in point-of-care diagnostic fields such as pregnancy testing and new coronavirus detection. At the same time, the industry is currently focusing on application fields such as protein-related peptide quantification and phosphate analysis, cell-related sugar chain and exosome characterization analysis, blood-related blood sugar and blood ion analysis, and water quality analysis. Currently, most research on microfluidic biosensing has been commercialized or entered the clinical stage. However, it is limited by factors such as chip size and performance. Microfluidic biosensing for complex samples such as infectious diseases, tumors, and drugs The technology is still in the laboratory research stage. In response to this problem, the industry has proposed a variety of smart phone-based detection solutions, which use high-resolution cameras to identify living cells or macromolecules, and then conduct qualitative or quantitative analysis through software, such as Ebola virus antibody detection and cell damage markers. Detection and other applications [49].

In the future, microfluidic biosensing is expected to get rid of auxiliary identification devices and play greater value in fields such as cancer [50] and eye diseases. In addition, with the combination of microfluidic technology and optical technology, the use of optofluidic technology to develop miniaturized and highly integrated optical instruments has opened a new chapter in manipulating light and fluids in the next generation of integrated optical devices, biochemical analyzers and environments. Monitoring and other fields have broad application prospects.

4.4 New structure

Sensing structure refers to the arrangement and combination of sensor hardware. Structural design is directly related to physical principles. Research on new structures mainly focuses on more complex sensor types. Inspired by the physiological functions and structures of humans or animals, bionic sensing technologies such as vision, smell, hearing and touch have also attracted much attention and have great development prospects. In addition, taking CMOS image sensing as an example, its structure is divided into three types: front-illuminated, back-illuminated and stacked. The front-illuminated structure has a low light utilization rate, while the back-illuminated structure improves the light utilization rate through structural changes, thereby improving the sensor sensitivity. In recent years, stacked structures have been continuously developed to improve light reception and processing efficiency by stacking multiple levels of circuits and photosensitive devices in the vertical direction, thereby achieving higher image quality, lower noise and better dynamic range. In the future, advances in sensing structures will continue promote the improvement of sensing capabilities and promote the overall development of sensor technology and industry.

4.4.1 Bionic visual sensing

Visual sensing is an important means of obtaining image information of the external environment, and is mainly composed of image sensors and other light auxiliary equipment. Traditional visual sensing has problems such as poor visual adaptability and low perception efficiency, making it difficult to adapt to the requirements of various new scenarios. Bionic visual sensing has become an important development direction of visual sensing due to its better performance in effective light intensity sensing range, sensing spectrum and adaptive ability. Bionic visual sensing is a new sensing technology that improves the performance of visual sensors by imitating the principles and structures of biological retinas. In order to adapt to the diverse and complex environments in nature, various organisms have evolved visual sensory systems to survive. Researchers have studied the structure and working principles of the biological visual system and imitated its implementation to form bionic visual sensing.

The light intensity distribution range in nature usually exceeds 280dB, and the commonly used silicon-based CMOS photosensitive element has a photosensitive range of about 70dB. Early research improved image quality by controlling optical aperture, adjusting exposure time and post-image algorithm, but the resource overhead was large, resulting in a significant reduction in operating efficiency. Although the human retina only has a photosensitive range of about 40dB, it can quickly adapt to changes in light intensity and maintain excellent visual performance in dark light environments. This is because the light-receiving cells of the human eye can conversion of cones and rods and the production and disappearance of photopigments are controlled by horizontal cells under different light environments. Based on this principle, researchers used molybdenum disulfide phototransistors to simulate the structure of horizontal cells and light-receiving cells, and developed a bionic vision sensor with pixel-level high localized and dynamic photosensitivity capabilities, with an effective sensing range of up to 199dB [52]. In addition, human cones can identify long waves (red light), medium waves (green light) and short waves (blue light) in the visible light band, distinguishing more than 150 colors through the combination of light intensity. However, the visual range of some insects in nature can be extended to the ultraviolet band, that is, they have four-color vision (tetrachromacy) capabilities. Inspired by this, artificial neural networks are used to filter red, green and blue noise in the sensing unit using OPTs. The sensor array can achieve ultraviolet light detection with light intensity as low as 31nWcm^{2}. The recognition accuracy has been increased from 46% to 90%, and it also has high-sensitivity image perception and memory capabilities [53].

In addition to biological structures, bionic visual sensing also involves the research of new materials. Materials with pyroelectric effects are one of the important directions for improving bionic visual capabilities. By applying new semiconductor materials such as γ-InSe,, the photothermal effect and the photoelectric effect can be combined to form a new working mechanism, making it possible to dynamically adapt to constant light stimulation at the device level and achieve human-like eye-like adaptive behavior, including Broad spectrum sensing, similar photosensitivity recovery ability and collaborative vision function [54] (Figure 4).

