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Application Research of Wireless Sensor Networks and the Internet of Things

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Abstract: In the context of the rapid iteration of information technology, the Internet of Things (IoT) has established itself as a pivotal hub connecting the digital world and the physical world. Wireless Sensor Networks (WSNs), deeply embedded in the perception layer architecture of the IoT, play a crucial role as "tactile nerve endings." A vast number of micro sensor nodes are widely distributed in monitoring areas according to preset deployment strategies, continuously and accurately perceiving and collecting real-time data on environmental parameters such as temperature, humidity, light intensity, air pressure, and pollutant concentration. These data are transmitted to the IoT cloud platform through stable and reliable communication links, forming a massive and detailed basic data resource pool. By using cutting-edge big data processing algorithms, machine learning models, and artificial intelligence analysis tools, in-depth mining and intelligent analysis of these multi-source heterogeneous data are conducted to generate high-value-added decision-making bases. This precisely empowers multiple fields, including agriculture, medical and health care, smart home, environmental science, and industrial manufacturing, driving intelligent transformation and catalyzing society to move towards a new stage of high-quality development. This paper comprehensively analyzes the technical cores of the IoT and WSNs, systematically sorts out the advanced key technologies of WSNs and the evolution of their strategic significance in the IoT system, deeply explores the innovative application scenarios and practical effects of the two in specific vertical fields, and looks forward to the technological evolution trends. It provides a detailed and highly practical guiding reference for researchers, technical engineers, and industrial decision-makers.

Keywords: Wireless Sensor Networks; Internet of Things; Key technologies; Application fields

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1. Introduction

In recent years, with the rapid development of information technology, wireless sensor networks (WSNs) and the Internet of Things (IoT), as emerging technologies, have exerted a profound impact on transforming the way people live and work in society. The IoT can organically connect the Internet with various objects, enabling real-time information sharing and interaction. As a core technical support for the IoT, wireless sensor networks play a crucial role. A wireless sensor network consists of a large number of micro sensor nodes, which are equipped with sensing, computing, and communication capabilities. These nodes can collect environmental information in real-time and transmit it to the network, providing a rich source of data for the IoT. Exploring the application modes and effects of wireless sensor networks and the IoT in different fields allows for the timely identification of development opportunities and potential risks. This, in turn, effectively promotes technological innovation and industrial upgrading, thereby injecting an inexhaustible driving force into social and economic development [1].

2. Overview of the Internet of Things and network sensor technology

2.1. Internet of Things

The Internet of Things breaks through the limitations of traditional internet, which only connects computer terminals. Through a three-layer technical architecture—perception, transmission, and processing—it creates a new space where physical entities and virtual information are deeply integrated. The perception layer uses diverse technologies such as sensors and RFID to realize the identification of all things and information capture. The network layer relies on the seamless integration of heterogeneous networks, including 5G, NB-IoT (Narrowband IoT), and Beidou satellite communication, to ensure high-reliability and low-latency transmission of data streams. The application layer focuses on deeply customized intelligent services for different industry scenarios, spawning massive application clusters such as intelligent transportation, intelligent medical care, and Industrial Internet of Things (IIoT), and reshaping industrial ecology. Currently, IoT platform technologies are developing vigorously. Platforms like PTC's ThingWorx and Alibaba Cloud IoT Platform, with their strong capabilities in device management, rule engines, and data analysis, provide one-stop support for IoT application development and operation [2].

2.2. Wireless sensor networks

Wireless sensor networks feature a distributed, multi-hop, and self-organizing structure, with each node integrating three functional modules: perception, computing, and communication. Edge computing technology is deployed at the sensor node end to realize distributed preprocessing of data, eliminating redundant information and reducing the burden on the cloud. Meanwhile, using the concept of Software Defined Network (SDN), it dynamically optimizes network topology and data transmission paths, significantly improving network energy efficiency and fault tolerance. Empowered by new materials and Micro-Electro-Mechanical Systems (MEMS) processes, sensor nodes continue to evolve toward miniaturization, low power consumption, and high performance, laying a hardware foundation for large-scale deployment [3].

3. Key technologies of Wireless Sensor Networks and their significance in the Internet of Things

3.1. Key technological innovations in Wireless Sensor Networks

First, intelligent topology control: Integrating swarm intelligence algorithms (such as ant colony algorithm, particle swarm optimization) with machine learning models (such as reinforcement learning) to monitor key indicators like network connectivity and remaining node energy in real-time, dynamically generating optimal topological structures, and ensuring long-term stability and efficiency of the network. In smart home scenarios, it intelligently regulates the activation status of sensor nodes based on family members' activity patterns and device usage modes, achieving a dynamic balance between energy efficiency and functionality [4].

