Design of Crop Irrigation Decision-Making System Based on ZigBee Technology

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Abstract: To promote the high-quality development of agriculture, meet the needs of agricultural products grown in greenhouses, and achieve precise monitoring of greenhouse plants, a small greenhouse micro-environment multi-parameter monitoring system was designed and implemented. The system consists of three parts: a monitoring node, a gateway node, and a remote management platform. The monitoring node used the ESP32 microcontroller as the main control chip, combined ZigBee technology, and embedded different sensors to complete the collection and transmission of environmental parameters. In the gateway node, the 4G Data Transfer Unit module was used as the carrier, and the communication protocol was used to realize data communication between the monitoring terminal and the gateway. The remote management platform was based on the PyCharm development platform. It used the PyQt5 graphical user interface (GUI) toolkit to complete the design of the host computer monitoring platform, establish a database, and realize the storage and analysis of environmental parameters. The remote management platform embedded the crop reference evapotranspiration, online calculation model, to provide irrigation decisions for greenhouse crop management and improve the applicability and accuracy of irrigation decisions. After the experimental test platform was built to test the system communication distance, communication reliability, control reliability, and data reliability, the small greenhouse micro-environment multi-parameter monitoring system designed in this paper can operate stably for a long time. Its functions meet the expected requirements and are in line with modern requirements for multi-parameter monitoring of smart greenhouses.

Keywords: Internet of things, Smart greenhouse, Remote monitoring, Wireless communication.

1. INTRODUCTION

Agriculture is the most basic livelihood industry in China, providing our people with the necessities of daily life [1]. The high-quality development of agriculture in China still faces challenges such as limited land resources, water shortage, and complex terrain conditions [2]. In recent years, greenhouse vegetable cultivation has become one of the emerging modes to carry out agricultural structural adjustment, which can help farmers to increase the yield of agricultural products under the harsh natural environment, alleviate the adverse effects of the natural environment on agriculture, and play an important role in improving the quality of life of people [3].

Conventional greenhouses lack automated monitoring equipment, and management relies on manual inspection and recording of changes in environmental factors, which suffers from monitoring difficulties and errors, leading to low productivity and reduced yields [4]. Traditional greenhouses have disadvantages such as energy waste, high labor costs, difficulties in environmental monitoring, and low productivity [3]. The continuous development of information and communication technology (ICT) has pushed various industries towards intelligence, and intelligence has also promoted agricultural production [5, 7]. Through the use of modern IoT equipment, smart greenhouses can achieve accurate analysis of crops and their surrounding environmental parameters [6,7], to achieve precise fertilizer application, irrigation, and other operations, which is of great significance in improving agricultural production efficiency [8, 9].

In recent years, many researchers have proposed new control ideas and algorithms to improve the control effect of greenhouse systems and substantially increase the level of intelligence and automation of greenhouse control systems [10]. Therefore, the research on intelligent monitoring and control of greenhouses deserves attention and innovation. In 2018, the Dutch company PHENOSPEX developed a drought simulation research platform called Drought Spotter. It uses high-precision weight sensors to monitor plants in real-time and calculate the dynamic transpiration rate and water utilization rate of each plant. It can operate stably for long periods of time and maintain high-precision automated irrigation [12]. In 2019, Gopal Chaudhary *et al*. designed a smart greenhouse based on the observer and fuzzy control using a MATLAB Simulink model for humidity and

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*Address correspondence to this author at the College of Information and Electrical Engineering, China Agricultural University, Beijing 100083, China; Tel:+86-13041254819; E-mail: cau_lihan@cau.edu.cn temperature with a Proportional-Integral-Derivative (PID) controller for CO2 enrichment, and the fuzzy inference was designed to optimize energy consumption and water use [13]. In 2021, Mellit Adel *et al*. designed a novel smart greenhouse remote monitoring system using IoT and deep convolutional neural networks to build a sensor network with appropriate sensors and a low-cost Wi-Fi module (NodeMCU V3). A low-cost camera is used to capture plant images, which enables remote monitoring and control of the greenhouse and can identify the state of the plants [14]. In 2022, Sultana Jahan Soheli *et al*. designed a smart greenhouse monitoring system utilizing IoT and AI, where the collected environmental data is fed into a fuzzy control system. The fuzzy control system processes the data and predicts the optimal values of meteorological parameters by ANFIS. This can allow farmers to monitor all the data and make informed decisions about the best temperature and humidity levels [15]. In 2023, Ikhlas Ghiat et al. developed a deep neural network model capable of predicting crop transpiration in greenhouse environments, which can be more accurately predicted to optimize greenhouse irrigation through the use of Hyperspectral-physiological techniques and deep learning models [31].

The Internet of Things (IoT) is a network that establishes connections between things and is one of the crucial technologies in the field today. Both at home and abroad take IoT as an important research content. In 2009, China put forward the IoT development strategy of "Sensing China", and the IoT of facility agriculture is one of the important applications. The development of wireless sensor networks also promotes the innovation and application of the IoT in agriculture. In 2018, Zhang XF *et al*. designed a ZigBee-based multi-coordinator backup mechanism for a greenhouse environment monitoring system to reduce the risk of damage caused by a single coordinator. greenhouse environment monitoring system, reducing the probability of system paralysis due to the failure of a single coordinator and improving the stability and safety of environmental data transmission [17]. In 2019, Niu PJ *et al*. designed a wireless greenhouse intelligent monitoring system based on multi-network fusion and node positioning technology, where each monitoring device is connected through ZigBee, Wi-Fi, and infrared, and designed to implement a system with environmental parameters collection and indoor positioning function of the ZigBee node, which has certain application value [18]. In 2021, Wan Y *et al*. designed an intelligent greenhouse group monitoring system based on Long Range (LoRa) technology, with STM32F103C8T6 microcontroller as the main controller chip, ATK-LoRa-01 SX1278 wireless module, and Narrowband Internet of Things (NB-IOT) module to achieve wireless communication, which can be used for long-distance monitoring of greenhouse clusters consisting of two and more greenhouses [19]. In 2022, Zhu DL *et al*. designed an intelligent monitoring system for greenhouses based on the Internet of Things (IoT), constructed a mathematical model of greenhouse temperature and humidity changes through experiments, and proposed a sub-time period multi-temperature interval control strategy, which can realize the remote and precise regulation of temperature and humidity [20]. In 2023, Mathi *et al*. proposed an IoT-based smart agriculture solution that uses machine learning algorithms to accurately predict the amount of water needed for farmland and automatically identify pests based on the requirements of the farmland with 84% identification accuracy to improve the efficiency and sustainability of agricultural production [32].

