Design and Implementation of an Unmanned Fire Detection and Extinguishing System for Greenhouse

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ABSTRACT

Greenhouse fires pose severe risks due to enclosed structures, dense equipment, and rapid flame propagation. To address the limitations of manual inspection and fixed monitoring devices, this paper presents the design and implementation of an unmanned fire detection and extinguishing system for greenhouses, based on an STM32 microcontroller with Raspberry Pi co-processing. The system integrates flame sensors, temperature–humidity sensors, LiDAR, and a high-definition camera, mounted on a wheeled platform with a rotatable extinguishing module. It supports autonomous patrol, manual control, and point-to-point extinguishing modes. Wireless video and data transmission enable real-time fire monitoring and remote command. Experimental results demonstrate flame recognition accuracy exceeding 95% within 10 m, positioning error below ±0.5 m, and fire response time under 8 seconds. Compared with conventional methods, the proposed system achieves faster response, broader coverage, and stronger adaptability, showing great potential for intelligent greenhouse fire prevention.

Keywords: *Unmanned system, Fire detection, Precision firefighting, Greenhouse safety, STM32*

1. INTRODUCTION

With the rapid development of modern agriculture, greenhouses have become critical infrastructures for efficient crop cultivation. However, their enclosed structures and dense equipment make them highly vulnerable to fire hazards [1]. Traditional fire prevention methods, such as manual patrols and fixed detectors, suffer from delayed response, limited coverage, and poor adaptability to complex environments. Once a fire occurs, flames can spread rapidly, making manual extinguishing difficult and leading to severe losses [2].

Internationally, semi-automated greenhouse fire suppression systems have been developed in countries such as Germany and the Netherlands [3], while U.S. research institutes introduced firefighting robots with autonomous patrol capabilities [4]. However, these systems are either costly or limited in adaptability. In China, most existing solutions focus on single functions, such as temperature monitoring or remote-controlled extinguishing, lacking full autonomy and precise localization [5].

To address these shortcomings, this paper proposes an unmanned fire detection and extinguishing system based on STM32 and Raspberry Pi co-processing. The system integrates flame recognition, environmental sensing, autonomous navigation, dynamic obstacle avoidance, and precise extinguishing, offering a cost-effective and intelligent solution for greenhouse fire safety.

2. SYSTEM DESIGN

The proposed system is built on a wheeled unmanned platform, which provides mobility and adaptability for greenhouse environments. A rotatable extinguishing module is mounted on the platform, enabling targeted suppression once fire sources are detected. To achieve full autonomy, the system integrates multiple functional layers in a unified architecture. The perception layer combines flame sensors, a DHT11 temperature–humidity sensor, LiDAR, and a high-definition camera to provide comprehensive environmental data.

These inputs are processed by the control layer, where an STM32F103RCT6 microcontroller serves as the main controller, while a Raspberry Pi assists in computationally intensive tasks such as image recognition and LiDAR data processing. The execution layer is responsible for system actions, including DC motors for locomotion, servo motors for camera and nozzle adjustment, and a water pump for extinguishing operations.

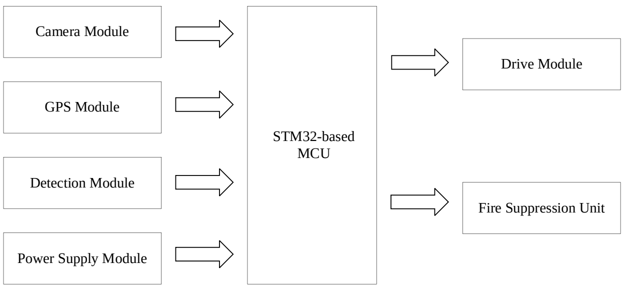

Fig. 1 *System Design Block Diagram*

This layered integration allows seamless collaboration among perception, control, and execution. The STM32 handles real-time data acquisition, motor control, and communication tasks, ensuring low-latency responses, while the Raspberry Pi enhances system intelligence through advanced sensing and recognition algorithms. The overall system design emphasizes modularity, enabling stable operation, flexible scalability, and robust adaptability to complex greenhouse conditions. The architecture of the system is illustrated in Fig. 1.

