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Design of an Intelligent Detection and Regulation System for Greenhouse Environment Based on the Internet of Things

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Abstract

This paper presents an intelligent environment monitoring and control system for greenhouses based on the STM32 microcontroller. Taking STM32 as the core, the system integrates sensors for air temperature and humidity, soil moisture, light intensity, CO_2 concentration, and soil pH to collect key environmental parameters in real time, providing comprehensive data for evaluating crop growth conditions. An OLED display is adopted for on-site visualization, and a WiFi module is employed to upload data to the MQTT cloud for remote monitoring via mobile devices. Furthermore, the system realizes automatic regulation: the water pump relay is activated for irrigation when soil moisture is below the threshold, and the fan relay is triggered for ventilation when temperature, humidity, or CO_2 concentration exceeds the limit, thus maintaining stable environmental conditions. The proposed system provides a comprehensive, real-time, and intelligent solution for greenhouse management, which contributes to higher crop yield and quality, lower management costs, and possesses significant practical application value.

Keywords

STM32 Microcontroller; Greenhouse; Environment Monitoring; Intelligent Control; Sensor Module.

1. Introduction

With the rapid development of modern agriculture, greenhouse cultivation has been widely adopted worldwide due to its advantages in breaking seasonal and geographical limitations and creating a relatively stable growth environment for crops. By manually regulating internal environmental parameters, greenhouses provide suitable conditions for crop growth, effectively improving the yield and quality of agricultural products. They have become an important means to ensure food security and promote the sustainable development of agriculture[1-6].

However, traditional greenhouse management mostly relies on manual experience for monitoring and regulating environmental parameters. Managers need to enter greenhouses regularly to manually record environmental data such as temperature, humidity, and light intensity, and then decide whether irrigation, ventilation, or other operations are necessary based on these data. This approach is labor-intensive and inefficient. Moreover, due to the subjectivity and limitations of manual judgment, it is difficult to achieve accurate monitoring and timely regulation of environmental parameters. For instance, the frequency of manual monitoring decreases at night or under severe weather conditions, which may lead to failure in detecting environmental anomalies in time and thus affect the normal growth of crops. In addition, with the continuous expansion of greenhouse scales, manual management has become increasingly inadequate to meet practical demands, resulting in high management costs[7-15].

To overcome the drawbacks of traditional management and realize intelligent greenhouse environment management, intelligent monitoring and control systems based on Internet of

Things (IoT) technology have emerged. As a cutting-edge technology in the information era, IoT features powerful capabilities in information perception, transmission, and processing. By deploying various sensors inside greenhouses, environmental parameters can be collected accurately in real time and transmitted to a central processor for analysis and processing. Meanwhile, wireless communication technologies such as WiFi can be used to upload data to the cloud, enabling remote monitoring and management. Combined with intelligent control algorithms, the system can automatically actuate equipment such as water pumps and fans according to preset thresholds to precisely regulate the greenhouse environment and create optimal conditions for crop growth[11-17].

This paper aims to design an intelligent greenhouse environment monitoring and control system based on the STM32 microcontroller. Featuring high performance, low power consumption, and low cost, STM32 microcontrollers are widely used in various embedded system developments. Taking the STM32 microcontroller as the core and integrating multiple sensor modules, this comprehensive, real-time, and intelligent system can provide effective technical support for the modernized management of greenhouses, with important theoretical significance and practical application value.

2. Hardware System Design

In the IoT-based intelligent monitoring and control system for greenhouse environments, the main control module of the minimum microcontroller system adopts the STM32C8T6 microcontroller. This microcontroller features high performance, low cost, and low power consumption, with a core based on the ARM Cortex-M3 architecture, enabling efficient processing of sensor-collected data and execution of relevant control commands.

