Proceedings of the 3rd International Conference on Software Engineering and Machine Learning
DOI: 10.54254/2755-2721/145/2025.21870

A Review of Research on Embedded Internet of Things Technologies Application in Environmental Monitoring

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Abstract: The integration of embedded Internet of Things (IoT) technology in environmental monitoring underscores its significance, facilitating precise and efficient data collection and analysis. This paper examines the current landscape, technical hurdles, and future directions of embedded IoT applications in environmental monitoring, aiming to inform research and practice in this domain. The pressing need for high-precision, real-time data has propelled the advancement of embedded IoT technology, which creates an effective monitoring system by merging sensor technology, wireless communication, and data processing. Recent domestic and international studies have yielded notable progress in environmental monitoring, exemplified by air quality, water quality, and soil monitoring applications, showcasing the benefits of embedded IoT in data acquisition, transmission, and analysis. Nonetheless, challenges remain, including energy supply, data security, and system stability. This paper suggests that future research should prioritize low-power design, edge computing, and optimization of artificial intelligence algorithms, while enhancing interdisciplinary collaboration and technological innovation to foster the comprehensive application and sustainable development of embedded IoT technology in environmental monitoring.

Keywords: Embedded internet of things, Environmental monitoring, Wireless communication, Energy supply, Sensors

1. Introduction

Environmental issues are increasingly central to global discourse, driving demand for precise, real-time monitoring. Traditional methods struggle to provide the necessary data, particularly regarding climate change and pollution control. The advent of embedded Internet of Things (IoT) technology has transformed environmental monitoring, enabling continuous tracking of parameters and delivering accurate status reports through intelligent analysis. This technology extends beyond air and water quality monitoring to areas like agricultural surveillance, disaster warning, and urban planning. For instance, IoT sensors in agriculture facilitate real-time monitoring of soil conditions, enhancing precision farming and resource efficiency. In urban settings, IoT can assess traffic and noise pollution, aiding city planners in optimizing infrastructure and improving residents' quality of life. This study aims to investigate the application of embedded IoT technology in developing a more efficient and accurate environmental monitoring system to address ecological challenges and promote sustainable development. It will examine the current landscape, technical hurdles, and future

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directions of IoT in environmental monitoring, emphasizing its role in advancing monitoring technology, enhancing efficiency and accuracy, and reducing reliance on human and material resources for effective environmental protection.

2. Key Technologies for Embedded IoT in Environmental Monitoring

2.1. Network Architecture

To develop a theoretical framework for embedded IoT technology in environmental monitoring, it is essential to grasp key concepts such as sensor technology, wireless communication, data processing, and IoT architecture. These components underpin an effective environmental monitoring system, with their integration crucial for accurate, real-time data acquisition. Sensor technology serves as the "eyes" of the system, collecting vital physical and chemical data like temperature and gas concentrations. Miniaturized sensors in IoT applications ensure reliable, low-power operation for extensive deployment. Wireless communication acts as the "nervous system," enabling swift data transmission to the processing unit through protocols like LoRa and NB-IoT, vital for stable communication in complex settings. Data processing functions as the "brain," converting raw data into actionable insights through techniques such as cleansing, fusion, and mining. This process is critical for extracting valuable information from large datasets to inform environmental monitoring decisions. Additionally, data security and privacy are paramount, necessitating measures to protect data integrity during transmission and storage, thereby preventing leakage or misuse.

2.2. Data Acquisition and Transmission

The choice of wireless communication technology is crucial in the data transmission chain. Currently, LoRa, NB-IoT, Zigbee, and Wi-Fi each present distinct advantages and limitations. LoRa, characterized by extensive coverage and low power consumption, is ideal for long-range, sustained environmental monitoring, particularly in agriculture. Conversely, Zigbee excels in short-range transmission, making it suitable for low-power, rapid-response monitoring tasks. NB-IoT is advantageous for urban and remote environmental monitoring due to its superior signal penetration and extensive connectivity capabilities.

In terms of transport protocols, lightweight protocols such as MQTT and CoAP are widely used in environmental monitoring systems. The MQTT protocol has become a common solution in IoT environmental monitoring due to its reliable data transmission in low-bandwidth and unstable network environments. The CoAP protocol, on the other hand, is especially suitable for data interaction of embedded devices under resource constraints. By reasonably selecting data transmission protocols and communication technologies, the environmental monitoring system can realize efficient data acquisition and real-time transmission, and effectively support various environmental monitoring tasks [1].