The system adopts a wheeled unmanned mobile platform architecture, which consists of an intelligent vehicle theme platform and a rotatable flame detection unit. Overall structural modeling is shown in Fig. 2.

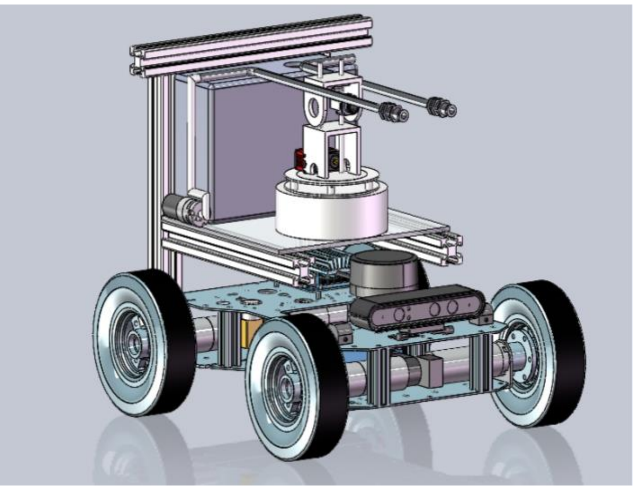

Fig. 2 *3D Structural modeling of the unmanned firefighting vehicle*

3. HARDWARE CIRCUIT DESIGN

3.1 MICROCONTROLLER MINIMUM SYSTEM MODULE

The hardware circuit design of this system is centered on the STM32F103RCT6 microcontroller as the core control unit, with a Raspberry Pi serving as an auxiliary processor for LiDAR and camera data. The overall layout and optimization focus on five main functional modules: stable power supply, driving control, precise detection, efficient communication, and responsive actuation.

To ensure stable operation of the main controller and peripheral modules as well as expandability of external interfaces, the hardware design incorporates power filtering, crystal oscillators, reset control, motor drivers, sensor interfaces, communication modules, and debugging interfaces [6]. A multiplexed circuit design method was adopted to enhance reliability, thereby establishing a robust hardware platform [7] – [8]. The schematic diagram of the microcontroller pin connection circuit is shown in Fig. 3.

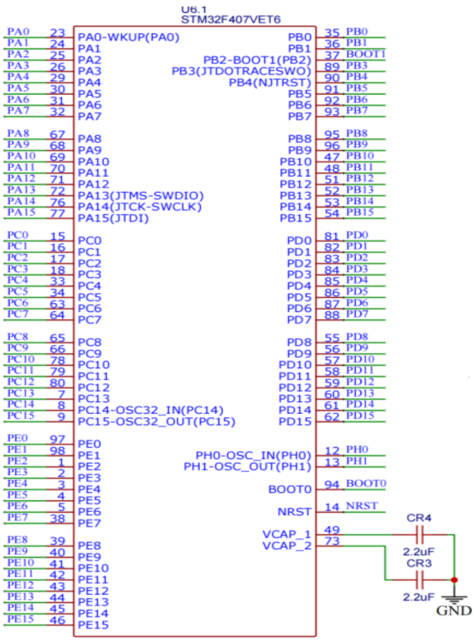

Fig. 3 *Circuit schematic of the STM32 minimum system*

3.2 POWER SUPPLY CIRCUIT

In this design, the motors require a 12 V supply, while the main controller, camera, LiDAR, and detection modules require 3.3 V and 5 V respectively. To step down from the 12 V source, an RT8289GSP buck converter was employed. This chip supports an input range of 5.5–32 V, an output range of 1.2–26 V, and a maximum output current of 5 A. Packaged in SOP8, it is suitable for efficient and stable power applications.

