An Autonomous Fire-Fighting Robotic System Based on Arduino RP2040

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***Abstract*—-This paper presents the design and implementation of an autonomous robotic system for fire detection and suppression, aimed at reducing human risk in fire-prone environments. Utilizing the Arduino RP2040 microcontroller, the system integrates multiple sensors—flame, gas, temperature, and ultrasonic—to detect hazardous conditions and respond effectively. The robot navigates autonomously and extinguishes detected fires using a water or chemical suppression mechanism controlled by a servo-actuated system. The platform enhances safety in inaccessible or dangerous areas and illustrates a practical application of embedded systems and robotics in emergency response.**

Keywords—*Arduino RP2040, Fire Detection, Flame Sensor, Motor Driver, Autonomous Robot, Fire Suppression*.

I. INTRODUCTION

The escalating incidence and intensity of fire-related emergencies in both residential and industrial sectors underscore the urgent necessity for advanced, intelligent solutions that prioritize human safety and operational efficiency [3], [4]. Traditional fire-fighting approaches, though effective in many scenarios, expose fire personnel to substantial danger, especially in environments characterized by extreme heat, toxic fumes, limited visibility, and structural instability. In response to these challenges, the integration of autonomous robotics into fire-fighting operations emerges as a transformative alternative [1], [6].

Robotics technology offers the capability to operate in hazardous, remote, or structurally compromised areas where human access is either limited or perilous [2], [5]. This study proposes the development and deployment of an advanced fire-fighting robotic system engineered to autonomously detect and suppress fires in real time, thereby eliminating the need for direct human intervention. By leveraging wireless communication technologies, the robot also facilitates remote monitoring and control, allowing operators to supervise operations from a safe distance.

The system is designed with environmental sustainability in mind, aiming to reduce the collateral impact associated with traditional suppression methods, such as the release of chemical agents or excessive water usage [3]. Equipped with a suite of intelligent sensors and powered by a highly efficient microcontroller, the robotic platform can autonomously navigate complex terrains, identify fire sources with high precision, and initiate timely suppression actions [1], [2].

This innovation not only advances the state of fire safety technology but also aligns with broader efforts to integrate automation and artificial intelligence into emergency response frameworks. By demonstrating the practical viability of robotics in life-critical applications, this research contributes significantly to the emerging field of autonomous disaster response systems and reinforces the essential role of intelligent machines in enhancing public safety and preserving human life [2], [6].

II. LITERATURE REVIEW

In recent years, the field of autonomous fire-fighting robotics has seen significant academic and industrial interest due to the pressing need for intelligent solutions in hazardous environments. Several notable studies have contributed foundational insights to the development of robotic fire suppression systems.

Sindhu et al. proposed a novel simulation-based approach using the Virtual Reality Toolbox in MATLAB to model fire-fighting robot behavior in controlled environments. While their simulation was effective for initial algorithm testing, the absence of environmental adaptability and real-world interaction significantly limited the model's practical applicability.

In another work, Ayuni Binti Abd Majid developed an autonomous fire-alarm robot tailored for smart building integration. The system utilized a PIC18F4550 microcontroller and employed a GSM module for wireless communication. It was equipped with three flame sensors to detect fire and relay alerts via the mobile network. Despite its smart capabilities, the platform's design focused more on alert generation rather than active fire suppression [1].

Verma et al. constructed a functional Arduino-based fire-fighting robot capable of detecting flames using infrared and flame sensors. The robot utilized gear motors and a submersible pump to extinguish fire sources. While it achieved basic fire-fighting capabilities, the system lacked real-time adaptability and environmental awareness, such as obstacle navigation or gas detection [3].

Another contribution by Dr. T. Guhan and colleagues introduced an autonomous fire suppression robot designed with flame-sensing and sprinkler activation mechanisms. Although the robot demonstrated promising fire-detection capabilities, the absence of flame-retardant structural materials posed safety risks in high-temperature environments [6].

These previous efforts collectively underscore the increasing sophistication in fire-fighting robotics, yet highlight gaps in adaptability, autonomy, multi-sensor integration, and material safety—areas which this current work aims to address comprehensively through the implementation of a robust, sensor-rich, and intelligent robotic platform [2], [3].

III. SYSTEM OVERVIEW

A. *Hardware Architecture*

The proposed autonomous fire-fighting robot is designed with a modular, cost-effective architecture that integrates multiple sensors and actuators to ensure accurate detection and rapid response. The primary hardware components include:

Microcontroller: Arduino RP2040 — a powerful dual-core ARM Cortex-M0+ microcontroller offering improved processing speed and real-time data handling.

Sensors:-

- Flame Sensor – For early-stage fire detection.
- Gas Sensor – To identify the presence of combustible or toxic gases.
- Temperature Sensor – For thermal profiling of the environment.
- Ultrasonic Sensors (4 total: front, rear, left, right) – For obstacle detection and autonomous navigation.

Actuation System:-

- DC Motors – Enable robot mobility.
- Servo Motor (SG90) – Controls the directional alignment of the fire suppression nozzle.
- Suppression Mechanism: A high-efficiency DC water pump or pressurized chemical disperser to extinguish flames.
- Motor Driver: L293D or L298N integrated driver IC for dual-motor control.
- Power Supply: A rechargeable Li-ion battery pack providing stable power to the entire system.

B. *Experimental Setup*

The robot is mounted on a lightweight chassis capable of traversing indoor environments. All electronic components are secured within the enclosure to protect them from external heat and potential splash damage. Sensors are strategically placed to ensure 360-degree coverage, and the extinguishing system is aligned on a servo axis to dynamically aim and discharge based on flame location. The system's firmware facilitates seamless interaction between sensor data inputs and actuation commands.

