Design and Experiment of a Web Server-Based Greenhouse Environment Monitoring System

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Abstract: In response to the complex wired transmission wiring issue in the current greenhouse environment monitoring systems in China, this paper presents a greenhouse environment monitoring system based on a web server architecture. The system utilized the wireless radio frequency technology of nRF24L01 for data transmission, established a web server, and developed a monitoring system web page. The Kalman filtering algorithm was applied for data denoising, which satisfies the requirement of remote real-time monitoring from multiple clients. The system architecture mainly consisted of the environmental information perception layer, transmission layer, and application layer, enabling functions such as greenhouse data collection, real-time data display, alarm notifications, real-time monitoring, data storage, and historical data queries. The maximum packet loss rate was 5.9 %, indicating good communication quality and reliability of the system. This research provides theoretical reference and practical value for information monitoring in environments such as greenhouses and plant factories.

Keywords: Greenhouse Environment; Information Monitoring; Microcontroller; Kalman Filtering; Data Collection

1. Introduction

In traditional agriculture, the growth environment of crops depended on natural weather conditions. When encountering natural disasters or weather changes, it is difficult to guarantee the quality and yield of crops, and production management is also very challenging. Facility agriculture can change the growth environment of crops, and greenhouse is one of its important forms. By adjusting the environmental variables inside the greenhouse, a good environment is provided for crop growth [1,2]. To better address the problems existing in the current greenhouse production management and achieve the goal of efficient management of greenhouse production systems, it is necessary to enhance the automation of environmental information monitoring technology. The Internet of Things (IoT) technology could fully leverage the advantages of data volume and remote real-time monitoring in facility agriculture, effectively solving this problem [3].

IoT was a new force in precision agriculture and smart greenhouse fields. It connects sensors, controllers, terminal devices, etc., using local area networks or the Internet. Users could remotely view the massive amount of information collected by sensors using computers, mobile phones, and other devices. They could remotely control and configure collection terminal devices through web pages or mobile app software, achieving comprehensive interconnection between sensors, people, and terminals

[4,5]. The greenhouse IoT system collected environmental information by installing collection nodes inside the greenhouse, and transmits it to the server using wired or wireless methods. This enabled farmers to remotely and in real-time understand the environmental information inside the greenhouse, reducing labor intensity [6].

In greenhouse environments, there were many factors that affect crop growth, with the main influencing factors being air and soil temperature and humidity, CO2 concentration, and light intensity. IoT technology could be used for automatic monitoring and control of environmental factors and physical variables inside the greenhouse [7], monitoring the entire growth process of greenhouse crops. This helped to improve the efficiency of crop cultivation, increase energy utilization efficiency, reduce production costs, and increase crop yields [8–10]. By combining deep learning, big data, artificial intelligence, and other technologies, virtual models of crops could be established based on collected crop information [11,12], and the collected environmental data could be processed to provide intelligent and optimal decisions [13]. This could predict climate changes in the greenhouse and crop growth trends [14–19], effectively preventing and reducing crop diseases and pests [20–23], aiding in reducing pesticide use, thereby improving the growing environment of crops and enhancing the quality of agricultural products [24].

Benyezza et al. [25] had proposed an IoT-based smart platform for monitoring and controlling greenhouse climate and irrigation. The proposed system utilized Wireless Sensor Networks (WSN) based on radio frequency communication to collect greenhouse data (temperature, humidity, and soil moisture). Subsequently, this data was transmitted to a Node-RED server hosted on a Raspberry Pi. The intelligent decision-making system employed fuzzy logic technology to process the collected data and send commands to provide optimal conditions for crops in the greenhouse. Song et al. [26], focusing on IoT as the core, combined sensor, actuator, and cloud platform technologies to construct an intelligent greenhouse control system. Environmental parameters such as temperature, humidity, and light intensity were obtained through sensors and uploaded to the cloud platform for storage and analysis. Simultaneously, the system automatically controlled lighting, ventilation, moisture, and fertilization in the greenhouse to optimize crop growth conditions. Zhou et al. [27] proposed a simple solution based on SoC and WeChat mini-program, emphasizing low-cost hardware, rapid development, and user-friendly application design. This solution utilized ESP8266 as the SoC to transmit sensor data to a remote server via Wi-Fi and provided a graphical user interface through the WeChat mini-program, simplifying device management and data access. Xu et al. [28] presented a method for monitoring agricultural environmental information using wireless sensors based on NB-IoT. The monitored environmental information was collected and processed by an STM32 MCU and transmitted to the OneNET cloud platform via an NB-IoT module. Liao et al. [29] proposed an IoT-based environmental monitoring system and a wireless imaging platform based on IoT. This system could simultaneously monitor environmental factors in orchid greenhouses and the growth status of phalaenopsis orchids, aiming to address issues in traditional greenhouse environmental monitoring methods and phalaenopsis orchid growth monitoring. The research results indicated that under specific temperature and relative humidity conditions, the leaf area growth rate of phalaenopsis orchids was higher. Xia et al. [30] designed a mobile greenhouse environmental monitoring system based on IoT. The system adopted a four-layer architecture, achieving automatic collection of greenhouse environmental information and low-cost collection of crop images. Using a combination of Raspberry

Pi and Arduino chips, Raspberry Pi served as the data server, and Arduino served as the main chip of the mobile system. Codeluppi et al. [31] proposed a low-cost, modular IoT platform utilizing LoRaWAN long-range wide-area network, called "LoRaFarM", aiming to optimize and environmentally manage agriculture by collecting, monitoring, and utilizing data related to agricultural processes.

