

Design and Experimental Evaluation of an STM32-Based Smart Agriculture Monitoring and Adaptive Control System

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ABSTRACT

This paper proposes an STM32-based smart agriculture environmental monitoring and adaptive control system integrating multi-sensor acquisition, wireless communication, and automatic actuator control. The system collects soil moisture, temperature, and light intensity data through multiple sensors, while an ESP8266 WiFi module and Message Queuing Telemetry Transport (MQTT) protocol are used for remote monitoring and control command interaction. An adaptive control strategy based on dynamic threshold adjustment and hysteresis control is proposed to improve environmental adaptability and reduce unnecessary actuator switching under changing conditions. The system controls irrigation, cooling, and supplementary lighting according to environmental variations. Experimental results demonstrate that the proposed system achieves stable sensing, communication, and control performance in an indoor simulated agricultural environment. The MQTT transmission success rate reaches 98.7% with an average delay of 146 ms, and the actuator response time remains within approximately one second. Compared with fixed-threshold control, the proposed strategy reduces actuator switching frequency by 59.1%. The results demonstrate the preliminary feasibility of the proposed embedded IoT system for smart agriculture monitoring and adaptive environmental control.

Keywords: STM32, Internet of Things, Smart Agriculture, Environmental Monitoring, Adaptive Control, MQTT, Hysteresis Control

1. INTRODUCTION

Recently, with the development of embedded systems, sensor technology and Internet of Things (IOT), intelligent graphics have become a good way to better observe the environment and manage resources. In the past, agricultural practices are now under the control of many people, and sometimes they are slow to respond or fail to make good use of resources. Therefore, small-scale smart agriculture needs more systems that can see the environment at any time and adjust automatically without spending money.

The existing agricultural systems using IoT mainly focus on collecting environmental data and watching from a distance, and the connection between sensor information and the automatic accelerator is not enough. Moreover, the method of moving with a fixed value is often used. If the value of sensor fluctuates near an important threshold, the actuator may switch frequently. This problem will reduce the stability of the system and increase unnecessary energy consumption. In addition, the reliability of communication is also important for the wireless monitoring and control system based on IoT.

In order to solve these problems, this paper puts forward an adaptive control system for intelligent agricultural environment monitoring based on STM32. The proposed system integrates multi-sensor information collection, ESP8266 WiFi communication, remote monitoring based on MQTT and automatic control of actuators. In order to improve the adaptability to the environment and reduce unnecessary actuator switching, an adaptive control method based on dynamic threshold adjustment and lag control is adopted.

The main achievements of this paper are as follows. Firstly, we made a low-cost embedded IOT platform based on STM32 for environmental monitoring and automatic control. An adaptive control strategy based on dynamic threshold adjustment and hysteresis control is introduced to improve environmental adaptability and reduce unnecessary actuator switching.

The main contributions of this paper are summarized as follows. First, a low-cost embedded IoT platform based on STM32 is designed for environmental monitoring and automatic control. Second, an adaptive control strategy combining dynamic threshold adjustment and hysteresis control is proposed to improve control stability under changing environmental conditions. Third, the system performance is evaluated through sensor accuracy testing, MQTT communication analysis,

actuator response measurement, adaptive threshold evaluation, fixed-threshold comparison, and continuous operation testing.

2. LITERATURE REVIEW

2.1 IoT-Based Smart Agriculture Monitoring Systems

IoT-based smart agriculture systems have been widely applied for real-time environmental monitoring and automated irrigation. García et al. ^[1] reviewed IoT-based smart irrigation systems and summarized the applications of sensors, actuators, and wireless communication technologies in precision agriculture. Obaideen et al. ^[2] further discussed the role of IoT-enabled irrigation systems in improving water efficiency and sustainable agricultural management.

For low-cost embedded applications, Nawandar and Satpute ^[3] developed an intelligent irrigation module based on microcontroller-based sensing and control. These studies demonstrate the feasibility of IoT-based monitoring platforms; however, many existing systems mainly focus on data acquisition and remote visualization, while adaptive control and actuator stability remain challenging.