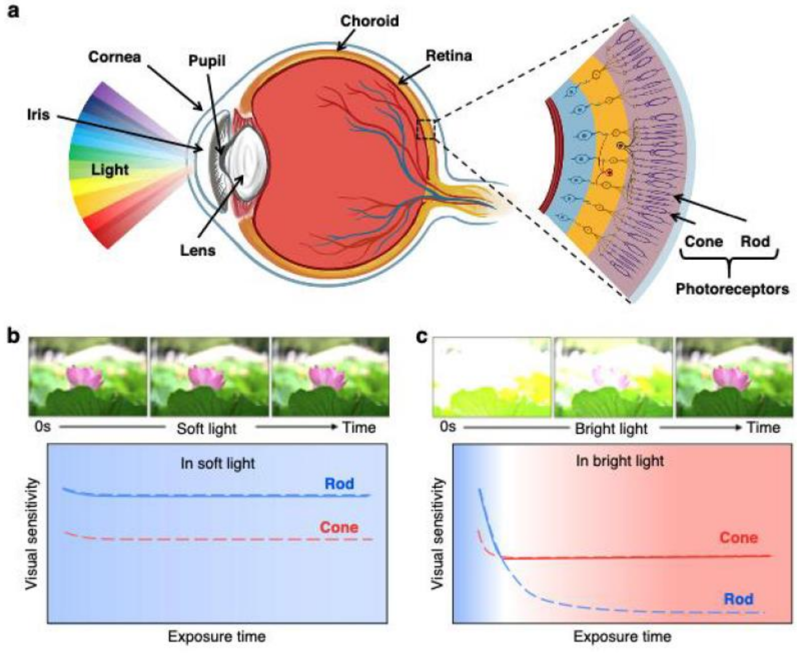

Figure 4. Schematic diagram of human cone cells’ adaptation to light perception.

Bionic visual sensing has broad application prospects in the fields of Internet of Vehicles, autonomous driving, robot navigation, industrial automation and intelligent monitoring. The current bionic visual sensing technology is still in the early stages of research, mostly based on the processing mechanism and implementation principles of the retina. In practical applications, the light adaptation speed and optical capabilities still have much room for improvement compared with biological vision levels, so it has not yet been developed. Large-scale commercial use. In the future, by implementing technologies such as larger-scale array preparation and heterogeneous integration, bionic visual sensing is expected to achieve an efficient artificial vision system similar to the human visual system, and further combine deep learning and artificial intelligence technology to improve resolution and sampling rate. From both the software and hardware levels, we jointly promote the generalization, miniaturization and low power consumption of visual sensors, improve the system's environmental perception capabilities, and help future development and improvement of production efficiency.

4.4.2 Stacked image sensing

Image sensors are one of the most widely used sensors in consumer electronics. The industry has been focusing on reducing size, increasing pixel count, color saturation and processing speed. The photodiodes and logic circuits of traditional CMOS image sensors are generally distributed on the same substrate, and in order to ensure structural strength, the substrate needs to be integrated on the supporting substrate, resulting in the inability to optimize the manufacturing process. The area of photosensitive pixels is also subject to many restrictions. In response to the above problems, image sensing technology based on stacked CMOS structure has been proposed, which uses a chip layer with logic circuits to replace the traditional support. The substrate required for the image sensor not only ensures the structural strength of the image sensor, but also removes many restrictions on the manufacturing of the pixel area (Figure 5).

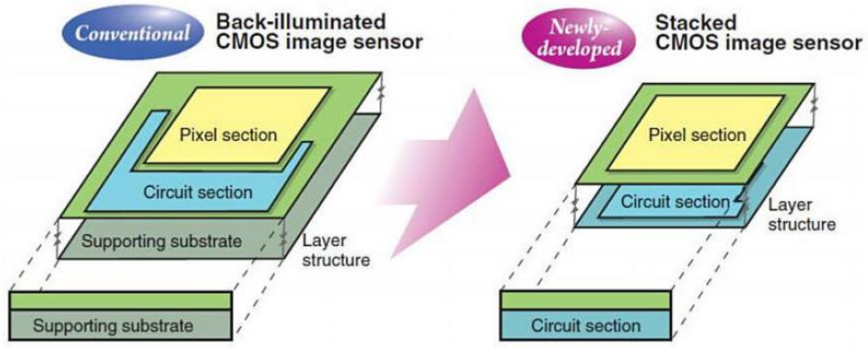

Figure 5. Schematic diagram comparing traditional back-illuminated image sensing and stacked image sensing [55]

The first-generation stacked CMOS image sensor used through silicon via (TSV) technology to realize the connection between photosensitive pixels and logic circuits [56]. Subsequently, Cu-Cu bonding method instead of TSV to further achieve miniaturization and improve efficiency, and many innovative methods such as direct integration of DRAM layer to enhance slow-motion photography capabilities. In recent years, as smartphones have developed toward multiple cameras, manufacturers have increasingly demanded high-pixel image sensing. Normally, increasing pixel density can bring higher resolution and more powerful telephoto capabilities, but an increase in pixel density also means a reduction in the size of a single pixel unit, which limits the size of the amplification transistor in the pixel unit, thereby increasing the random noise signal, resulting in a decrease in final image quality. In 2021, double-layer transistor pixel stacked CMOS image sensing technology was proposed [57], which further splits the photodiodes and pixel transistors originally at the pixel layer to form a two-layer stacked structure (Figure 6), allowing the photodiode and pixel transistor to be optimized independently. Layered processing allows the use of larger-size amplification transistors while increasing the number of photodiodes, increasing the saturated signal amount to approximately 2 times while maintaining a high pixel count, expanding the dynamic range and reducing noise, further improving images at night or other performance in dark scenes.