A 6.8 μH inductor was added to the peripheral circuit to enhance current storage capability. Capacitors C53, C57, and C58 were placed at the output for voltage stabilization, and diode D7 was introduced to prevent short circuits. The circuit is shown in Fig. 4.

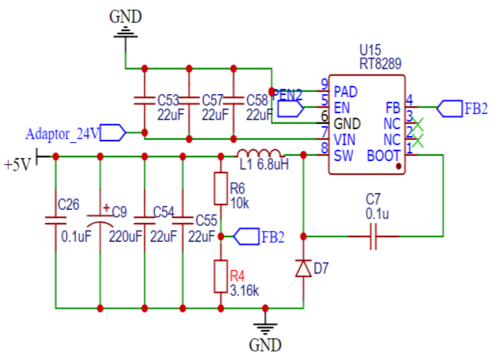

Fig. 4 *Schematic of 5 V power supply circuit*

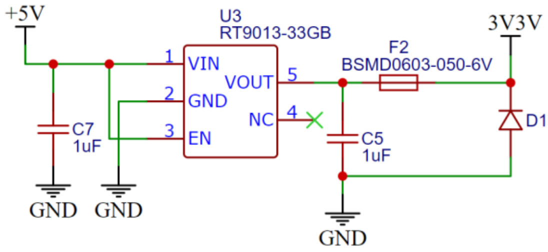

Fig. 5 *Schematic of 3.3 V power supply circuit*

For the 3.3 V supply, an RT9019-33GB regulator was used, with capacitors C7 and C5 providing high-frequency filtering, and a diode was added to prevent reverse connection, yielding a stable 3.3 V voltage. The design is shown in Fig. 5.

3.3 VIDEO TRANSMISSION AND LIDAR MODULE

Since the system requires both video transmission and LiDAR-based mapping, a USB hub was designed to optimize serial port utilization. The USB hub expands a single USB interface into multiple channels for simultaneous use, allowing the camera to connect to USB1+ and USB1–, while the LiDAR connects to USB2+ and USB2–. The circuit is shown in Fig. 6.

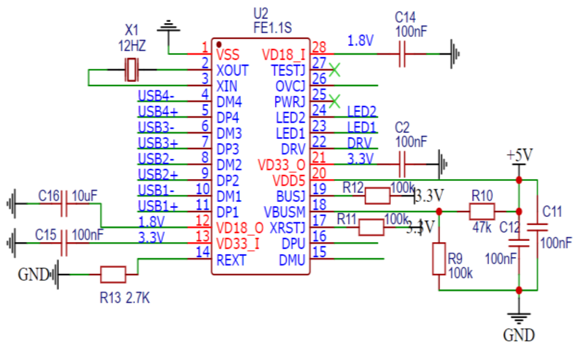

Fig. 6 *Video transmission and LiDAR circuit*

3.4 BUZZER ALARM MODULE

When abnormal temperature or humidity is detected, an audible alarm is triggered. An active buzzer was adopted, driven by an 8050 NPN transistor [9]. The transistor operates under high-level conduction. The buzzer's data pin is connected to the STM32 microcontroller's PB10 pin; when PB10 outputs a high level, the buzzer is activated. The circuit is shown in Fig. 7.

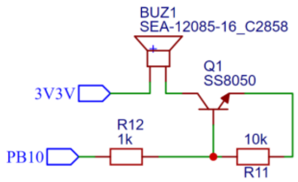

Fig. 7 *Buzzer alarm circuit*

3.5 TEMPERATURE AND HUMIDITY DETECTION MODULE

The DHT11 sensor is employed to measure temperature and humidity inside the greenhouse [10]. The DATA pin is connected to the microcontroller, which processes signals and activates the buzzer if values exceed thresholds. In the circuit, VCC connects to 3.3 V, DATA to the STM32 PC1 pin, NC is left floating, and GND connects to ground. Once powered, the sensor communicates data via the DATA line. The circuit is shown in Fig. 8.

