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Design of an Internet of Things Monitoring System for Understory Crops Based on Information Fusion

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Abstract. Enhancing the productivity, economic efficiency, and ecological sustainability of understory crops under limited forest resources represents a critical challenge. To address this issue, the project investigates and implements an IoT-based monitoring system integrated with information fusion. The main contributions are as follows: a) The design and development of wireless acquisition nodes characterized by low power consumption, low cost, and high reliability.
b) The construction of a wide-coverage, energy-efficient, and intelligent IoT monitoring architecture tailored to complex understory environments. The framework leverages LoRaWAN and MQTT protocols to satisfy the stringent requirements of large forest areas with dense obstacles, ensuring reliable data transmission. c) The development of a high-accuracy information fusion scheme. Real-time monitoring of understory crop environmental parameters is conducted, and advanced fusion algorithms are employed to maximize the efficiency and utility of IoT-derived information.

Keywords: Understory crops; Internet of Things (IoT); LoRaWAN; MQTT protocol; Information fusion; Precision agriculture; Environmental monitoring

1. Introduction

Against the backdrop of China's continuous promotion of ecological civilization, forestry, as a critical component of the ecosystem, plays an essential role in safeguarding ecological security and driving regional economic growth. The understory economy not only balances ecological conservation with economic returns but also embodies the concept that "lucid waters and lush mountains are invaluable assets[1]." However, due to the wide cultivation areas, complex terrain, and frequent obstacles in forest environments, traditional monitoring methods remain insufficient for refined management, resulting in low resource utilization efficiency and increased environmental stress. With the rapid advancement of information technologies, smart agriculture provides new opportunities for the sustainable development of the understory economy. IoT-based sensing and transmission technologies enable real-time acquisition of key environmental parameters, including soil, moisture, temperature, and illumination, while information fusion methods effectively process heterogeneous multi-source data, reducing redundancy and improving accuracy to support precision management. Compared with single-sensor or centralized processing paradigms, the integration of multi-sensor networks with data fusion improves system stability, fault tolerance, and efficiency while controlling costs and energy consumption.

In the evolution of agricultural informatization, the Internet of Things (IoT) and wireless sensor networks (WSN) have been widely applied in crop environmental monitoring and intelligent management[2][3]. Early systems primarily relied on ZigBee, GPRS[4][5], and other communication technologies to monitor soil moisture, temperature, and humidity in both open fields and greenhouse scenarios[6]. However, these systems often encountered limitations in large-scale or complex understory environments, including short transmission range, high energy consumption of nodes, and unstable network performance[7]. With the emergence of Low-Power Wide-Area Networks (LPWAN), LoRaWAN has demonstrated significant advantages in long-range communication, low power consumption, and flexible networking. Its application in greenhouse monitoring, orchard management, and intelligent irrigation has been validated, substantially

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enhancing coverage and energy efficiency. Meanwhile, the rapid growth in the number of sensor nodes has led to multi-source, redundant, and uncertain agricultural data, which traditional centralized processing architectures cannot efficiently handle in terms of real-time and reliability. To address this, researchers have proposed multi-sensor information fusion and edge computing methods. Techniques such as adaptive weighted fusion, Kalman filtering, and Bayesian estimation have been adopted to reduce data redundancy and improve monitoring accuracy, with positive outcomes in applications like pest and disease prediction and crop growth assessment. Nevertheless, existing studies remain largely focused on open-field or facility agriculture, with limited attention to complex understory terrains. Further breakthroughs are still required in balancing low cost and low power consumption, ensuring robust communication in complex environments, and achieving efficient utilization of multi-source data.

2. System Design Scheme

Given the large planting area of understory crops and the presence of many obstacles, higher requirements are imposed on agricultural IoT systems in terms of coverage, node deployment density, transmission reliability, networking convenience, power consumption, and network lifetime. To address these challenges, this paper proposes an IoT-based monitoring scheme with information fusion. The design scheme is as follows.

2.1 Overall Research Framework

The overall framework of this study is constructed as a three-layer architecture consisting of the perception, network, and application layers. In the perception layer, heterogeneous sensor nodes are deployed to collect environmental parameters such as soil moisture, temperature, and illumination. In the network layer, a LoRaWAN-based communication framework is adopted to achieve long-range, low-power, and flexible networking. In the application layer, multi-source information fusion methods, including adaptive weighted fusion, Kalman filtering, and Bayesian estimation, are introduced to reduce data redundancy and improve monitoring accuracy. Through this layered design, the system aims to realize wide coverage, low energy consumption, and high-precision monitoring of understory crop environments, thereby providing reliable support for precision management.