The researchers mentioned above had proposed smart greenhouse control systems based on different sensor modules, controllers, and IoT cloud platforms. However, from the perspective of greenhouse IoT technology development, these studies had all been based on IoT technology to monitor and control greenhouse environmental factors. They had only focused on certain aspects affecting crop growth, and the collected environmental factors had been limited, with low levels of visualization. Additionally, some developed monitoring systems had not considered the users' operating costs, and a rental-based IoT platform had not been conducive to building low-cost smart greenhouse monitoring systems.

China has the world's largest greenhouse construction area, and greenhouse IoT technology has achieved precise monitoring of environmental information in some research and demonstration greenhouses [32]. However, compared to developed countries abroad, China's greenhouse IoT technology still faces issues such as lack of uniform communication protocols and complexity in selecting diverse databases.

In response to the current problems with the generality and cost of China's greenhouse environmental monitoring system, this paper conducted a study using a typical greenhouse in Beiluo Village, Shouguang City, Shandong Province as the experimental environment. A low-cost, user-friendly, and feature-rich IoT environmental monitoring system was researched and designed. This monitoring system can be used to collect the main parameters of air and soil environment inside the greenhouse, and the collected environmental data is uploaded to the Internet through a Raspberry Pi-based data storage server. Additionally, the monitoring system also designed a data storage server based on a Web server architecture to replace leased cloud platform servers, allowing users to remotely and in real-time view the environmental information inside the greenhouse. This research is of significant importance for the development and promotion of current greenhouse facility agriculture.

2. Materials and Methods

2.1 The Overall Scheme of the Greenhouse Environmental Information Monitoring System

The internal environment of a greenhouse was relatively enclosed, and crops have high requirements for environmental stability. The main environmental information that needs to be monitored includes air temperature, air humidity, light intensity, CO2 concentration, and soil environmental factors. The main functions of system include greenhouse data collection, real-time data display, alarm notifications, real-time monitoring, data storage, and historical data queries.

A web server was autonomously constructed using a Raspberry Pi development board. The system hardware primarily comprised an STC89C52 microcontroller, nRF24L01 module, various sensors, and Raspberry Pi 4B development board. The STC89C52 microcontroller served as the main controller at the collection end, driving various sensors to collect environmental parameters of air and soil inside the greenhouse. These parameters were transmitted to the Raspberry Pi receiver end via nRF24L01 radio frequency technology and stored in a MySQL database. Users could remotely access the system website using internet-connected devices such as smartphones, tablets, or computers to view real-time environmental information inside the greenhouse. The system architecture mainly consisted of the environmental information perception layer, transmission layer, and application layer (Figure 1a).

The perception layer is mainly used to collect various environmental information inside the greenhouse [33]. The system had a total of six collection nodes. Among them, nodes 1, 2, and 3 were air information collection nodes responsible for collecting environmental information such as light intensity inside the greenhouse. Nodes 4 and 5 were soil temperature, humidity, and conductivity collection nodes. Node 6 was a soil nitrogen, phosphorus, and potassium content collection node (Figure 1b). The perception layer is at the bottom layer of the monitoring system, providing important basis for data management and analysis at the application layer.

The transmission layer was responsible for sending the environmental information data collected by the perception layer to the Raspberry Pi receiver end. This was achieved by configuring the transmit-receive mode of the nRF24L01 chip for data collection and transmission. After collecting data, the STC89C52 microcontroller at the collection end would send it by configuring the nRF24L01 module. The Raspberry Pi, acting as the server, received the data, and the nRF24L01 module connected to it would receive the data sent by the perception layer and store it in the corresponding data table under the MySQL database. The transmission layer is in the middle layer of the monitoring system, capable of securely and reliably displaying the collection information from various sensors of the perception layer to the application layer.

The application layer is responsible for viewing and managing the environmental information inside the greenhouse. It mainly refers to the user end accessing the built web server through communication devices such as smartphones, computers, or tablets. Through the web interface, users can remotely monitor environmental information related to greenhouse crop growth, including real-time data, monitoring images, alarm messages, and historical data queries. This helps farmers make adjustment decisions during the crop growth period based on environmental change trends.

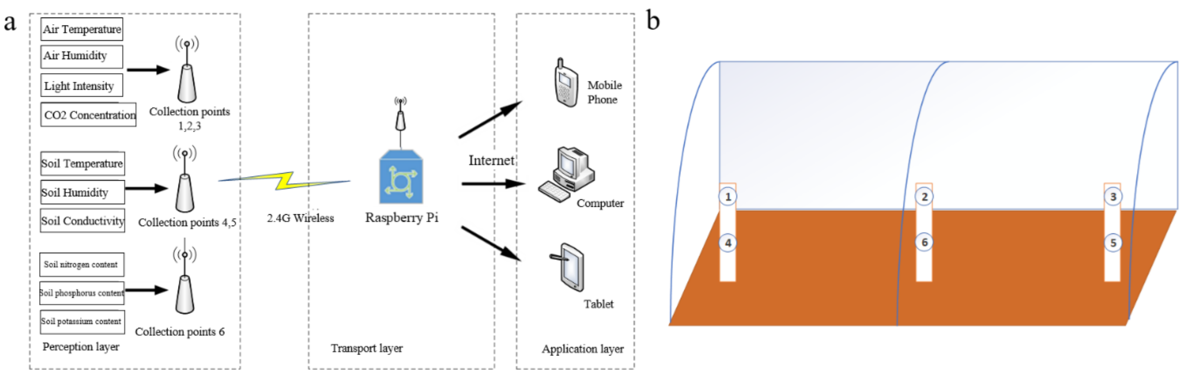

Figure 1: Schematic diagram of the overall system architecture and collection nodes: (a) The overall architecture of the system; (b) Acquisition nodes.

