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Autonomous Fire Detection and Suppression System Using IoT and Robotic Platform with Video Monitoring

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Abstract

In practical scenarios such as industrial plants, warehouses, laboratories, residential complexes, and forest monitoring zones, there is a critical requirement for intelligent systems capable of early fire detection, real-time monitoring, and rapid response without risking human lives. These environments demand autonomous or remotely controlled solutions that can operate efficiently under extreme conditions. Traditional firefighting methods rely heavily on manual intervention, which can be dangerous, time-consuming, and often delayed due to accessibility challenges. Furthermore, conventional systems lack real-time monitoring, automated detection, and precise fire targeting mechanisms, reducing their effectiveness in critical situations. To address these challenges, the proposed Fire Bot Sentinel utilizes the ESP32 microcontroller integrated with robotic and IoT technologies to develop an intelligent firefighting system. The system employs flame sensors to detect fire presence and automatically activates a water pump to extinguish flames. A mobile robotic platform enables the system to navigate toward the fire source, while a servo motor controls the direction of water spraying for precise targeting. The integration of an ESP32-CAM allows real-time video streaming and remote monitoring of fire conditions. An LCD display provides system status updates, and the battery-powered design ensures portability in hazardous environments. This intelligent system enhances early fire detection, minimizes human risk, enables rapid response, and provides a reliable and scalable solution for modern fire safety and disaster management applications.

Keywords: Autonomous Robot, ESP32, ESP32-CAM, Fire Detection, Firefighting Robot, Internet of Things, Remote Monitoring, Safety Systems, Servo Control, Water Pump System

1. Introduction

The increasing frequency of fire accidents in industrial, residential, and forest environments has made fire safety a critical global concern. Reports indicate that thousands of fire-related incidents occur annually, leading to significant loss of life, property, and environmental damage [1]. In high-risk zones such as industrial plants, warehouses, laboratories, residential complexes, and forest monitoring areas, early fire detection and rapid response are essential to minimize damage [2]. With the advancement of robotics and IoT technologies, there is a growing demand for intelligent systems capable of real-time monitoring, autonomous operation, and remote accessibility, ensuring effective fire management without endangering human lives [3].

Problem Statement: Traditional firefighting methods rely heavily on manual intervention by firefighters and basic fire alarm systems. While these methods are essential, they often involve significant risks, especially in hazardous environments with high temperatures, smoke, and toxic gases [4]. Manual response can be delayed due to accessibility issues, especially in confined or dangerous areas. Additionally, conventional systems lack automated fire detection, real-time monitoring [5], and precise targeting capabilities, limiting their effectiveness in rapidly evolving fire situations [6]. The absence of intelligent control systems also prevents efficient coordination and timely response.

Motivation: In real-time scenarios, these limitations lead to several critical challenges that can escalate fire hazards [7]. Delayed detection and response can cause fires to spread rapidly, increasing damage and risk to human life. The lack of automated systems means that fires may not be addressed immediately, especially in remote or unmanned locations [8]. Furthermore, firefighters are exposed to dangerous conditions, increasing the risk of injuries or fatalities. The absence of real-time monitoring and remote-control limits situational awareness and decision-making during emergencies [9]. These challenges highlight the need for an intelligent, IoT-enabled robotic firefighting system capable of early detection, autonomous navigation, precise fire suppression, and real-time monitoring, thereby enhancing safety, reducing response time, and improving overall fire management efficiency.

2. Literature Survey

Yandouzi et al. [10] proposed a forest fire detection and monitoring system using semantic segmentation and thermal imaging integrated with drone platforms. Talaat et al. [11] proposed an improved fire detection approach based on You Only Look Once version 8 (YOLOv8) for smart city environments. Alsamurai et al. [12] proposed a YOLOv8-based system for detecting animals and humans in forest fire scenarios to support rescue operations.

Yang et al. [13] proposed an enhanced YOLOv8 model for precision-boosted forest fire target detection using improved feature extraction and detection strategies. Zheng et al. [14] proposed a real-time fire detection algorithm using MobileNetV3 and YOLOv4 for deployment on small, embedded devices. The system enabled efficient fire detection with reduced computational requirements. Lv et al. [15] proposed a lightweight fire detection algorithm based on YOLOv5s for detecting small fire targets with improved efficiency.