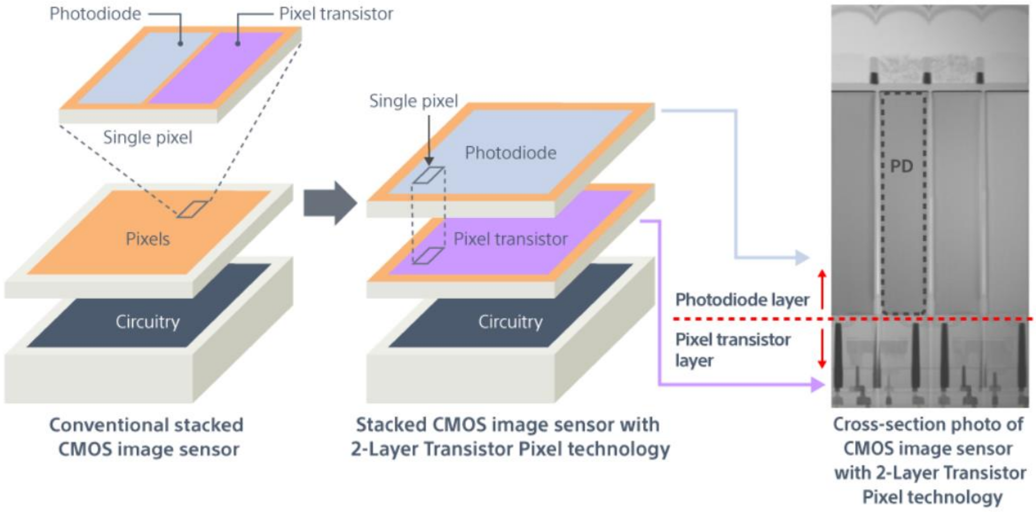

Figure 6. Comparison of traditional pixel structure and double-layer transistor pixel structure [58]

In addition to continuous structural optimization, with the evolution of stacking technology, the industry has begun attempts to add AI signal processing layers based on the stacked structure. By stacking the image processor (ISP), convolutional neural network (CNN) accelerator, memory and main processor below the image sensor, the signal acquired by the pixel array can be directly inside the chip processing without the need for an external high-performance processor or memory, thereby significantly reducing image transmission. The amount of data output by the sensor increases the processing speed. Based on the addition of AI capabilities, stacked image sensing will no longer be able to simply capture images in the future. Its processing circuit will be able to integrate complete intelligent image processing algorithms and storage space, bringing such things as 3D Improved capabilities such as ranging imaging and augmented reality.

Image sensors are widely used in downstream fields including smartphones, computers, security monitoring, automotive electronics, consumer, industry, national defense and aerospace, and medical care, among which the smartphone industry accounts for the highest proportion. In recent years, new technologies that have been featured in smartphones, such as facial recognition, heart rate detection and HDR photography, all rely on image sensors. However, due to its higher specifications and cost, the latest stacked image sensing is currently mainly used in high-end mobile phones and professional-grade cameras, and has not yet achieved widespread popularity. In the future, as technology and processes continue to mature, stacked image sensing will be further widely used, replacing traditional image sensing and playing an important role in micro-nano processing and other fields, pushing the development of image sensors into a new era.

4.5 New Algorithm

With the continuous development of Internet of Things technology, application scenarios continue to expand, and users have higher and higher requirements for sensing capabilities. However, the development cycle of sensor hardware is long, making it difficult to quickly meet market demand. Therefore, various sensor manufacturers have gradually shifted from competing purely around hardware to competing around "algorithms + hardware". New algorithms can be used to improve sensing accuracy or enable new sensing capabilities based on raw data. Taking odor sensing as an example, based on deep learning algorithms, by establishing a layer-by-layer abstract network, complex functions can be realized and hierarchical expressions of data can be formed. It can learn the ability to represent information features with a small amount of data, and obtain higher perception accuracy. In the future, new algorithms will largely compensate for or improve the performance of sensor hardware, allowing sensors to evolve towards more accurate sensing results and stronger sensing capabilities.

4.5.1 Optical fiber sensing

In kilometer-level continuous monitoring scenarios such as dams, railways, power cables, and petrochemical pipelines, for the measurement of parameters such as temperature and pressure, the traditional point-based sensor deployment method has problems such as difficulty in deployment and discontinuous monitoring data. Optical fiber can be used as both a sensing medium and a transmission medium for measured signals. There is no need for additional cables or power supply on site. It has the characteristics of low cost, easy deployment and continuous monitoring, and has attracted widespread attention. Fiber optic sensing, also known as distributed fiber optic sensing technology (DFOS), evolved from fiber optic communications. It was originally used to detect the transmission of fiber optics, and later became a perception of the fiber optic environment. technology [59] (Figure 7). due to light. When propagating in optical fibers, parameters such as amplitude, phase, wavelength, polarization and transmission time will be affected by the environment. Therefore, optical fibers can be used as sensitive components to detect physical quantities such as temperature, vibration, stress and sound. [60].

