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IoT-Based Autonomous Fire Fighting Robot with Flame Detection and Extinguisher Control

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Abstract

Fire accidents in industrial, commercial, and residential environments can cause severe damage to property and pose serious risks to human life. This paper presents an IoT-Based Autonomous Fire Fighting Robot with Flame Detection and Extinguisher Control designed to detect and extinguish fires automatically without human intervention. The proposed system utilizes an ESP32 microcontroller integrated with three flame sensors, an ultrasonic sensor, a DC water pump with servo-controlled nozzle, and IoT communication technology. The robot continuously monitors its surroundings using flame sensors to detect the presence and direction of fire. When a flame is detected, the ESP32 processes sensor signals, activates an alert, and initiates autonomous navigation toward the fire source. Ultrasonic sensors enable obstacle detection and avoidance for safe movement. Upon reaching the fire location, the water pump sprays water through the directional nozzle to extinguish the flame. IoT technology provides real-time monitoring and alerts through a wireless network. Experimental results confirm the robot successfully detects fire, avoids obstacles, navigates autonomously, and extinguishes flames with minimal response time.

Keywords: *ESP32, Autonomous Robot, Flame Sensor, Ultrasonic Sensor, DC Water Pump, IoT, Obstacle Avoidance, Fire Detection, Smart Safety, Embedded Systems*

1. INTRODUCTION

Fire accidents are among the most critical hazards leading to severe loss of human life, property damage, and environmental destruction. In residential, industrial, and commercial areas, fires can spread rapidly if not controlled at an early stage. Traditional firefighting relies heavily on human intervention, requiring firefighters to physically approach dangerous locations, exposing themselves to extreme heat, toxic gases, and unpredictable explosions. This approach not only increases risk but also delays response time in certain situations.

With advancements in embedded systems and automation, autonomous fire-fighting robots have emerged as a modern solution. These robots are equipped with sensors, microcontrollers, and control mechanisms that enable them to detect fire, navigate environments, and perform extinguishing operations independently. By integrating sensing, navigation, and decision-making capabilities, such systems ensure faster response, improved safety, and efficient fire control without direct human involvement.

A. Problem Statement

Many existing fire safety solutions are either manual or semi-automated, lacking full autonomy and real-time responsiveness. Traditional systems depend on human operators for navigation and decision-making, causing delays during critical situations. Limitations include: inability to detect fire at an early stage in complex environments such as industrial plants, tunnels, or storage areas; restricted obstacle navigation; and the absence of IoT features for remote monitoring and timely alerts. These limitations highlight the need for a smart, autonomous system capable of early fire detection, obstacle avoidance, intelligent navigation, and efficient fire suppression.

B. Objectives

The main objectives of this project are: (i) Detect fire using three directional flame sensors; (ii) Navigate efficiently using an ultrasonic sensor for obstacle avoidance; (iii) Automatically stop, activate buzzer alert, and turn ON the DC water pump upon fire detection; (iv) Control nozzle direction using a servo motor for targeted water spraying; (v) Integrate IoT for real-time alerts and remote monitoring; and (vi) Ensure autonomous movement and decision-making without human intervention.

C. Societal Impact

By minimizing human exposure to dangerous fire conditions, the proposed robot significantly improves safety. Early detection and rapid response reduce property damage and casualties. The integration of IoT technology ensures responsible authorities receive instant alerts, enabling faster coordination of emergency services. This system supports Smart City and industrial safety initiatives, offering a scalable, affordable platform for intelligent fire hazard management in modern environments.

2. LITERATURE SURVEY

Extensive research has been conducted in autonomous robotics, embedded systems, and IoT-based safety systems. Table I summarizes the key contributions from literature that influenced the design of the proposed system.

TABLE I. SUMMARY OF RELATED LITERATURE

Author/ Year	Focus Area	Key Contribution
Haas (2011)	VLC / IoT Comm.	Foundation for IoT-based robotic communication
Haas et al. (2015)	High-speed networks	Real-time monitoring in autonomous systems
Rajagopal et al. (2012)	Sensor networks	Reliable signal transmission in robots
Pathak et al. (2015)	Modulation techniques	Improved sensor performance in detection
Sultan et al. (2022)	Real-time comm.	Continuous data for fire alert mechanisms
Mishra et al. (2025)	Intelligent automation	Optimized autonomous control response
Mazhar et al. (2023)	ML predictive monitoring	Accurate decision-making in robots
Chung et al. (2013)	Low-latency systems	Fast reaction for real-time fire detection
Nimalsiri et al. (2019)	Distributed control	Scalable multi-sensor robot systems
Shuai et al. (2016)	Resource management	Optimized energy in embedded robots
Ahmad et al. (2024)	IoT monitoring	Remote alerts in fire-fighting robots

