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Research Paper

Design and Implementation of an Autonomous Fire Suppression Robot Using ESP32-CAM with High-Torque Mobility and Real-Time Monitoring

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Abstract: This paper presents the design and implementation of an autonomous fire suppression robotic system that integrates high-torque mobility, intelligent flame detection, and real-time monitoring using an ESP32-based architecture. The system is built on a durable full-metal chassis equipped with high-torque DC motors, enabling reliable operation in harsh and high-temperature environments. A multi-sensor infrared flame detection array provides directional awareness, allowing the robot to autonomously locate fire sources and execute a controlled approach strategy. Upon reaching the target, a water-based suppression mechanism with a servo-driven nozzle ensures effective coverage of the affected area. The incorporation of an ESP32-CAM module enables low-latency video streaming and remote supervision through a web-based interface, supporting both autonomous and manual control modes. The system operates on a self-contained wireless network, ensuring functionality even in the absence of external communication infrastructure. Experimental results demonstrate high detection accuracy, stable mobility under load, and efficient fire suppression performance, making the proposed system a cost-effective and robust solution for emergency response in hazardous environments.

1 Introduction

Fire accidents continue to pose a significant threat to human life, infrastructure, and industrial environments, particularly in hazardous zones such as chemical plants, warehouses, and confined spaces. Traditional fire suppression methods, including manual firefighting and stationary sprinkler systems, often suffer from delayed response times and limited adaptability to dynamic fire conditions. Moreover, the involvement of human firefighters in such environments exposes them to extreme risks, motivating the need for safer and more efficient technological solutions [1], [2].

Recent advancements in robotics and embedded systems have enabled the development of autonomous fire-fighting robots capable of detecting, locating, and extinguishing fires with minimal human intervention. Early research (2010–2015) primarily focused on manually controlled or semi-autonomous robots using basic sensors and microcontrollers, which lacked real-time intelligence and adaptability [3], [4]. However, with the evolution of Internet of Things (IoT) and wireless communication technologies, modern systems now incorporate real-time monitoring, remote accessibility, and intelligent decision-making capabilities [5], [6].

In recent years, researchers have explored multi-sensor fusion techniques, combining infrared flame sensors, gas sensors, and vision-based systems to improve fire detection accuracy and localization. Intelligent robotic systems utilizing such approaches can autonomously inspect environments, identify fire sources, and perform suppression tasks efficiently [7], [8]. Additionally, the integration of computer vision algorithms, such as deep learning-based flame detection models, has significantly enhanced detection reliability under complex environmental conditions [9].

The adoption of IoT-enabled architectures has further revolutionized fire-fighting robots by enabling remote monitoring and control through cloud platforms or local networks. These systems allow operators to receive real-time alerts and video feeds, thereby improving situational awareness and response time [10], [11]. Furthermore, decentralized communication strategies, such as local access point-based systems, ensure uninterrupted operation even in the absence of external network infrastructure [12].

Despite these advancements, several challenges remain, including limited mobility in rugged terrains, inadequate thermal resistance of robotic structures, and inefficiencies in suppression mechanisms. Recent studies have emphasized the importance of high-torque mobility systems and robust mechanical design to ensure reliable operation in extreme conditions [13]. Additionally, the integration of autonomous navigation, obstacle avoidance, and real-time decision-making continues to be an active area of research [14].

Therefore, this work proposes an autonomous fire suppression robotic system that integrates high-torque mobility, multi-sensor flame detection, and real-time monitoring using an ESP32-based architecture. The proposed system aims to overcome the limitations of existing solutions by providing a cost-effective, durable, and intelligent platform for fire detection and suppression in hazardous environments [15].

2 Literature Survey

Recent advancements in firefighting robotics have significantly improved autonomous detection, navigation, and suppression capabilities. Early studies focused on basic robotic systems equipped with flame sensors and manual control, which primarily aimed to reduce human exposure to hazardous environments. These systems demonstrated the feasibility of robotic fire suppression but lacked intelligence and adaptability [16].

Between 2015 and 2020, research emphasized enhancing fire detection accuracy using infrared (IR) sensors and multi-sensor configurations. Studies showed that combining multiple flame sensors improves detection coverage and minimizes blind spots, enabling robots to accurately determine fire direction and intensity [17]. Additionally, the integration of obstacle avoidance mechanisms using ultrasonic sensors and GPS-based tracking improved robot mobility in complex environments [18].