2.2 Hardware System Design

2.2.1 Sensor Selection Scheme

Sensors belong to the hardware of the perception layer, and their main function is to collect environmental information data, including air temperature and humidity sensors, light intensity sensors, CO2 concentration sensors, soil temperature, humidity, and conductivity sensors, and soil nitrogen, phosphorus, and potassium content sensors. The selection and main technical parameters of the sensors are shown in Table 1.

Table 1: Mechanical Contact Parameters.

Sensor Category		Range	Accuracy
DHT11 air temperature and humidity sensor		- 20 ~ 60 ℃/5 ~ 95 %RH	±2 ℃/±5% RH
BH1750 light intensity sensor		1 ~ 65535 Lux	/
MH-Z19B Carbon dioxide concentration sensor		0 ~ 5000 ppm	/
Soil temperature and humidity conductivity sensor	Soil temperature	- 40 ~ 80 ℃	±0.5 ℃
	Soil humidity	0 ~ 100 %	±3%
	Soil electric conductivity	0 ~ 20000 us/cm	±5%
Soil nitrogen, phosphorus and potassium content sensor		1 ~ 1999 mg/kg(mg/L)	±2% FS

2.2.2 Other Hardware Selection and Circuit Design

The collection end of the system employed the STC89C52RC chip produced by STC company, with a crystal oscillator of 11.0592 MHz. To ensure the stable operation of the crystal oscillator, two 20 pF capacitors (C17, C18) were added. The system also included power supply and reset circuits (Figure 2a).

For the power circuit design, considering the unified power supply of the six collection nodes using a 5 V lithium battery with a capacity of 3200 mAh, the system selected the IP5306 chip, which could display remaining battery power, manage charging, and perform boost conversion. To ensure the normal operation of the nRF24L01 module, an AMS1117 - 3.3 chip was selected for voltage reduction conversion. Additionally, a 1000 uF decoupling capacitor was added to the power output terminal to ensure stable chip operation (Figure 2b).

Considering the system's display requirements and overall circuit compatibility, an LCD1602 liquid crystal display was chosen to display the data collected by the collection end inside the greenhouse. This facilitated farmers' real-time understanding of environmental information while working in the greenhouse (Figure 2c).

The system was designed with four buttons for adjusting the alarm thresholds of various environmental information at the hardware end of the microcontroller. Due to the different environmental requirements of different crops, and to facilitate flexible adjustment by farmers based on crops, varieties, and environmental conditions during use, the system enhanced human-machine interaction by labeling the four buttons with Chinese characters for toggle, increase, decrease, and return, respectively. These buttons were positioned below the PCB board for easy operation (Figure 2d).

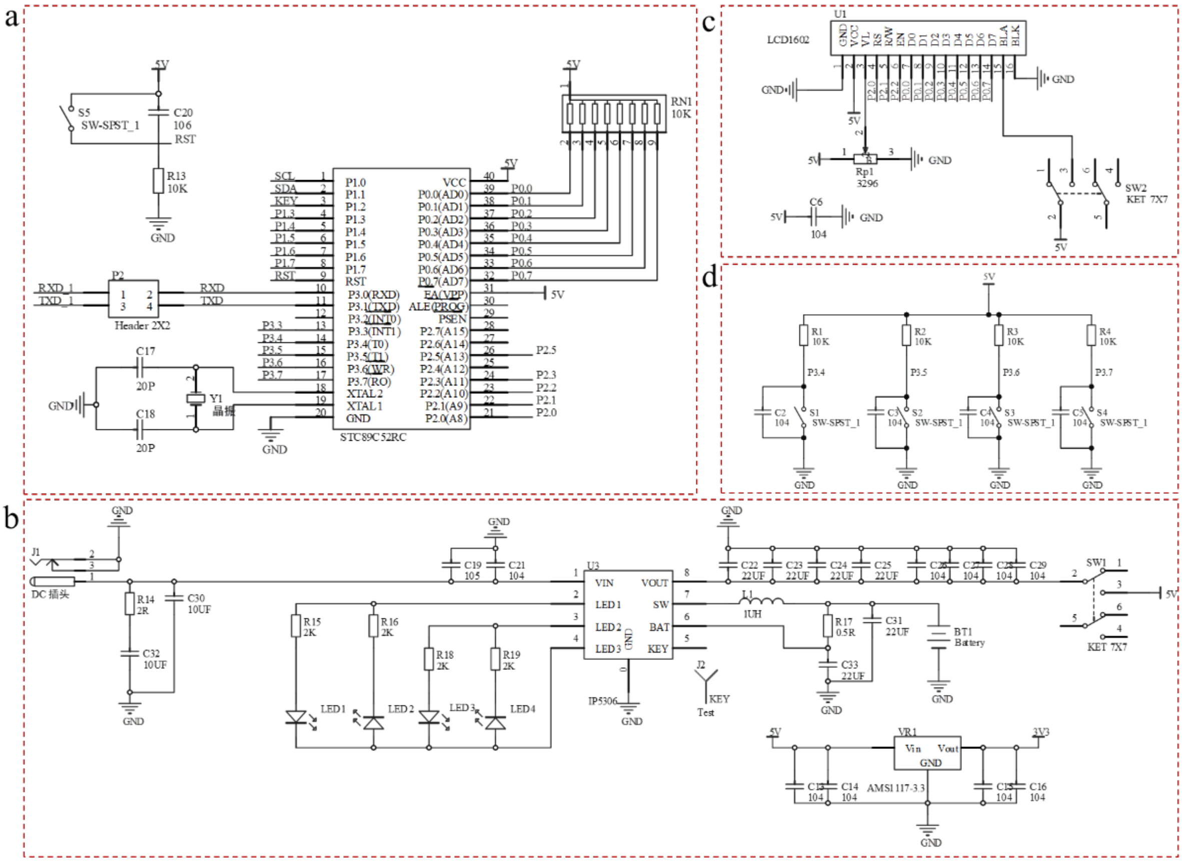

Figure 2: Schematic diagram of circuit design: (a) Minimum system circuit diagram; (b) Power circuit diagram; (c) Display circuit diagram; (d) Button adjustment circuit diagram.

