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A Real-time IoT-based Fire Fighting Robot and Security Surveillance using ESP-32 Controller

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ABSTRACT
Fire accidents represent a major threat to human life, industrial infrastructure, forests, and residential environments, often resulting in severe economic loss, environmental damage, and casualties. Conventional firefighting methods mainly depend on human intervention, where firefighters manually enter hazardous locations to control flames and rescue victims. However, traditional firefighting approaches face several limitations, including delayed response, restricted accessibility in dangerous environments, exposure to toxic gases, high temperatures, and poor visibility caused by smoke. These challenges create the need for an intelligent automated firefighting system capable of detecting and suppressing fire incidents without directly risking human safety. To address this issue, the proposed Fire Bot Sentinel introduces a smart robotic firefighting system integrated with embedded sensing, robotic mobility, and real-time monitoring technologies. The system is built using an ESP32 (Espressif 32) microcontroller, which functions as the central processing unit for sensor monitoring and actuator control. A fire sensor continuously detects flame presence and automatically activates a water pump to extinguish the fire. The robotic platform can move toward the fire source, while a servo motor controls the direction of water spraying for precise targeting. An ESP32-CAM (Camera Module) provides live visual monitoring of the affected environment, and an LCD (Liquid Crystal Display) presents operational alerts and status updates. The proposed system enhances firefighting efficiency, enables rapid emergency response, reduces human exposure to hazardous conditions, and supports improved safety in industrial, commercial, and residential environments.

Keywords: IoT-based Firefighting System, ESP32, Fire Detection, Autonomous Robot, Embedded Systems, Flame Sensor, Water Pump Control, Servo Motor, Robotic Mobility, Emergency Response Automation

1. INTRODUCTION

Thermal disaster incidents remain one of the most destructive safety challenges affecting residential buildings, industrial facilities, storage warehouses, research laboratories, forests, commercial establishments, and public infrastructure. Once ignition occurs, flames can expand aggressively within a very short duration, resulting in extensive structural destruction, operational disruption, environmental pollution, financial loss, and serious threats to human survival. Conventional emergency suppression practices mainly depend on trained rescue personnel who must physically approach hazardous locations to identify the affected region and perform extinguishing operations manually. Such environments often contain dense smoke, elevated temperatures, combustible chemicals, toxic gases, and unstable structures, significantly increasing the probability of injury or fatality among emergency responders. In large industrial environments and hazardous processing units, delayed response or limited accessibility can further intensify the severity of the disaster. These limitations create a strong demand for autonomous safety platforms capable of rapidly identifying hazardous conditions and initiating suppression procedures without exposing human operators to dangerous surroundings. Recent advancements in intelligent robotics, embedded computing, wireless communication, automated sensing, and real-time monitoring technologies have enabled the development of sophisticated robotic emergency-response systems for hazardous environments. Autonomous firefighting platforms equipped with environmental sensing modules, mobility mechanisms, and embedded control units can continuously monitor surroundings, detect abnormal thermal activity, and perform immediate suppression actions with minimal human intervention. Such systems are highly beneficial in petroleum refineries, chemical industries, electrical substations, manufacturing plants, warehouses, underground facilities, and disaster-prone regions where manual firefighting operations are difficult, delayed, or unsafe. By integrating robotic automation with intelligent sensing mechanisms, modern safety systems can significantly improve emergency response efficiency while minimizing risks to rescue personnel.

The proposed Fire Bot Sentinel is an advanced autonomous firefighting robotic platform developed to perform rapid flame detection, environmental monitoring, and automatic fire suppression in hazardous conditions. The system architecture is centered around an ESP32 microcontroller that functions as the embedded processing and control unit responsible for coordinating sensing, robotic movement, actuator control, and communication operations. A flame detection module continuously analyzes the surrounding environment to identify the presence of fire and immediately initiates suppression procedures upon hazard detection. Once activated, a water pumping mechanism automatically sprays water toward the affected area to prevent further flame propagation. The robotic platform is capable of moving toward the hazardous zone, enabling localized suppression instead of stationary operation. To improve targeting precision, a servo-controlled nozzle mechanism dynamically adjusts the direction of water discharge according to the detected fire location. For enhanced situational awareness and remote supervision, the system integrates an ESP32-CAM module capable of transmitting live visual information through real-time image and video capture. This functionality allows operators to remotely monitor environmental conditions, identify the location and intensity of the hazard, and supervise firefighting activities from a safe distance. An LCD module displays continuous operational information, including emergency notifications, hazard detection status, and system activity updates for local monitoring purposes. The entire robotic platform operates using a portable battery-powered energy source, enabling flexible deployment across multiple indoor and hazardous environments without dependence on fixed electrical infrastructure. Through the integration of autonomous sensing, robotic mobility, embedded control, visual monitoring, and automated suppression technologies, the Fire Bot Sentinel provides an intelligent and reliable emergency-response solution capable of improving safety, accelerating disaster response, minimizing infrastructure damage, and reducing human exposure to dangerous fire-related environments.