2.2 MQTT Communication and Automatic Irrigation Control

Wireless communication is an essential component of IoT-based agricultural systems. Hunkeler et al. ^[4] introduced MQTT-S, demonstrating that lightweight publish/subscribe communication is suitable for resource-constrained sensor and actuator devices. Therefore, MQTT is widely adopted in embedded IoT systems requiring efficient data transmission and remote interaction.

Intelligent graphics also studies the method of automatic control in smart agriculture. Karar ^[5] proposed an IoT-based irrigation control system using environmental sensor data and neural networks. However, the complex intelligent algorithm has a lot of computational burden, so it is sometimes not suitable for the cheap microcomputer platform. In the embedded system using STM32, the rule-based adaptive control is not difficult to create an adaptive environment, and it has reached a proper balance between how to move.

2.3 Research Gaps

So far, great progress has been made in the research of agricultural monitoring based on IoT, but there are still some places to be improved. First, cheap systems are mostly devoted to sensing and visualization, rather than closed-loop actuator control. Second, the practice of fixing the threshold is not suitable in a changing environment. Thirdly, because the value of the sensor will fluctuate, I don't care much about the driver switching on and off many times.

In order to solve these problems, this paper proposes an adaptive control system for intelligent agriculture monitoring based on STM32. The system combines data acquisition based on multi-sensors, MQTT communication, dynamic threshold adjustment and hysteresis control. The goal of the system is to improve the adaptability to the environment and the stability of control while reducing the computational complexity.

3. METHODOLOGY

3.1 System Architecture and Data Communication

The proposed system is designed as a low-cost embedded IoT platform for smart agriculture monitoring and automatic control. As shown in Fig. 1, the system consists of four functional modules: environmental sensing, local processing, wireless communication, and actuator control.

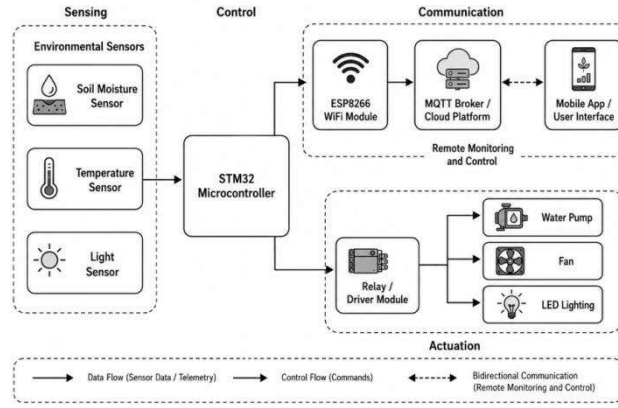


Figure 1. Overall architecture of the proposed smart agriculture environmental monitoring and control system.

The sensing module collects soil moisture, temperature, and light intensity information. The STM32 microcontroller is responsible for sensor data acquisition, filtering, decision-making, and actuator control. The ESP8266 WiFi module communicates with the STM32 through Universal Asynchronous Receiver/Transmitter (UART) and uploads processed data through the Message Queuing Telemetry Transport (MQTT) protocol. The actuator module includes a water pump, fan, and LED lighting module controlled through relay or driver circuits.

The collected sensor data are first processed by STM32 and then transmitted through MQTT for remote monitoring and command interaction. At the same time, local control decisions are performed by the STM32 to achieve automatic irrigation, cooling, and supplementary lighting control. This architecture enables both local closed-loop control and remote IoT monitoring.

3.2 Adaptive Control Strategy Based on Dynamic Threshold and Hysteresis Mechanism

To improve environmental adaptability, an adaptive control strategy is proposed. Unlike traditional fixed-threshold control, the proposed method dynamically adjusts the control threshold according to environmental conditions. Soil moisture is considered the main control variable, while temperature and light intensity are used as auxiliary parameters.

The dynamic threshold is calculated as:

$$M_{th} = M_{base} + \alpha(T - T_{ref}) + \beta(L - L_{ref}) \quad (1)$$

where M_{th} is the dynamic soil moisture threshold, M_{base} is the basic irrigation threshold, T is the current temperature, T_{ref} is the reference temperature, L is the current light intensity, L_{ref} is the reference light intensity, and α and β are adjustment coefficients.