The main control module, with the STM32C8T6 as its core, is connected to several key components. It is equipped with power pins to provide stable power supply for the microcontroller and ensure its normal operation; crystal oscillator pins are connected to an external crystal oscillator to supply precise clock signals for the system; reset pins enable system reset operations, ensuring the system can reinitialize under abnormal conditions. In addition, this microcontroller has abundant I/O ports for communication with various sensor modules, OLED display, WiFi module, and relays, realizing functions such as collection, display, data upload, and intelligent regulation of greenhouse environmental parameters, serving as the core control hub of the entire system.

In the hardware design of the IoT-based intelligent greenhouse environment monitoring and control system, the reset module plays a crucial role. This module consists of a button S2, a resistor R6 (10KΩ), and a capacitor C12 (104). Resistor R6 is pull-up connected to VCC3V3, ensuring the NRST pin maintains a high level and the microcontroller operates normally when no reset operation is performed. When button S2 is pressed, capacitor C12 is short-circuited for discharge, the NRST pin becomes low level, triggering the microcontroller reset. After releasing the button, capacitor C12 charges through resistor R6, and after a certain period of time, the NRST pin restores to high level, the microcontroller exits the reset state and resumes normal operation. This reset module has a simple and reliable circuit, which can effectively ensure the system recovers to normal operation under abnormal conditions.

The design of the power interface is crucial in the IoT-based intelligent greenhouse environment monitoring and control system. The power interface in the diagram adopts a USB-B (Mini) interface, namely USB_SLAVE1. Its VCC pin is connected to 5V power input to provide basic power for the system. D- and D+ pins can be used for data transmission, which may be applied to program downloading or debugging in this system. The NC pin is unconnected. The GND pin is grounded to ensure a consistent circuit potential reference point. The 5V power supply, after processing, provides an appropriate VCC3V3 operating voltage for other modules such as the STM32 microcontroller through resistor voltage division, ensuring the stable operation of all system components and providing reliable power support for the accurate monitoring and intelligent regulation of greenhouse environmental parameters.

The crystal oscillator circuit provides precise clock signals for the STM32 microcontroller and is a key component for stable system operation. This circuit is composed of a crystal oscillator Y2 (32.768kHz) and capacitors C11 and C13 (both 20pF). The two ends of the crystal oscillator are connected to the PC14 and PC15 pins of the microcontroller respectively, and the other ends of the two capacitors are grounded. Capacitors C11 and C13 play a role in stabilizing the oscillation frequency and enabling rapid oscillation, and cooperate with the crystal oscillator to provide a stable clock reference for the microcontroller, ensuring the microcontroller can execute programs according to precise timing, thereby guaranteeing the accurate collection and processing of various environmental parameters in the greenhouse and the timely issuance of intelligent control commands to maintain the stability of the greenhouse environment.

The programming interface is an important channel for writing programs into the STM32 microcontroller. The programming interface in the diagram is J1, adopting a 4-pin Header 4 form. Among them, the SWIO pin is used for bidirectional data transmission to realize the interaction of program data between the programming tool and the microcontroller; the SWCLK pin provides clock signals to coordinate the timing of data transmission. VCC3V3 supplies 3.3V power to the interface to ensure the normal operation of the interface circuit during programming, and the GND pin is grounded to provide a stable potential reference for the entire interface. This programming interface is designed to be concise and practical, meeting the requirements of system program downloading and debugging, and laying a foundation for the realization of intelligent greenhouse environment monitoring and control functions.

The display module adopts an OLED display for real-time presentation of environmental parameters and system working status, providing users with an intuitive local viewing method. The OLED display is connected to the STM32 microcontroller through a specific interface. It can be seen from the schematic diagram that its GND pin is grounded to ensure electrical stability; the VCC pin is connected to the power supply to power the display. PB12 and PB13 pins are connected to the corresponding pins of the microcontroller respectively, and the I2C communication protocol is adopted to realize data transmission. This connection method makes full use of the pin resources of the STM32 microcontroller, and I2C communication features simple wiring and high transmission efficiency. Through this communication link, the microcontroller accurately transmits collected key environmental parameters such as air temperature and humidity, soil moisture, as well as information such as the current working mode of the system to the OLED display for presentation. Without external devices, users can quickly obtain greenhouse environmental information on-site, timely understand the crop growth environment, and provide strong support for subsequent management decisions.