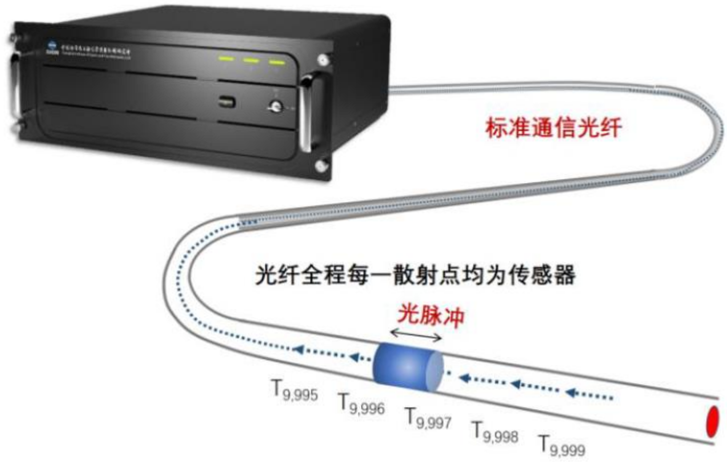

Figure 7. Distributed fiber optic sensing technology [61]

Fiber optic sensing is mainly based on the principle of scattering spectrum generated by the interaction between incident light waves and fiber media for environmental analysis. The scattering spectrum consists of Rayleigh scattering, Raman scattering and Brillouin scattering. Various scattering principles have different sensitivities to different physical quantities [62]. Rayleigh scattering is caused by the elastic collision between incident photons and unevenly transmitted mesons (such as small density and refractive index changes) in the optical fiber. The frequency of the incident light and scattered light remains consistent and the light wave energy is stronger. It can affect vibration and sound. It has a good response to the physical quantities that cause slight deformation of the optical fiber. Raman scattering is produced by inelastic collisions. During this process, photons exchange energy with transmitted mesons, and their scattered light changes with changes in fiber temperature. Brillouin scattering is an inelastic scattering phenomenon caused by the interaction between phonons in the fiber and incident light photons. The magnitude of the frequency shift between the scattered light and the incident light has a positive linear relationship with temperature and vibration, so it is better response to temperature and vibration. However, the Brillouin scattering frequency shift is small and the bandwidth is narrow, and the laser has a stable frequency and extremely narrow pulse width, which leads to an increase in system cost.

Optical fiber sensors usually use common single-mode or multi-mode communication optical fibers to achieve sensing functions, mainly involving optical time domain reflection (OTDR), optical frequency domain reflection (OFDR), light Analysis and testing methods commonly used in traditional optical fiber communication technology such as time domain analysis (OTDA) and optical frequency domain analysis (OFDA) analyze the light intensity, time difference, optical path difference and frequency of scattered light. Detection and analysis of other parameters. Therefore, unlike traditional sensors that focus on sensitive units, its research direction is mainly through optical noise suppression [63], optical pulse encoding [64]. time-frequency domain feature extraction [65], Methods such as modifying the demodulation equation [66] or introducing deep learning [67] can improve the signal-to-noise ratio, optimize spatial resolution, compensate for fiber attenuation, improve sensing accuracy, and reduce scattering crosstalk.

Optical fiber sensing can use deployed optical fiber equipment for environmental monitoring. It has formed corresponding solutions and has strong technical advantages in long-distance continuous sensing. Currently, it is mostly used for illegal digging, leakage, and leakage of long-distance pipe networks and cables. Breakpoint detection, as well as structural stress monitoring of large-scale buildings, in petrochemical, metallurgy and gas, etc. The industry has played a huge application value. At the same time, in addition to traditional sensor companies, many communication companies have also begun to carry out research and development of optical fiber sensing related technologies based on their communication optical fiber laying foundation, further promoting the development of optical fiber sensing technology. However, fiber optic sensing is currently limited by algorithm accuracy and instrument equipment cost, and its commercial scale is still small, requiring further development and promotion of technology and industry.

In the future, fiber optic sensing technology will focus on two aspects. First, it will further improve its sensing accuracy in single point or distributed point measurement, and further explore more cost-effective solutions for short-distance deployment scenarios; However, the detection capability of existing fiber optic sensing is still limited by the axial one-dimensional structure of the fiber. In the future, three-dimensional positioning of disturbance sources and multi-component detection of signals will be further realized to support the further promotion of fiber optic sensing.

4.5.2 Hypersensitive odor sensing

An odor sensor is a sensor that can detect and analyze the odor and components in the object to be measured. It can sense and measure odor molecules and volatile organic compounds in the gas. Odor sensing can detect odor components through chemical reactions or physical adsorption with gases. It can also use biological reactions of organisms (such as bacteria, yeast, enzymes, etc.) to detect odor components and convert them into electrical signals or light signals. output. However, a single odor sensor can only identify specific odors, and the recognition sensitivity and accuracy are low. To solve these problems, an ultra-sensitive odor sensing system consisting of a cross-sensitive sensor array and a pattern recognition algorithm is proposed. This sensing system, also called an electronic nose, achieves accurate identification of multiple odors.