Narkhede et al. [16] proposed a multimodal Artificial Intelligence (AI)-based sensor fusion system for gas detection and identification using multiple sensing modalities. Saeed et al. [17] proposed an optimal path planning method for drones using swarm intelligence algorithms to enhance navigation efficiency. Zhu et al. [18] proposed a deep reinforcement learning-based trajectory planning approach for unmanned aerial vehicles to minimize energy consumption in wireless sensor networks.

Lin et al. [19] proposed an energy-optimal data collection framework for unmanned aerial vehicle-assisted wireless sensor networks in agricultural monitoring. Wang et al. [20] proposed a blockchain-based system for risk prediction and credibility detection in network public opinion analysis. Mugnai et al. [21] proposed autonomous firefighting unmanned aerial vehicles with online path planning for obstacle avoidance and payload delivery. Li et al. [22] proposed a multi-criteria decision-making approach for selecting optimal firefighter protective clothing sizes based on safety and ergonomic parameters.

Shahid et al. [23] proposed a forest fire segmentation method using a temporal transformer model applied to aerial imagery. Venturini et al. [24] proposed a distributed reinforcement learning approach for controlling unmanned aerial vehicle swarms to achieve flexible and efficient coordination. Soderlund et al. [25] proposed an evidence-based information fusion method to estimate the spread of wildland fires using multiple data sources.

3. Proposed System

Figure 1 illustrates the architecture of the Fire Bot Sentinel; an intelligent robotic firefighting system built around the ESP32. The system integrates a fire sensor and ESP32-CAM as input modules to detect fire and monitor the environment in real time. A battery powers the entire system, ensuring portability. The ESP32 processes sensor inputs and controls output devices such as a water pump for extinguishing fire, a servo motor for directional control, an LCD for system status display, and a robotic platform for mobility. This integrated design enables automatic fire detection, targeted suppression, and real-time monitoring, making it highly effective for hazardous environments.

Step 1: Power Supply (Battery Unit): The system is powered by a battery, providing a portable and independent energy source for all components including the ESP32, sensors, and actuators.

Step 2: Fire Detection Sensor: The fire sensor continuously monitors the surroundings for the presence of flames. When fire is detected, it sends a signal to the ESP32 for immediate action.

Step 3: Visual Monitoring using ESP32-CAM: The ESP32-CAM captures real-time images or video of the environment, enabling remote monitoring and helping identify the location and intensity of the fire.

Step 4: Data Processing by ESP32: The ESP32 acts as the central controller, processing inputs from the fire sensor and camera. It determines the presence of fire and initiates appropriate control actions.

Step 5: Water Pump Activation: Upon detecting fire, the ESP32 activates the water pump, which sprays water to extinguish the fire. This rapid response helps control fire at an early stage.

Step 6: Servo Motor Control: The servo motor adjusts the direction of the water nozzle, allowing precise targeting of the fire source and improving firefighting efficiency.

Step 7: Robot Mobility System: The robotic platform enables movement toward the fire location, allowing the system to reach and suppress fire even in inaccessible or dangerous areas.

Step 8: LCD Display Output: The LCD provides real-time information such as fire detection status and system operation, helping users monitor the system locally.

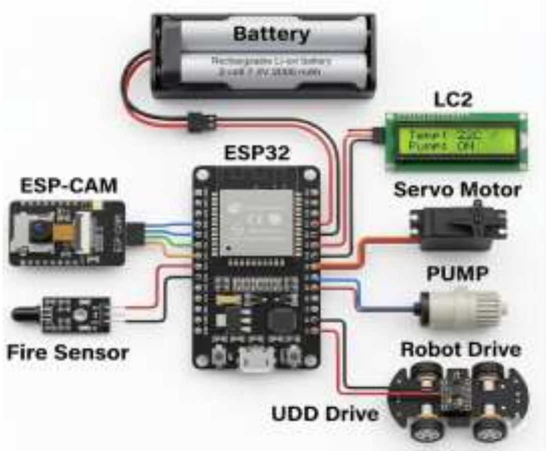

Figure 1. Proposed Block Diagram.