In summary, it can be seen that the improvement of science and technology content and technology level has become an inevitable trend of greenhouse development [17]. However, some of the existing research still stays at the simulation level and lacks practical application support. Besides, some intelligent greenhouse monitoring system functions are rich, but the cost is high, which is not conducive to market promotion and application, and there is a low practicality of the design, which makes it difficult to popularize the environmental monitoring and control of small greenhouses, and it is impossible to solve the problems of single-plant accurate monitoring and control [21]. Based on ZigBee technology, this paper designed a multi-parameter monitoring system for the micro-environment of small greenhouses. The system utilized ZigBee technology to design the communication network, enabling the collection and control of greenhouse environmental information. Using the 4G-DTU module as the carrier, the system employs TCP/IP communication protocol to achieve data communication between the monitoring system and the gateway node, and develops the upper computer monitoring system with Python programming language. Furthermore, the system study intelligent irrigation methods for the greenhouse environment, designed an automatic irrigation method based on weight measurement and water balance analysis, and achieved precise irrigation for individual plants.

The paper consists of five main sections, which were as follows:

INTRODUCTION: Study and analyze the related technologies of greenhouse monitoring system at home and abroad, and put forward the main work and research content of this paper.

SYSTEM DESIGN: Describe the system composition and hardware and software design scheme.

METHOD: Study two different methods of irrigation decision making to achieve plant water demand and water conservation.

RESULT AND ANALYSIS: Test and draw conclusions on various parts of the system.

CONCLUSION: Summarize this paper and present effective open problems and future issues.

2. SYSTEM DESIGN

2.1. System Overview

The crop irrigation decision-making system proposed in this paper, consisted of three parts: the monitoring node, the gateway node, and a remote management platform. Figure **1** shows the block diagram of the system design. The subsystems were designed to be independent, reliable, and flexible. This design approach offers several advantages in dealing with uncertainty, disturbance, and model-reality mismatch. The independence of the subsystems ensures that any issues or uncertainties in one subsystem do not affect the others, thus minimizing the overall system's vulnerability to uncertainties. Furthermore, the flexibility of the subsystems facilitates easy troubleshooting, maintenance, replacement, and upgrading. It allows for adaptive adjustments and optimizations to be made as needed.

2.1.1. Monitoring Node

The monitoring node consisted of a power supply, the CC2530 microcontroller, the ESP32 microcontroller, sensors, and an actuator module. The Monitoring Node is mainly responsible for data acquisition, equipment control, and local data transmission. The ESP32 microcontroller serves as the core unit to analyze and process the greenhouse environment data. The CC2530 microcontroller served as a terminal node, responsible for establishing a wireless sensor network, enabling wireless data transmission, exchanging data with the ESP32 microcontroller, receiving broadcast data from the coordinator, and requesting sensor data on demand.

2.1.2. Grid Node

The gateway node consisted of a power supply, the CC2530 microcontroller, the 4G-DTU module, and the RS232 to TTL module to complete the work of data remote transmission. Among them, the CC2530 microcontroller served as a coordinator to receive environmental data uploaded by the terminal and communicate serially with the 4G-DTU module, and the data was uploaded to the remote monitoring platform by the 4G-DTU module; when the 4G-DTU module received control commands issued by the upper computer, it would be broadcasted to the terminal by the coordinator.

2.1.3. Remote Monitoring Platform

The remote monitoring platform was built upon PyQt5 (Python Qt Toolkit 5) to realize the functions of

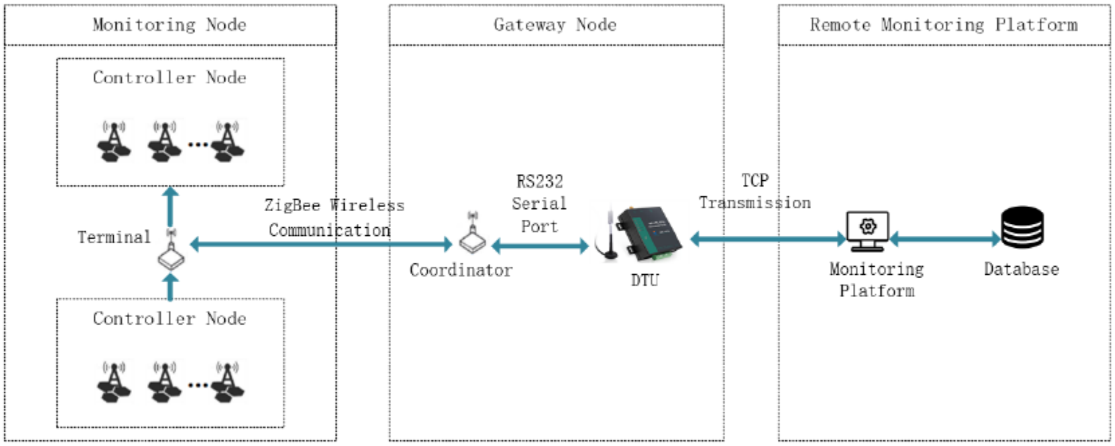


Figure 1: Block diagram of system design.

data display and storage, and irrigation decision-making. Users can monitor the growing environment and state of crops in each pot on the PC, and realize the precise irrigation for different crops and crop growing environments with different growing periods.

2.2. Hardware Framework

The hardware of the Crop irrigation decision-making system consists of a microcontroller, four sensors, the ZigBee modules, and a 4G-DTU module. Figure **2** shows the system hardware composition. In addition, the specific types and functions of all devices are shown in Table **1**.

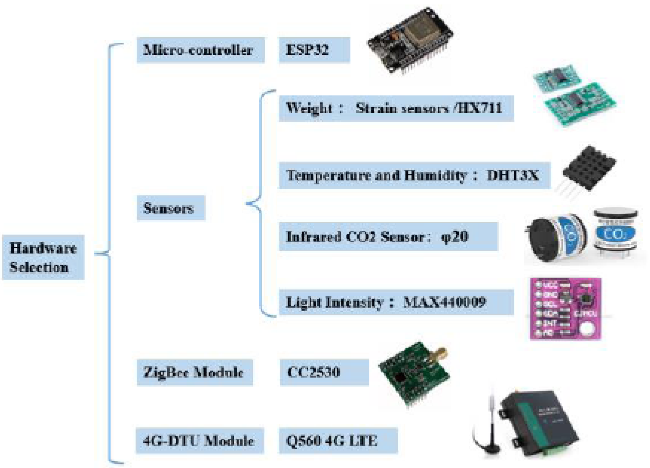


Figure 2: System Hardware Composition.

2.2.1. System Hardware Selection

To ensure stable and efficient processing, the system selects a low-power, high-performance ESP32-DevKitC microcontroller as the main control of the system. It adopts a dual-core 32-bit processor with a main frequency of up to 240MHz and has a built-in 512KB SRAM and 4MB flash memory. With multiple GPIO pins and a variety of communication interfaces, including SPI, I2C, and UART, it can be used to communicate and interact with other devices or sensors.