The temperature and humidity detection module selects the DHT11 sensor, which has the advantages of low cost and stable performance, and can meet the requirements of greenhouse environmental temperature and humidity detection. It can be seen from the schematic diagram that the DHT11 sensor has three pins connected to the outside. Among them, the GND pin is grounded to provide a stable reference potential for the sensor; the VCC pin is connected to the power supply to ensure the normal power supply for the sensor; the DQ pin is connected to the PB14 pin of the STM32 microcontroller and is responsible for bidirectional data transmission. DHT11 adopts a single-bus data format to communicate with the microcontroller through this pin. During detection, the microcontroller sends a start signal to DHT11, and then DHT11 transmits the detected temperature and humidity data back to the microcontroller in the form of digital signals through the DQ pin. After receiving and parsing the data, the microcontroller can display it on the local OLED display on the one hand, upload it to the cloud platform on the other hand, and judge whether to start the fan for ventilation and other regulation operations according to the set threshold to ensure the greenhouse environment is suitable for crop growth.

The soil moisture detection module adopts a specific sensor that can accurately sense soil moisture conditions and provide key data for irrigation decisions. The sensor has four pins, among which the AO pin is connected to the PA1 pin of the STM32 microcontroller for outputting analog signals, the magnitude of which is related to soil moisture. The microcontroller can obtain specific humidity values through AD conversion. The DO pin can set humidity thresholds as needed to output digital signals for simple judgment. The GND pin is grounded to ensure the electrical stability of the sensor; the VCC pin is connected to the power supply to provide power support for the normal operation of the sensor. The sensor is placed in the soil to detect soil moisture information in real time. After obtaining the data, the microcontroller displays it on the OLED screen for local viewing on the one hand, and uploads it to the cloud platform for remote monitoring on the other hand. When the soil moisture is lower than the set threshold, the system automatically starts the water pump relay for irrigation to ensure the soil moisture is suitable for crop growth, facilitating the intelligent management of greenhouses.

The light intensity detection module is an important component, which is mainly responsible for real-time monitoring of light intensity in the greenhouse and providing key data support for the regulation of crop photosynthesis. In this design, the light intensity detection module adopts a specific photosensitive sensor, which can convert light intensity into corresponding electrical signals for output. When the light intensity changes, the output voltage or current of the sensor changes accordingly. The STM32 microcontroller reads the analog signal through the ADC channel and converts it into a digital quantity, and then calculates the actual light intensity value according to pre-calibrated data. The circuit design of this module is simple and reliable, with good anti-interference ability, ensuring stable operation in the complex greenhouse environment. The detected light intensity data can not only be displayed in real time on the local OLED screen but also uploaded to the cloud through the WiFi module for users to view remotely, and can be linked with other regulation modules to realize intelligent greenhouse environment management.

The CO_2 concentration detection module selects a carbon dioxide sensor, which features high precision and fast response, and can accurately measure the CO_2 concentration in the air inside the greenhouse. It has a TX (transmit pin) for data communication with the STM32 microcontroller to transmit the detected CO_2 concentration data to the microcontroller; the SCL pin may be used for some control signal transmission or connection with other buses here; the 5V pin provides operating voltage for it to ensure the normal operation of the sensor; the GND pin is grounded. By connecting the sensor detection pin to the corresponding pin of the microcontroller, such as PA10 in the schematic diagram, the microcontroller can obtain CO_2 concentration data in real time, thereby providing key parameters for judging whether the greenhouse environment is suitable for crop growth, and triggering the fan relay for ventilation and other intelligent regulation operations when the concentration exceeds the threshold.

