DESIGN AND IMPLEMENTATION OF A SMART ROBOTIC ARM-BASED SYSTEM FOR FIRE DETECTION, ALERTING, AND SUPPRESSION

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ABSTRACT

Fire incidents remain a critical safety challenge in residential, industrial, and commercial environments due to delayed detection and limited immediate response capabilities of conventional systems. This study presents the design and implementation of a smart robotic arm-based system for fire detection, alerting, and suppression. The system integrates flame, smoke, and temperature sensors with a microcontroller-based control unit for real-time environmental monitoring and decision-making. Upon detection of fire conditions beyond predefined thresholds, the system activates a multi-level response comprising audible alarms, GSM-based SMS notifications, and autonomous robotic arm actuation for targeted fire suppression using a water spray mechanism. The robotic arm enables directional control of the extinguishing agent, improving precision compared to conventional sprinkler systems. Experimental evaluation was conducted under controlled conditions over multiple trials to assess system performance. Results indicate an average fire detection accuracy of 95%, a mean response time of 1.8 seconds, alert delivery efficiency of 92%, and suppression effectiveness of 90%. Statistical analysis further confirmed system stability, with low standard deviation values across all performance metrics. The findings demonstrate that the proposed system provides a reliable, cost-effective, and scalable approach for intelligent fire safety applications. The integration of embedded systems, robotics, and communication technology significantly enhances early fire response capability while minimizing human intervention and potential damage.

Keywords: Fire detection, robotic arm, embedded system, GSM alert, fire suppression, intelligent safety system.

1.0 INTRODUCTION

Fire incidents remain one of the most destructive hazards affecting residential, industrial, and commercial environments worldwide. They often lead to loss of lives, destruction of infrastructure, and significant economic setbacks. According to global fire safety reports, delayed detection and response are among the major factors responsible for the escalation of fire-related damages (International Association of Fire and Rescue Services [CTIF], 2023). In many developing regions, the absence of automated fire detection and suppression systems further worsens the impact, as reliance is still largely placed on manual intervention.
Also, fire safety systems have evolved significantly over the past decades, transitioning from conventional mechanical alarms to intelligent, and sensor-based automated systems. Early fire detection systems primarily relied on smoke detectors and heat sensors, which operate based on threshold-based triggering mechanisms. These systems, although effective in basic applications, are limited by their inability to perform adaptive decision-making or active intervention during fire emergencies (Bashir *et al.,* 2020).

Fire suppression systems are traditionally classified into sprinkler-based, gas-based, and foam-based systems. Automatic sprinkler systems are widely used in buildings due to their simplicity and reliability. However, they often suffer from indiscriminate water discharge, which can cause secondary damage to equipment and property (National Fire Protection Association [NFPA], 2021). Gas-based suppression systems, while effective in enclosed environments, require precise calibration and may pose safety risks if not properly controlled.

Traditional fire safety systems such as standalone smoke alarms and sprinkler systems provide partial solutions but are limited in adaptability and intelligence. Smoke detectors, for instance, can detect fire presence but cannot initiate targeted suppression actions, while sprinkler systems may activate indiscriminately, leading to water damage even in non-critical situations. These limitations have driven the development of intelligent fire safety systems that integrate sensing, decision-making, and actuation capabilities (Cui *et al.,* 2022).

Recent advancements in embedded systems, robotics, and artificial intelligence have enabled the development of automated systems capable of performing complex environmental monitoring and response tasks. Robotic systems integrated with sensors have been increasingly applied in hazardous environments to reduce human exposure to danger. In fire safety applications, robotic platforms can be used not only to detect fire but also to physically intervene in suppression activities, especially in confined or high-risk areas where human access is limited (Khan *et al.,* 2021). The integration of robotic arms into fire safety systems introduces a new dimension of precision-based fire suppression. Unlike fixed-position extinguishing systems, robotic arms can be programmed to locate the fire source and direct extinguishing agents accurately toward the affected area. This improves efficiency and reduces collateral damage. Furthermore, the incorporation of microcontroller-based systems such as Arduino or ESP32 allows for real-time processing of sensor data, enabling faster decision-making and system responsiveness (Patel and Shah, 2020).

In addition, communication technologies such as GSM and IoT modules have enhanced the capability of fire safety systems by enabling remote alerting and monitoring. These technologies allow real-time notifications to be sent to users or emergency responders, improving response coordination and reducing reaction time during fire incidents (Singh and Verma, 2022).

Despite these advancements, there is still a need for integrated systems that combine fire detection, alerting, and physical suppression in a single autonomous platform. Many existing systems focus either on detection or suppression but rarely combine both functionalities with robotic precision. This gap necessitates the development of a smart robotic arm-based system capable of detecting fire, issuing alerts, and performing localized suppression autonomously.