According to the sensor and other hardware selection scheme, the actual equipment is finally selected (Figure 3).

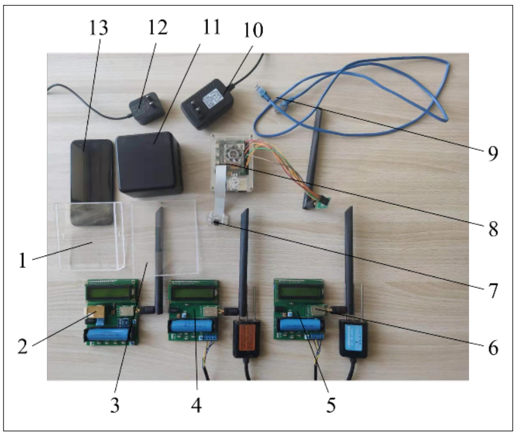

Figure 3: Shows the physical layout of the devices: 1. Soil node enclosure box, 2. Air sensor collection node, 3. Air node enclosure box, 4. Soil temperature, humidity, and conductivity sensor collection node, 5. Soil nitrogen, phosphorus, and potassium sensor collection node, 6. 2.4GHz wireless module, 7. Raspberry Pi camera, 8. Raspberry Pi, 9. Ethernet cable, 10. Raspberry Pi power cable, 11. Wireless router, 12. Wireless router power cable, 13. Mobile phone.

2.3 Software System Design

The software system design consists of two parts: the single-chip microcontroller (MCU) end and the web end. The former mainly includes program design for collecting data from various sensors, LCD screen display, buzzer alarm, and button adjustment functions. The latter includes functions such as real-time display of data collected from the web end, real-time monitoring of greenhouse conditions, dynamic line graphs and bar charts displaying environmental information in real-time, historical data inquiry, and web-based alarm prompts.

2.3.1 Sensor Information Acquisition Program Flow Design

During the greenhouse environmental information collection process, the first step was the initialization of the temperature and humidity sensor DHT11. The microcontroller sent an initialization signal to it, prompting the sensor to switch to working mode. Upon receiving the drive signal, the DHT11 sensor was awakened to begin collecting temperature and humidity data inside the greenhouse. After collecting data, the DHT11 sensor sent 40 bit data to the STC89C52RC, completing one collection cycle. Once the data was verified correctly, the temperature and humidity values were outputted. After the data collection was completed, the DHT11 sensor switched to sleep mode until it was awakened for the next collection by the microcontroller (Figure 4a).

The light intensity sensor BH1750 communicated with the STC89C52 microcontroller using the IIC protocol and featured a built-in 16-bit analog-to-digital converter. The microcontroller sent a power-on command to the sensor, followed by a measurement command using the "start signal - acknowledgment - end signal" instruction sequence after power-on. After the measurement was completed, the data was read and stored in the buffer (Figure 4b).

The CO2 gas concentration sensor MH-Z19B communicated via serial port (UART). Before normal operation, it needed to preheat for at least 3 minutes. Once preheating was complete, the microcontroller sent a command to the sensor to collect the value, and then the sensor feedback the data to the microcontroller (Figure 4c).

For the soil temperature, humidity, and conductivity sensor, all three parameters needed to be sent in a single inquiry frame, and the response frame contained both high and low data for the three parameters. As for the soil nitrogen, phosphorus, and potassium content sensor, separate inquiry frames for nitrogen, phosphorus, and potassium content were sent, each returning a corresponding response frame (Figure 4d).

During the operation of the system, the sensor collection nodes generate a large amount of data flow, causing noise interference to the system and resulting in inaccurate data collection and distortion phenomena. To address this issue, the system adopts the Kalman filtering algorithm to process the raw data, thereby reducing noise interference and measurement errors, improving the measurement accuracy of the monitoring system, and providing users with more accurate environmental information.