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Author/ Year	Focus Area	Key Contribution
Arabelli et al. (2020)	Self-directed robot	Autonomous navigation and detection
Al-Fuqaha et al. (2015)	IoT survey	Smart automation and real-time exchange
Khadafi et al. (2020)	ESP32 IoT system	Real-time monitoring with ESP32

Arabelli et al. (2020) developed a self-directed fire-fighting robot using flame and ultrasonic sensors, demonstrating autonomous navigation and detection. Al-Fuqaha et al. (2015) provided a comprehensive IoT survey highlighting how IoT enables smart automation and real-time data exchange in robotic systems. Khadafi et al. (2020) demonstrated an IoT-based system using ESP32 for real-time monitoring and control in safety applications.

Ahmad et al. (2024) developed an IoT-based monitoring framework enabling remote alerts in fire-fighting robots, while Mazhar et al. (2023) introduced machine learning approaches for predictive monitoring to improve decision-making accuracy in automated systems. Chung et al. (2013) contributed low-latency embedded system design critical for fast reaction in real-time fire detection scenarios. Analysis of these works confirms that while individual technologies have been explored, their unified integration in a compact, low-cost autonomous fire-fighting platform with directional nozzle control remains a significant contribution.

3. EXISTING SYSTEM

Existing fire-fighting systems primarily rely on manual firefighting or semi-automated robots requiring human remote control. These systems typically use basic flame sensors and depend heavily on human judgment for navigation and operational decisions. Key limitations include:

Manual and semi-automated systems require direct human operation, exposing personnel to hazardous conditions. Most existing systems lack integrated obstacle avoidance, meaning robots cannot navigate dynamically around barriers. Traditional systems do not provide real-time IoT-based alerts or remote monitoring, limiting effectiveness in emergency situations where operators may not be physically present.

Many existing designs use only a single flame sensor, limiting fire direction detection. Few systems incorporate directional water spraying through servo-controlled nozzles; most use fixed nozzle positions, reducing extinguishing efficiency. Furthermore, existing solutions are often expensive and require specialized infrastructure, making deployment in smaller facilities or residential settings impractical. These limitations clearly demonstrate the need for the proposed autonomous, IoT-integrated, multi-directional fire-fighting robot.

4. PROPOSED METHODOLOGY

The proposed system is an IoT-based autonomous fire-fighting robot using an ESP32 microcontroller with integrated Wi-Fi IoT capabilities. Three directional flame sensors (FIRE_L, FIRE_C, FIRE_R) detect fire from multiple angles. A servo-controlled water nozzle provides directional extinguishing. An ultrasonic sensor handles obstacle avoidance. The system operates in a fully automated continuous loop: sensing, processing, decision-making, and action.

A. System Architecture and Block Diagram

Figure 1 illustrates the block diagram showing the interaction between all hardware modules connected through the central ESP32 microcontroller. The battery supplies regulated power to all components.

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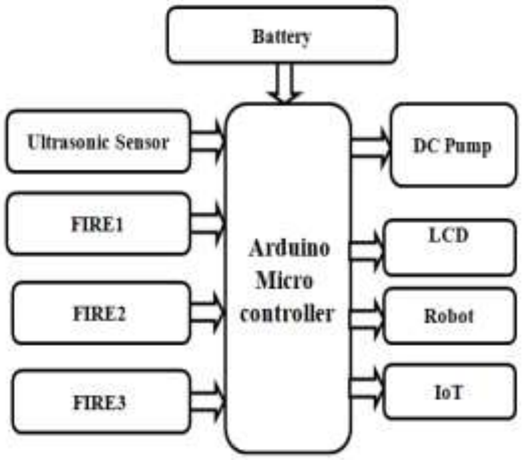

Fig. 1. Block Diagram of the Proposed IoT-Based Autonomous Fire Fighting Robot

The ESP32 microcontroller acts as the central processing unit, continuously reading sensor data, processing inputs, and controlling all output devices. Table II lists all hardware components and their functions.