2. LITERATURE SURVEY

A. Ranjan et al. [1] proposed an autonomous firefighting robotic system designed to detect and suppress fire incidents using embedded sensing and automated extinguishing mechanisms. The system utilized flame detection sensors to continuously monitor the surrounding environment and automatically activated a water spraying mechanism whenever fire was detected. The robot was capable of moving toward the affected area and performing firefighting operations without direct human involvement. Their study demonstrated the practical feasibility of integrating embedded controllers, flame sensors, and robotic mobility for indoor firefighting applications. The research highlighted how autonomous robotic systems reduced response time and improved safety in hazardous situations. This work strongly supported the automated flame detection and water suppression architecture implemented in the proposed Fire Bot Sentinel system. S. Sharma et al. [2] developed a fire detection and suppression robot using microcontroller-based embedded control systems integrated with flame sensors and temperature monitoring devices. The robot continuously analyzed

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environmental conditions to identify potential fire hazards and automatically activated extinguishing mechanisms upon detection. Their work emphasized the importance of combining intelligent sensing technologies with robotic mobility for improving firefighting efficiency and minimizing human exposure to dangerous conditions. The study also demonstrated the effectiveness of embedded automation in handling emergency response operations with minimal manual intervention. This research directly supported the sensor-controlled fire detection and robotic firefighting functionality implemented in the proposed system. P. Kumar et al. [3] designed a wireless firefighting robotic platform using embedded systems and wireless communication technologies for remote firefighting operations and environmental monitoring. The robot incorporated camera modules capable of transmitting real-time images and video streams to remote operators during emergency situations. The system allowed users to supervise hazardous environments from a safe location while controlling firefighting operations remotely. Their research demonstrated the importance of integrating wireless communication and visual monitoring technologies into robotic firefighting systems for improved operational awareness and safety. This work validated the ESP32-CAM-based real-time monitoring and remote accessibility functionality integrated into the proposed Fire Bot Sentinel framework. M. Abdullah et al. [4] introduced an intelligent firefighting robot equipped with ultrasonic sensors, flame detectors, and embedded navigation mechanisms capable of autonomously locating and approaching fire sources. The system utilized obstacle detection technologies to navigate safely through hazardous environments while continuously monitoring flame intensity and environmental conditions. Once the fire source was identified, the robot activated its extinguishing mechanism to suppress the flames automatically. Their work highlighted the advantages of autonomous robotic firefighting systems in reducing direct human involvement in dangerous environments containing heat, smoke, and toxic gases. The study supported the autonomous movement and intelligent firefighting capabilities implemented in the proposed robotic platform.