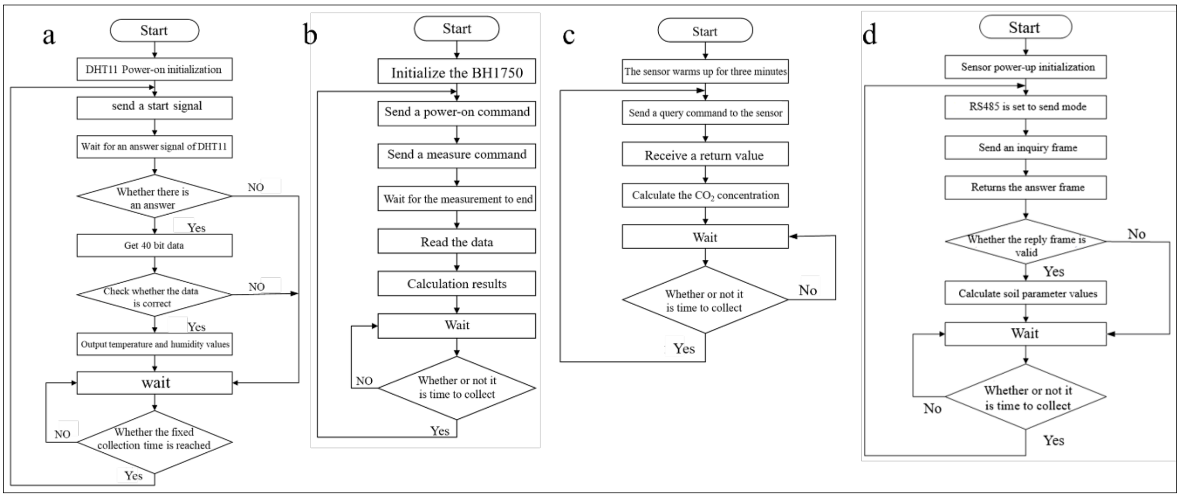

Figure 4: Data acquisition program flow of the perception layer: (a) Air temperature and humidity collection process; (b) Light intensity acquisition process; (c) Carbon dioxide collection process; (d) Soil information collection process

2.3.2 Perceptual Layer and Transport Layer Program Flow Design

The perception layer primarily includes functions such as real-time display of sensor data on the LCD1602 liquid crystal display, alarm functionality using a buzzer, and adjustment functionality using buttons. The LCD1602 distinguished the different environmental information collected by each node by setting letters. It was set different character input positions and outputs the corresponding information values to the LCD screen. Threshold values for various environmental parameters were set in the system. When the parameters collected by the system exceed the corresponding threshold values, the buzzer emitted a sound. The system's four buttons were used to adjust the threshold values of various parameters (Figure 5a).

The transmission layer mainly involved data communication between the collection circuit and the Raspberry Pi. The system used the nRF24L01 for one-to-six communication. The wireless module on the microcontroller side was configured as the transmitter mode, sending the data collected by the sensors. The wireless module on the Raspberry Pi side was configured as the receiver mode, receiving the data sent by the transmitter.

In the transmitter mode, the nRF24L01 wireless module first initializes, defining various I/O ports and configuring various register commands. After entering the initialization process in the transmission mode, the system configures the nRF24L01 mode. Once the configuration mode was complete, transmission began. When the STC microcontroller detected updated data collected by the sensors, it reads the newly collected data and sends it to the transmission buffer for sending. After the transmission was complete, a new cycle of data collection detection began (Figure 5b).

In the receiver mode, the 2.4G wireless module was connected to the Raspberry Pi. A driver program running on the Raspberry Pi terminal was responsible for receiving and storing data. The driver program was written in Python. It first initialized the wireless module, defining various pins and configuring various register commands. After entering the initialization process in the receiver mode, the system configured the nRF24L01 mode. Once the configuration mode was complete, reception began. The system distinguished between the channels through which the six nodes send information using conditional statements. When the Raspberry Pi receives updated data on a channel, the terminal interface of the Raspberry Pi printed the channel number and the corresponding node-collected data. It also stored this data in the MySQL database. After the reception was complete, a new cycle of data detection for each channel began (Figure 5c).

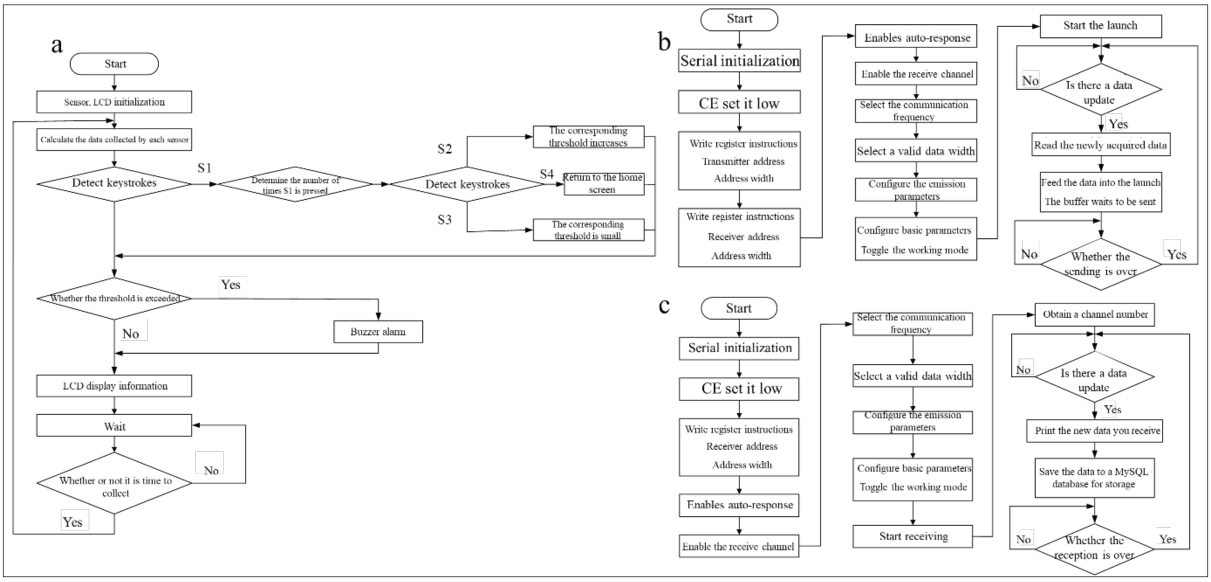

Figure 5: Program flow of perception layer and transport layer: (a) Perceptual layer design process; (b) Transmission layer emission mode process; (c) Flow of the transport layer receiving mode.

2.3.3 Building and Configuration of Software Development Platform

The system adopts the LAMP (Linux + Apache + MySQL + PHP) website architecture, where each component was independent, and their combination can build a versatile web platform. The system is designed with a B/S architecture, utilizing the client-server-database model.