The sensors include four parts: DHT3X temperature and humidity sensor, MAX44009 light intensity sensor, HX711 strain sensor, and φ20 infrared CO2 sensor. Among them, DHT3X was used to measure the temperature and humidity of the environment, which has the characteristics of easy-to-use, low cost, and high measurement accuracy. MAX44009 was used for light intensity measurement, which has the characteristics of high accuracy, low power consumption, and ease to be integration. HX711 was used for the weight detection of crops, which adopts the patented technology of Haixin Technology's integrated circuits and is a kind of 24-bit A/D converter chip commonly used in the weight detection application, with the characteristics of high accuracy, low power consumption, and easy to be integrated. HX711 was used for crop weight detection. HX711 is a 24-bit A/D converter chip commonly used in weight detection applications, which has the advantages of high precision, low noise, low power consumption, and ease of use. The infrared φ20 CO2 sensor was used to detect the carbon dioxide concentration in the crop environment, which has characteristics of high precision, high sensitivity, and low power consumption.

The designed system used the ZigBee wireless module for the network end node, and it was used for setting up the wireless sensing network. The star topology network structure was chosen. The ZigBee wireless module used the CC2530 chip produced by Texas Instruments, which has a built-in IEEE 802.15.4

Table 1: Specific Models and Functions of Equipment

Constitute	Model	Function
Micro-controller	ESP32	Analyze, process, and control greenhouse environmental data as a core unit
Strain sensors	HX711	Weight detection of crops
Temperature and Humidity sensors	DHT3X	Measure the temperature and humidity
Infrared CO2 Sensor	φ20	Detect the carbon dioxide concentration in crop environment
Light Intensity Sensor	MAX440009	Light intensity measurement
ZigBee Module	CC2530	Act as an end node and is responsible for setting up the wireless sensing network
4G-DTU	Q560-4G LTE	Receive terminal data for uploading to the remote platform and receiving control commands from the upper computer

RF transceiver and an 8051 microcontroller. It is characterized by low power consumption, high performance, and low cost, which meets the design requirements of a small greenhouse monitoring system.

Q560-4G LTE DTU is a Netcom wireless data transmission terminal device, designed and produced by Chengdu Mobile Technology. The device adopts 4G/3G/2G network adaptive technology, can be connected to a variety of industrial communication interfaces, such as RS232, RS485, etc., and provides fully transparent data, protocol transmission, and other protocols working modes, which has the advantages of diversified communication modes, rich communication interfaces, and strong processing capability. It can meet the requirements of long-distance data transmission between gateway nodes and the remote monitoring platform in a greenhouse environment.

2.3. Hardware Circuit Design

2.3.1. Weighing Module Circuit Design

The weighing module is mainly composed of three parts, including microcontroller pin extension, HX711 module, and a power supply circuit. Figure **3** shows the weighing module circuit design, and its circuit design is as follows:

Power supply circuit: The 7805 series buck tube using integrated circuit technology, can be stabilized to output 5 V DC voltage. This system uses lithium batteries to provide 12 V input voltage, using 7805 power supply system power supply conversion to 5V. To mitigate sudden voltage fluctuations and filter out high-frequency noise, capacitors C9 and C10 are connected in parallel at the output end of the power supply. Furthermore, to prevent excessive voltage backflow at the output terminal during power failures, capacitors C11 and C12 are connected in parallel.

HX711 module: Considering that the output of the bridge sensor is analog and of a small magnitude, it is necessary to amplify, filter, and convert the signal using the HX711 module. The analog differential input of Channel A is connected to the differential output of the bridge sensor. The DOUT pin is connected to ESP32 pin 14, and the PD_SCK pin is connected to ESP32 pin 12.

2.3.2. Water Pump Module Circuit Design

The water pump control module consists of a microcontroller pin extension, a relay module, and a power supply module. The SRD-05VDC-SL-C is a common single-cut electromagnetic relay, also known as a 5 V relay. Rated voltage of 5 V, the flow rate of 25 ml / s pump power line into the terminal J1. IN port and CC2530 pin P0_4 is connected, when the IN port gets a high level, the relay suction, and the pump open. Figure **4** shows the water pump module circuit design.

2.3.3. Gateway Node Circuit Design

The gateway node circuit module consists of a coordinator, a TTL to RS-232 module, and a power supply circuit. Considering that the CC2530 serial port adopts the TTL level and 4G-DTU adopts the RS-232 serial protocol, it is necessary to use the MAX3232 chip to convert the TTL level to the RS-232 level. AMS1117 is a widely used linear voltage regulator chip with the

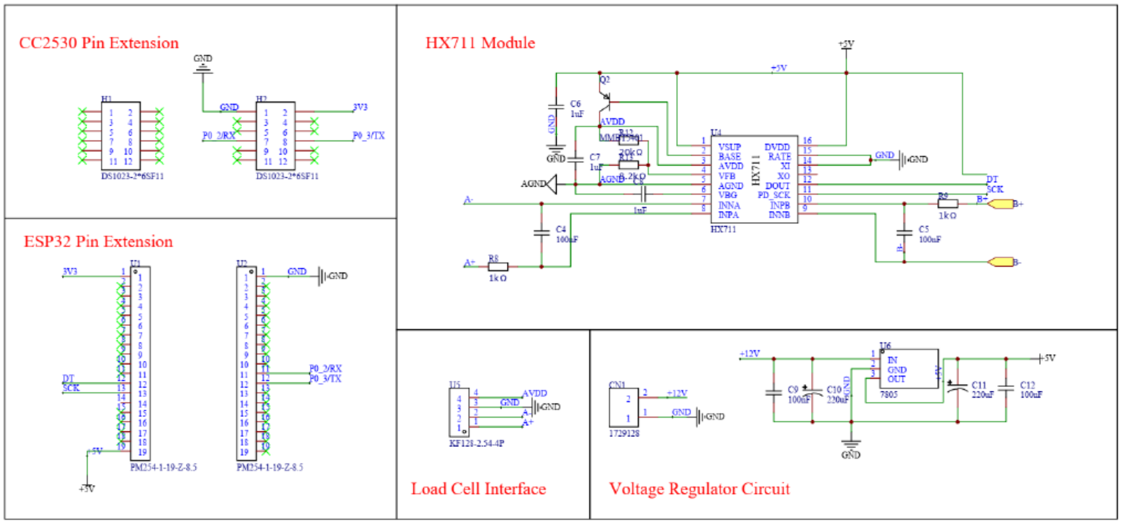


Figure 3: Weighing Module Circuit Design.