J. Patel et al. [5] proposed an IoT-based fire monitoring system capable of detecting fire incidents and transmitting emergency alerts through internet-enabled communication platforms. The system continuously monitored environmental conditions using embedded sensing technologies and immediately notified users when abnormal fire conditions were detected. Their work emphasized the significance of remote monitoring, rapid alert generation, and wireless communication in improving emergency response efficiency and minimizing disaster impact. The study demonstrated how IoT-enabled safety systems provided continuous supervision of hazardous environments through real-time communication technologies. This research supported the IoT-based monitoring and status reporting mechanisms integrated into the proposed Fire Bot Sentinel architecture. A. Verma et al. [6] developed a smart fire detection system using embedded technologies and temperature sensing mechanisms for identifying hazardous environmental conditions associated with fire outbreaks. The proposed framework continuously analyzed temperature variations and automatically triggered suppression responses whenever abnormal thermal conditions were detected. Their research demonstrated the effectiveness of embedded automation and intelligent sensing for improving fire safety and reducing manual dependency during emergency situations. The authors also highlighted the importance of rapid hazard detection and automated response systems in minimizing fire damage and improving operational safety. This work directly supported the automated sensing and fire response mechanisms implemented in the proposed firefighting robotic system. R. Mehta et al. [7] designed a robotic fire extinguisher system using flame sensors, microcontroller-based control mechanisms, and automated water pumping technology for rapid fire suppression applications. The system continuously monitored the environment for flame presence and automatically activated the extinguishing mechanism whenever fire was detected. Their work demonstrated improved response speed and effective suppression capability for small-scale fire outbreaks. The study highlighted the importance of integrating embedded sensing technologies with automated firefighting systems to minimize damage and improve emergency response efficiency. This research supported the flame sensing and automatic water spraying mechanism implemented in the proposed Fire Bot Sentinel system. T. Nguyen et al. [8] introduced a vision-based fire detection framework using image processing techniques for real-time flame and smoke identification. The system analyzed visual information captured through camera modules to detect fire-related patterns and environmental abnormalities. Their research demonstrated that camera-assisted monitoring systems improved detection accuracy and enabled continuous visual surveillance of hazardous areas. The study emphasized the effectiveness of image-based monitoring for early fire identification and emergency response applications. This work supported the ESP32-CAM-based visual monitoring and real-time surveillance functionality integrated into the proposed robotic firefighting platform.

S. Mohanty et al. [9] explored IoT-enabled safety systems designed for smart environments using embedded sensors, wireless communication technologies, and automated monitoring architectures. Their study emphasized the importance of integrating sensing devices with connected communication platforms for continuous hazard monitoring and rapid emergency response. The research demonstrated how IoT-based systems improved operational awareness, remote accessibility, and automated control in safety-critical applications. Their work strongly supported the IoT communication and remote monitoring mechanisms implemented in the proposed Fire Bot Sentinel architecture. D. Chavan et al. [10] proposed an obstacle-avoiding firefighting robot equipped with flame sensors and navigation mechanisms capable of automatically locating and approaching fire sources. The robot utilized obstacle detection technologies to safely navigate through complex environments while continuously monitoring hazardous conditions. Once the fire source was identified, the system activated an extinguishing mechanism to suppress the flames automatically. Their study demonstrated the importance of autonomous mobility and intelligent navigation in improving robotic firefighting efficiency. This work supported the robotic movement and automated targeting functionality implemented in the proposed firefighting system. K. Bansal et al. [11] developed a microcontroller-based firefighting robot integrating multiple sensing modules for accurate fire detection and automatic suppression operations. The proposed system continuously monitored environmental conditions and activated extinguishing mechanisms immediately after identifying fire hazards. Their work focused on improving system reliability, response speed, and operational stability in emergency situations. The research demonstrated the effectiveness of combining embedded control systems with multiple sensors for intelligent firefighting applications. This study supported the embedded automation and multi-sensor integration approach implemented in the proposed Fire Bot Sentinel framework. H. Jain et al. [12] implemented an embedded fire monitoring system integrated with camera modules for continuous real-time surveillance of hazardous environments. The system captured live images and video streams to provide users with remote visual access to fire incidents and surrounding conditions. Their research highlighted the significance of camera-assisted monitoring for improving situational awareness and enabling remote supervision during emergencies. The study demonstrated how embedded visual monitoring systems enhanced operational safety and emergency management efficiency. This work validated the real-time visual monitoring functionality provided by the ESP32-CAM module in the proposed robotic firefighting system.

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3. PROPOSED SYSTEM

The system architecture is designed as a comprehensive IoT-enabled autonomous fire detection and suppression framework centered on the ESP32, integrating sensing, control logic, actuation, user interaction, and cloud communication into a continuous real-time operational pipeline. During the system initialization phase, the ESP32 configures all peripheral modules, including setting up serial communication at 9600 baud rate, attaching and positioning the servo motor for nozzle control, initializing motor driver pins for robotic movement, configuring the buzzer for alert signaling, and preparing the water pump in an inactive state, while also initializing the LCD to present system status messages such as readiness and connectivity. Simultaneously, the WiFi (Wireless Fidelity) module is configured using predefined SSID and password credentials, establishing a stable internet connection that enables remote monitoring and data transmission capabilities.