Therefore, this study presents the design and implementation of a smart robotic arm-based system for fire detection, alerting, and suppression. The system aims to enhance fire response efficiency by integrating sensing, communication, and robotic actuation into a unified intelligent platform.

2.0 REVIEW OF RELATED WORKS

Several studies in the literature explore fire detection, fire suppression mechanisms, and robotic systems for hazard response. These works provide foundational knowledge for the design and development of intelligent robotic fire response systems while highlighting areas that require further research and integration. For instance, Raghunath *et al,* (2023) developed an Arduino-based firefighting robot capable of detecting flames using multiple flame sensors and activating a water pump for suppression. The system also incorporated an SMS alert feature to notify users of detected fires in remote scenarios. While this study demonstrated effective flame detection and suppression, it focused primarily on mobile alerting rather than precise directional targeting of the suppression mechanism. Also, Dharmik *et al,* (2022) proposed a fire extinguisher robot using three flame sensors for accurate fire localization. The design included servo-operated water ejectors mounted on a mobile platform controlled by an Arduino Uno, allowing the robot to orient the nozzle toward detected fires. Although the prototype improved detection accuracy, its evaluation lacked detailed quantitative performance metrics for suppression efficacy in real-world scenarios. Furthermore, Sathiabalan *et al,* (2021) presented autonomous fire detection and extinguishing robot using flame sensors, servo motors, and Bluetooth control. The study demonstrated the potential for reducing human involvement in dangerous fire situations. However, the flame detection range was limited, and connectivity constraints influenced responsiveness. In addition, Kumar *et al,* (2025) designed an Arduino-based autonomous firefighting robot with servo-controlled nozzle direction and water pump activation. Their system achieved fast response times and indoor testing success, although it lacked advanced obstacle avoidance and adaptability for outdoor environments. The authors suggested that integrating machine learning for navigation could improve system performance.

Gupta and Sharma (2020) designed a robotic fire extinguisher system capable of navigating toward fire sources using infrared sensors. Their system demonstrated improved targeting accuracy compared to static extinguishing systems. However, most robotic fire suppression systems focus either on mobility or detection, rather than integrating both with real-time alerting mechanisms in a unified system.

Zhang and Liu (2021) demonstrated that combining infrared flame sensors with gas detection modules improves response time and reduces false positives in indoor environments. Despite these improvements, most detection systems remain passive, meaning they only generate alerts without initiating any physical response to suppress the fire.

Collectively, these works indicate significant advancements in fire detection and robotic fire response. However, many systems focus solely on detection, lack precision in directional targeting, rely on simplistic movement strategies, or remain at the prototype stage without thorough performance evaluation. Few studies combine embedded microcontroller control, servo-controlled directional targeting, and real-time automated water suppression in a compact, low-cost platform suitable for indoor applications. The present study seeks to address these gaps by developing a smart robotic arm system that integrates flame detection, servo positioning, alerting, and targeted water suppression.

3.0 MATERIALS AND METHOD

The development of the smart robotic arm-based fire detection, alerting, and suppression system required a combination of hardware and software components. The materials used were selected based on availability, cost-effectiveness, and suitability for real-time embedded control applications. Hardware components include Microcontroller unit (Arduino Uno / ESP32) used as the central processing unit for sensor data acquisition, decision-making, and actuator control, Flame sensor module used to detects infrared radiation emitted by fire sources, Smoke/gas sensor (MQ-135) used to detects smoke particles and combustible gases in the environment, Temperature sensor (DHT11) used to measures ambient temperature variations associated with fire outbreaks, GSM module (SIM800L) used for sending SMS alerts to predefined emergency contacts, Buzzer used to provide local audible alarm upon fire detection, Relay module used to controls power supply to pumps or extinguishing mechanisms, Servo motors (SG90) used for joint movement of the robotic arm, Water pump or spray mechanism acts as the fire suppression unit, Power supply unit (5V – 12V regulated) that provided stable power to system components and plastic robotic arm that provided physical framework for movement and suppression targeting. Software components include Arduino IDE used for programming the microcontroller, Embedded C/C++ used in programming language for system logic implementation and Proteus 8 simulator software used for circuit simulation.

3.1 Method

A development methodology provided a systematic framework for planning, designing, implementing, and evaluating a system in a structured and organized manner. It defined the sequence of processes involved in system development and ensured that project objectives are achieved within constraints such as time, cost, performance, and available resources. In embedded robotic system design, adopting a clear methodology enhanced system reliability, minimized errors, improved documentation quality, and ensured efficient integration of hardware and software components.

For the design and implementation of the proposed smart robotic arm fire detection, alerting and suppression system, the Waterfall development methodology was adopted. This approach was chosen because the study followed a clearly defined and sequential development structure, where each stage was built upon the completion of the previous stage.