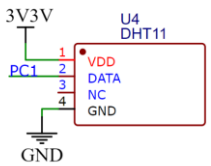

Fig. 8 *Temperature and humidity detection circuit*

3.6 SERVO DRIVE MODULE

The servo circuit is critical for precise camera positioning and flame tracking. The LD-3015MG servo, known for its accuracy and fast response, was selected. It converts digital pulse signals into angular displacement, ensuring the camera remains focused on the flame. The servo is powered by a stable supply and receives control signals from the STM32, enabling precise angle adjustment and supporting efficient firefighting. The circuit is shown in Fig. 9.

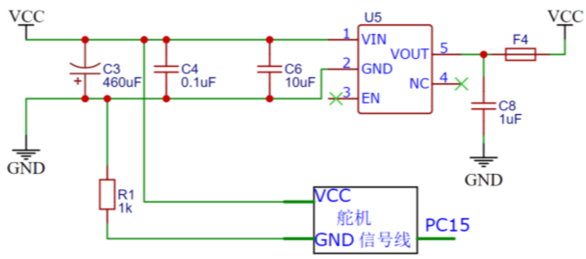

Fig. 9 *Servo drive circuit*

3.7 MOTOR DRIVE MODULE

In this greenhouse firefighting vehicle, the STM32 controls motor operation through PWM signals to enable both locomotion and extinguishing mechanisms. The D50A driver was selected for its stability and safety. The VCC pin is connected to 3.3 V, while STM32 pins PC6, PC7, PC10, and PC12 connect to INA and INB inputs.

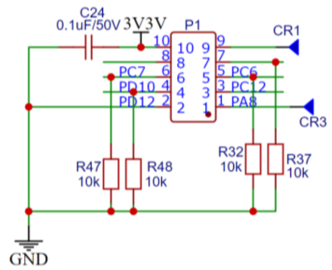

Fig. 10 *Motor drive circuit*

The driver includes protections against over-voltage, under-voltage, and overheating, and supports driving DC motors up to 290 W.

All control signals are electrically isolated, compatible with 3–5 V logic, and capable of high-speed PWM operation. The circuit diagram is presented in Fig. 10.

4. SOFTWARE PROGRAM DESIGN

The system software was developed and debugged in Keil 5, using the STM32 standard peripheral library to implement hardware drivers and system functions.

The main controller collects sensor data (flame, temperature, humidity, obstacle distance), receives LiDAR and camera inputs, and transmits fused results to the monitoring terminal via WiFi. The terminal issues control commands for motion, extinguishing, and navigation mode switching.

Upon startup, the system initializes peripherals (ADC, GPIO, UART, SPI), collects and packages sensor data, fuses external information, and executes control instructions if received. Updated status is transmitted back to the monitoring terminal. The programming interface and flow are shown in Fig. 11 and Fig. 12.

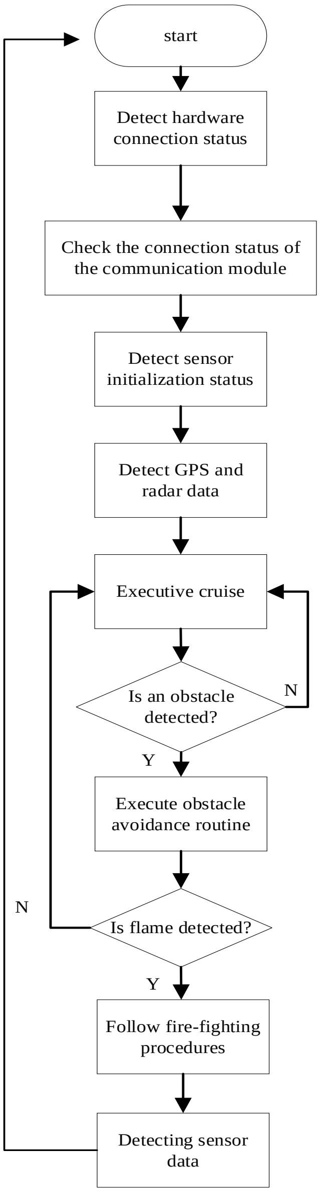

Fig. 11 *Main program flowchart*

5. SYSTEM DEBUGGING AND FUNCTIONAL TESTS

5.1 TEST PLAN AND ENVIRONMENT

To validate real-world performance, tests covered navigation stability, control responsiveness, sensor precision, WiFi and video transmission quality, and system coordination. A simulated greenhouse with artificial crops and obstacles was used. The system was powered by lithium batteries and evaluated using standard flame sources, calibrated temperature–humidity meters, and obstacle models.