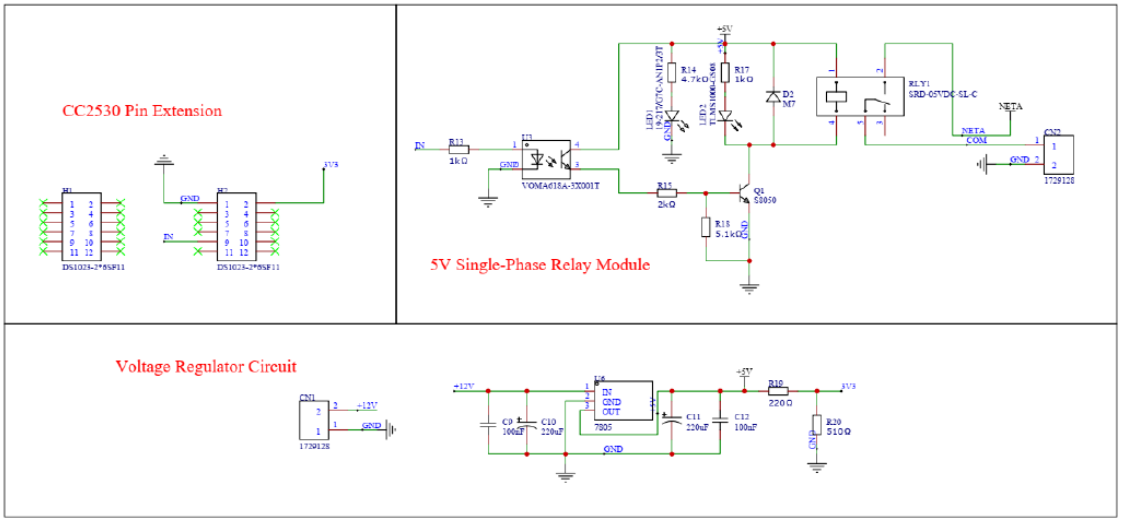


Figure 4: Water Pump Control Module Circuit Design.

advantages of small size, low cost, strong protection, etc. In the gateway node circuit, AMS1117-3.3 is used to reduce the input voltage to 3.3 V. The gateway node circuit diagram is shown as follows The input voltage is reduced to 3.3 V. Figure **5** shows the gateway node circuit design.

2.4. Software Framework

The small greenhouse microenvironment multi-parameter monitoring system designed in this paper mainly includes two parts: embedded software development and a PyCharm-based remote management platform.

2.4.1. Embedded Software Development

(1) ZigBee module software design

This system adopts a star topology network structure, so the software design is mainly divided into two parts: coordinator and terminal.

The terminal node is responsible for uploading sensor data to the coordinator and receiving control commands from the coordinator. The coordinator node is responsible for broadcasting control commands and receiving environmental parameters collected by the terminal.

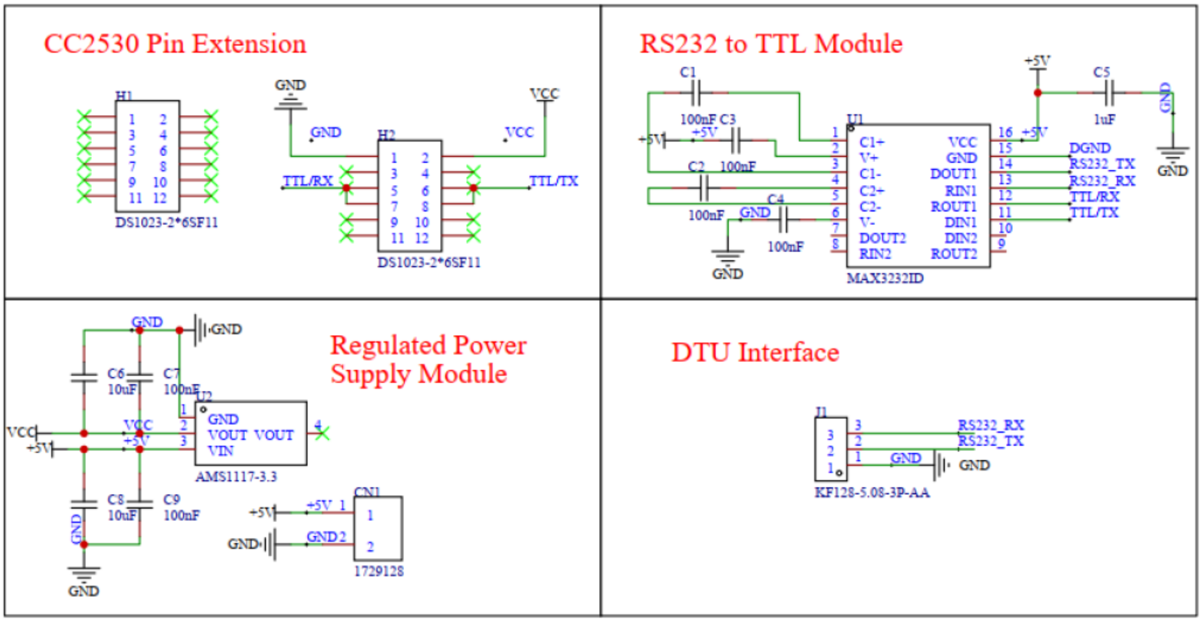


Figure 5: Overall circuit design for gateway nodes.

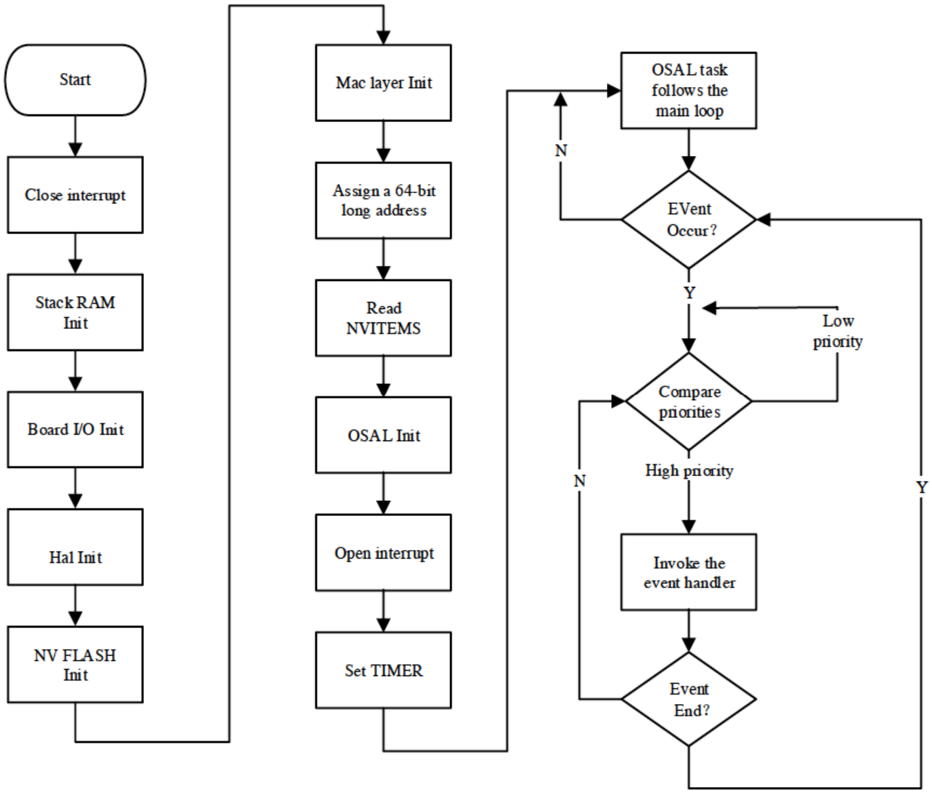


Figure 6: Overall program flow of the ZigBee module.