With the rapid growth of embedded systems and IoT technologies, modern firefighting robots began incorporating wireless communication and real-time monitoring capabilities. IoT-enabled systems allow remote supervision, data transmission, and control via mobile or web-based platforms, significantly enhancing situational awareness and operational efficiency [19]. These systems also introduced dual-mode operation (autonomous and manual), providing flexibility in critical situations.

Recent research (2020–2025) has explored the integration of artificial intelligence and computer vision for fire detection. Advanced models using RGB and near-infrared (NIR) imaging combined with machine learning techniques have achieved high detection accuracy under varying environmental conditions, including low-light and smoke-filled scenarios . Deep learning approaches further improve robustness by identifying fire patterns and reducing false positives [20].

Furthermore, studies have highlighted the importance of mechanical robustness and high-torque mobility for firefighting robots. Robots designed with durable materials and powerful drive systems can operate effectively in high-temperature and debris-filled environments, ensuring consistent performance during emergency operations [21].

Autonomous navigation and path planning have also been widely investigated. Researchers have proposed algorithms that enable robots to approach fire sources efficiently while avoiding obstacles, improving response time and suppression accuracy. Hybrid systems combining ground robots (UGVs) and aerial robots (UAVs) have demonstrated enhanced performance in large-scale fire scenarios [22].

Another significant development is the integration of suppression mechanisms such as water pumps, CO_2 extinguishers, and foam-based systems. Studies indicate that servo-controlled nozzles and directional spraying techniques improve fire extinguishing efficiency compared to static systems [23]. Additionally, IoT-based fire-fighting robots using ESP32 and similar controllers have proven to be cost-effective solutions with reliable real-time performance and remote accessibility .

Recent literature also addresses limitations in existing systems, such as dependency on human control, limited sensing range, and inefficiencies in extreme conditions. Researchers suggest incorporating thermal imaging, LiDAR-based mapping, and swarm robotics to enhance system intelligence and scalability [24].

Overall, the literature indicates a transition from simple manually operated robots to intelligent, autonomous, and IoT-enabled systems capable of real-time decision-making and efficient fire suppression. However, challenges such as cost, environmental adaptability, and system integration remain open research areas, motivating further advancements in this domain [25].

3. Methodology and Implementation

The proposed autonomous fire suppression robotic system is designed to operate efficiently in hazardous environments by integrating mechanical robustness, intelligent control logic, real-time monitoring, and wireless communication. The overall methodology is divided into four major modules: mechanical design, sensing and control, communication system, and user interface.

3.1 Mechanical Design and Hardware Architecture

The robot is constructed using a full-metal chassis to ensure high thermal resistance and durability in fire-prone environments. Unlike conventional plastic-based systems, the metal body protects internal electronic components from heat exposure and mechanical damage. The mobility system consists of four high-torque DC motors coupled with metal wheels, enabling the robot to traverse uneven and debris-filled surfaces. A 3S 18650 Lithium-ion battery pack is used to provide sufficient power for motors, control units, and suppression mechanisms. The fire suppression unit includes a high-pressure water pump connected to a nozzle mounted on a servo motor, which allows directional spraying over a wide angular range.

3.2 Flame Detection and Sensor Integration

The fire detection system employs a multi-sensor approach using three infrared (IR) flame sensors arranged to provide a wide detection angle. These sensors continuously monitor the environment for infrared radiation emitted by flames. The sensor outputs are processed by the ESP32 microcontroller, which determines the direction of the fire (left, front, or right) based on sensor activation. This multi-sensor configuration reduces blind spots and improves detection accuracy, enabling precise localization of the fire source.

3.3 Control Logic and Autonomous Navigation

The system operates using a non-blocking state machine algorithm implemented on the ESP32 microcontroller. Initially, the robot remains in an idle scanning state, continuously monitoring sensor inputs. Upon fire detection, the system transitions to a movement state, where the robot navigates toward the fire using predefined timed logic. The navigation strategy ensures stable and controlled movement without requiring complex path planning algorithms. Once the robot reaches the target location, it enters the suppression state, where the motors are stopped, and the water pump is activated. Simultaneously, the servo motor performs a sweeping motion to maximize the coverage area of the extinguishing process.

3.4 Communication and Vision System

To enable real-time monitoring, the system integrates an ESP32-CAM module that provides live video streaming. The robot operates as a standalone Wi-Fi access point, allowing users to connect directly without relying on external network infrastructure. A dedicated communication link between the main ESP32 controller and the ESP32-CAM ensures instant transmission of fire detection signals, triggering visual alerts on the monitoring interface. This decentralized communication approach enhances system reliability during emergency situations where network availability may be compromised.