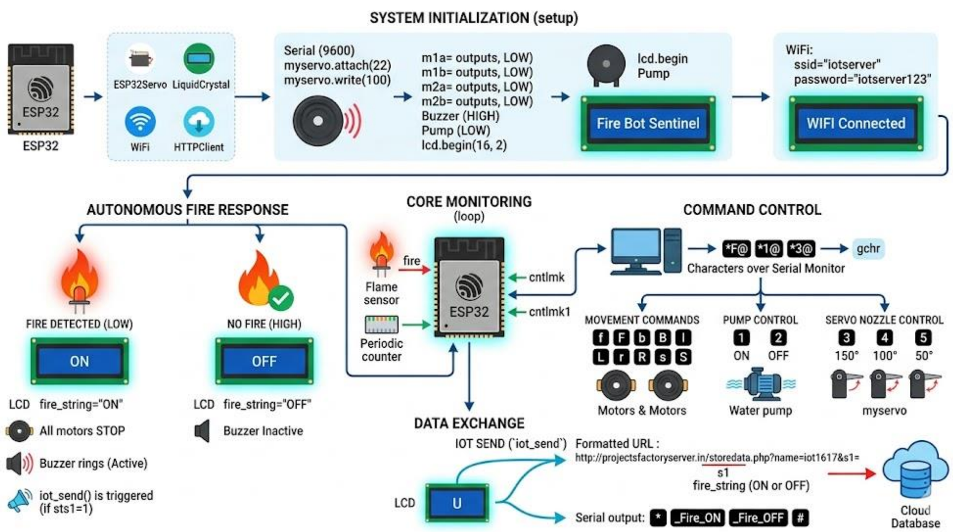

Fig. 1: Proposed system architecture

Once initialization is complete, the system enters the core monitoring loop, where the flame sensor continuously detects fire presence by generating digital signals that are interpreted by the ESP32 using internal counters and control logic to ensure reliable detection and avoid false triggers. When a fire condition is detected (LOW signal), the system immediately transitions into an autonomous response mode, where all motion-related motors are halted to stabilize the platform, the buzzer is activated to generate an audible alarm, and the water pump is turned ON to initiate fire suppression, while the LCD is updated with a "Fire ON" status to provide real-time feedback; additionally, an IoT transmission routine is triggered to send the fire status to a cloud server. Conversely, when no fire is detected (HIGH signal), the system maintains a safe idle state with motors inactive, pump OFF, and buzzer silent, while updating the LCD with a "Fire OFF" indication. In parallel, the architecture supports a command control subsystem that allows manual override through serial input commands, enabling users to control robot movement directions (forward, backward, left, right), operate the water pump independently, and adjust the servo motor angle for precise nozzle positioning, thereby enhancing operational flexibility in complex environments. The data exchange module formats system status information into structured HTTP (Hypertext Transfer Protocol) requests and sends it to a remote cloud server, where a backend script processes and stores the data in a database, enabling remote monitoring, logging, and analysis of fire events. Additionally, serial output logs provide debugging information such as Fire_ON or Fire_OFF messages, ensuring transparency and ease of system validation. The architecture also incorporates synchronization mechanisms between sensing, decision-making, and actuation processes to ensure minimal latency and reliable performance under real-time conditions. As illustrated in Fig. 1, this integrated design demonstrates seamless coordination between detection, response, user control, and IoT communication layers, resulting in a robust, scalable, and intelligent fire monitoring and suppression system suitable for dynamic and safety-critical environments.