3.1 Working Procedure

The battery acts as the primary power source for the entire system as shown in Figure 2. It supplies the required electrical energy to the ESP32 microcontroller and other connected components such as sensors, motors, camera module, LCD display, and water pump. The use of a battery makes the robot portable and suitable for operation in different locations.

The ESP32 microcontroller is the central processing unit of the system. It receives input signals from the fire sensor and ESP32-CAM module and processes the information to make appropriate decisions. The ESP32 controls all the output components such as the servo motor, water pump, LCD display, and robotic movement mechanism. The fire sensor continuously monitors the surrounding environment for flames. When a fire is detected, the sensor sends a signal to the ESP32 microcontroller. This signal triggers the firefighting process and activates the required components to control the fire.

The ESP32-CAM module captures images or video of the surrounding environment. This allows real-time monitoring and helps identify the location and intensity of the fire. The camera module can also assist in navigation and observation during firefighting operations. The LCD display is used to show system information such as fire detection status, system alerts, and operational messages. It helps users monitor the system's performance in real time.

The servo motor controls the direction of the water spraying mechanism. By rotating the nozzle of the water pump, the servo motor ensures that water is sprayed directly toward the fire source.

The water pump acts as the firefighting mechanism. When the ESP32 detects fire through the fire sensor, it activates the pump to spray water on the flames, helping extinguish the fire quickly. The robotic movement system allows the robot to move toward the location of the fire. This mobility enables the system to reach the fire source and effectively perform firefighting operations.

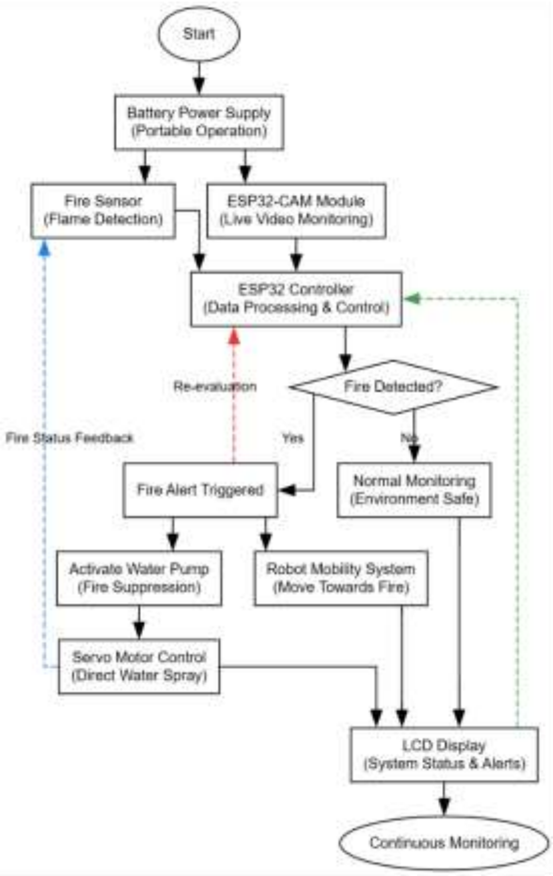

Figure 2. Proposed Flowchart.

Figure 3 illustrates the circuit diagram of the Fire Bot Sentinel, an IoT-based intelligent firefighting robot designed for autonomous fire detection and suppression. The system is powered through a regulated power supply unit comprising a step-down transformer, bridge rectifier, filter capacitors, and a 7805 voltage regulator to provide a stable +5V output.

The ESP32 microcontroller serves as the central control unit, interfacing with fire detection sensors to identify flame presence and trigger appropriate responses. A robotic drive system is connected for navigation, enabling the robot to move toward fire locations, while a servo motor controls the direction of the water pump mechanism for targeted fire extinguishing. An IoT camera module is integrated to provide live video surveillance and remote monitoring capabilities. Additionally, a 16×2 LCD displays system status and alerts in real time. This integrated system ensures rapid fire detection, autonomous navigation, and efficient suppression, making it highly suitable for hazardous environments where human intervention is risky.