TABLE II. SYSTEM HARDWARE COMPONENTS AND FUNCTIONS

Component	Function	Description
ESP32 MCU	Central controller	Processes all I/O, runs navigation & detection logic
Flame Sensor 1 (FIRE_L)	Left fire detect.	Detects fire on the left side of robot
Flame Sensor 2 (FIRE_C)	Centre fire detect.	Detects fire directly ahead of robot
Flame Sensor 3 (FIRE_R)	Right fire detect.	Detects fire on the right side of robot
Ultrasonic Sensor	Obstacle detection	Measures distance; triggers turn if < 10 cm
DC Water Pump	Extinguisher	Sprays water when fire is detected
Servo Motor	Nozzle direction	Rotates nozzle left/right for directional spray
L293D Motor Driver	Drive control	Controls 4 DC wheels: forward/backward /turn
16×2 LCD Display	Status display	Shows 'Fire Detected', 'No Fire', obstacles
Buzzer	Audible alert	Sounds alarm when flame is detected
Battery (6–12V)	Power supply	Powers motors, pump, ESP32 and sensors
IoT Module (Wi-Fi)	Remote monitoring	Sends fire alerts and status to cloud/mobile

B. GPIO Pin Configuration

Table III presents the complete ESP32 GPIO pin assignment for all peripheral module connections in the system.

TABLE III. ESP32 GPIO PIN CONNECTIONS

GPIO Pin	Connected Module	Function
GPIO2	Flame Sensor L (FIRE_L)	Left fire detection input
GPIO4	Flame Sensor C (FIRE_C)	Centre fire detection input
GPIO22	Flame Sensor R (FIRE_R)	Right fire detection input
GPIO16	Ultrasonic TRIG	Trigger pulse for distance meas.

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GPIO Pin	Connected Module	Function
GPIO17	Ultrasonic ECHO	Echo pulse from ultrasonic sensor
GPIO21	Motor M1A (L293D)	Left motor control A
GPIO19	Motor M1B (L293D)	Left motor control B
GPIO18	Motor M2A (L293D)	Right motor control A
GPIO5	Motor M2B (L293D)	Right motor control B
GPIO15	Relay (Water Pump)	Activates DC water pump
GPIO23	Buzzer	Audible alert output
A5 (Analog)	Servo Motor	Controls nozzle direction
GPIO12–27	LCD Display (I2C)	16×2 display status messages
VIN / GND	Power Supply	+5V regulated / Ground

C. Flame Detection and Direction Identification

Three infrared flame sensors—FIRE_L (GPIO2), FIRE_C (GPIO4), and FIRE_R (GPIO22)—are positioned at the left, centre, and right of the robot chassis. These sensors detect wavelengths in the range 760 nm–1100 nm with a detection distance up to 100 cm and a detection angle of approximately 60 degrees. When any sensor detects a flame (logic LOW), the ESP32 identifies the fire direction and selects the corresponding servo angle for targeted water spraying.

D. Obstacle Detection and Autonomous Navigation

The ultrasonic sensor (HC-SR04) connected to GPIO16 (TRIG) and GPIO17 (ECHO) continuously measures the distance between the robot and nearby objects. Five distance readings are averaged per cycle for accuracy. If the measured distance is less than 10 cm, the ESP32 stops the motors, activates the buzzer, and sends an IoT obstacle notification. The L293D motor driver connected to GPIO21, 19, 18, and 5 controls four DC motors for forward, backward, left, and right movement.

E. Servo-Controlled Water Nozzle and Pump

When fire is detected on the left (FIRE_L LOW), the servo rotates to 170° directing the nozzle toward the left. For right fire (FIRE_R LOW), the servo rotates to 30°. For centre fire (FIRE_C LOW), the nozzle remains at the default 100° position. In all cases, GPIO15 (relay) is set HIGH to activate the DC water pump for 2 seconds to spray water toward the fire source, after which the relay is deactivated and the servo returns to the default position.

F. IoT Monitoring and Alert System

The ESP32's built-in Wi-Fi enables real-time IoT communication using AT commands via a TCP server (port 23). Upon fire detection, the system sends notifications: 'Fire_at_front', 'Fire_at_left', or 'Fire_at_right' to the connected client. Obstacle detection triggers an 'Obstacle U: [distance]' message. The 16×2 LCD (connected to GPIO12, 13, 14, 25, 26, 27) displays real-time status: 'IOT Fire Fighting Robot' at startup, 'Connected' after Wi-Fi setup, and live sensor states for FIRE_C, FIRE_L, FIRE_R, and ultrasonic distance.