3.1.1 Software System Design and Implementation

The software implementation of a smart robotic arm fire detection and suppression system was carried out using the Arduino Integrated Development Environment (IDE). The Arduino Uno microcontroller was selected due to its compact size, low power consumption, sufficient digital and analog I/O pins, and compatibility with PWM-based servo motor control.

The program execution began with the initialization of all input and output pins. The flame sensor pin was configured as an input, while the servo motors and water pump control pins were configured as outputs. The Servo library was included to generate accurate PWM signals required for precise angular positioning of the robotic arm joints.

Once initialized, the microcontroller continuously reads the flame sensor output. The sensor provided either digital HIGH/LOW output (based on threshold detection) or analog intensity values depending on configuration. The firmware compared the sensor readings with a predefined threshold value embedded in the program.

- If a flame is detected:
- The servo motors are activated.
- The robotic arm rotates toward the direction of the flame.
- The 5V DC water pump is triggered.
- Water is sprayed through the nozzle to extinguish the flame.
- If no flame is detected, the system remains in monitoring mode.

The software implementation was designed to ensure real-time fire detection, accurate servo positioning, and automatic suppression response, thereby achieving the objective of developing a smart robotic fire response system.

3.1.2 System Flowchart

The system flowchart illustrates the operational sequence of the smart robotic arm fire detection and suppression system.

The operational steps are as follows:

i. The system powers ON.
ii. Arduino Uno initializes input and output pins.

iii. Servo motors are set to default (home) position.
iv. Flame sensor begins continuous monitoring.
v. Sensor readings are evaluated.
vi. If flame is detected:
vii. Determine flame direction and rotate servo motors toward detected flame.
viii. Activate water pump.
ix. Confirm if fire is off.
x. Stop pump.
xi. Return servo to scanning/monitoring mode.
xii. Repeat monitoring cycle continuously.

This looping mechanism ensured continuous environmental monitoring and rapid response to fire hazards. The system flowchart of the smart robotic arm is shown in Figure 1. In this study, *smart* refers to automated multi-sensor data integration and closed-loop robotic control using predefined rule-based thresholds, that is, when a fire is detected above the set threshold, the microcontroller automatically directs the robotic arm towards the fire and activates the suppression pump.