4. RESULTS AND DISCUSSION

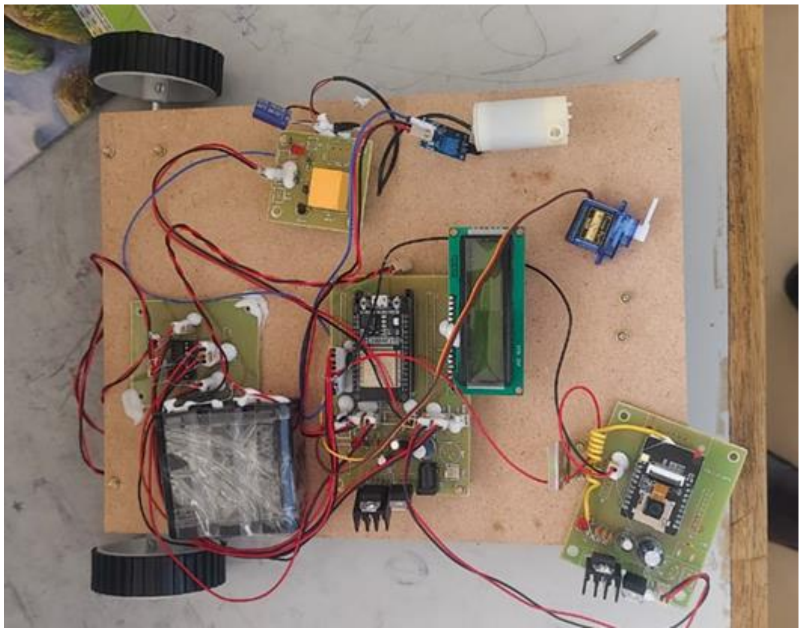

Fig. 2: Hardware Setup of Fire Bot Sentinel

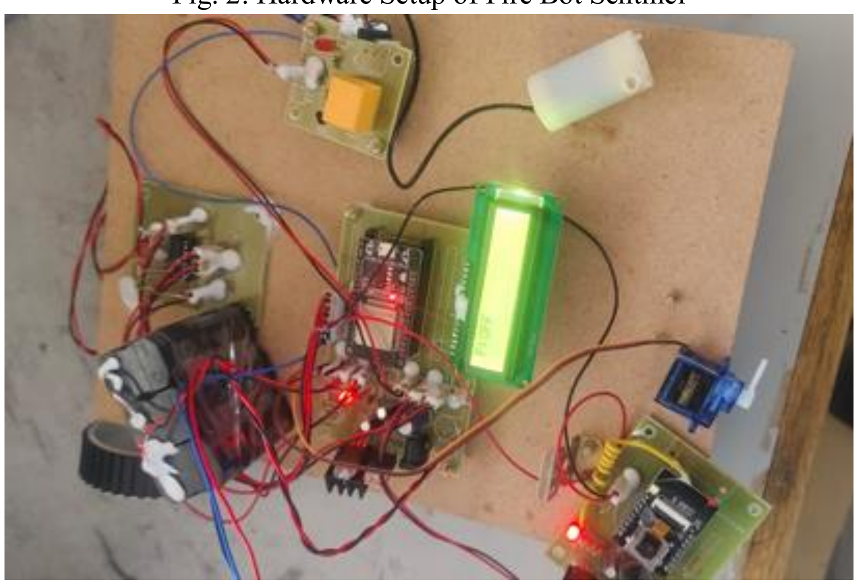

Fig. 3: LCD Display Showing System Status

Fig. 2 illustrates the hardware setup of the Fire Bot Sentinel system, integrating components such as the Arduino microcontroller, L298N motor driver module, DC motors with wheels, relay module, water pump, battery pack, voltage regulator circuit, ESP communication module, LCD display, and connecting circuitry. It depicts the interconnection between control, actuation, communication, and power units required for autonomous fire detection and suppression operations. The figure represents how the motor driver controls robotic movement while the relay module activates the water pump for extinguishing actions. It highlights the coordinated functioning of sensing, mobility, and control hardware within the robotic platform. Furthermore, it demonstrates the practical implementation of an embedded robotic firefighting system designed for real-time response.

Fig. 3 illustrates the LCD display interface of the Fire Bot Sentinel system, incorporating the Arduino microcontroller, LCD module, sensor interfacing circuits, and communication modules to present system status and operational messages. It depicts how sensor inputs and control logic are processed and reflected on the display in real time. The figure represents the role of the LCD module in providing continuous feedback regarding system activity and execution flow. It highlights the integration of display hardware with control and communication components for monitoring system performance. Additionally, it demonstrates how embedded hardware modules work together to ensure user awareness and system transparency during operation.

5. CONCLUSION

The Fire Bot Sentinel project successfully demonstrated an automated robotic solution for detecting and controlling fire incidents with minimal human involvement. The system continuously monitored the environment using flame sensors and responded instantly by activating a water pump to suppress the fire. The integration of a servo mechanism ensured precise targeting of the water spray, improving extinguishing efficiency. Real-time monitoring through the camera module allowed remote observation, while the display unit provided clear system status and alerts. The battery-powered design made the robot portable and suitable for operation in different environments without dependency on external power sources. Overall, the system reduced the risks faced by firefighters and improved response time during emergencies. Future enhancements can focus on autonomous navigation, advanced sensing techniques, and intelligent decision-making to further increase reliability and effectiveness.

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