Second, protocol innovation: For Low Power Wide Area Network (LPWAN) scenarios, optimizing protocol stacks such as LoRaWAN (Long Range Wide Area Network) and Sigfox by trimming redundant functions and enhancing security authentication mechanisms to meet the needs of large-scale IoT device access. Meanwhile, quantum communication technology has initially explored its application in the key distribution process of sensor networks, significantly enhancing communication security and defending against the threat of quantum computing attacks [5].

Third, security enhancement: Building a "Zero Trust" security architecture, abandoning the traditional boundary-based defense mindset, and implementing strict identity authentication and authorization for every data access and device connection. Combining blockchain technology to achieve distributed storage of data and tamper-proof traceability, laying a solid foundation for high-security demand scenarios such as IoT finance and supply chain traceability; applying homomorphic encryption algorithms to complete complex calculations in the encrypted state of data, ensuring both data privacy and availability [6].

3.2. The significance of Wireless Sensor Networks in the Internet of Things

The evolutionary path of IoT perception layer technologies focuses on four key dimensions: "ultra-low power consumption, ultra-high precision, ultra-wide perception, and ultra-intelligent integration". Wireless sensor networks deeply collaborate with micro-energy harvesting technologies (such as vibration energy and temperature difference energy harvesting) to achieve energy self-sufficiency and break free from the constraints of an external power supply. Breakthroughs in nanosensor technology have improved perception precision to the molecular and atomic levels, expanding applications into microscale fields such as biomedicine and materials science. Seamless integration with diverse sensing technologies like Radio Frequency Identification (RFID), visual sensors, and Inertial Measurement Units (IMU) has built an all-round, multimodal perception system. With the help of digital twin technology, physical entities and virtual models map each other in real-time, coexist and grow together, enabling accurate modeling, intelligent diagnosis, and predictive maintenance of complex IoT systems. This stimulates the original innovation momentum of the IoT, gives birth to innovative applications such as intelligent predictive maintenance and smart twin cities, and reshapes industrial value networks [7].

4. Specific applications of Wireless Sensor Networks and the Internet of Things

4.1. Industry 4.0 and intelligent manufacturing

Under the Industry 4.0 framework, wireless sensor networks are deeply embedded in the architecture of digital workshops and smart factories. High-precision displacement sensors, pressure sensors, and fiber optic sensors comprehensively monitor the operating status of production equipment. The data is transmitted to edge computing nodes via industrial Ethernet and TSN (Time-Sensitive Networking). AI fault diagnosis models (such as Convolutional Neural Networks (CNN) in deep learning and Long Short-Term Memory (LSTM), a variant of Recurrent Neural Networks (RNN)) are used to provide real-time early warnings of equipment failures. The accuracy of fault prediction exceeds 90%, reducing equipment downtime by more than 30%. In automobile manufacturing production lines, collaborative robots (Cobots) based on sensor networks, relying on precise environmental perception, work side by side with human workers, improving assembly efficiency by 40% and creating a new paradigm of flexible, intelligent, and efficient smart manufacturing. Meanwhile, digital twin technology is used to build virtual images of factories, enabling real-time optimization of production processes, virtual debugging, and capacity forecasting, thus achieving full-life-cycle management and control of factory operations [8].

4.2. Smart agriculture 4.0

Smart agriculture is advancing into the 4.0 stage, where wireless sensor networks, in collaboration with drone remote sensing and satellite positioning systems, are building an integrated space-ground agricultural monitoring network. On large-scale farms, soil moisture sensors, nutrient sensors, and hyperspectral cameras mounted on drones work in tandem. Based on crop growth models and real-time environmental data, agricultural big data platforms enable intelligent decision-making to precisely regulate irrigation, fertilization, and pesticide application. This has achieved water and fertilizer savings of 30–50% while increasing crop yields by 20–30%. Blockchain traceability systems are deeply integrated into the agricultural product supply chain. Information from the entire process—from farm cultivation, agricultural input application, harvesting, and processing to logistics and sales—is recorded on the blockchain. Consumers can instantly access the "full life cycle" information of agricultural products by scanning a QR code. This reshapes the trust system for agricultural products, empowers agricultural brand building and value enhancement, and drives the digital, intelligent, and brand-oriented transformation of the agricultural industry [9].

4.3. Medical Internet of Things and remote smart healthcare

Under the architecture of the medical Internet of Things, wearable wireless sensor devices (such as heart rate, blood glucose, and gait sensors integrated into smart bracelets and smart insoles) collect real-time vital sign data of patients, which is transmitted to cloud-based medical platforms via 5G networks with low latency. AI-assisted diagnostic systems (such as deep learning-based medical imaging diagnostic models) accurately analyze the data to generate health assessment reports, enabling early warning and remote intervention for chronic diseases and geriatric illnesses. In the scenario of remote surgery, tactile sensors, force feedback sensors, and 5G networks work in synergy to help surgeons precisely control robotic arms to perform complex surgeries, breaking through geographical limitations and improving the accessibility of medical resources. Meanwhile, digital twin technology empowers hospital operation management by building virtual digital models of hospitals, optimizing resource allocation and process management, enhancing hospital operation efficiency and service quality, and creating a new ecosystem for medical and healthcare [10].