5.2 HARDWARE DEBUGGING

Prototype verification was conducted on breadboards to confirm circuit functions such as motor driving, sensor transmission, and communication. All modules operated normally without short circuits or overheating. Stable outputs were achieved, and the final assembly is shown in Fig. 13 and Fig. 14.

Fig. 13 Hardware circuit connections

Fig. 14 *Assembled unmanned firefighting vehicle*

5.3 OVERALL OPERATION TEST

In manual mode, the vehicle demonstrated smooth acceleration, deceleration, and responsive turning with an appropriate turning radius. In autonomous mode, it followed pre-set routes with minimal deviation and successfully avoided obstacles, maintaining reliable path tracking. The navigation modeling result is shown in Fig. 15.

To evaluate the closed-loop navigation ability of the unmanned firefighting vehicle, a circular cruising test was performed with six monitoring points arranged along the patrol route. The vehicle departed from Point 1 and traveled sequentially through Points 2 to 6, finally returning to Point 1 to complete one loop. The cruise route is shown in Figure 16. The distance between each pair of adjacent points and the time consumed were recorded, as summarized in Table 1.

```
int main(void)
{
  /*Module initialization*/
  DHT11_Init();//Temperature and humidity sensors
  pump_Init();//water pump
  Servo_Init();   //Servo initialization
  //Key_Init();     //Button initialization
  OLED_Init();
  uart_init(115200);
  // Initialize the PID controller
  PID_Init(&panPID,  0.005f, 0.0f, 0.003f);
  // The horizontal axis PID parameters need to be adjusted according to the actual situation
  PID_Init(&tiltPID, 0.005f, 0.0f, 0.003f);
  // The vertical axis PID parameters need to be adjusted according to the actual situation
  PID_SetSetpoint(&panPID,CAMERA_WIDTH/2);
  PID_SetSetpoint(&tiltPID,CAMERA_HEIGHT/2);
  Angle=90;
  while (1)
  {
    OLED_ShowString(1, 2, "temp");
    OLED_ShowString(2, 2, "humi");
    DHT11_Read_Data(&temp,&humi);//
    OLED_ShowNum(1,6,temp,2);
    OLED_ShowNum(2,6,humi,2);
    ballX=(uint8_t)data1;
    ballY=(uint8_t)data2;
    float deltaX = ballX - CAMERA_WIDTH / 2;
    float deltaY = ballY - CAMERA_HEIGHT / 2;
    if(ballX==0){
    if(data3 == 1)
    {
    if (data3 == 0)
    {
```