3. Current status of Domestic and International Research

3.1. Progress in Air Quality Monitoring Research

In air quality monitoring, the integration of embedded IoT technology enhances real-time data collection and refines environmental monitoring. Qin Xiaoliang et al. [2] noted that the rising demand for precise urban air quality management and pollution source control necessitates low-cost wireless sensor networks, which facilitate dense atmospheric grid monitoring. However, challenges such as data accuracy, calibration difficulties, and limited sensor lifespan persist. Future advancements should prioritize sensor calibration, accuracy enhancement, lifespan extension, data processing

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optimization, and improved integration with other monitoring systems. R. Senthilkumar et al. [3] highlighted that traditional air quality monitoring systems are inadequate due to high costs, inefficiency, and prolonged processing times. They proposed an IoT system leveraging fog computing for real-time data collection and preliminary processing via fog nodes, circumventing direct cloud transmission. This approach enhances service speed and efficiency by intelligently filtering and processing data, pre-processing non-critical information, and transmitting only essential data to cloud servers for long-term storage and analysis, thereby offering robust support for environmental monitoring.

Wang et al. [4] developed a multi-sensor air quality monitoring system utilizing the BeiDou module for environmental data acquisition, integrating clustering and hierarchical analysis for comprehensive air quality assessment, with results displayed via mobile software to inform personal health decisions. In industrial and urban monitoring, Sani ABBA et al. [5] created an intelligent framework employing MQ-2 gas and LMVR sound sensors for real-time monitoring of hazardous gases and noise, enabling intelligent environmental quality control. Field tests confirm the system's efficiency and adaptability in urban, industrial, and public health contexts, supporting sustainable development.

In domestic research, Peng Zhang [6] designed a smart agricultural environment monitoring system based on LoRa technology, which not only solved the transmission distance and power consumption problems of the traditional monitoring system, but also realized the remote monitoring and regulation of various parameters, such as air, in the agricultural environment, which demonstrated the broad application prospects of IoT technology in the field of agriculture. Meanwhile, Nie Huun et al. [7] proposed a two-stage parallel-type data fusion technology based on NB-IoT technology for the data fusion problem in environmental monitoring, which improves the accuracy and reliability of the comprehensive evaluation of the environmental quality, and provides users with a more comprehensive environmental information.

3.2. Water Quality Monitoring Techniques and Practices

The integration of embedded IoT technology in water quality monitoring underscores its significance in environmental surveillance. This monitoring is crucial for human health and ecological safety. IoT enhances the real-time accuracy and facilitates remote data transmission and intelligent analysis, thereby bolstering water resource management and protection.

Water quality monitoring has been extensively explored by researchers globally. In China, significant advancements have been made in IoT-based water quality monitoring systems. Huang Jianqing et al. [8] developed a wireless sensor network system that addresses the limitations of traditional methods, such as time consumption, limited monitoring range, and prolonged cycles. This system enables real-time data collection and remote monitoring of water quality and environmental parameters. Utilizing wireless transmission without a power supply, it effectively captures dynamic changes in the aquatic environment, making it particularly suitable for aquaculture monitoring.

Shifeng Fang et al. [9] constructed an integrated environmental monitoring management system that utilizes Internet of Things (IoT) technology, cloud computing, geo-information and e-science to effectively monitor climate change and ecosystem change. In a case study in the Xinjiang region, the system revealed changes in temperature and precipitation trends over the past 50 years, highlighting the importance of water resources to terrestrial ecosystems. Through this integrated system, data collection, web services and cloud-based platform applications have been significantly enhanced, improving the efficiency of the monitoring process and decision-making.

Sensor technology innovation is crucial for designing water quality monitoring systems. Zhuoran Li [10] developed an aquaculture monitoring system utilizing embedded Linux and ZigBee wireless networks for continuous monitoring and control of water parameters. The system features a three-layer architecture for data acquisition, processing, and user interface, enabling stable, reliable, and cost-effective real-time monitoring through various sensors essential for aquaculture.

The optimization of system architecture is an important factor to improve the efficiency of water quality monitoring. Liu Yuqing et al. [11] designed a crab aquaculture base monitoring system based on the Internet of Things (IoT) three-layer architecture, which realizes real-time monitoring of water quality parameters, including dissolved oxygen, ph, and temperature, and at the same time integrates the functions of meteorological monitoring, video monitoring, and intelligent control, so that the user can remotely access and manage the system via computer or cell phone, demonstrating the IoT technology's This demonstrates the potential of IoT technology to be widely used in the aquaculture industry.

Overall, the application of embedded IoT technology in water quality monitoring is developing from single-parameter monitoring to multi-parameter integrated monitoring, transforming from localized monitoring to large-scale and real-time monitoring, and extending from data collection to data analysis and intelligent decision-making.

3.3. IoT Solutions for Agricultural Monitoring

The application of embedded Internet of Things (IoT) technology in the field of agricultural environmental monitoring is driving the development of modern agriculture in the direction of precision and intelligence. Cao-Hoang, T. [12] pointed out in his research that the environmental factors, such as temperature and humidity, have an important impact on crop growth, and an environmental monitoring system based on wireless sensor networks has become the key to realize precision agriculture. The system not only monitors and transmits environmental parameters in real time to help farmers make decisions, but also evaluates the effectiveness of agricultural measures. With the continuous progress of technology, such systems use lower-cost and easier-to-use equipment that can operate stably for a long period of time, providing strong technical support for agricultural production.