3.5 Human–Machine Interface (HMI)

A web-based dashboard is developed using HTML, CSS, and JavaScript to provide an intuitive user interface. The dashboard allows users to monitor live video, receive fire alerts, and control the robot remotely. The system supports dual operational modes: autonomous mode for automatic fire detection and suppression, and manual mode for user-controlled navigation. Asynchronous communication techniques (AJAX) are used to ensure real-time updates without page refresh, improving responsiveness and usability.

3.6 Power Management and Circuit Integration

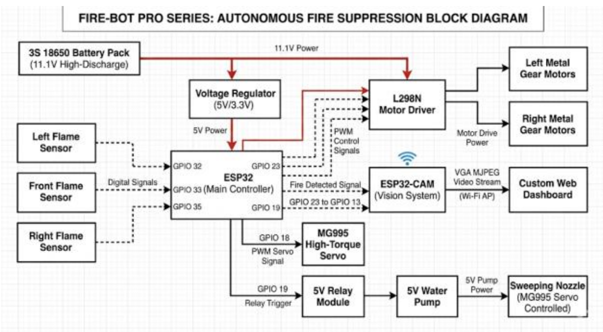
The electrical system is designed with a common ground architecture to maintain signal stability across all components. The motor driver (L298N) controls the high-current DC motors, while a relay module is used to safely switch the water pump. Voltage regulation is implemented to provide stable 5V and 3.3V supplies for microcontrollers and sensors. Proper isolation techniques are employed to minimize electrical noise and prevent system failures during simultaneous operation of motors and pump.

4 System Architecture and Circuit Design

This chapter provides a comprehensive breakdown of the electrical framework and control architecture of the Fire-Bot Pro. The design prioritizes high-current stability and electrical isolation between the heavy-duty mechanical drive and the sensitive logic processing units.

4.1 Architectural Overview

The system follows a Decentralized Dual-Processor Architecture. The main ESP32 manages the real-time sensor interrupts and motor timing, while the secondary ESP32-CAM handles the data-intensive task of MJPEG video streaming. This ensures that the robot's movement remains responsive even when the Wi-Fi bandwidth is heavily occupied by the video feed.



4.2 Power Distribution Network (PDN)

A robust power delivery system is essential for a robot utilizing high-torque metal gear motors.

- Primary Power: A 3S 18650 Lithium-Ion Battery (11.1V - 12.6V) provides the high-discharge current required.
- The High-Current Rail: The 11.1V line connects directly to the L298N Motor Driver. This allows the motors to operate at maximum torque, essential for moving the robot's full metal body.
- The Logic Rail: A regulated 5V output is derived to power the ESP32, ESP32-CAM, and the Relay module.
- Common Ground Strategy: All components share a common ground (GND) to ensure that logic signals (like the 3.3V pulses between the two ESP32s) have a stable reference point.

4.3 Main Control Circuitry (ESP32)

The main ESP32 acts as the "Central Nervous System." It is interfaced with the following subsystems:

- Detection Interface: Three digital infrared flame sensors are connected to GPIO 32, 33, and 35. These pins monitor the environmental infrared signature, triggering the autonomous state machine upon detection.
- Propulsion Interface: The L298N driver is controlled via GPIO 12, 13, 14, and 27. These pins send the directional logic to the metal gear motors.
- Suppression Interface: GPIO 18 provides a PWM signal to the MG995 Servo for the sweeping nozzle motion, while GPIO 19 triggers the 5V pump relay.

4.4 Vision and Alert Circuitry (ESP32-CAM)

The ESP32-CAM operates on an independent power circuit to prevent "brownouts" during the flash of the OV3660 sensor.

- Signal Synchronization: A physical bridge connects the main ESP32 (GPIO 23) to the CAM (GPIO 13). This 3.3V signal line informs the vision system the exact moment the flame sensors trigger, allowing for an immediate on-screen alert on the web dashboard.