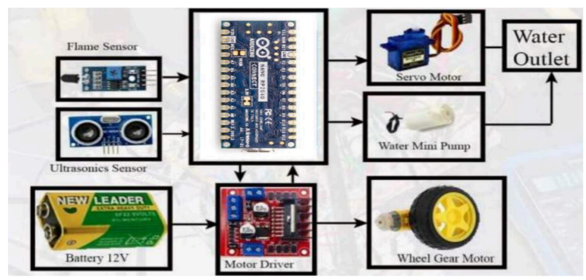

Figure 1. Experimental Setup

IV. METHODOLOGY

The development lifecycle of the proposed robotic system followed a structured engineering approach encompassing the following phases:

1) Research and Analysis: An extensive review of current literature, patents, and commercial implementations was conducted to identify shortcomings and user needs. This included studying sensor specifications, microcontroller performance benchmarks, and fire behavior patterns in enclosed spaces.

2) Component Selection and Circuit Design: Based on performance criteria, the Arduino RP2040 was selected for its dual-core efficiency and low-power operation. Sensors and actuators were chosen for compatibility and reliability. Schematic diagrams were drafted to ensure logical interfacing between components, and

simulations were used to validate the design before physical implementation.

3) Hardware Integration: The robot was assembled with careful consideration of sensor placement, center of gravity, and mechanical stability. Wiring was optimized to minimize interference and power loss. The extinguishing mechanism was integrated with a relay control circuit for seamless switching.

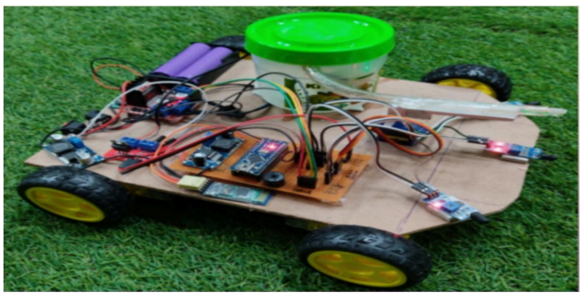

Figure 2. Module Design

4) Software Development: Using the Arduino IDE, custom control algorithms were developed. These algorithms handle sensor data acquisition, threshold-based fire detection, servo motor positioning, pump activation, and obstacle avoidance using ultrasonic feedback. The logic flow was verified using serial debugging and simulation tools.

5) Testing and Validation: Each module underwent unit testing followed by full system integration testing. Scenarios with varying fire intensities, distances, and obstacle layouts were simulated to assess the robot's response time, accuracy, and robustness. Calibration procedures were implemented to fine-tune sensor sensitivity and motor speeds.

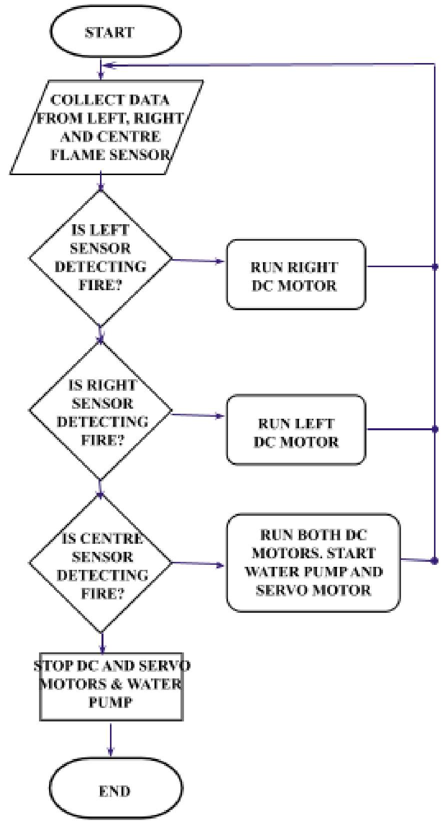

Figure 3. Program Flowchart

V. RESULTS AND DISCUSSION

The prototype robot was tested in a controlled indoor environment with simulated fire sources using a flame-emitting source and heat-generating elements. The results are summarized as follows:

TABLE 1. OBSERVED PERFORMANCE METRICS

Metric	Observed Performance
Flame Detection Range	Up to 50 cm with ±5° angular accuracy
Suppression Activation	< 3 seconds post-detection

Obstacle Avoidance Range	2–80 cm (Ultrasonic sensors)
Battery Runtime	Approx. 1.5 hours continuous operation
False Positives Rate	< 4% under varied lighting conditions

The integration of multiple sensors allowed the system to cross-validate environmental data, significantly minimizing false triggers [2]. However, the robot exhibited reduced effectiveness under strong ambient lighting and had limited extinguishing duration due to the onboard reservoir size. These issues will be addressed in future iterations.

VI. CONCLUSION

This paper demonstrates the development and implementation of a low-cost, sensor-integrated autonomous robotic system capable of detecting and suppressing fires in indoor environments. The Arduino RP2040 microcontroller, paired with a suite of flame, gas, temperature, and ultrasonic sensors, forms the backbone of this intelligent fire-response platform.

The robot successfully achieved autonomous navigation, real-time fire detection, and directional suppression with minimal human oversight. The system serves as a proof-of-concept for deploying robotics in disaster response applications, offering an effective solution to reduce risks to human fire-fighters and mitigate property damage.

Future improvements will focus on extending battery life, integrating advanced environmental modeling through AI-based decision-making, and equipping the robot with thermal imaging cameras. These enhancements will pave the way for scalable deployment in industrial, residential, and public infrastructure settings, revolutionizing fire safety standards through automation [3], [5].

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