Wireless transmission technology plays an important role in IoT solutions for agricultural monitoring. Chi-Mou Lin [13] designed an environmental monitoring system based on Lora and NB-IoT communication technologies, which utilizes the advantages of these two technologies to achieve low cost, low power consumption, wide coverage, and ease of installation.The Lora module is responsible for the local data acquisition and transmission, while the NB-IoT module is responsible for the remote transmission, and the combination of the two makes the system, when monitoring the agricultural environment, to cover a wider range and the data transmission is stable and reliable. In addition, Zhu Junchao et al. [14] designed an IoT-based environmental monitoring system for agricultural greenhouses, which utilizes RS485 communication and STM32 microcontroller to process the sensor data, and then transmits them to the network layer via GPRS, and combines with a cloud computing platform to realize real-time remote monitoring and intelligent management of environmental information in agricultural greenhouses.

Kai Zhu et al. [15] designed a greenhouse environmental monitoring system based on open-source IoT technology, proposing an environmental monitoring system based on wireless sensor networks and IoT open-source gateways, using low-cost hardware and an open-source gateway platform based on the Linux system to form a completely new IoT system. The development of this system simplifies the process of data collection and management in agricultural production environments, and effectively promotes the connection and integration of devices related to agricultural IoT.

IoT technology has also been applied to other aspects of agriculture. Pan Tan et al. [16] designed a farmland information monitoring system based on the ZigBee network and embedded 3S technology, the system is able to automatically collect the farmland environmental parameters and geographic location information, and transmit and manage them over a long distance through ZigBee network

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and GPRS network, utilizing the combination of GIS technology and Internet technology, providing a low-cost and convenient farmland environment monitoring method, which contributes to the development of precision agriculture. And Ji Jianwei et al. [17] realized a low-cost and low-complexity information collection and transmission of agricultural remote monitoring system through ZigBee sensor network and embedded technology, which further enhanced the informatization level of agricultural production.

3.4. Integration and Application of Embedded System in Environmental Monitoring

The combination of embedded systems and IoT technology provides a powerful tool for environmental monitoring, enabling real-time, low-cost and high-precision data collection.

Weixing Zhu et al. [18] Focusing on the environmental monitoring of nursery pigsties, the environmental regulation and control system developed through Internet of Things (IoT) technology utilizes Zigbee wireless network technology to achieve communication between devices, which improves the stability and maintainability of the system, eliminates the need for wiring, and is easy to install. They adopt ARM-LINUX embedded server as the field control center, and realize remote real-time monitoring through B/S structure, which improves the flexibility of operation. The experimental results show that the system has stable performance, and the wireless collection of information, automatic environmental regulation and remote visualization and control meet the actual demand, which is suitable for the intelligent and precise management of the environment of the nursery pig house.

While in foreign studies, Nikolas Vidakis et al. [19] emphasized that through the implementation of Wireless Sensor Networks (WSNs) and the Internet of Things (IoT), it is possible to create an ecologically friendly and controlled environment, which minimizes or even eliminates environmental contamination by monitoring, storing and analyzing environmental data. The system is capable of designating and identifying those environmental spaces where human activities may be harmful, such as World Heritage sites and archaeological sites, and by collecting and analyzing data, it helps to assess the impact of human behavior on the environment and supports immediate decision-making.

These research examples highlight the integration and application of embedded systems in environmental monitoring, which not only improves the real-time and accuracy of monitoring, but also promotes the intelligent analysis of environmental data and decision-making, providing a scientific basis and technical support for environmental protection and sustainable development. In the future, with the continuous progress of technology, the integration of embedded systems and Internet of Things technology will play a more critical role in environmental monitoring and promote the continuous innovation and development of environmental monitoring technology.

4. Conclusion

Comprehensively reviewing the current status and future trends of the application of embedded IoT technology in environmental monitoring, this review reveals how the technology profoundly affects the efficiency, accuracy and intelligence level of environmental monitoring. From air quality monitoring, water quality monitoring to agricultural monitoring, the application of IoT technology not only enhances the real-time and accuracy of data collection, but also promotes the scientific and refined environmental management, showing its great potential and value in the field of environmental monitoring. A comprehensive review of domestic and international research indicates notable progress in IoT technology for environmental monitoring, yet challenges remain in data security, energy supply, and system stability. Current studies emphasize the necessity for improved encryption and access control as monitoring systems become increasingly complex, warranting further investigation and innovative solutions. Energy supply is a significant obstacle, particularly in remote regions, leading to explorations of renewable sources such as solar and wind for self-sufficiency. System stability, encompassing sensor accuracy, communication reliability, and data processing efficiency, demands interdisciplinary collaboration and technological advancements to ensure dependable operation. Future advancements in the sustainable integration of embedded IoT technology in environmental monitoring will depend on such collaboration, facilitating knowledge exchange and fostering innovative research to address the intricate challenges in this domain.

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