2.2 Technical Roadmap

In line with the research objectives of this project, the adopted technical roadmap is presented in Fig. 1.

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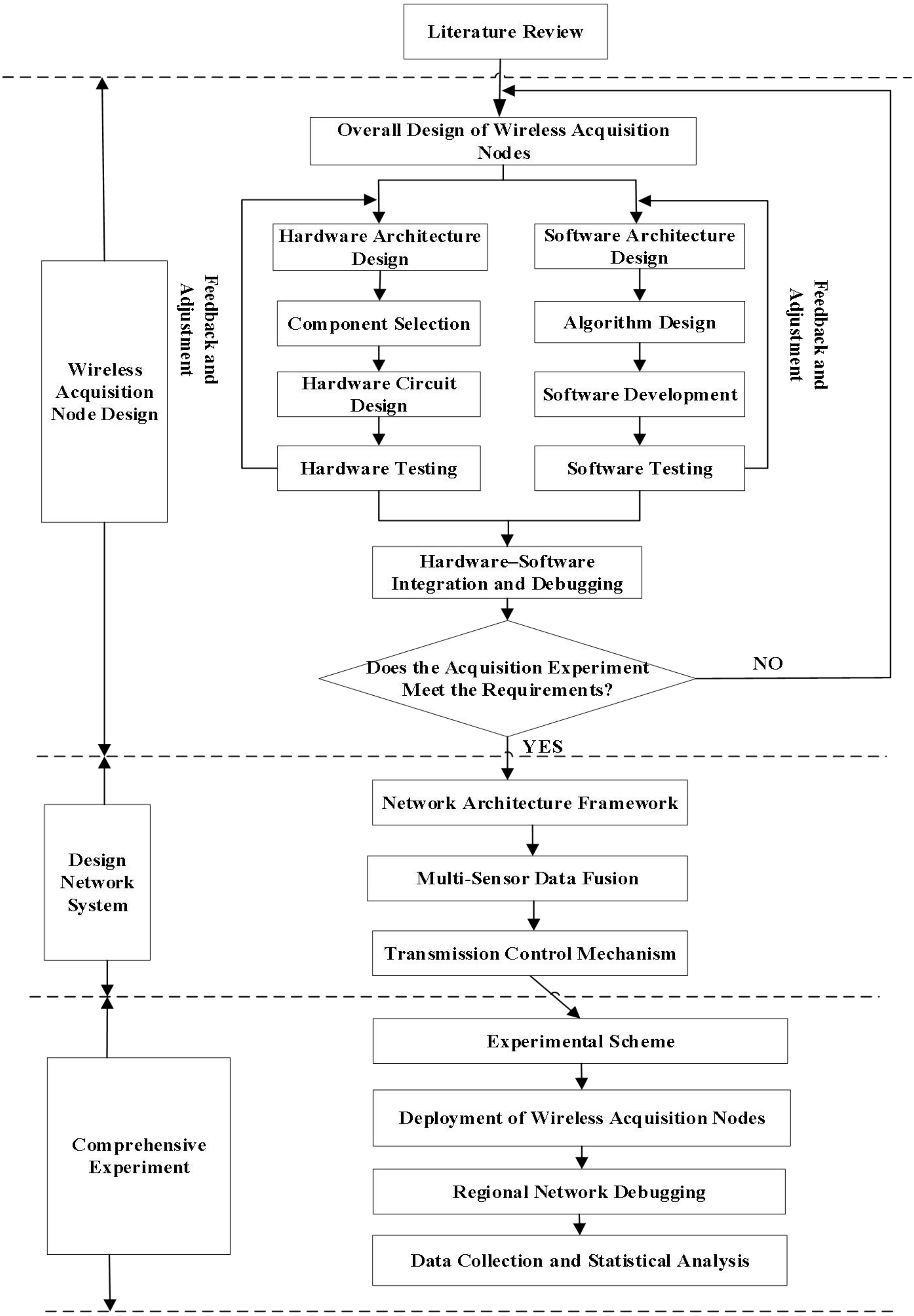

Fig. 1 Technical roadmap of the proposed system

Afterwards, a combined hardware–software approach is adopted for the overall design of wireless acquisition nodes, with hardware and software modules developed in parallel. On the hardware side, following the architecture design, component selection and circuit design are carried out, followed by unit testing. Adjustments to hardware modules are made based on the test results.