The adaptive decision-making process is shown in Fig. 2. In order to better control the stability, hysteresis control is used. Use two different reference values instead of one switching reference value. For example, if the soil moisture is below 40%, the water pump is started, and if it is above 60%, it is stopped. When the value of moisture is within this range, the previous actuator state is maintained. The same hysteresis logic is also used in the control of fan and LED.

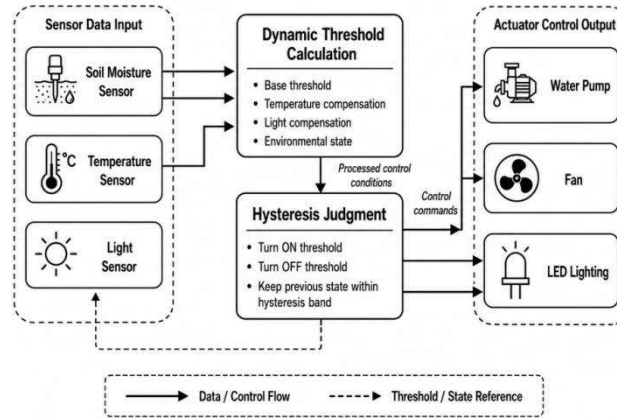


Figure 2. Dynamic threshold and hysteresis control logic.

Through this control method, the system can be prevented from switching frequently near the important threshold and the stability of the actuator can be improved. This method has less computational complexity and clear rule logic, and is also suitable for embedded systems based on STM32.

4. RESULTS AND DISCUSSION

4.1 Experimental Setup and Evaluation Metrics

To evaluate the proposed STM32-based smart agriculture environmental monitoring and adaptive control system, experiments were conducted in an indoor simulated agricultural environment. Soil moisture conditions were adjusted by adding water to the soil sample, while temperature and light conditions were varied using indoor heating and lighting sources. The test platform consisted of an STM32F103C8T6 microcontroller, an ESP8266 WiFi module, soil moisture, temperature and light sensors, a relay/driver module, a water pump, a fan, and an LED lighting module.

The sensor sampling interval was set to 2 s, and the MQTT data uploading interval was set to 5 s. The system was evaluated in terms of sensor accuracy, MQTT communication stability, actuator response time, switching reduction, and continuous operation reliability. Table1 summarizes the experimental configuration and main performance results.

Table 1. Experimental Configuration and Main Performance Results.

Item	Result
Controller	STM32F103C8T6
Communication module	ESP8266 WiFi module
Communication protocol	MQTT
Sampling interval	2 s
MQTT uploading interval	5 s
Communication test scale	1000 messages
MQTT transmission success rate	98.7%
Average communication delay	146 ms
Soil moisture average absolute error	0.83%
Temperature average absolute error	0.30°C
Light intensity average absolute error	18 lux
Water pump average response time	0.82 s

Table 1. (continued) Experimental Configuration and Main Performance Results.

Item	Result
Fan average response time	0.74 s
LED lighting average response time	0.69 s
Continuous operation test	72 h
Overall communication success rate in 72 h	98.85%

4.2 System Performance Analysis

The first experimental results show that the proposed system can provide stable environmental sensing, wireless communication, and actuator control. The soil moisture measurement had an average absolute error of 0.83%, while the temperature measurement had an average absolute error of 0.30°C. In the measurement of light intensity, the average error is slightly larger, which is 18 lux. However, the system we proposed does not use the high precision of the laboratory, but the range of threshold, so there is no problem for the cheap environmental control. We also find that the basic filtering is helpful to reduce the short fluctuation caused by the unstable contact between analog noise and sensor.