The ultra-sensitive odor sensing system mainly consists of three parts: gas sensor array, signal acquisition and processing unit, and pattern recognition algorithm [68] (as shown in Figure 8). The sensitive material of the gas sensor array reacts chemically with the target gas to convert the chemical signal into an electrical signal. The preprocessing unit performs noise elimination, signal amplification, signal feature extraction, and data normalization on the electrical signal. The pattern recognition algorithm is used to analyze the processed data.

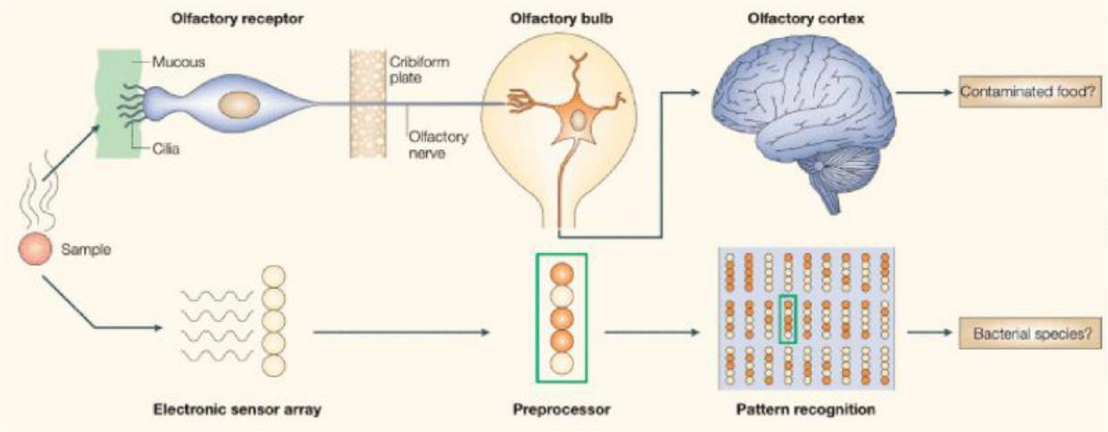

Figure 8. Schematic diagram of ultra-sensitive odor sensing system

In recent years, the performance improvement of ultra-sensitive odor sensing has received more and more attention, and the innovation of pattern recognition algorithms is an important way to achieve performance optimization. When identifying mixed gases with low similarity or when rapid identification is required in a short period of time (such as explosives detection), use PCA, LDA simple algorithms such as, SVM and DT can predict the results in a short time. However, for scenarios where ambient temperature and humidity interfere significantly and where highly similar mixed gases need to be identified, it is difficult for the above method to implement complex functions and produce hierarchical expressions of data. The method based on neural network can extract the invariant characteristics of the gas to be measured from the complex noise background, learn the characteristics that represent the information, and provide reliable identification accuracy. In order to achieve efficient odor detection, an odor analysis method based on graph neural network (GNN) was proposed [69], by establishing a mapping relationship between molecular structure and odor, and thus describing the structure of chemical molecules odor. In this method, each odor molecule is represented as a graph, where each atom is defined by its valence state, number of bonds, number of hydrogens, hybridization, charge form, and atomic number. Different from traditional fingerprint technology, GNN can optimize the weight of components with different chemical structures in specific odors. Finally, the odor is judged through the prediction layer and the corresponding odor descriptor is output. Test results showed that the model's odor perception level was comparable to humans trained in odor recognition.

Odor sensing systems are widely used in various fields, including environmental monitoring, food quality testing, industrial safety, medical diagnosis and robot sensing, etc. to help monitor and control harmful gases in the air, detect odor or spoilage in food, and assisted medical diagnosis, etc. Focusing on these application scenarios, many sensor companies at home and abroad have carried out research and development of odor sensing technology and launched consumer-grade digital olfactory sensing products. However, limited by the sensing accuracy and product size, the commercial scale is still small, and it is difficult to meet people's growing demand. demand for odor sensing services. Currently, ultra-sensitive odor sensing systems still face three challenges: First, there is a lack of standardized protocols for data collection and signal processing; Second, the inevitable influence of environmental humidity and temperature and the presence of unknown gases can easily cause unexpected bias in the sensing response signal. The third is how to implement the gas identification algorithm on hardware with limited resources.

In the future, ultra-sensitive odor sensing systems will standardize the input and output of each step of signal processing, explore robust algorithms that can compensate for environmental variables, and reduce hardware requirements through resource utilization optimization of recognition algorithms or cloud deployment, thereby reducing the overall size of the system, bringing opportunities for wearable and compact ultra-sensitive odor sensing systems in future IoT applications.

5 Sensing fusion technology

With the continuous deepening of the digitalization process in the industry, various applications have put forward higher requirements for perception. In addition to the requirements for sensing capabilities such as accuracy, sensitivity and stability, they also require wireless communication methods and computational processing of the perception system. Efficiency, ubiquitous intelligent services and passive energy supply. Therefore, sensing will be deeply integrated with communications, computing, intelligence, and energy to form sensing fusion technology, which will continue to empower new scenarios and new businesses in life, production, and society.

