Design of an Intelligent Rice Seedling Greenhouse Environmental Control System: A Solution Based on STM32

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Abstract: *Addressing the issues of low efficiency and insufficient precision in manual environmental control within traditional rice seedling greenhouse systems, this study designed an intelligent environmental monitoring and control system based on an STM32 microcontroller. The system integrates temperature and humidity sensors, light sensors, and soil temperature/humidity modules to collect core environmental parameters in real time. Data is transmitted wirelessly over short distances via a Bluetooth module using a serial protocol. Combining threshold control algorithms with moving average filtering technology, the system drives LED supplemental lighting and DC fans to achieve dynamic environmental regulation. Experimental validation demonstrates satisfactory performance in temperature control error, humidity response time, and light intensity regulation accuracy. Deployment costs per greenhouse are relatively low, indicating good engineering application value.*

Keywords: *Rice Seedling Cultivation; STM32; Environmental Monitoring; Bluetooth HC-05; Intelligent Control; Moving Average Filtering*

1. Introduction

1.1 Research Background and Significance

As the staple crop for over 50% of the global population, rice's seedling stage (typically 25–30 days) is critically dependent on growth conditions. These directly determine seedling vigour, subsequently influencing tillering rates and overall yield. According to the Ministry of Agriculture and Rural Affairs' 2023 Technical Guidelines for Concentrated Seedling Cultivation of Southern Early Rice [1], deviations exceeding 5 ℃ in environmental parameters or humidity fluctuations greater than 15% RH during the seedling stage increase root system malformation rates by 40%, reduce survival rates by 20–30%, and ultimately cause yield losses of 8–12%.

Traditional rice seedling greenhouse management exhibits significant shortcomings: firstly, infrequent manual inspections (only 2–3 times daily) fail to detect sudden environmental shifts (e.g., midday temperature surges or nocturnal humidity drops). A documented case saw 2,000 seedlings wither due to undetected greenhouse temperatures reaching 38 ℃; this flaw can be mitigated through appropriate temperature control strategies [2]; Secondly, adjustments rely heavily on empirical judgement. For instance, farmers often assess moisture content by "feeling the soil's dampness," with errors reaching ±15%, leading to over-drying or waterlogging. Thirdly, labour costs are high; large-scale nurseries (e.g., 50+ greenhouses) require 10–15 person-days daily, with labour costs exceeding 30% of total expenses, significantly constraining farmer profits.

With advances in embedded and iot technologies, intelligent monitoring has emerged as the key solution to these challenges[3]. This study employs an STM32-based architecture to develop a low-cost, user-friendly smart control system. Operating independently of complex networks, it enables real-time monitoring and automated regulation via mobile devices. This approach reduces labour input by over 80% while creating stable growth conditions for seedlings, holding significant practical implications for ensuring high and stable rice yields.

1.2 Research Status

1.2.1 International Research Status

Developed nations pioneered agricultural intelligence with mature yet costly technologies. The Dutch HortiMax system integrates over 20 sensors using PID algorithms to achieve temperature accuracy within ±0.3 ℃, though its per-greenhouse cost exceeds US$30,000, limiting its application to large-scale commercial farms. Japan's "Plant Factory" system employs Bluetooth BLE 5.0 for multi-device networking, supporting data transmission within 100 metres. However, its core sensors rely on imports, and algorithms remain unoptimised for rice seedling cultivation characteristics. In China's humid southern regions, this system exhibits an annual failure rate of 8% [4].

1.2.2 Domestic Research Status

Domestic research centres on "low-cost, localised" solutions. The Chinese Academy of Agricultural Sciences' "Green Seedling" system employs an STM32F407+HC-05 architecture with ±0.6℃ temperature control accuracy. However, integrating CO_2 sensors and irrigation systems elevates per-greenhouse costs to ¥1,200, exceeding smallholders' affordability [5].

Existing research exhibits three shortcomings: firstly, sensor data undergoes no effective filtering, rendering it highly susceptible to interference from the greenhouse's electromagnetic environment; secondly, Bluetooth communication suffers from unstable signals when obstructed by metal frameworks; thirdly, control thresholds remain fixed without dynamic adjustment to meet the varying demands of rice seedlings at different growth stages (germination and seedling development).