For the greenhouse environmental monitoring system, a web interface needs to be developed to allow users to remotely view real-time environmental data inside the greenhouse. In this paper, the mainstream Bootstrap framework was used for web frontend development. The user login and registration interfaces were designed using a combination of HTML + CSS + JavaScript + PHP (Figure 6a).

The greenhouse environment monitoring system monitors various environmental information, with differences in monitoring information between different nodes. To display information from nodes 1 to node 6, a tabular format was used for presentation, showcasing the latest data collected from each node on the web interface (Figure 6b).

To facilitate users in viewing historical data, a historical data query function was designed on the web interface. Data from the respective tables in the database was retrieved and displayed in tabular format on the web page. Additionally, a date range option was added on the web page, allowing users to select a start date and end date to view data within a specified time period. The collected data was arranged in descending order (Figure 6c).

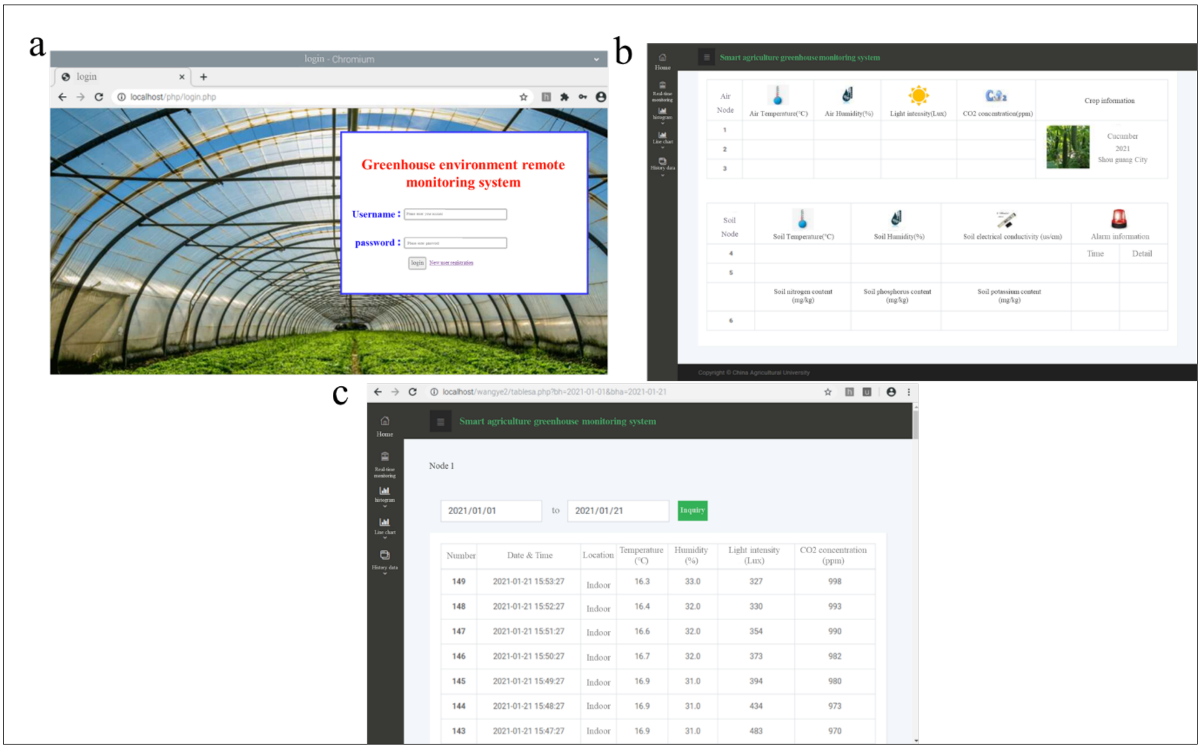

Figure 6: Webpage interface of greenhouse environmental information monitoring system: (a) User login and registration interface; (b) Node data information interface; (c) Query historical data.

Observing Table 1, it can be observed that various interactive technologies, based on their characteristics, are suitable for various teaching environments and have unique advantages. Injecting new vitality into classroom communication, breaking the traditional one-way communication mode between teachers and students, making interactive forms more diverse and in-depth, and improving students' learning enthusiasm and teaching effectiveness. By utilizing these technological tools, teachers can carefully plan classroom interactive activities and quickly optimize teaching plans based on real-time feedback from students, achieving personalized and tailored teaching goals [3].

2.4 Experimental Test

To verify the reliability of the monitoring system, field tests were conducted at a typical farmer's greenhouse in Beiluo Village, Shouguang City, Shandong Province, and at the vegetable production greenhouse of Weifang University of Science and Technology (Figure 7). The typical farmer's greenhouse is 60 meters long and 10 meters wide, while the vegetable production greenhouse at Weifang University of Science and Technology is 96 meters long and 12.24 meters wide. The tests included web end functionality testing, Kalman filtering processing comparison, and system reliability testing.

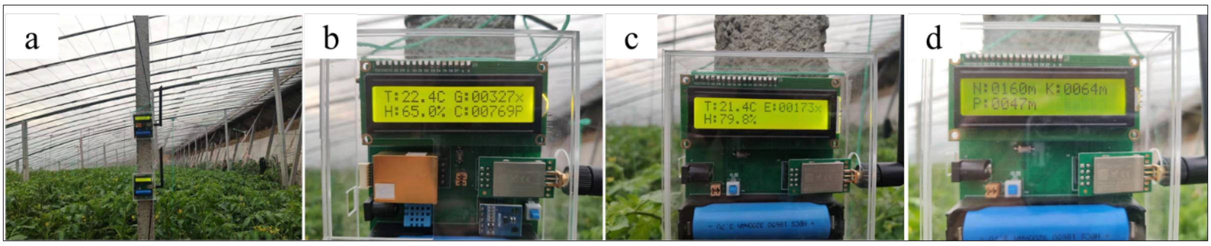

Figure 7: Experimental test site: (a) Installation effect; (b) Air node 1 data collection terminal display; (c) Soil node 4 data collection terminal display; (d) Soil node 6 Data collection end display.