5.1 Communication integration

The application of wired sensors is restricted due to the high cost of laying wires and the difficulty of construction. Wireless communication technology can meet the needs of "braid-cutting" and facilitate the flexible deployment of sensors. In addition, by analyzing changes in wireless communication signal parameter characteristics, changes in sensing targets can be inferred, communication and sensing integration can be achieved, and communication and sensing capabilities can achieve mutual assistance and a win-win situation. Communication convergence technology focuses on wide-area and local-area, as well as micro-area and short-range wireless communication technologies.

In terms of wide area and local area, cellular networks have the characteristics of wide area continuous coverage and can provide long-distance data transmission for sensors. At the same time, by deploying integrated communication and sensing base stations and analyzing changes in cellular signals between base stations or between base stations and terminal nodes, sensing functions can also be realized in scenarios such as precipitation monitoring, smart transportation, and drone monitoring (Figure 9). In terms of local area, the passive Internet of Things represented by RFID is based on the principle of backscattering. On the one hand, it can realize data transmission within the local area and realize the free operation of sensing nodes through environmental energy collection. With the advantages of no maintenance, easy deployment and passive. On the other hand, based on RFID can also realize the perception of massive targets. By analyzing the strength and phase of the received passive tag backscattered communication signal. Parameters such as this can realize the perception of the target location while taking inventory [70], thereby realizing functions such as cargo search, entry and exit detection, and passenger flow analysis. With the evolution of RFID technology and the introduction of cellular technology [71], the future passive Internet of Things will be deeply integrated with cellular networks to further improve communication distance and support identification based on new architecture and new protocols. The entire life cycle management of objects truly realizes “one code to the end”.

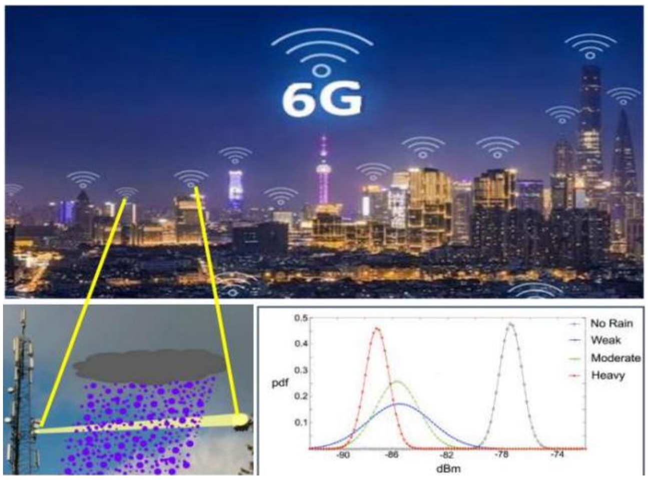

Figure 9. Climate environment monitoring application based on synesthesia integration [72]

Micro-domain and short-range networks are networks where the communication distance is only a few centimeters to a few meters, and the terahertz band has the advantages of large bandwidth and short wavelength, which can realize ultra-high-rate data transmission in the micro-domain range. And realize high-precision sensing, providing a new pass-sense one network. Terahertz radiation wavelength between millimeter waves and infrared, with strong penetration and good directionality and other technical characteristics, not only can detect the metal, but also identify non-metal, colloid, powder, ceramics and liquids, etc., which can be applied to national defense, security, astronomy and medical care, and many other fields. Compared with X-rays, terahertz does not generate harmful photoionization in the human body, thus realizing safer human detection and providing advanced sensing means for major disease diagnosis and biological intervention. The deep integration of wireless communication and sensing ability on the one hand can solve the traditional sensor deployment difficulties, high-cost problems, the realization of the sensing ability of “ready to use”, on the other hand, based on the integration of communication and sensing, so that the wireless network in the high-quality communication and interaction at the same time, to achieve high-precision and refinement of the sensing function. In the future, with the further optimization of communication protocols and data transmission modes, it is an important trend of communication convergence to extend the transmission distance, increase data throughput and ensure data security within the restricted energy consumption range, as well as to collaborate with multi-nodes, multi-frequency bands, and multi-standards for sensing.

5.2 Computing fusion

Sensors usually generate a huge amount of data, especially in the case of real-time monitoring and large-scale deployment, which will have a great impact on network transmission efficiency and equipment reliability. At the same time, the calculation of sensor data requires high computing power and Low latency and low power consumption requirements. Computing fusion technology mainly includes data compression, in-sense computing and heterogeneous computing.

Data compression technology can be used to compress redundant data generated by massive sensors deployed with high density and overlapping coverage areas [73]. The difficulty of compression algorithms lies in the balance between compression rate and fidelity. Data compression algorithms based on deep learning can automatically learn the feature representation of data from massive data, avoid information loss caused by artificial restrictions, model complex nonlinear relationships, better adapt to the complex structure and changes of data, and help improve the accuracy and fidelity of data compression [74].