After the coordinator is powered on and initialized, it will first perform network detection. If it detects that there is no existing network around it, it starts channel scanning to find an available channel. If it finds a free channel, the coordinator sets up a new PANID and establishes a local area network (LAN), which is used to connect the coordinator to nearby terminal nodes. Figure **6** shows the overall program flow of the ZigBee module.

(2) Software design of weighing module

This part of the software uses the HX711 library to access the ESP32 development board and sets the scale value concerning the input digital quantity of HX711 and the actual weight. The scale-converted weight data is output to the UART2 serial port according to a certain protocol.

(3) Irrigation module software design

This part of the software is responsible for processing the control commands issued by the host computer. The host computer sends control commands according to a certain communication protocol. The CC2530 analyzes the control instructions, determines the control equipment number, and turns on the water pump.

2.4.2. Remote Management Platform Software Development

(1) Database Design

To effectively query and manage greenhouse data, this paper designed a greenhouse data table for storing environmental data based on the MariaDB database.

At the same time, the monitoring system designed in this paper used SQL language to write a series of database operation functions for different needs in practical applications, including greenhouse data query function, average temperature query function in hours, and average humidity query function in hours.

Five environmental parameter tables are mainly set up in this system, which is used to store parameter data such as temperature, humidity, carbon dioxide concentration, light intensity, weight, and so on. Each table includes six fields, the specific meaning of which is shown in Table **2**.

Table 2: Meanings of Parameter

Parameter	Meaning
Temperature	Storage of temperature data
Humidity	Storage of humidity data
Illumination	Storing light intensity data
Carbon_dioxide	Storage of CO2 concentration data
Weight	Storage of weight data

(2) Monitoring interface design

In this paper, we use the PyQt5 GUI (Graphical User Interface) toolkit in the Python programming language environment to design the monitoring interface, including real-time monitoring, historical data query, and irrigation program setting and processing. Figure **7** shows the overall program flow of the ZigBee module.

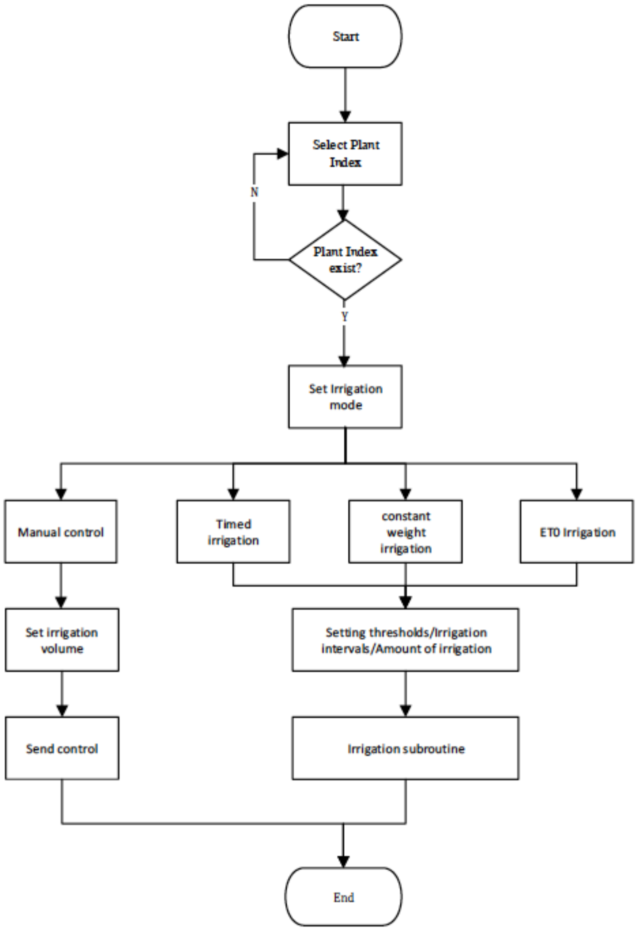
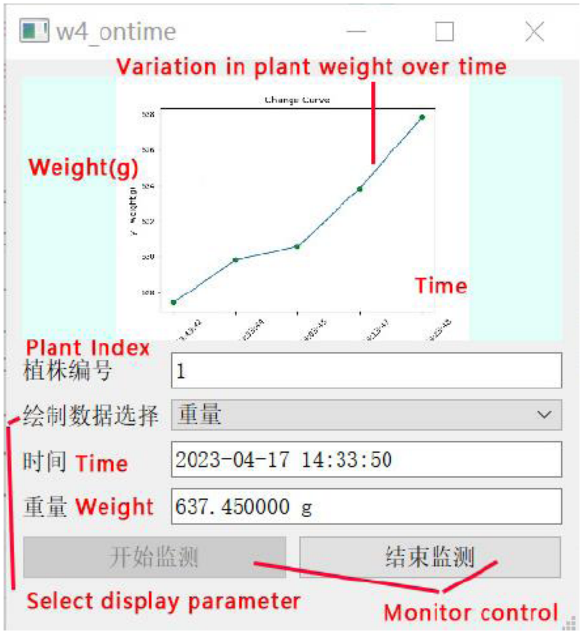


Figure 7: Overall program flow of the ZigBee module.

Figure **8** shows the real-time monitoring window, it is mainly responsible for the real-time display of greenhouse data and trend line plotting. Users can select the sensor type and node ID they want to monitor and visualize the changes of environmental parameters in the greenhouse.



植株编号 1

绘制数据选择 重量

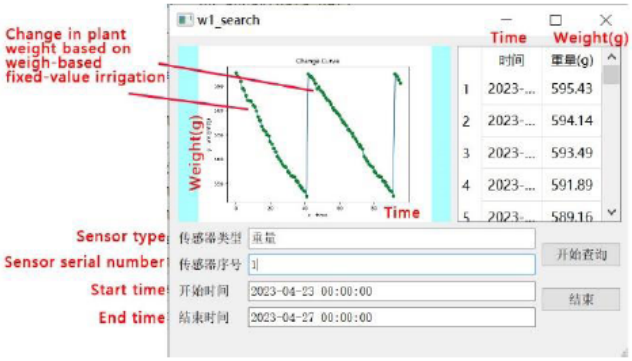
时间 Time 2023-04-17 14:33:50

重量 Weight 637. 450000 g

Figure 8: Real-time monitoring window.