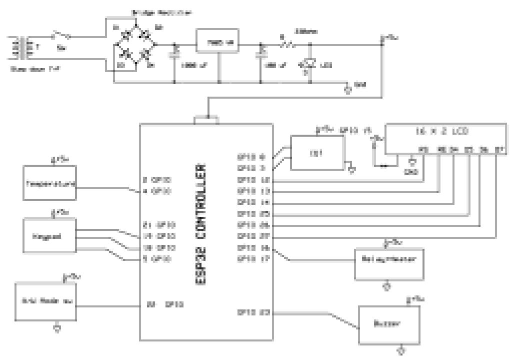

Figure 3. Circuit Diagram of Fire Bot Sentinel – IoT-Based Intelligent Firefighting Robot.

4. Results and Discussion

Figure 4 shows the complete hardware implementation of the Fire Bot Sentinel robotic system. The setup includes the ESP32 microcontroller, fire detection sensor, relay control circuit, battery supply, servo motor, and water pump integrated into a mobile robotic platform.

The LCD display shows the operational status of the Fire Bot Sentinel system as shown in Figure 5. It indicates system conditions such as fire detection alerts and pump status (ON/OFF), providing real-time feedback about the robot's firefighting operation.

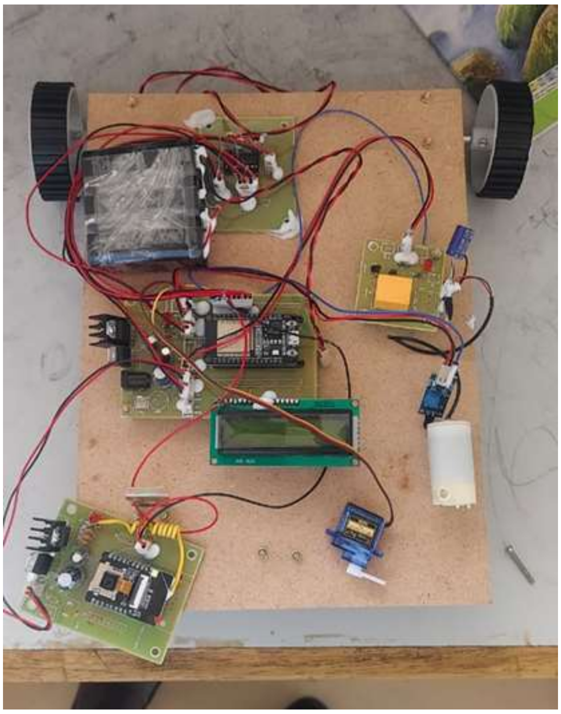

Figure 4. Hardware Setup of Fire Bot Sentinel

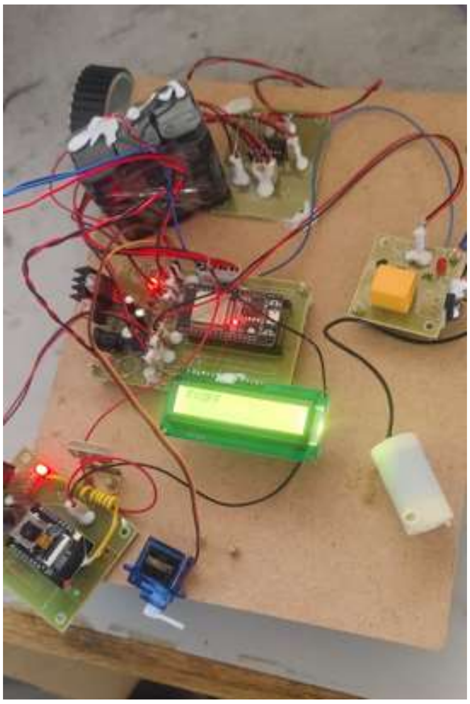

Figure 5. LCD Display Showing System Status

5. Conclusion

The system illustrates the practical implementation and real-time operational feedback of the Fire Bot Sentinel system, highlighting its effectiveness as an intelligent robotic firefighting solution. The hardware setup demonstrates seamless integration of key components such as the ESP32 microcontroller, fire sensor, relay module, water pump, and mobility mechanisms, forming a fully functional autonomous system capable of detecting and responding to fire hazards. The LCD display further enhances usability by providing real-time system status, including fire detection alerts and pump operation, enabling easy monitoring and control. Together, these components ensure reliable fire detection, rapid response, and efficient firefighting action while minimizing human involvement in hazardous situations. Finally, the system proves to be a robust, efficient, and scalable solution for improving safety in fire-prone environments.

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