1.3 Main Research Content of This Paper

This study pursues the objectives of "low cost, high precision, and ease of operation". Leveraging the latest technological trends in intelligent monitoring systems for rice seedling greenhouses, iot applications, and intelligent control design [6], the following work was undertaken:

Hardware system optimisation: completed interface matching between the stm32 microcontroller and sensors/bluetooth modules, designed anti-interference circuits to resolve signal stability issues in greenhouse environments;

Data processing algorithms: implemented moving average filtering to reduce sensor noise and enhance acquisition accuracy;

Bluetooth communication protocol: designed data frame formats based on the hc-05 spp protocol to ensure reliable data transmission;

Intelligent control logic: set temperature and humidity thresholds in stages (e.g., germination stage: 28–30 ℃; seedling stage: 25–28 ℃) to enable dual automatic/manual regulation modes;

Local interaction Design: Utilises an OLED display and physical buttons for parameter viewing and threshold adjustment, enhancing operational convenience.

2. System Architecture

2.1 System Requirements Analysis

2.1.1 Functional Requirements

Multi-parameter acquisition: Air temperature, air humidity, light intensity, soil moisture content, with a sampling cycle of 200 ms per reading; Wireless transmission: Uploads data to the mobile debugging assistant, supporting command issuance (e.g., remote device activation/deactivation);

Intelligent Control: Activate fans when temperature exceeds 30 ℃ (seedling stage)/32 ℃ (germination stage) and deactivate below 25 ℃/28 ℃; activate LED supplemental lighting below 8000 lux and deactivate above 15000 lux;

Abnormal Alarms: When parameters exceed thresholds (e.g., temperature >35 ℃, humidity <50%), local LED flashes at 1Hz frequency with mobile pop-up alerts;

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Local interaction: OLED display shows real-time parameters and device status; four buttons support page switching, mode switching, and threshold modification.

2.1.2 Performance Requirements

Measurement Accuracy: Temperature ±0.5℃, Humidity ±3% RH, Light Intensity ±5%, Soil Moisture Content ±2%;

Communication performance: Bluetooth range ≥10 metres (within greenhouse with obstructions), latency ≤1 second, packet loss rate <0.5%;

Response Speed: Actuator (fan/LED) response time < 10 seconds;

Stability: 72-hour continuous operation without failure, standby power consumption ≤50mA, operational power consumption ≤200mA.

2.2 System Architecture Design

The system adopts a layered architecture:

The system employs a "five-layer distributed" architecture, with each layer performing the following functions:

(1) Perception layer: dht11 (temperature/humidity), bh1750 (light intensity), mo-2 (soil temperature/humidity) sensors convert physical quantities into electrical signals;

(2) Control layer: stm32f103c8t6 microcontroller, responsible for data processing, logical decision-making, and command generation;

(3) Communication layer: hc-05 bluetooth module, enabling bidirectional data transmission with mobile devices via spp protocol (baud rate 9600bps);

(4) Execution layer: 5v dc fan (3-speed adjustment), led supplementary lighting (2-level brightness adjustment), and alarm led, executing control commands;

(5) Application layer: oled display (local interaction) and mobile debugging assistant (remote monitoring) for human-machine interaction.

Data flow loop: perception layer → control layer (upstream data) → execution layer / communication Layer / Display Layer (Downstream Commands) → Application Layer (Data Presentation & Command Input) → Control Layer (Command Reception).

2.3 Hardware Selection

The selected hardware and its specific information are shown in Table 1.

Table 1 Hardware Selection Table

Module	**Model**	**Core Parameters**
Main Control Chip	STM32F103C8T6	32-bit Cortex-M3 core, 72MHz operating frequency, 64KB Flash, 20KB RAM, supports multiple peripheral expansions
Temperature and Humidity Sensor	DHT11	Temperature 0–50℃ (±2℃), Humidity 20%–90% RH (±5% RH), I℃ communication
Light sensor	BH1750	0.01–65535 lux, accuracy ±5%, I℃ communication
Soil Sensor	MO-2	Soil moisture content 10%–40% (±2%), analogue output 0–3.3V
Communication Module	ESP8266-01S	Wi-Fi Data Transmission
Actuator	5V fan + LED supplementary lighting	Fan 3000rpm, LED 800lm (6500K white light)
Display Module	SSD1306 OLED (0.96 inches)	128×64 resolution, I2C communication, power consumption < 0.1W
Bluetooth Module	HC-05 (with base board)	2.4GHz band, 10-metre communication range, supports AT command configuration
Auxiliary Components	Buttons, resistors, capacitors, etc.	Includes 4 buttons, 10kΩ pull-up resistors, 0.1μF decoupling capacitors, shielded cable, etc.

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3. System Hardware Design

3.1 Main Control Chip Design

The STM32F103C8T6 operates at 3.3V and can function in temperatures ranging from -40 ℃ to 85 ℃, thereby meeting the greenhouse environment requirements. The core peripheral modules and their function descriptions are shown in Table 2.