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On the software side, after the architecture design, algorithms are developed, applications are programmed, and unit testing is performed. Once the hardware and software development of the nodes is completed, hardware–software integration and debugging are conducted. If the design specifications are not satisfied, the process returns to the modification of the hardware and software design; otherwise, the workflow proceeds to the design of the wireless network architecture. At this stage, detailed designs are performed for the perception, network, and application layers. The perception layer focuses on the selection and development of heterogeneous sensors; the network layer addresses topology construction and transmission control mechanisms; and the application layer involves the design and implementation of monitoring software. Upon completion, a comprehensive network architecture is established. Subsequently, experimental schemes are designed, and network deployment is carried out, including multi-region network testing and data acquisition trials. The collected data are then subjected to in-depth statistical and analytical processing, and the results are summarized.

2.3 Research Methods

2.3.1 Design of Wireless Acquisition Nodes for Understory Crop Environment Monitoring[8][9][10]

The wireless acquisition node is primarily responsible for data collection, with two major tasks: first, receiving user instructions and processing sensor information; and second, transmitting the acquired data to the sink node through multi-hop wireless networking. Each node mainly consists of modules for storage, processing, wireless communication, sensing, power supply, and other peripheral circuits.

The microcontroller unit (MCU) of the sensor node plays a crucial role in determining the power consumption, cost, and compatibility of the entire monitoring node. In this project, the STM32F103, developed based on the ARM Cortex-M3 architecture, is selected as the MCU. It features low power consumption and strong anti-interference capability, making it well-suited for long-term understory monitoring.

Given the large cultivation areas of understory crops, stringent requirements are imposed on the transmission range and receiver sensitivity of the communication module. To address this, the project employs the SX1276 RF integrated circuit (IC), which provides high sensitivity, low power consumption, low cost, and long-range transmission. The SX1276 achieves high sensitivity through the use of low-power crystal materials, thereby resolving the traditional trade-off between transmission distance and energy consumption, and enabling ultra-long-range communication under low-power conditions. Moreover, the SX1276 integrates automatic spread-spectrum calculation and hardware error-checking functions, which substantially reduce the computational burden on the MCU.

2.3.2 Construction of an IoT Architecture for Understory Environment Monitoring Based on LoRaWAN[11-15]

An IoT monitoring framework is designed based on the LoRaWAN and MQTT protocols, in which the overall architecture for understory environment monitoring is divided into three layers: perception, transmission, and application. In the perception layer, distributed monitoring nodes are deployed across the understory cultivation area to collect real-time environmental parameters, such as atmospheric conditions and soil moisture. In the transmission layer, data fusion techniques are employed to process the acquired heterogeneous environmental data, which are then uploaded to the wireless gateway via the LoRaWAN protocol. In the application layer, the gateway transmits the aggregated information to the cloud server through the MQTT protocol. This IoT architecture enables online monitoring of understory crop growth conditions in a more intuitive, three-dimensional, and comprehensive manner. The overall architecture of the understory environment monitoring IoT system is shown in Fig. 2.

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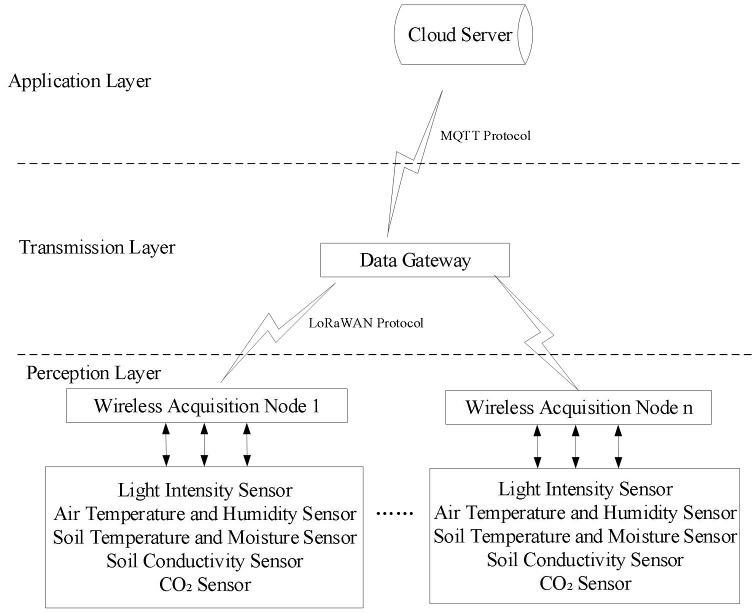