The soil pH detection module is a key part of realizing soil pH monitoring. This module adopts a dedicated pH sensor, which can accurately measure the soil pH and provide important data for the evaluation of the crop growth environment. As shown in the diagram, the pH sensor is connected to the STM32 microcontroller through pins, where VCC and GND provide power and grounding for the module respectively, and the PO pin (connected to PA1) is used to transmit the analog signal output by the sensor. The STM32 microcontroller reads the analog signal through the ADC channel, converts it into a digital value, and then converts it into the actual pH value according to the sensor characteristic curve. This module is compactly designed with high sensitivity and stability, and can work stably for a long time in complex soil environments. The detected pH data can not only be displayed in real time on the local OLED screen but also uploaded to the cloud through the WiFi module to realize remote monitoring. Users can timely adjust soil improvement measures according to the pH data to ensure crops are in the optimal growth environment.

The WiFi module is the core component for realizing remote monitoring and data transmission. This system selects the 8266-01 WiFi module, which has the advantages of low power consumption, high stability, and easy integration, and can meet the demand for long-term continuous operation of greenhouses. The module communicates with the STM32 microcontroller through a serial port, with TXD and RXD pins connected to PA3 and PA2 pins of the microcontroller respectively to realize data receiving and sending. VCC provides operating voltage for the module, and pins such as GPIO0 and RST are used for module configuration and reset operations. In addition, a Zener diode is added to the VCC power supply line, which can effectively prevent voltage mutations from damaging the module and improve system reliability. Through the WiFi module, the system can upload collected environmental parameters to the MQTT cloud service in real time. Users only need to use smart terminals such as mobile phones to remotely view greenhouse environmental information and receive early warning information sent by the system, realizing true intelligent management and greatly improving the management efficiency of greenhouses.

The relay module undertakes the key role of controlling executive equipment. This module is mainly composed of a relay (connected to control pins such as PB10 as shown in the diagram) and related protection circuits. As an electronic control switch, the relay can control high-voltage electricity with low-voltage electricity. In this system, when the STM32 microcontroller detects specific conditions such as soil moisture being lower than the threshold, it outputs a control signal through the PB10 pin. This signal drives the relay to act through the circuit, thereby controlling the start and stop of external equipment such as water pumps to realize functions such as irrigation. The diode in the diagram plays a voltage stabilization and protection role to prevent reverse electromotive force from damaging the circuit. Through the relay module, the system realizes intelligent regulation of equipment such as water pumps and fans in the greenhouse. When environmental parameters exceed the preset range, the corresponding equipment is automatically started for adjustment to maintain the stability of the greenhouse environment and provide suitable conditions for crop growth, fully reflecting the intelligence and automation characteristics of the system.

The button module provides a local human-computer interaction method. One end of the button S in the schematic diagram is connected to the PC13 pin, and the other end is grounded. When the button is pressed, the level state of the PC13 pin changes, and the STM32 microcontroller identifies the button operation by detecting the level change of this pin. Users can switch display pages through this button, facilitating flexible local control of the system. The button module is designed to be simple, reliable, and low-cost, adding practical local control functions to the system. Combined with the remote monitoring method, it further improves the humanization and usability of the system.

The LED light module plays a supplementary lighting role. This module adopts an LED, which is connected to the PB0 pin of the STM32 microcontroller with a 680Ω current-limiting resistor R. The current-limiting resistor can prevent excessive current from damaging the LED and ensure its normal service life. VCC3V3 provides stable power for the module. By controlling the level of the PB0 pin through the microcontroller, the on and off of the LED can be realized to indicate different working states of the system, such as data transmission and alarm prompts, facilitating users to intuitively understand the system operation status locally.

3. System Software Design

In the software design of the IoT-based intelligent monitoring and control system for greenhouse environments, the main program plays a pivotal role in overall coordination. After the main program starts, it first performs system initialization, including configuration of the STM32 microcontroller's clock, GPIO ports, interrupts, etc., while initializing various sensor modules, OLED display, WiFi module, and relays to ensure all components are in normal working condition. Upon completion of initialization, the program enters the main loop. In the main loop, the program continuously calls sensor data collection functions to obtain real-time environmental parameters such as air temperature and humidity, soil moisture, light intensity, CO_2 concentration, and soil pH value. The collected data is, on the one hand, displayed in real time on the OLED screen for on-site viewing by users; on the other hand, transmitted to the MQTT cloud service via the WiFi module to enable remote data transmission, allowing users to check greenhouse environmental information anytime and anywhere through mobile devices.