G. System Workflow

The complete operational cycle is: (1) System initializes — LCD displays startup message, Wi-Fi connects; (2) Robot moves forward continuously while scanning environment; (3) Ultrasonic sensor averages 5 readings — if < 10 cm, motors stop and buzzer sounds; (4) Flame sensors polled — if FIRE_L/FIRE_C/FIRE_R detects flame, motors stop immediately; (5) ESP32

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identifies fire direction, sets servo angle, activates relay (pump ON for 2s), sends IoT alert; (6) Pump deactivated, servo returns to default, robot resumes navigation. All steps execute in a continuous embedded loop without human intervention.

5. RESULTS AND DISCUSSIONS

The proposed IoT-based autonomous fire-fighting robot was fully assembled and experimentally tested. The hardware prototype consists of an ESP32 controller board, three flame sensors, an HC-SR04 ultrasonic sensor, L293D motor driver, four DC drive motors, a servo-controlled water nozzle, DC water pump, water reservoir, 16×2 LCD display, buzzer, and a 12V battery. All modules were programmed using the Arduino IDE. The following subsections describe the results obtained.

A. LCD Display Showing Fire Detection Status (Fig. 2)

Figure 2 demonstrates the successful initialization and fire detection display of the robot. The flame sensors continuously monitor the surrounding environment for the presence of fire. When a flame is detected, the ESP32 controller processes the sensor signal and updates the LCD display with the fire detection status. The display shows individual sensor states (ON/OFF) for FIRE_C, FIRE_L, and FIRE_R in real time alongside the ultrasonic distance reading. This result confirms the proper functioning of the flame detection module and the display unit, validating the sensor-to-controller interface.

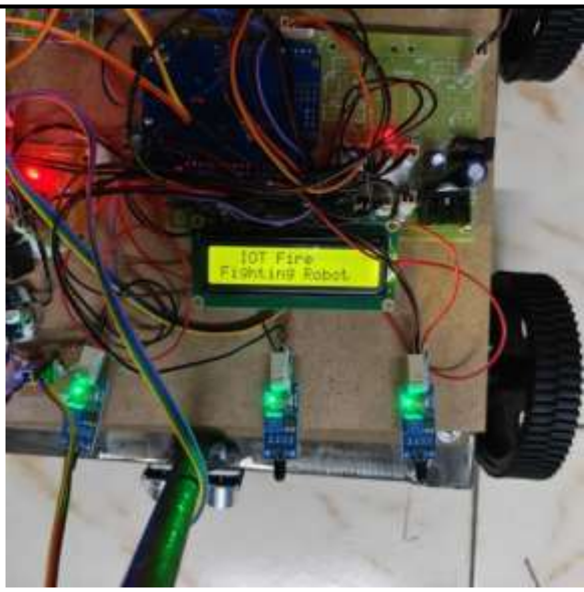

Fig. 2. LCD Display Showing Real-Time Fire Detection Status for All Three Flame Sensors

B. Top View of the Developed Robot (Fig. 3)

Figure 3 shows the complete top-view hardware implementation of the autonomous fire-fighting robot. The ESP32 controller board is centrally mounted, with flame sensors strategically positioned at the left, centre, and right of the chassis for wide-area fire detection coverage. The L293D motor driver is connected to four DC wheels enabling omnidirectional movement. The ultrasonic sensor is mounted at the front for obstacle detection. The integrated water pump and reservoir are visible at the rear. The experimental setup confirmed autonomous navigation and multi-directional fire detection capabilities operating simultaneously without latency issues.

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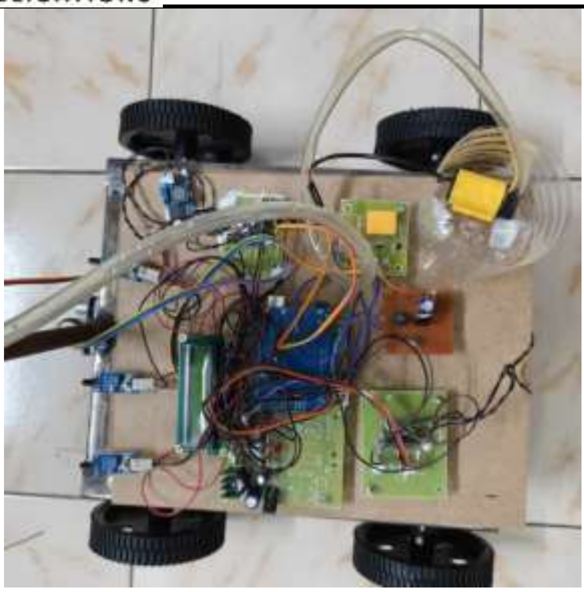