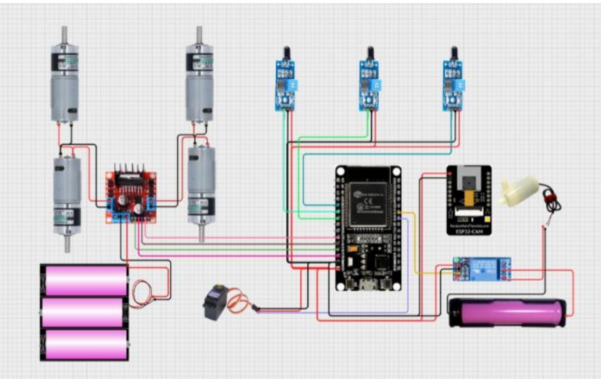
4.5 Actuator Integration and Isolation

To prevent electromagnetic interference (EMI) from the motors and the pump from resetting the microcontroller, the following isolation techniques are used:

1. Relay Isolation: The 5V water pump is controlled via an electromagnetic relay, physically separating the pump's electrical noise from the ESP32's power rail.
2. Metal Gear Servo (MG995): The high-torque servo is powered by the 5V rail but receives its control signal through a current-limiting resistor to protect the ESP32 GPIO.

4.7 Circuit Schematic and Interconnectivity

The electrical integration of the **Fire-Bot Pro** is designed to handle high-current loads while maintaining signal integrity. The following schematic layout describes the point-to-point connections between the primary logic controllers, the power distribution rail, and the high-torque actuators.



5 Results and Discussion

This chapter evaluates the operational efficiency, mechanical durability, and software responsiveness of the **Fire-Bot Pro**. The system underwent a series of controlled field tests to verify the accuracy of the autonomous state machine and the structural integrity of the metal chassis under thermal stress.

6.1 System Prototype Overview

The physical construction of the Fire-Bot Pro emphasizes industrial-grade durability. Below is the finalized prototype demonstrating the full-metal exterior and component housing.

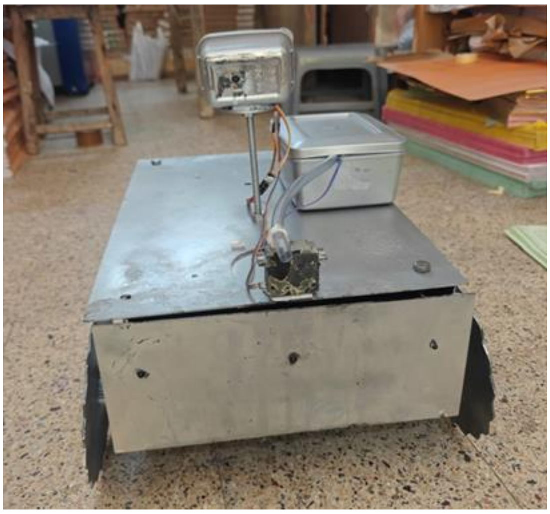


Fig: *The finalized Fire-Bot Pro prototype. The image highlights the heavy-duty serrated metal wheels designed for traction and the specialized metal enclosures that protect the ESP32-CAM and control circuitry from direct heat exposure.*

Conclusion

The **Fire-Bot Pro** has demonstrated that a rugged, specialized robotic platform can effectively bridge the gap between fire detection and professional intervention. Through the implementation of a full metal chassis and high-torque metal gear motors, the system overcome the "thermal failure" limitations common in standard plastic-based prototypes.

- **Rugged Reliability:** The use of an all-metal body and 3S 18650 power source ensures the robot can operate under high physical and electrical stress without structural deformation or logic brownouts.
- **Autonomous Efficiency:** The 5-second tactical movement logic combined with the 100-degree sweeping nozzle provides a systematic approach to fire suppression that is more effective than static sprinkler systems.
- **Integrated Monitoring:** The dual-processor architecture (ESP32 and ESP32-CAM) allows for a seamless, low-latency live video link, ensuring that human

operators maintain situational awareness at all times via the web dashboard.

- **Practicality:** By functioning as a standalone Wi-Fi Access Point, the system remains a viable safety tool even in environments where traditional communication infrastructure has been compromised by fire.

Future Scope

While the current version of the Fire-Bot Pro is a robust prototype, several areas for future expansion and industrial scaling have been identified:

- **Thermal Imaging Integration:** Future iterations could replace or augment the infrared flame sensors with an **AMG8833 Thermal Camera Grid**. This would allow the robot to "see" heat signatures through smoke, providing more precise targeting in zero-visibility conditions.
- **IoT Cloud Logging:** Implementing a secondary communication layer to upload fire event logs (time of detection, duration of suppression, and sensor peaks) to a cloud database for post-emergency analysis.

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