In the test of MQTT communication, 987 messages out of 1000 messages arrived successfully, with a success rate of 98.7% and an average delay of 146 ms. The value of agricultural environment often changes slowly, and if it is delayed to this extent, it is enough for real-time monitoring and remote operation. During the 72-hour continuous test, the system sent 51,840 messages, of which 51,245 messages arrived successfully, with an overall success rate of 98.85%. Although there were two disconnections of short MQTT, both of them were restored to the original state without authorization. During the test, no abnormal movement of the actuator was found.

The reaction time of the actuator is also within the range of no problem. The average reaction time of water pump, fan and LED lighting module is 0.82 s, 0.74 s and 0.69 s respectively. These results show that the control system using STM32 can respond to the use of smart agriculture quickly enough.

4.3 Adaptive Threshold Adjustment Evaluation

In order to confirm the adaptability of the proposed control strategy, the relationship between environmental conditions and threshold adjustment was investigated. Under the same soil moisture range, experiments were carried out under the conditions of changing various temperatures and light intensity. Fixed-threshold method makes the threshold of kettle always the same, but the proposed adaptive strategy will change the threshold with the change of environment.

As written in Table 2, the proposed method improves the threshold of the kettle when the temperature is high and the light is strong. This means that the controller can change the judgment standard according to the change of the environment without relying on a fixed threshold. Therefore, the proposed adaptive strategy improves the flexibility of environmental control under different operating conditions.

Table 2. Adaptive Threshold Adjustment Under Different Environmental Conditions.

Environmental Condition	Temperature	Light Intensity	Fixed Threshold	Adaptive Threshold
Normal condition	25°C	500 lux	50%	50%
High temperature	35°C	500 lux	50%	55%
Strong light	25°C	1200 lux	50%	57%
High temperature and strong light	35°C	1200 lux	50%	62%

4.4 Comparison with Fixed-Threshold Control

To further evaluate the control stability of the proposed adaptive threshold and hysteresis strategy, traditional fixed-threshold control was compared with the proposed dynamic threshold and hysteresis control under the same test conditions.

The comparison focused on actuator switching frequency, which is an important indicator of control stability and actuator lifetime.

Table 3. Comparison Between Fixed-Threshold and Proposed Control.

Control Method	Pump Switches	Fan Switches	LED Switches	Total Switches	Stability
Fixed-threshold control	18	14	12	44	Medium
Dynamic threshold + hysteresis control	7	6	5	18	High

After using dynamic threshold and hysteresis control strategy, the number of actuator switches is reduced from 44 to 18, as shown in Table 3. This is a reduction of about 59.1%. This good result is because we used the adjustment of adaptive threshold and hysteresis control together. Adaptive mechanism can improve the adaptability to the environment, while hysteresis control can reduce unnecessary actuator switching.

4.5 Discussion

The results show that the proposed system achieves the balance of low cost, practicality and control stability. Compared with the complicated machine-learning irrigation method, the proposed rule-based adaptive control strategy requires less computational resources and is easier to implement in STM 32 microcontroller. In addition, it has clear judgment logic, which is helpful for debugging and actual deployment.

However, the system still has limitations. First, low-cost sensor may be affected by environmental interference and long-term drift. Second, MQTT communication depends on the network quality of WiFi. Third, the dynamic threshold model is still rule-based, which does not include crop growth forecast and weather forecast. Future research may add sensor calibration, local data storage, energy optimization, fault detection and cloud-based data analysis to improve the system.

5. CONCLUSION

This paper presented an STM32-based smart agriculture environmental monitoring and adaptive control system integrating multi-sensor acquisition, MQTT-based wireless communication, and automatic actuator control. The proposed adaptive control strategy combines dynamic threshold adjustment and hysteresis control to improve environmental adaptability and reduce unnecessary actuator switching.

The experimental results show that the system has stable sensing, communication and control performance in indoor simulated agricultural environment. The transmission success rate of MQTT is 98.7%, and the average delay is 146 ms. Compared with control with fixed threshold, the proposed adaptive threshold and hysteresis method reduce the number of actuator switches by 59.1%.

Generally speaking, we found that the scheme system can be used initially in indoor simulated environment. In the future, we will try our best to confirm in the actual field, correct the sensor, optimize the energy and improve the reliability of the network for practical use.

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