In-sensor computing (in-sensor computing) is a new sensor computing paradigm. By building a new perception computing module inside the sensor, the sensor becomes a relatively independent perception, storage and computing unit, and realizes intelligent information preprocessing from the source of information collection to reduce the scale of data transmission and simplify the post-processing process, thereby improving the comprehensive performance indicators of the system [75] (as shown in Figure 10). At present, in-sensor computing is mostly used in image sensors. By introducing new sensor devices and pixel circuits, pixel-level information processing is performed in two-dimensional space. It can use the physical effects of devices and circuits to complete the processing of spatiotemporal information in the analog domain and filter redundant information at the pixel level. Due to the current challenges in pixel structure, function definition and system architecture design, new materials, new mechanisms and new structures need to be tried and explored. In the future, we can combine the sensor computing structure and introduce efficient artificial intelligence algorithms to adapt to new devices to achieve intelligent sensor computing.

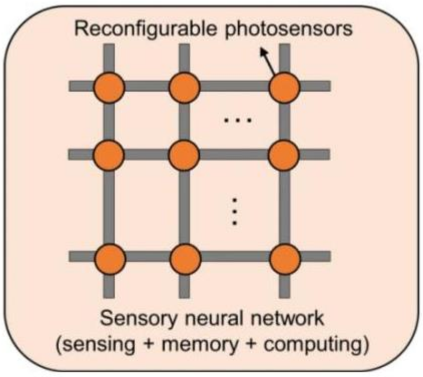

Figure 10. Sensor computing structure [76]

When processing sensor data with on device, different heterogeneous computing units such as CPU, GPU, FPGA and ASIC work together to perform joint computing. Because different computing units are suitable for processing different computing problems, for example, GPU can be used for high-speed parallel computing, FPGA can be used for fast and customized data processing. According to the characteristics of sensor data and processing requirements, different types of processing units can be flexibly configured to reasonably distribute and coordinate computing loads and optimize the computing process [77]. For heterogeneous computing, co-design between software and hardware is crucial. Specific software requirements need to be considered in hardware design to provide hardware acceleration functions. At the same time, software optimization design is performed for specific hardware architectures to achieve a higher level. computing power and efficiency.

Sensing data is generated quickly, the data scale is large and the data types are diverse. Efficient computing methods are needed to support the high-speed collection, storage, processing and analysis of data. The research and application of new computing technologies will provide real-time monitoring and large-scale monitoring of sensor networks. Large-scale deployment provides efficient and reliable solutions to truly realize ubiquitous perception.

5.3 Intelligent integration

Intelligence is an important development direction for sensors in the future. The deep integration of sensing technology and intelligent technology will give sensors intelligent capabilities such as electronic calibration, data filtering, self-awakening, self-diagnosis and self-repair, and based on device-edge-cloud collaboration, combined with artificial intelligence algorithms, the stability, accuracy and work efficiency of the perception system are further improved. Intelligent fusion technology focuses on intelligent microsystems, distributed computing and crowd sensing.

Intelligent microsystems are a technology that is deeply intertwined with microsystems and intelligent technology, forming a technology that covers elements such as architecture, microelectronics, MEMS, optoelectronics, algorithms and software. Intelligent microsystems have the capabilities of miniaturization, wirelessness, and self-supply of energy, and can meet the rapid deployment needs of massive equipment. The hardware level can realize ultra-high-density chip-level integration of different functional modules to achieve ultra-high sensitivity sensing and detection, ultra-high-performance processing and computing, ultra-high-density storage and transmission, ultra-high-precision operation and execution, and ultra-high efficiency. energy management and supply. At the software level, AI algorithms such as neural networks and deep learning are used to fuse and analyze multiple sensor data to improve perception capabilities and quality. At the hardware and software collaboration level, through technologies such as closed-loop feedback and multi-sensor information fusion, intelligent capabilities such as sensor self-calibration, self-organization, and self-adaptation are realized, promoting the development of sensors toward autonomy and unmanned operation.

Distributed computing can be used for data processing and decision-making tasks between sensor network nodes [79]. By distributing computing tasks to multiple nodes for parallel processing, it can reduce single-point computing pressure, achieve resource sharing, reduce energy consumption, and improve the system. performance. Distributed computing also has good scalability and fault tolerance. The number of nodes can be adjusted as needed, eliminating problems such as reduced system reliability caused by single points of failure. In distributed computing, it is crucial to effectively manage node resources and achieve load balancingI801. Through task allocation and scheduling algorithms, task distribution can be dynamically negotiated and adjusted between nodes, and node load conditions can be predicted based on historical data and trends, task migration and offloading can be done in advance, and resource allocation can be optimized.

Crowd sensing using crowdsourcing to collect sensing data, and can use crowd-generated mobile devices as sensing nodes. It has node openness, on-demand deployment and on-demand deployment. It requires scheduling and other advantages. Through interconnection and collaborative operations between nodes, it can meet the requirements of large-scale and fine-grained sensing tasks at the city level. Among technologies related to crowd intelligence sensing, the decomposition and dynamic allocation of complex tasks, the deployment and selection of sensing nodes, the collection of high-quality sensing data and the selection of redundant data are the focus and difficulty of technical research. Combining deep learning to achieve group intelligence. The knowledge acquisition of perception and the fusion and enhancement of crowd intelligence in an open and dynamic environment can improve the efficiency of large-scale perception node construction and improve the resilience and execution effect of perception.