The historical data query window mainly realizes the query display of the greenhouse historical environmental data and presents it to the user in the form of drawing charts and line graphs. Users can input the start time and end time, and select the sensor number and type to realize the monitoring of greenhouse data in the specified period. Figure **9** shows the historical data inquiry window.

The Irrigation Mode Settings window is used to select the irrigation scheme. Users can specify the plant number and set the working modes of manual irrigation, timed irrigation, fixed-weight irrigation, and automatic irrigation based on the water balance analysis method. Figure **10** shows the Irrigation mode setting window.



	时间	重量(g)
1	2023-...	595.43
2	2023-...	594.14
3	2023-...	593.49
4	2023-...	591.89
5	2023-...	589.16

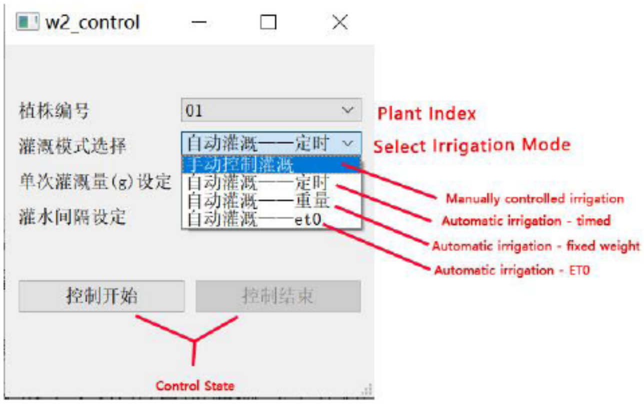
传感器类型 重量

传感器序号 1

开始时间 2023-04-23 00:00:00

结束时间 2023-04-27 00:00:00

Figure 9: Historical Data Inquiry Window.



植株编号 01

灌溉模式选择 自动灌溉——定时

Figure 10: Irrigation mode setting window.

3. METHOD

Traditional greenhouse irrigation methods usually use time control, according to a certain time interval to turn on the irrigation system for watering. However, this method is not ideal for crops at different stages of growth and can lead to waste and water shortages.

It is important to find a reasonable and feasible irrigation scheme to realize the water demand of crops and save water resources. To realize water balance, this paper sets two automatic irrigation schemes based on the weighing method and water balance analysis method.

3.1. Irrigation Strategy Based on Weighing Method

This system is designed to automatically regulate irrigation based on real-time data collected from the load cell. The irrigation decisions based on weight are typically made by calculating the amount of irrigation water required in weight units. Before this calculation can be made, we should determine the crop's growth cycle and its water demand at each growth stage. Then, at each stage of growth, weighing decisions are made to determine the amount of irrigation water required for each crop. This method determines when and how much water to irrigate by monitoring crop weight changes in real time, as well as soil moisture evaporation, which can be achieved through the use of load cells and automatically controlled pumps [25, 28].

By using this irrigation strategy, the weighing device, a pump, a planter, a plant crop, and a bucket are formed into a single irrigation unit. Figure **11** shows the schematic diagram of the composition of the irrigation unit.

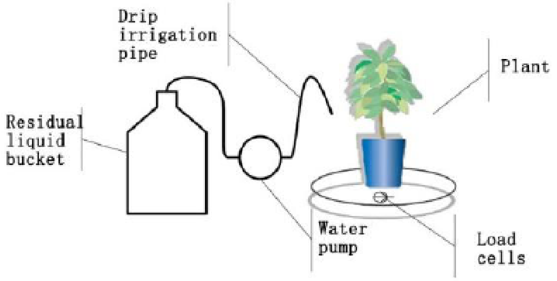


Figure 11: Schematic diagram of the composition of the irrigation unit.

Figure **12** shows the physical drawing of the weighing module. The pot has a diameter of 13 cm, and an electronic scale is installed under each tomato plant pot respectively. The electronic scale is designed based on the parallel beam load cell, the HX711AD conversion module, and the microcontroller. For the digital-to-analog conversion module, the HX711 product from the China Haixin Technology Company was selected. Through the load cell to collect voltage data, the use of the HX711AD conversion module on the bridge sensor output analog amplification filtering, digital-to-analog conversion, and microcontroller to collect the HX711 output digital quantity, and with the actual weight of the linear fit, to achieve the conversion of the voltage and weight to get the accurate weight data to determine the amount of water required by the crop, and ultimately through the microcontroller to the data collection interval control.

Figure 12: Physical drawing of the weighing module.

The system provides a user-defined preset weight parameter function for each pot of plants, through the online weighing of each crop and container, the real-time acquisition of load cell data, the calculation of cumulative evapotranspiration, and comparison with the preset weight of each pot of plants, to be able to judge its state of water shortage, the appropriate amount of water supplementation, preventing the supplementation of too much or too little water. Thus, when the crops are in different climates, different growth cycles, etc., the system has good robustness to cope with a variety of situations and make irrigation decisions according to the actual situation, and the specific robustness verification is discussed in detail in the next section.

3.2. Irrigation Strategy Based on the Water Balance Analysis Method

Irrigation strategy based on the water balance analysis method calculates the reference crop's ET0 using meteorological data and sensor-collected information. This value is then multiplied by the crop coefficient Kc to obtain the actual crop's evapotranspiration rate (ETC), which serves as a basis for determining the crop's water requirements [26]. Users can determine whether irrigation is necessary for the day by querying the water balance value from the start of irrigation until the current day.

3.2.1. ET0 Calculation

Considering that the water-heat transport patterns are quite different between solar greenhouse and open-air environments, J Wang *et al*. analyzed the applicability of the P-M (Penman-monteith) formula based on experiments under the condition of wind speed of 0 in the solar greenhouse, and proposed a calculation method to calculate the amount of evaporative transpiration of crops in the solar greenhouse [27]. The P-M formula takes into account the atmospheric, crop, and other factors, and puts the energy balance, aerodynamic resistance, and surface resistance together to calculate crop evapotranspiration, which can effectively ensure the water supply of crops.

The P-M formula is categorized into hourly, daily, and monthly calculation methods on a time scale, and the hourly-scale P-M formula is more accurate when hourly environmental data can be obtained. In this paper, the hourly calculation method is used to calculate the current ET0. The modified Penman-monteith formula is shown in formula 1.