Fig. 2 Overall architecture of the IoT-based monitoring system for understory environment

2.3.3 Information Fusion Scheme [16-18]

By comparing different types of information fusion schemes and considering the specific conditions of understory cultivation, this study adopts a dynamic weighted adaptive method. The dynamic weighted adaptive method, also known as the adaptive weighted fusion estimation algorithm, is based on the principle that when n sensors are deployed, each sensor is assigned a distinct weighting factor. During the measurement process, the algorithm ensures that the overall mean square error is minimized as the optimal criterion. At the same time, according to the measurement values obtained from individual sensors, the algorithm adaptively determines the optimal weighting factor for each sensor, so that the fused result achieves the optimal state.

2.4 Experimental Scheme and Feasibility Analysis

The experimental scheme adopts a stepwise approach, beginning with modular experiments and followed by comprehensive experiments, as detailed below.

First, the project is divided into modular experimental groups, including wireless acquisition node testing, wireless network module testing, and application-layer testing.

a) The wireless acquisition node experiments focus on sensor data collection and wireless communication tests.

b) The wireless network module experiments examine the communication between acquisition nodes and gateways. By deploying distributed nodes across the understory cultivation area and adjusting transmission power and antennas, the actual system parameters are obtained to achieve a reasonable balance between energy consumption and performance.

c) The application-layer experiments mainly involve deploying a database on the cloud server to implement efficient information fusion algorithms.

Based on the latest developments in IoT and electronic technologies, the wireless acquisition nodes are designed with mature and reliable hardware solutions to achieve low-cost, low-power, and high-reliability performance. For the IoT framework, the LoRaWAN and MQTT protocols are adopted to construct a wide-coverage, energy-efficient, and intelligent monitoring system that is well suited to large understory areas with complex terrain and numerous obstacles. Furthermore, the dynamic weighted adaptive method is employed for information fusion, enabling efficient integration of sensor data. This not only improves data accuracy but also reduces redundancy, thereby lowering the energy consumption of wireless transmission.

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In summary, the research scheme and technical roadmap are both feasible, the experimental methods are effective, and the project can be completed within the scheduled timeframe.

3. Summary

Taken together, this study focused on the design and implementation of an IoT-based monitoring system for understory crops, through which an overall framework was established and preliminarily validated. On this basis, the project further concentrates on addressing the key technical challenges in practical deployment and discusses the major difficulties and innovations involved.

3.1 Key Technical Issues to Be Addressed

*Power consumption control***.** In sensor networks, a large number of widely distributed nodes are generally required to operate unattended for long periods. Frequent battery replacement is impractical. To ensure stable and continuous system operation, it is essential to minimize node power consumption so as to extend battery lifetime.

Low-cost implementation. Since a vast number of sensor nodes are deployed to perform relatively simple functions such as data acquisition and transmission, the cost of each node has a significant impact on the overall system expense. Therefore, reducing the cost per node while maintaining performance can effectively lower the total system cost. In practice, this is achieved by simplifying communication protocols and optimizing software processes to reduce hardware requirements.

Accurate and efficient data transmission. In agricultural soil information acquisition systems, sensor nodes continuously collect parameters such as temperature, soil moisture, and salinity, and transmit the fused results to the sink node. However, high redundancy often exists: neighboring nodes may collect almost identical data, and the same node may produce repeated values within short time intervals. Thus, efficient fusion and transmission mechanisms are required to ensure data accuracy and reduce redundancy.

3.2 Technical Challenges and Innovations of This Project

Balancing low cost, low power consumption, and high reliability. This is achieved by multi-level optimization, including hardware component selection, printed circuit board (PCB) design, IoT framework development, and software design, to reduce energy consumption while maintaining cost-effectiveness and reliability.

Integration of IoT and information fusion technologies. The organic combination of these two not only ensures low-power operation but also provides a practical pathway for the realization of smart agriculture in complex environments.

Looking ahead, the proposed IoT-based monitoring system for understory crops still has room for further optimization. With the continuous advancement of low-power chipsets, intelligent sensors, and artificial intelligence algorithms, the system can be further enhanced in terms of energy management, intelligent data analysis, and predictive decision-making. Future work will focus on integrating more heterogeneous sensors and edge computing technologies, as well as exploring the applicability of the system in larger-scale and more diverse understory scenarios. These efforts are expected to provide stronger technical support for the sustainable development of smart agriculture and the ecological economy.

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