The integration of sensing technology and intelligence is an important development goal and trend of sensing technology. In the future, based on the widespread application of new sensing paradigms such as crowd sensing, and the in-depth blessing of deep learning and other AI algorithms, sensing systems It can more effectively capture and interpret various information in the real world, achieve more accurate data analysis, more efficient data processing, stronger system reliability and lower power consumption, and further expand "perception + thinking + execution" New application models bring new opportunities to business layout.

5.4 Energy fusion

With the large-scale application of sensors in industrial, energy, urban and other fields, energy acquisition and management have become one of the important challenges they face. The limited battery life not only limits the wide application of sensors in long-distance wireless transmission scenarios, but also brings high maintenance costs. Discarded batteries will also cause a greater burden on the environment. The challenge of energy supply has driven the research and development of new energy technologies such as passive self-power, allowing sensors to obtain energy from the natural environment rather than relying on batteries or other power sources. Energy fusion technology involves energy collection and perception and energy management.

In terms of energy collection and sensing, self-supply can use renewable energy to achieve a certain energy paradigm shift, enabling equipment to automatically draw power from the environment, with the goal of extending the service life of equipment [81] and replacing batteries or other power sources. The environmental energy that can be collected includes light energy, wind energy, temperature difference energy, vibration energy, radio frequency energy, etc. Environmental energy can not only provide power for the sensor, but also support the sensor to obtain energy information. For example, vibration can not only supply energy to the sensor, but also serve as the sensing object of the sensor to collect information on the vibration amplitude of the equipment for equipment status monitoring. Among environmental energies, light energy is one of the most common and widely used energies. Its principle is mainly to use the photoelectric effect of semiconductor materials (silicon-based photovoltaic panels and molybdenum disulfide) to directly convert light energy into electrical energy. Radio frequency can use radio frequency signals to distribute energy from source nodes to energy consumption nodes. It is suitable for ultra-low power consumption scenarios. Its typical representative is RFID. As the number of wireless transmitters doubles every day, the use of radio frequency signals to power sensors is becoming a trend.

In terms of energy management, it mainly includes energy collection management, storage management, distribution management and usage management. Energy collection management needs to monitor the energy collection situation and control the time and amount of energy collection to avoid excessive collection and waste of energy. Energy storage management requires monitoring the capacity and usage of energy storage devices such as supercapacitors, batteries, and mechanical energy storage devices, controlling storage time and amount, and avoiding excessive storage and waste of energy. Energy distribution management needs to monitor the energy demand and operating status of sensors, allocate and control energy according to business priorities and energy demands, so as to reduce energy waste and provide stable energy supply for system circuits. Energy optimization management requires monitoring energy usage, analyzing energy usage efficiency and optimization potential, and taking corresponding optimization measures to improve energy usage efficiency.

Energy fusion technology has great application value and can eliminate the pain points of limited battery life, high deployment costs, and difficult later maintenance caused by traditional active power supply (battery/wiring). In the future, energy fusion technology will continue to be optimized in terms of multi-sensor integration and composite micro-energy collection, supporting the deployment of IoT sensors in warehouses. It can be applied on a large scale in scenarios such as storage management, environmental sensing, and power line monitoring to achieve long-term battery life throughout the entire life cycle of the sensor.

6 Summary and outlook

In recent years, cutting-edge sensing technology has continued to innovate and develop around the five aspects of new mechanisms, new materials, new processes, new structures and new algorithms. Sensing fusion technology revolves around communication fusion, computing fusion, Intelligent fusion and energy fusion and other aspects are accelerating evolution and change, forming an advanced sensing technology trend of "five new and four fusions", supporting sensing technology moving towards "sensing-communication-computing" -The direction of integrated integration of intelligence and energy continues to develop, further realizing resource reuse and data integration. In the future, sensing technology will support the evolution of sensors towards miniaturization, integration, wireless, flexibility, intelligence and passiveness to meet the needs of sensing capabilities in life, production and social fields. in-depth needs. Miniaturization allows sensors to be deployed in more complex and tiny environments, such as inside living organisms. Integration supports the development of sensors from a single functional form to intelligent terminals with diversified functions such as sensing, communication, computing, storage, execution and energy supply, further increasing functional density. Wirelessization is conducive to enhancing the mobility of sensors, optimizing space utilization, and achieving rapid deployment. The flexible support sensor has good flexibility, ductility, and bendability, allowing it to be used flexibly according to the needs of the application scenario. Intelligence will endow sensors with intelligent capabilities such as electronic calibration, data filtering, self-awakening, self-diagnosis, and self-repair, enhance end-side intelligence, and improve stability, accuracy, and work efficiency. Passivity allows sensors to get rid of the constraints of battery power supply through multi-source energy collection and achieve long-life operation.

This white paper combs and proposes the advanced sensing technology trends of "Five New and Four Integration", focusing on the new mechanisms, new materials, new processes, new structures and new algorithms of sensing frontier technologies, as well as the technical directions of sensor technology. In the technical fields of communication fusion, computing fusion, intelligence fusion and energy fusion of sensory fusion technology, we select representative technologies, interpret technical principles, sort out the current status of technology, analyze technical challenges, and explore technology trends, hoping to accelerate research breakthroughs and breakthroughs in advanced sensing technology. Provide reference for product implementation.