Subsequently, the program compares the collected environmental parameters with preset thresholds for judgment. If the soil moisture is below the threshold, the water pump relay is automatically triggered to start irrigation; if the temperature, humidity, or CO_2 concentration exceeds the threshold, the fan relay is automatically activated for ventilation. Through this intelligent regulation mechanism, the stability of the greenhouse environment is maintained, providing suitable conditions for crop growth. The entire main program runs in a continuous loop, consistently offering comprehensive, timely, and intelligent support for greenhouse environment management.

In the software design of the IoT-based intelligent greenhouse environment monitoring and control system, the sensor data collection subprogram is of critical importance. This subprogram is developed with the STM32 microcontroller as the core. After startup, it first initializes and configures each sensor module to ensure normal operation, then enters the cyclic collection phase to sequentially read data from the air temperature and humidity detection module, soil moisture detection module, light intensity detection module, CO_2 concentration detection module, and soil pH detection module. After each data reading, preliminary verification is performed to eliminate abnormal values. Upon completion of collection, valid data is stored in the designated memory area, and the real-time data on the OLED display is updated simultaneously for local viewing. In addition, the collected data is uploaded to the MQTT cloud service via the WiFi module at set time intervals, providing data support for remote monitoring.

In the software design of the IoT-based intelligent greenhouse environment monitoring and control system, the data display subprogram is responsible for intuitively presenting collected environmental parameters to users. Relying on the STM32 microcontroller, this subprogram works closely with the OLED display. After startup, it initializes the OLED display by setting parameters such as display mode and font size. It then reads key environmental parameters (air temperature and humidity, soil moisture, light intensity, CO_2 concentration, soil pH value) collected and processed by sensors, as well as the system's current working status information from memory. These data are then displayed one by one on the OLED screen according to the preset display layout. To ensure clear and readable display effects, data formatting is performed (e.g., adding units, reasonable line breaks). Through the local OLED display, users can real-time and intuitively understand the environmental conditions inside the greenhouse.

In the software design of the IoT-based intelligent greenhouse environment monitoring and control system, the intelligent regulation subprogram is the key to ensuring the stability of the crop growth environment. With the STM32 microcontroller as the control core, this subprogram continuously reads data (air temperature and humidity, soil moisture, CO_2 concentration, etc.) collected by sensors and compares them with preset thresholds. If soil moisture falls below the threshold, the microcontroller immediately outputs a signal to activate the water pump relay for irrigation until the humidity meets the standard; when air temperature/humidity or CO_2 concentration exceeds the threshold, the fan relay is quickly triggered to start ventilation and adjust the greenhouse environment, and the system real-time monitors the operating status of regulation equipment. Through this intelligent regulation mechanism, the system can automatically maintain a greenhouse environment suitable for crop growth, reduce manual intervention, improve management efficiency, and provide strong support for high crop yield and quality.

In the software design of the IoT-based intelligent greenhouse environment monitoring and control system, the WiFi communication subprogram is a key link to realize remote monitoring. Centered on the STM32 microcontroller, this subprogram establishes a connection with the MQTT cloud service via the WiFi module. After startup, it first initializes and configures the WiFi module, including setting the working mode, connecting to the specified wireless network, and obtaining an IP address. It then completes connection to the cloud server and topic subscription in accordance with MQTT protocol requirements. During system operation, environmental parameters (air temperature and humidity, soil moisture, etc.) collected and processed by sensors are regularly encapsulated into data packets of a specific format and uploaded to the cloud service via the WiFi module. It also continuously monitors instructions from the cloud service; if remote control instructions (e.g., starting or stopping regulation equipment) are received, they are immediately fed back to the main program for execution, realizing remote interaction and control.