4.4. Smart home and smart building

In the current Internet of Things, the smart home is one of the key development projects. Its core definition is an advanced home automation system that relies on modern technologies such as computer networks, automated control, and remote control. According to the specific needs of different users, it adopts matching management strategies to achieve the goal of intelligent management and control of household appliances, ensuring the comfort of the living environment, improving the safety and convenience of home appliance management, and enabling users to obtain better services [11]. The details are as follows: First, accurately grasp the family living conditions, such as temperature, humidity, and changes in indoor light intensity. This information mainly relies on the application of wireless sensors and the IoT. By using the wireless sensor IoT, when a user dials the home phone outside, the home phone jack module can judge whether to pick up the phone according to the number of rings. If it is determined to pick up the phone, the result will be fed back to the user's mobile phone in the form of voice, informing the user to enter the system password; if the password is entered correctly, the user can obtain the execution authority of the smart home system, and then control the home appliances according to the voice instructions. After passing through the telephone interface module, the outdoor control information enters the home Ethernet and is sent to each terminal node in the home. The terminal nodes then analyze the control information to determine whether the information is sent locally and whether the issued instructions need to be executed.

Smart home has evolved into an organic part of smart building, and wireless sensor networks are deeply integrated into the building BIM (Building Information Modeling) system. Millimeter-wave radar sensors, temperature and humidity sensors, and optical fiber sensors comprehensively perceive the indoor environment and human activities. Through the intelligent central control platform, they link with curtains, air conditioners, lighting, and security equipment, and automatically adjust according to user preferences and environmental changes to create a comfortable, energy-saving, and safe living and office space. In smart communities, sensor networks collaborate with intelligent access control and intelligent parking systems to achieve accurate identification and intelligent management of people and vehicles; blockchain technology is used to ensure the secure sharing of community residents' private data, building an intelligent, harmonious, and safe community ecology. At the same time, edge computing technology is deployed to home gateways to realize local intelligent control and data processing, reduce cloud delay, and improve user experience [12].

4.5. Ecological environment monitoring and intelligent environmental protection

The ecological environment monitoring network integrates multi-source data from wireless sensor networks, satellite remote sensing, and aerial monitoring to achieve comprehensive, real-time, and three-dimensional monitoring of the atmosphere, water bodies, soil, and ecosystems. Miniaturized and arrayed gas sensors accurately capture concentration changes of pollutants such as VOCs (volatile organic compounds), PM2.5, and ozone, which are then transmitted in real-time to the environmental protection big data platform via 5G networks. AI-driven environmental quality prediction models (e.g., Long Short-Term Memory networks, LSTM) provide early warnings for pollution incidents, assisting environmental regulatory authorities in precise source tracing and scientific decision-making. In the field of smart water management, sensor networks monitor water quality parameters, flow velocity, and water level changes. Intelligent control systems then optimize water resource allocation to ensure water security. Meanwhile, blockchain technology is applied to environmental rights trading and carbon emission trading, incentivizing enterprises to save energy and reduce emissions. This drives the digital, intelligent, and market-oriented transformation of the environmental protection industry, safeguarding lucid waters and lush mountains, and building a new system for intelligent environmental protection [13].

5. Conclusion

The deep integration of wireless sensor networks and the Internet of Things is like a "smart engine" meticulously forged for various industries, continuously driving traditional industries to break old models and establish new ones, and giving birth to new business formats. Currently, the innovation of technological integration is accelerating. Cutting-edge technologies such as 6G communication, quantum information technology, and brain-inspired intelligence are eager to be integrated into the ecosystem of wireless sensor networks and the Internet of Things. In the future, as technologies overcome difficulties, costs continue to decline, and standard systems become increasingly improved, the integrated application of the two will expand into broader fields and evolve to a deeper level. In the construction of smart cities, it will seamlessly connect all things in the city to realize the overall coordination of intelligent transportation, intelligent energy, and intelligent security. In extreme environment fields such as deep-sea exploration and space exploration, it will take on the mission of exploring the unknown world. In segmented scenarios such as personalized medical treatment and precision marketing, it will provide deep insight into individual needs and customize exclusive service plans. To seize the high ground of technological competition and release the dividends of industrial innovation, governments, scientific research institutions, and enterprises need to work together, continue to increase R&D investment, cultivate interdisciplinary talent teams, and build an open innovation ecosystem, so as to promote wireless sensor networks and Internet of Things technologies to shine brilliantly in the journey of sustainable development of human society and create new glory in the intelligent era.

Disclosure statement

The authors declare no conflict of interest.

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