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\frac{1713(e_a-e_d)}{T+273}}{\Delta+1.64\gamma} \tag{1}$$

The meaning of each variable is shown in Table **3**

Table 3: Meaning of Each Parameter

Variable	Meaning	Unit
ET0	Crop evaporation	Mm/day
Rn	Average net radiation on the crop surface	MJ/m^{2}day^1
G	Soil heat flux	MJ/m^{2}day^1
T	Average temperature	℃
e_d	Saturated water vapor pressure	KPa
e_a	Actual vapor pressure	KPa
Δ	Slope of saturated water vapor pressure curve	KPa/℃
γ	thermometer constant	KPa/℃

3.2.2. ETc Calculation

Crop coefficient Kc can reflect the impact of different crop types and different reproductive periods on evapotranspiration, which is a dynamic change in a growing season [29], Figure **13** shows the time period average crop coefficient change process [28]. The reference crop evapotranspiration ET0 and the crop transpiration coefficient Kc can be multiplied to get the actual crop evapotranspiration ETc. The actual crop evapotranspiration ETc is the sum of soil evaporation and crop transpiration, which can approximate the crop standard for calculating crop water demand [30]. The actual crop evapotranspiration ETc is the sum of soil evaporation and crop transpiration, which can be approximated as the standard for crop water requirement calculation [30]. In the paper, the FAO recommended ETc was used for online calculation, The ETc calculation formula is shown in formule 2.

$$\mathrm{ET}_c = ET_0 \times K_c \tag{2}$$

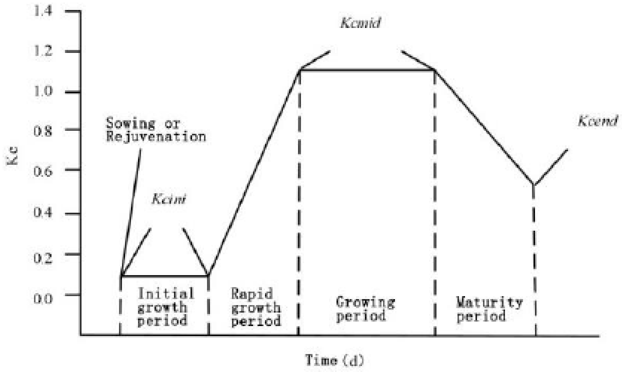


Figure 13: Crop coefficient change process line.

3.2.3. Digitization of Water Balance Model

With the increasing shortage of water resources, it is very important to rationally calculate the irrigation water demand of crops. This system calculated and published the daily water balance value of the greenhouse through formules 3. The water balance value of the day was the cumulative rainfall minus the cumulative ETc since the sowing date. When the water balance value is negative, it means water shortage. When it is positive, it means no water shortage. Since the rainfall of the greenhouse is 0, the value of cumulative ETc represents the water shortage condition of the crop. The system calculates ET_0 every hour, and can determine whether to irrigate and automatically irrigate by judging the water balance value so far on the day of irrigation.

$$b = r - ETc \tag{3}$$

b represents the water balance value, r represents the rainfall, and ETc represents the actual crop evapotranspiration.

Based on the modified Penman's formula to calculate the crop reference evapotranspiration ET0, combined with the crop coefficient Kc to calculate the actual crop evapotranspiration ETc, the amount of irrigation required for crops in the solar greenhouse can be determined. Through accurate measurement and calculation, it can meet the water demand of crop growth without wasting water, and also avoid problems such as soil salinization caused by overwatering.

4. RESULT AND ANALYSIS

4.1. System Physical Demonstration

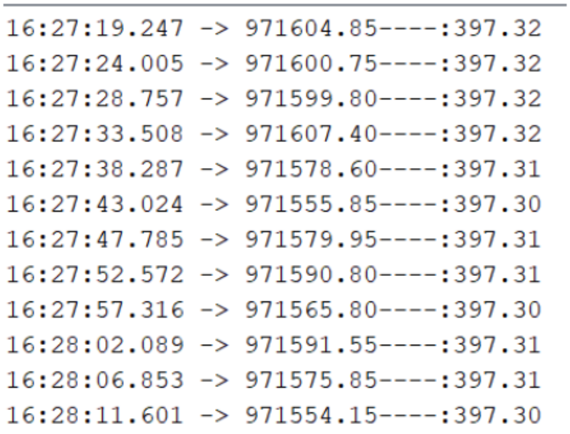
To test the system, a small greenhouse model was built in the laboratory, and while accessing the greenhouse data acquisition nodes for temperature and humidity, carbon dioxide concentration, light intensity, etc., an irrigation module and a weighing module were configured for each pot of plants, and after testing, the functions of each module operated normally and reached the expected design goals. Figure **14** shows the small greenhouse model display.

Figure 14: Small greenhouse model display.

4.2. System Testing

4.2.1. Data Acquisition Test

In the actual test, three ZigBee networks were built, distinguished by different PANIDs and channels, which were used to transmit plant weight, pump control commands, temperature and humidity, and other environmental parameters, respectively. Each network adopted a star network topology. This section focused on the testing of the weight acquisition module. The collected weight data was outputted through the serial port and monitored using a serial port monitor. Figure **15** shows the nodal data collection situation, which shows that the data collection module can operate stably.

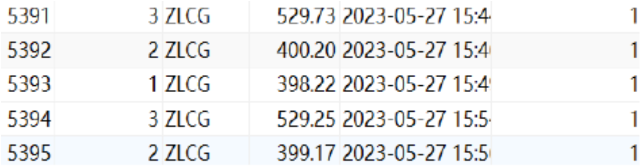


```
16:27:19.247 -> 971604.85----:397.32
16:27:24.005 -> 971600.75----:397.32
16:27:28.757 -> 971599.80----:397.32
16:27:33.508 -> 971607.40----:397.32
16:27:38.287 -> 971578.60----:397.31
16:27:43.024 -> 971555.85----:397.30
16:27:47.785 -> 971579.95----:397.31
16:27:52.572 -> 971590.80----:397.31
16:27:57.316 -> 971565.80----:397.30
16:28:02.089 -> 971591.55----:397.31
16:28:06.853 -> 971575.85----:397.31
16:28:11.601 -> 971554.15----:397.30
```

Figure 15: Nodal data collection situation.

4.2.2. Remote Communication Test

In the monitoring system designed in this paper, the 4G-DTU module was used to realize the uploading of sensor data and the issuing of control commands. This system adopted the Ansinko Technology Transmission Cloud V1.0 platform for remote communication tests. After burning the program to the gateway node, connect the computer to the serial port of the gateway node, send data to the gateway through the serial port assistant, and observe whether the PTZ can receive remote data normally. Figure **16** shows the reception situation, which shows that the remote communication function operates normally.



5391	3	ZLCG	529.73	2023-05-27 15:4	1
5392	2	ZLCG	400.20	2023-05-27 15:4	1
5393	1	ZLCG	398.22	2023-05-27 15:4	1
5394	3	ZLCG	529.25	2023-05-27 15:5	1
5395	2	ZLCG	399.17	2023-05-27 15:5	1

Figure 16: Remote communications testing.

4.3. Results and Analysis of Irrigation Decision Based on Weighing Method

A set of comparative experiments were conducted based on the principle of the weighing method, and two pots of plants were irrigated with the fixed-value irrigation mode based on the weighing method and the traditional timed-quantity irrigation mode based on the conventional timed-quantity irrigation mode, respectively. Figure **17** shows the change curves of the weights of tomato pots of No. 1 and No. 3 collected in the fixed-value and timed-quantity irrigation modes from 0:00 on April 22nd to 0:00 on April 27th, with a sampling interval of 10 minutes.