This IoT-based intelligent monitoring and control system for greenhouse environments is constructed with the STM32 microcontroller as the core, combined with various sensor modules, a display module, a communication module, and regulation execution modules. The physical system is compact and rational as a whole, with clear layout of each module; stable operation is ensured through reasonable circuit connection and fixation. Acting as the "brain", the STM32 microcontroller precisely coordinates the work of all modules. Sensor modules are distributed at different positions of the system to accurately collect environmental parameters. The OLED display clearly presents real-time data and system status for convenient local viewing. The WiFi module enables data upload and remote communication, while the regulation execution modules automatically adjust the environment based on collected data. All modules work collaboratively to provide reliable support for greenhouse environment management. The overall physical diagram of the system is shown in Figure 1.

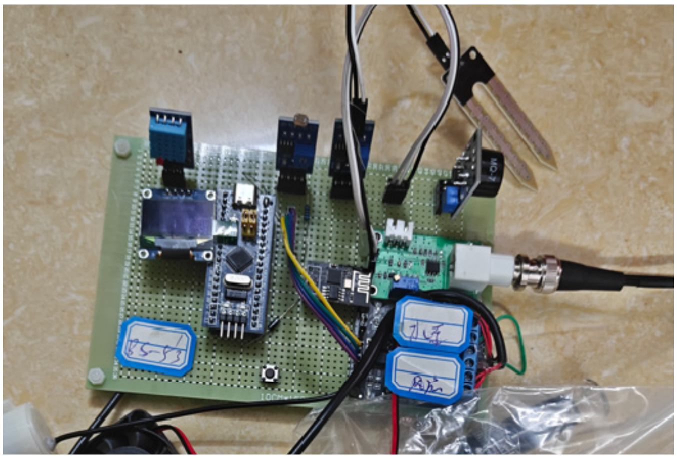

Figure 1. Overall physical diagram of the system

4. Conclusion

This paper designs and implements an intelligent greenhouse environment monitoring and control system based on the STM32 microcontroller, aiming to address the problems of high labor intensity, low efficiency, and difficulty in accurate monitoring and timely regulation in traditional greenhouse management. In terms of system design, a comprehensive system integrating environmental data collection, local display, remote transmission, and intelligent regulation is constructed with the STM32 microcontroller as the core. For hardware selection, considering performance, cost, and development difficulty, the STM32 microcontroller is adopted as the core processor, an OLED display for local monitoring, the DHT11 sensor for temperature and humidity detection, the YL-69 sensor for soil moisture measurement, and the ESP8266 WiFi module for remote communication. The hardware design elaborates on the circuit connections and working principles of the minimum microcontroller system, sensor modules, display module, communication module, relay module, and other components to ensure stable system operation. In the software design, the main program takes overall control; after system initialization, it enters the main loop to continuously collect, display, and upload sensor data, and perform intelligent regulation according to preset thresholds. Subprograms for sensor data collection, data display, intelligent regulation, and WiFi communication are developed to perform respective functions, and they cooperate with each other to guarantee normal system operation. In the system test, comprehensive tests were carried out on each hardware module. The air temperature and humidity sensor shows small measurement errors under different environments; the soil moisture sensor accurately reflects soil wetness and dryness; the light intensity sensor precisely perceives light changes; the CO_2 concentration sensor correctly indicates concentration levels in various environments; the soil pH sensor measures accurately; the OLED display provides clear and complete information; the WiFi module achieves stable data transmission and remote monitoring; and the regulation execution module responds quickly and acts accurately. In summary, the system has been fully tested, and all modules perform well, realizing the expected functions stably and reliably. By collecting key environmental parameters such as air temperature and humidity, soil moisture, light intensity, CO_2 concentration, and soil pH value in real time, displaying them locally and transmitting data remotely, the system automatically controls water pumps, fans, and other equipment according to preset thresholds to maintain a stable greenhouse environment and create suitable conditions for crop growth. This system provides users with a comprehensive, timely, and intelligent solution for greenhouse environment management, which helps improve crop yield and quality, reduce management costs, and has important practical application value

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