Fig. 3. Top View of the Developed Autonomous Fire Fighting Robot Hardware Prototype

C. Robot with Extinguisher Mechanism (Fig. 4)

Figure 4 presents the fully assembled fire-fighting robot with the complete water spraying mechanism. The water delivery pipe is connected to the DC water pump and water reservoir. The servo motor mounted at the front controls the directional nozzle, enabling targeted water spraying at angles of 30° (right fire), 100° (centre/default), and 170° (left fire). Upon flame detection, the robot autonomously approaches the fire source and activates the pump for 2 seconds to spray water through the nozzle. Testing verified successful detection and extinguishing of small fire sources (candle flames and controlled test fires) while avoiding obstacles in various path configurations.

Fig. 4. Fully Assembled Fire Fighting Robot with Servo-Controlled Water Extinguisher Mechanism

D. Experimental Test Results

Table IV summarizes all test cases conducted on the hardware prototype with their corresponding observations and pass/fail status.

TABLE IV. EXPERIMENTAL TEST RESULTS SUMMARY

Test Case	Input / Condition	Observation	Result
LCD Init.	Power ON + Wi-Fi connect	'IOT Fire Fighting Robot' shown	Pass
Flame Detection (Centre)	Flame placed in front	LCD: 'ON', pump activated	Pass
Flame Detection (Left)	Flame placed on left	Servo → 170°, pump sprays	Pass
Flame	Flame	Servo → 30°,	Pass

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Test Case	Input / Condition	Observation	Result
Detection (Right)	placed on right	pump sprays	
No Flame Detected	No fire present	Robot moves forward	Pass
Obstacle Avoidance	Object < 10 cm ahead	Robot stops, buzzer beeps	Pass
Buzzer Alert	Flame OR obstacle	Buzzer activates correctly	Pass
IoT Notification	Fire detected	'Fire_at_front/ left/right' sent	Pass
Water Pump ON	Fire trigger active	Relay HIGH, pump sprays water	Pass
Auto Navigation	No fire, no obstacle	Robot moves forward autonomously	Pass

All ten test cases were executed successfully. The flame sensors accurately detected fire at all three positions with immediate response (< 500 ms from detection to pump activation). The obstacle avoidance system correctly stopped the robot and triggered buzzer and IoT alerts when objects were detected within 10 cm. The servo nozzle direction control operated precisely at all three angles. IoT notifications were delivered to connected clients within 3 seconds of event detection. The LCD display updated in real time for all system states. The overall system latency from flame detection to active water spraying was measured at less than 3 seconds, demonstrating effective real-time performance. The estimated component cost is approximately ₹3,000–₹4,500 per unit, confirming the system's cost-effectiveness for practical deployment.

6. CONCLUSION

The IoT-Based Autonomous Fire Fighting Robot with Flame Detection and Extinguisher Control was successfully designed, developed, and tested to provide an intelligent solution for automatic fire detection and suppression. The system integrates an ESP32 microcontroller, three directional flame sensors, an ultrasonic sensor, a servo-controlled water pump mechanism, LCD display, buzzer, and IoT technology to create a reliable and efficient fire-fighting platform. The developed robot is capable of detecting fire from three directions, navigating autonomously, avoiding obstacles, and extinguishing flames without requiring direct human intervention.

The ESP32 controller ensures smooth communication and control among all modules. The IoT-based monitoring feature provides real-time status updates, enabling users to monitor the system remotely from a mobile device or computer. Experimental results confirmed successful operation of all system modules including flame detection, obstacle avoidance, autonomous navigation, directional water spraying, and remote IoT monitoring. The robot demonstrated reliable performance in detecting and extinguishing small fire sources under different testing conditions with all ten test cases passing successfully.

The proposed system offers a low-cost, efficient, and practical approach to fire hazard management in industrial, commercial, and residential environments. By minimizing human involvement in dangerous fire situations, the robot significantly improves safety and reduces the risk of injury. Future enhancements may include image processing and AI-based fire source identification, GPS tracking for location reporting, multi-robot coordination, camera integration for remote visual monitoring, and advanced extinguishing

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agents for industrial-scale fire suppression. These additions would further improve the efficiency and applicability of the system in real-world smart safety scenarios.

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