3. Results and Discussion

3.1 Web Side Function Test

Taking the greenhouse at Weifang University of Science and Technology as an example, cucumbers are grown in the greenhouse, and real-time information from six nodes is collected (Figure 8). The information from the six nodes was clearly displayed on the web page, allowing farmers to understand environmental changes based on the different node data, especially differences in soil humidity and fertility. The bottom right corner of the web page displays alarm messages when environmental conditions exceed the threshold.

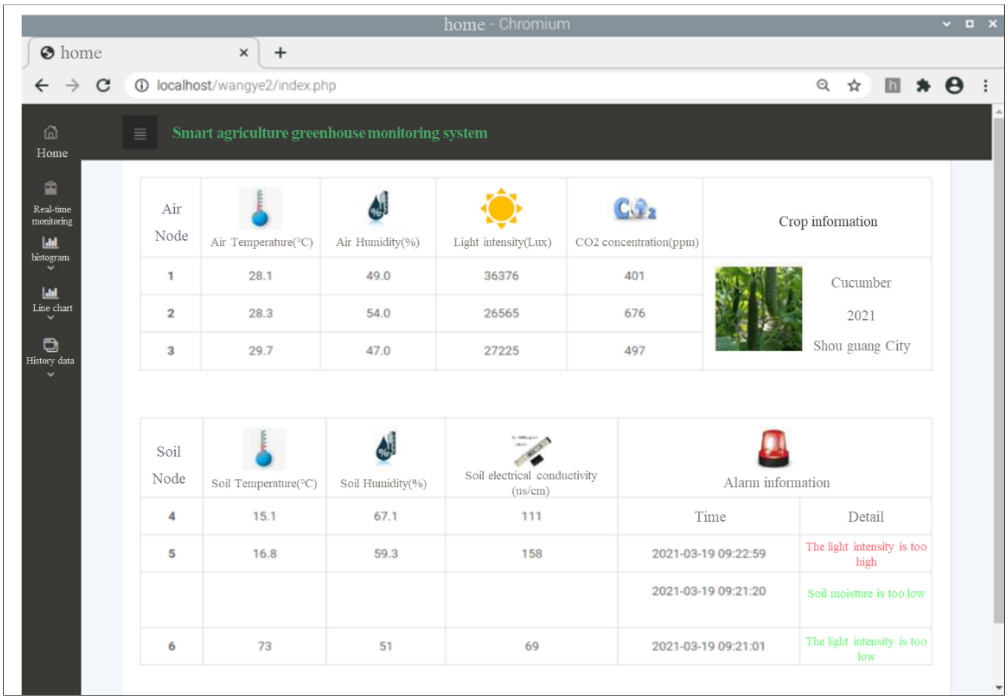

Figure 8: Real-time data display of six nodes on the Web side.

3.2 Kalman Filter Processing Comparison

To further verify the noise reduction effect of the Kalman filtering algorithm on the system, raw data collection was performed on node 1 during the 8:00 to 18:00 time period. Data was collected at a frequency of 1 sample per minute, totaling 600 sets. Temperature data was selected for analysis. A Kalman filtering algorithm program was written in MATLAB, and comparison results before and after filtering were generated (Figure 9).

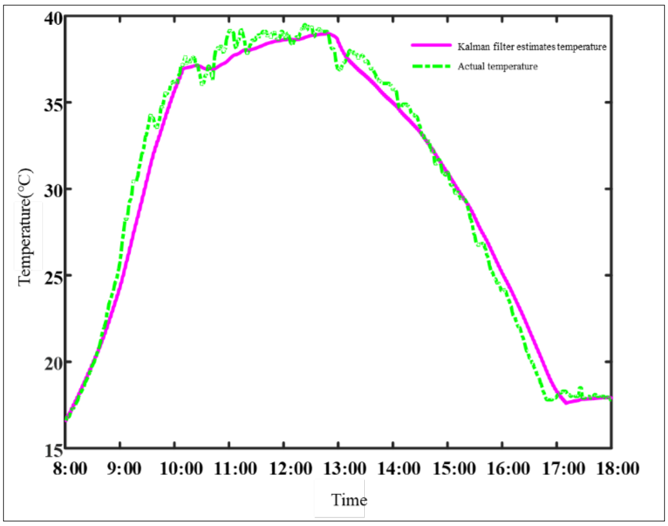

Figure 9: Comparison of Kalman filter processing.

The temperature fluctuations were significant, prone to oscillation, leading to unstable data readings at the monitoring end. After applying the Kalman filter, the collected data became smoother, reducing the instability caused by frequent fluctuations, effectively reducing external interference and sensor measurement errors, resulting in data closer to actual conditions. Around 18:00, the temperature change slowed down, likely due to the farmer operating the curtain machine to cover and insulate. These results confirm the significant noise reduction effect of the Kalman filtering algorithm in the practical application of this system, effectively improving data quality.