Fig. 12 *Main program interface*

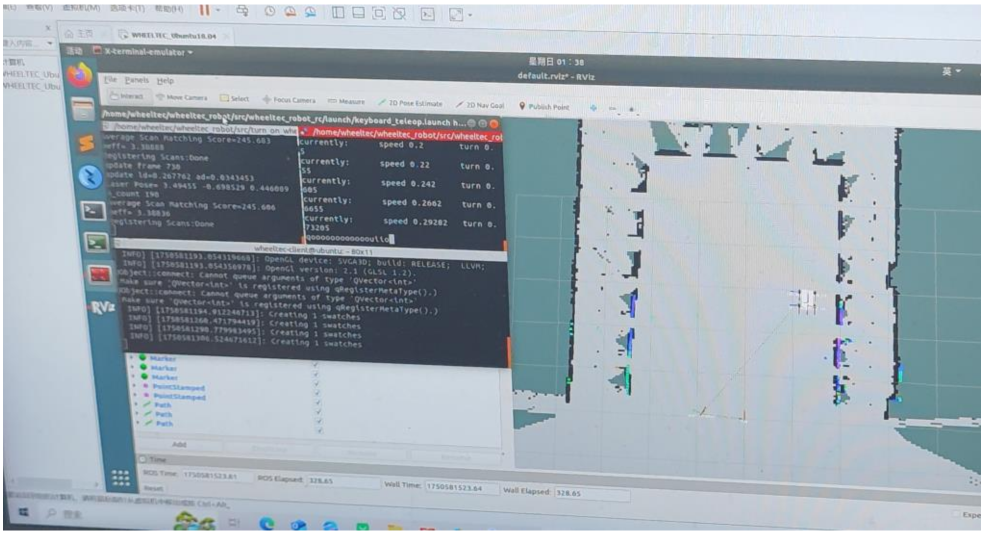

Fig. 15 *Navigation modeling result*

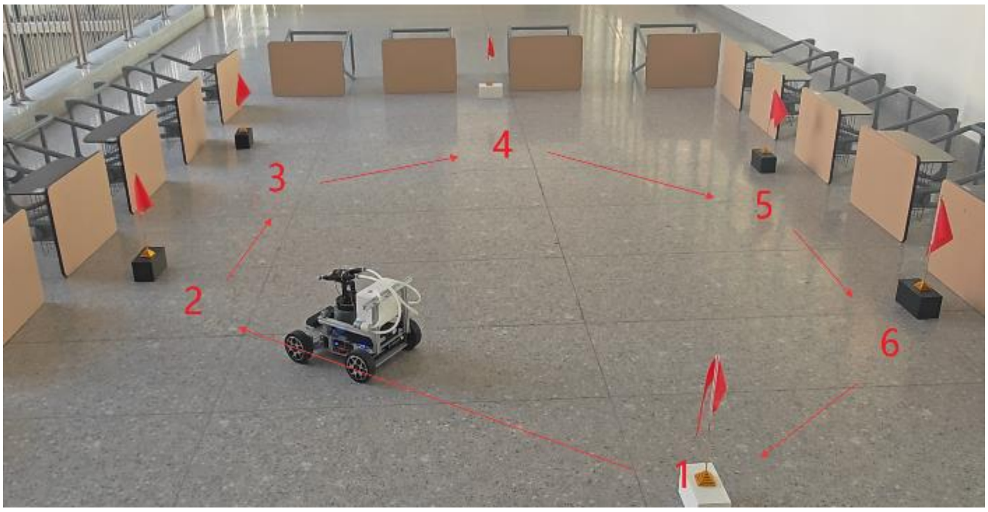

Fig. 16 *Cruise route*

Table 1*. Multi-point Circular Cruising Test Results*

Segment	Distance (m)	Time (s)	Average Speed (m/s)
Point 1 □ Point 2	2.4	2.9	0.83
Point 2 □ Point 3	2.6	3.1	0.84
Point 3 □ Point 4	2.3	2.8	0.82
Point 4 □ Point 5	2.7	3.3	0.82
Point 5 □ Point 6	2.5	3.0	0.83
Point 6 □ Point 1	2.5	3.0	0.83
Total	15.0	18.1	0.83 (average)

5.4 FLAME RECOGNITION TEST

To evaluate the performance of the flame recognition module, tests were carried out at different flame sizes and distances, including interference conditions such as smoke and strong light. The results showed that within 0.5–10 m, the recognition accuracy remained above 95%, and the average delay was less than 0.8 s, which meets the requirements for rapid fire response. The recognition effect is shown in Fig. 17.