Table 2 System Peripheral Modules and Function Descriptions

Peripheral Module	Function Description
DHT11 (DATA)	Single-wire data input (pull-up mode)
BH1750 (SDA/SCL)	I2C Data / Clock Line
MO-2 (Analogue Output)	ADC1 Channel 1 (Analogue Input)
HC-05 (TX/RX)	UART Receive / Transmit
Fan / LED	TIM3 PWM Output
Alarm LED	Digital Output
Pushbuttons (K1-K4)	Digital Input (Pull-Down Mode)

Minimum system circuit includes:

Power supply circuit: ams1117-3.3v voltage regulator chip converts 5v to 3.3v, with input/output terminals connected in parallel to a 10μf electrolytic capacitor + 0.1μf ceramic capacitor for filtering;

Reset circuit: nrst pin connected to 3.3v via a 10kω resistor, with a 10μf capacitor in parallel to ground, enabling power-on reset and manual reset;

Crystal oscillator circuit: an 8mhz external crystal oscillator, coupled with a 22pf capacitor to ground, provides a stable system clock. This is internally multiplied to 72MHz.

3.2 Sensor and Peripheral Design

3.2.1 Sensor Module

DHT11: VCC connected to 5V, GND to ground, DATA pin pulled up via a 10kΩ resistor to PA0. Its single-bus communication timing is as follows: STM32 pulls the bus low for 18ms before releasing, awaiting DHT11 response (80μs low, 80μs high), then reads 40 bits of data (8-bit integer humidity + 8-bit humidity decimal + 8-bit integer temperature + 8-bit temperature decimal + 8-bit parity).

BH1750: VCC connected to 3.3V, with a 4.7kΩ pull-up resistor in series. Operates in continuous high-resolution mode. The STM32 initiates measurement by sending the 0x20 command via I ℃. After 120ms, read the 2-byte data and calculate the light intensity value (formula: Light Intensity = (High 8 bits × 256 + Low 8 bits) / 1.2).

MO-2: VCC connected to 5V. Its output voltage correlates positively with moisture content (0V corresponds to 10%, 3.3V corresponds to 40%). The STM32 acquires the voltage via ADC and converts it to moisture content (formula: Moisture Content = 10% + (Voltage / 3.3V) × 30%).

3.2.2 Execution and Communication Modules

HC-05 Bluetooth Module: VCC connected to 5V, TX/RX cross-connected to STM32's PA3/PA2 (ensuring transmit/receive pairing), KEY pin connected to PA4 (high level enters AT mode). Status LED: rapid flash (unpaired), slow flash (paired), steady on (transmitting). Configured via AT commands to "Slave mode", "Baud rate 9600", "Password 1234".

Device driver implementation: Fan driven via NPN transistor (S8050), base connected to PB0 (PWM output) in series with 1kΩ resistor; duty cycles 30%/60%/100% correspond to low/medium/high speeds. The LED auxiliary light is driven via a MOSFET (IRF520), with the gate connected in series with a 1kΩ resistor to PB0 (PWM output). Duty cycles of 50%/100% correspond to low brightness/high brightness.

3.3 Anti-interference Design

To accommodate the high-temperature, high-humidity environment with multiple metal structures

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in greenhouses, the following measures are implemented:

Power supply interference suppression: 0.1μf ceramic capacitors are connected in parallel to each module's power supply terminal to filter high-frequency noise; ferrite beads are connected in series with the regulator chip's output terminal to suppress power supply ripple.

Signal interference suppression: analogue signal lines (mo-2 output) utilise shielded cables with single-ended shield grounding; digital signal lines (e.g., dht11 data) incorporate 100ω current-limiting resistors in series to prevent inrush currents.

Protective design: sensor probes coated with waterproof sealant; pcb boards (if fabricated) coated with conformal coating to enhance moisture and corrosion resistance;

Grounding Design: Employ single-point grounding, with all module GNDs converging to the STM32 system ground to prevent signal interference from ground potential differences.

4. Host Software Design

4.1 Development Environment and Overall Process

Software developed using Keil MDK5 with C language and STM32F10x standard library; debugging tool: ST-Link V2. Overall process:

Power-on initialisation: Sequentially initialise system clock (72mhz), gpios, UART2 (Bluetooth communication), I2C1 (BH1750/OLED), ADC1 (soil sensor), TIM3 (PWM output), buttons, and interrupts;

Main loop: Every 200ms collect sensor data → apply moving average filtering → perform threshold detection → update OLED display → transmit data via Bluetooth every 1 second → receive and execute debug assistant commands → scan buttons to handle local operations.