3.3 System Reliability Test

To verify whether the wireless communication between the system's collection nodes and the Raspberry Pi receiver end is normal, packet loss rate was used as an indicator. Packet loss may occur during data collection and transmission due to environmental factors or distance. The packet loss rate, which represents the proportion of lost packets to the total sent, reflects the quality of communication. A high packet loss rate indicates poor communication, meaning the receiver cannot properly receive data from the collection end, resulting in the web end being unable to display greenhouse data properly, affecting users' understanding of greenhouse environmental information and their ability to take effective management measures.

The distance between the collection nodes and Raspberry Pi, the number of received data packets, and the packet loss rate for the typical farmer's greenhouse and the vegetable production greenhouse are shown in Table 2 - 3.

The wireless transmission using the nRF24L01 module is affected by transmission distance. Within a range of 6 m, the data packet loss rate is within 1%. In limited trials conducted in greenhouse environments, the packet loss rate increases with the distance between the collection nodes and the Raspberry Pi receiver. For the typical farmer's greenhouse, with a maximum transmission distance of 60 meters, the packet loss rate is within 4.1 %. In the vegetable production greenhouse, with a maximum transmission distance of 96 meters, the packet loss rate is within 5.9 %. All nodes in the system exhibit good communication quality (PRR > 90 %, where PRR represents Packet Reception Rate).

To further enhance the system's reliability, measures were taken to improve data packet loss. Automatic retransmission functionality of the nRF24L01 chip was utilized to automatically detect and resend lost data packets during wireless transmission. The retransmission time and frequency can be controlled via software, further reducing the packet loss rate.

In the vegetable production greenhouse, 13 sets of temperature data were collected from node 1 between 9:00 am and 11:00 am. To eliminate occasional collection errors, data was collected at 10-minute intervals and compared with readings from a standard thermometer (Figure 10). The temperature readings collected by the system closely matched those from the standard thermometer, exhibiting similar trends and high coincidence. This indicates that the designed system is highly reliable and capable of stable and continuous operation.

Table 2: Greenhouse test data of typical farmers

Acquisition node	Distance between acquisition node and Raspberry Pi (m)	Number of packets sent	Number of packets received	Packet Loss Rate
1	5	1000	995	0.5 %
2	30	1000	986	1.4 %
3	60	1000	959	4.1 %
4	5	1000	993	0.7 %
5	60	1000	963	3.7 %
6	30	1000	979	2.1 %

Table 3: Greenhouse test data of vegetable production base

Acquisition node	Distance between acquisition node and Raspberry Pi (m)	Number of packets sent	Number of packets received	Packet Loss Rate
1	6	1000	994	0.6 %
2	50	1000	968	3.2 %
3	96	1000	941	5.9 %
4	6	1000	998	0.2 %
5	96	1000	972	2.8 %
6	50	1000	974	2.6 %

The greenhouse environmental monitoring system designed in this study, based on a web server architecture, has achieved its intended goals, fulfilling all expected functions. However, further research and development can be undertaken: (1) The collection end involves multiple sensors and functional modules, consuming significant power. Consideration may be given to replacing lithium batteries with solar panels for self-powering. (2) Information fusion technology can be employed to merge data of the same type from similar nodes, making it easier for farmers to observe. (3) Threshold alarms in the greenhouse are based on a single standard throughout the day, but certain environmental parameters may vary significantly between day and night, leading to invalid alarm signals. Designing a corresponding database for time-based alarm settings could address this issue. (4) Agricultural expert guidance functionality can be added to the web interface, transmitting real-time data to agricultural experts' client applications for the dissemination of professional production advice.

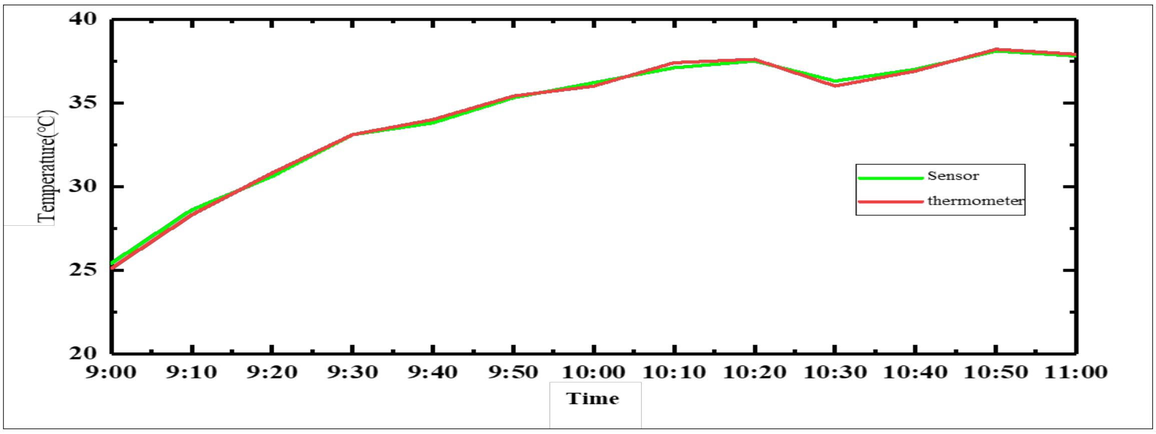

Figure 10: Results of temperature benchmarking experiment.

4. Conclusions

(1) A greenhouse monitoring system hardware and software were designed based on a web server architecture to meet greenhouse environmental requirements.

(2) The system architecture comprises environmental perception, transmission, and application layers, enabling functions such as greenhouse data collection, real-time data display, alarm notifications, monitoring, data storage, and historical data queries.

(3) Kalman filtering effectively reduces noise and measurement errors. The maximum packet loss rate is 5.9 %, indicating good communication quality and reliability of the system.

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