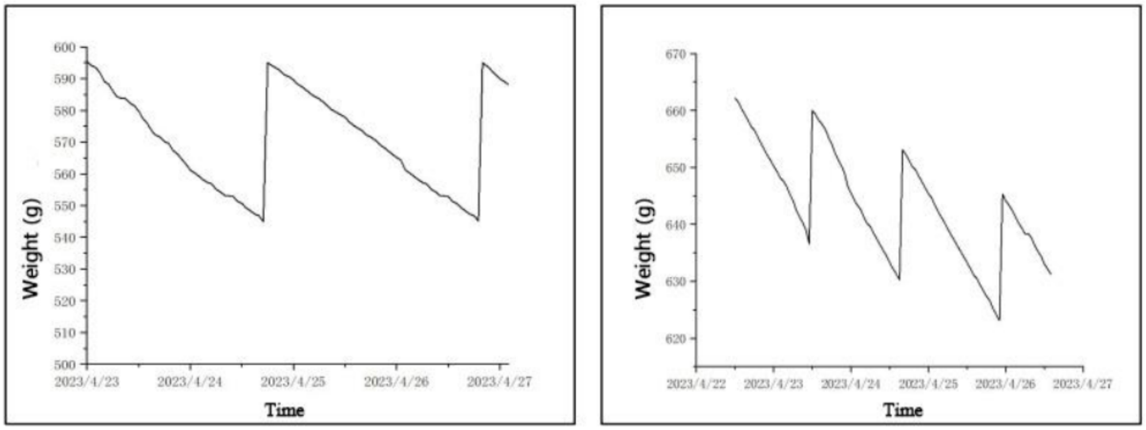
The experiments showed that the weight of the plants could always have sufficient water over the time period using the fixed value irrigation model based on the weighing method, while the potting water content of the control plants using the traditional timed and rationed irrigation model decreased over time and could not satisfy the water requirements of the plants for their growth.

4.4. Results and Analysis of Irrigation Decision Based on Water Balance Analysis Method

To observe the difference between the plant weight data and the ETc data calculated by the formula on the same day, the weight change in one day is compared with the water requirement calculated by the water balance analysis method. The system has a data comparison sub-module that visually displays the weight change of each potted plant in one day and the crop evapotranspiration change calculated based on meteorological information. The corresponding water requirement for ET can be calculated by formula 4. W is the water requirement corresponding to ET and S is the potting area.

$$\mathrm{W} = \mathrm{E}T_0 \times Kc \times S \times 0.1 \tag{4}$$

The comparison results are the records of weight and ET data changes collected during the period from 0:00 on May 18, 2023, to 0:00 on May 28, 2023. Table **4** and Figure **17** show the comparison results. From the analysis of the comparative results, the difference between weight change and water requirement was 1.52, 0.29, 0.13, and 0.19 respectively in the four days



(**a**) Fixed-value irrigation mode (**b**) Timed and rationed irrigation mode

Figure 16: Load cell data collection.

Table 4: **Comparison of Weight Change and Water Requirement**

Time (day)	Weight variation (g)	ET_0(mm/day)	ET_C(mm/day)	Water demand (g)	Difference（g）
2023-4-23	23.17	2.613	1.829	24.69	1.52
2023-4-24	24.59	2.673	1.871	24.88	0.29
2023-4-25	24.94	2.693	1.885	25.07	0.13
2023-4-26	24.78	2.683	1.878	24.97	0.19

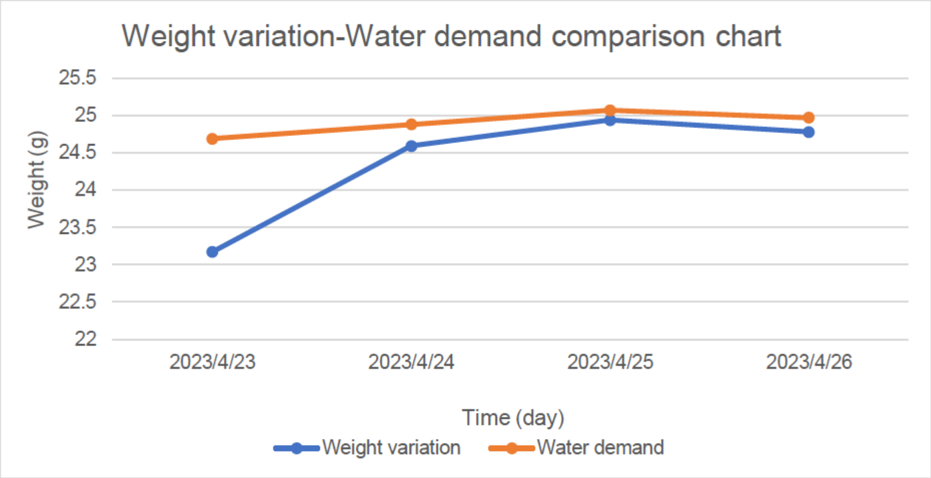


Figure 17: Weight-Water Requirement Comparison Chart.

of the experiment, which showed that with the passage of time, the weight change was close to the water requirement in the early stage of tomato growth, and the data error was controlled within 0.3g in the three days after the experiment was stable.

We can conclude that the amount of weight change is closer to the amount of water requirement in the early stage of tomato growth.

The analysis shows that during the tomato growth stage, the water weight change is closer to the ET corresponding to the amount of water required, so this method can be used to make irrigation decisions during the tomato's current growth stage.

5. CONCLUSION

This paper presented a crop irrigation decision-making system based on ZigBee technology. The system implements the scheme through software and hardware, accurately detects the growth status of crops, and monitors the environmental parameters of greenhouses in real time. Based on the Internet of Things technology, the system realized wireless transmission and control functions. At the software level, based on the weighing method and water balance analysis method, a remote management software was designed to calculate the water demand of crops online and send control commands for irrigation decisions. Through the experimental verification of the system, the crop water weight variation is closer to the crop water requirement obtained based on the water balance analysis method, with an average error of no more than 1g, which has good stability and robustness.

Although the experimental results verify that the proposed system had a good monitoring and control effect in greenhouse planting, there is still a limitation. The system is only designed for greenhouse growing environments, and its adaptability to different crops, different growth stages, and different soil types needs to be further verified.

Future work will focus on how to adjust and optimize system parameters and algorithms to suit the irrigation decision-making needs of different crops, different growth stages, and different soil types, and improve the versatility and flexibility of the system. At the same time, more diverse information such as crop physiological characteristics and meteorological factors can be considered as decision-making factors, and a more accurate and dynamic irrigation decision-making model can be established through deep learning and data mining technologies.

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