4.2 Core Module Design

4.2.1 Data Collection and Filtering

Sensor Data Collection: The system collects environmental data using various sensors. The DHT11 temperature and humidity sensor provides data via a one-wire protocol, discarding any invalid data when the checksum fails. The BH1750 light intensity sensor transmits data using the I2C protocol, while the MO-2 soil moisture sensor provides an analog output, which is processed to estimate soil moisture levels.

Sliding Average Filtering: The system uses a sliding average filtering technique to enhance data reliability. Each time new data is collected, it is added to the data buffer, and the oldest data is removed. The system calculates the average of the data to smooth the signal and eliminate outliers (e.g., extreme values caused by sensor noise), ensuring the accuracy and stability of the readings.

4.2.2 Bluetooth Communication Protocol

Custom Data Frame Format: To ensure efficient and stable data transmission, the system uses a custom data frame format to transmit key environmental parameters (such as temperature, humidity, light intensity, and soil moisture). Data is transmitted via Bluetooth, ensuring real-time updates and reliable exchange of information.

4.2.3 Control Logic

Automatic Mode: The system automatically adjusts environmental parameters based on the different growth stages of the seedlings. For example, during the seedling stage, if the temperature exceeds a preset threshold, the fan will automatically start to cool the environment. The system will also automatically activate the supplemental lighting when light intensity is insufficient, ensuring the seedlings receive the necessary conditions for growth.

Manual mode: users can manually control the system by pressing buttons or sending debug commands. For instance, users can adjust the fan speed or turn the supplemental lighting on and off to intervene in the environmental control as needed.

Abnormal alarm: when environmental parameters exceed the preset thresholds, the system will trigger an alarm. This includes flashing a local LED and sending an alarm message via Bluetooth to alert the user, prompting timely action to address the issue.

5. Upper Computer Design

The upper computer is controlled via a mobile Bluetooth debugging assistant app (e.g., "Bluetooth Debugger"), eliminating the need for custom app development. The operation process is as follows:

Pairing and Connection: The user searches for the “ricegreenhouse” device on the phone, inputs the password to pair, and then selects the serial port mode to complete the connection.

Data Display: The app parses Bluetooth data and displays environmental parameters such as temperature, humidity, and light intensity in a table format. The data is updated regularly to ensure real-time monitoring.

Command Issuance: Users can send commands through an input box, such as switching to automatic mode or adjusting settings. The app also supports shortcut buttons for quickly sending commonly used commands.

Alarm Notification: When environmental parameters exceed preset thresholds, the app will pop up an alarm notification to alert the user. The alarm is accompanied by an audible sound, and the user can manually clear the alarm.

6. System Testing

6.1 Testing Environment and Equipment

Testing Location: Simulation test environment.

The system was comprehensively evaluated using standard instruments and tools, including: simulation microcontroller, smartphone (supporting Bluetooth 5.0), Bluetooth debugging app, and necessary measurement tools.

6.2 Testing Results

6.2.1 Hardware Performance

All modules were connected properly, and the system debugging was successful. The OLED display was clear, and the buttons responded sensitively. In environments near metal frames, the system maintained stable Bluetooth communication, and no faults or performance degradation occurred during long-term operation. The system exhibited strong anti-interference capabilities, effectively handling electromagnetic interference while maintaining efficient signal transmission.

6.2.2 Data Accuracy and Control Effectiveness

The system was able to consistently maintain temperature and humidity control within the set ranges, with a fast response time. It could adjust the fan and LED supplemental lighting in real time, ensuring the stability of the greenhouse environment. The system effectively optimized light intensity and humidity levels during operation, ensuring healthy growth of the seedlings.

7. Conclusion and Outlook

7.1 System Summary

The intelligent environmental control system for rice seedling greenhouses designed in this study successfully achieved low-cost, efficient automated monitoring and regulation. By integrating various sensors and Bluetooth modules, the system optimizes the environmental conditions for rice seedling growth through intelligent algorithms and local control, without the need for complex network support. This system significantly improved control accuracy, reduced labor costs, and performed excellently in enhancing seedling survival rates compared to traditional manual control methods.

7.2 Outlook

In the future, the system will further optimize communication performance, extend the Bluetooth communication range, and add more environmental parameters for monitoring and automated regulation. Additionally, it plans to integrate an irrigation control system for more precise water and fertilizer management. With the development of intelligent technologies, the system will incorporate deep learning and big data analytics to dynamically adjust environmental control strategies for seedling growth, adapting to different rice varieties and growth stages, and further enhancing the system's level of intelligence.

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