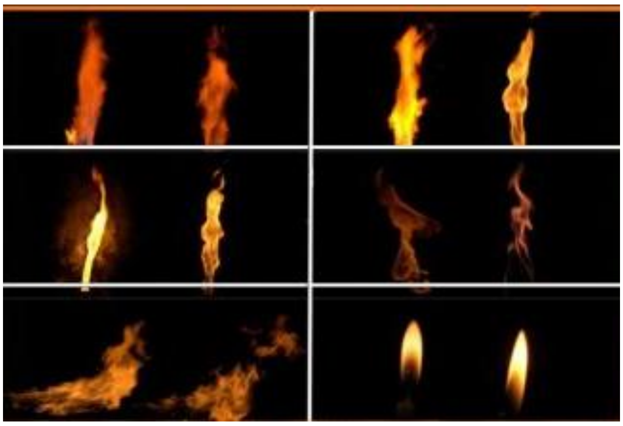

Fig. 17 *Flame recognition performance*

Table 2*. Flame recognition test results*

Distance (m)	Flame Size	Condition	Accuracy (%)	Avg Delay (S)
0.5	Small	Normal	100.0	0.42
2.0	Medium	Normal	96.7	0.47
5.0	Medium	Normal	96.7	0.51
8.0	Medium	Smoke	96.7	0.62
10.0	Large	Backlight	96.7	0.73

The flame recognition test results are shown in Table 2. The results confirm that the system can recognize flames quickly and reliably under different conditions, fulfilling the real-time requirements for practical applications.

5.5 SENSOR TESTING

To evaluate the accuracy and reliability of the onboard sensors, comparative experiments were conducted under simulated greenhouse conditions. The test covered the extinguishing unit, temperature and humidity sensor, LiDAR, and camera positioning module. Standard instruments were used as reference values for calibration. Each sensor was tested multiple times at representative points within its operating range to verify measurement precision.

The results, summarized in Table X, indicate that all sensors achieved stable and accurate performance. The extinguishing unit maintained a maximum deviation of ±0.3 m within a 10 m range. The DHT11 sensor achieved a temperature accuracy of ±0.5 □ and humidity accuracy of ±2 % RH, meeting the requirements of greenhouse monitoring. LiDAR demonstrated high ranging precision, with deviations within ±0.3 m, suitable for mapping and obstacle avoidance. The camera positioning module maintained accuracy within ±0.5 m for distances up to 50 m, supporting effective navigation and flame localization. The test results are shown in Table 3.

***Table 3**. Sensor test results*

Device Type	**Test Range**	**Reference Value □ Measured Value**	**Max Error**
Extinguishing Unit	0–10 m	3.0 m □ 2.8 m 8.0 m □ 8.2 m	±0.3 m
Temperature Sensor	0–50 □	25.0 □ □ 24.8 □ 38.0 □ □ 38.2 □	±0.5 □
Humidity Sensor	20–90 % RH	40 % □ 39.5 % 70 % □ 71.3 %	±2 % RH
LiDAR	0–30 m	5.0 m □ 5.1 m 20.0 m □ 20.2 m	±0.3 m
Camera Positioning	0–50 m	10.0 m □ 9.8 m 30.0 m □ 30.4 m	±0.5 m

6. CONCLUSION

This paper presents the design and implementation of an autonomous greenhouse firefighting vehicle, integrating an STM32F103RCT6 microcontroller, Raspberry Pi 4B, sensors (flame, temperature–humidity, LiDAR, camera), and actuators (motors, servos, pump, buzzer). The system combines flame recognition, environmental monitoring, autonomous navigation, obstacle avoidance, and precise extinguishing, with wireless data transmission for remote control.

The hardware design covered power, motor drivers, communication, and sensor interfaces, while software development implemented sensing, recognition, navigation, and monitoring functions. Experimental results confirmed the system's high accuracy in flame positioning, stable navigation, and rapid firefighting response. The design offers cost-effective, expandable, and intelligent solutions for greenhouse fire prevention, with potential for algorithm refinement and broader deployment in agricultural and industrial applications.

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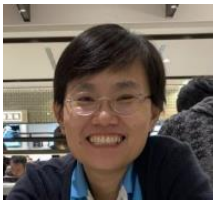

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