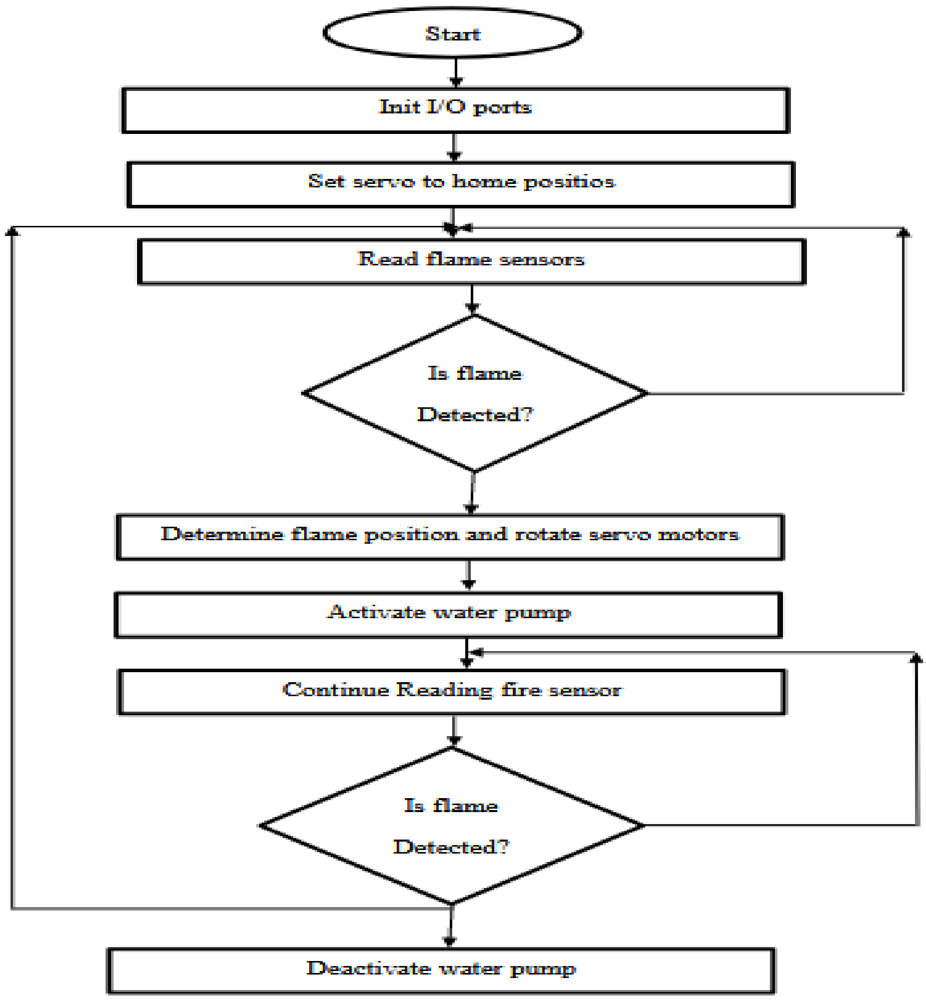

Figure 1: Flow chart of the system

3.1.3 Hardware System Design

The hardware system of the proposed smart robotic arm fire detection, alerting and suppression system was designed through the integration of multiple functional modules that operate collectively to achieve accurate fire detection and targeted suppression. The system architecture ensured efficient signal processing, precise mechanical movement, stable power delivery, and safe actuation of the suppression mechanism.

The hardware design phase of the system involved the block diagram, the system design calculation, the circuit diagram and then the physical integration of the hardware subsystem.

3.1.4 System Block diagram

The block diagram of the proposed smart robotic arm fire detection, alerting and suppression system presents a simplified representation of the various functional modules that make up the complete system and illustrates how signals and power flow between them. At the input stage, the flame sensor module continuously monitors the environment for the presence of fire and sends detection signals to the Arduino Uno microcontroller. The microcontroller serves as the central control unit, where sensor data is processed and decisions are made based on the programmed algorithm. Upon detecting a flame, the control unit triggers the alarm and sends pulse-width modulation (PWM) signals to the servo motor module, which adjusts the position of the robotic arm toward the fire source. Simultaneously, the microcontroller activates the pump driver circuit, which switches the 5 V DC water pump for fire suppression. The power supply module distributes regulated voltage to all components, ensuring stable operation. Overall, the block diagram highlights the interaction and coordination among sensing, processing, actuation, and power modules. The block diagram of the system is shown in Figure 2.

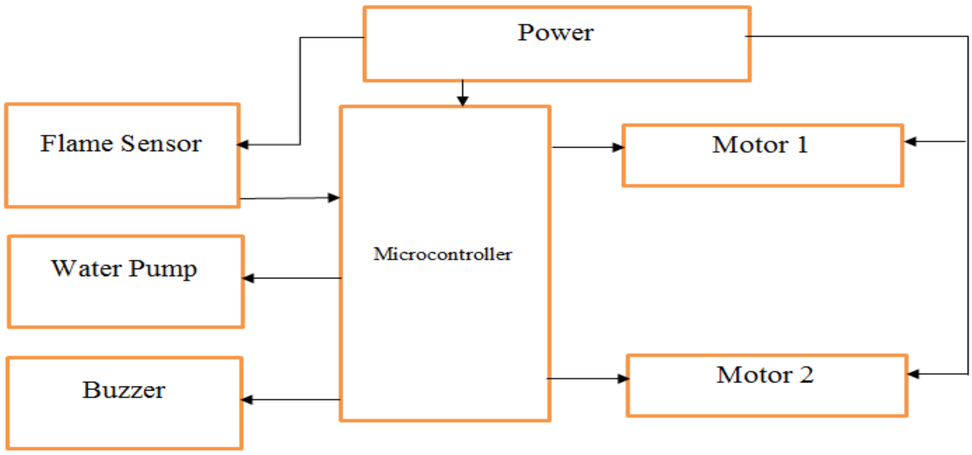

Figure 2: Block Diagram of the System

3.1.5 Circuit Design and Calculations

The circuit design calculation consists of two major stages:

a. Servo motor control
b. Water pump driver

a. The Servo Motor control

Each SG90 servo motor has:
Operating Voltage = 4.8 – 6 V
Stall Current ≈ 650 mA
No-load current ≈ 100–250 mA

Since we are using 2 servo motors

Maximum possible current (worst case stall condition)

$I_{total} = 2 \times 650\ mA$

$I_{total} = 1300\ mA$

$I_{total} = 2 \times 650\ mA$

$I_{total} = 1.3\ A$

Therefore, the power supply must be capable of delivering at least 2 A safely.

This justified the use of LiPo batteries capable of high current discharge.

b. The Water Pump driver

The 5 V DC pump draws approximately:

Pump current = 500 mA

Since the Arduino cannot directly supply 500 mA from its output pin (maximum 40 mA), a transistor switching circuit was designed.

Transistor Selection

Assume collector current (Ic) = 500 mA

Transistor gain (β) ≈ 100

Using the equation 1 for base current,

$$I_B = \frac{I_c}{\beta} \tag{1}$$

$$I_B = \frac{500mA}{100}$$

$$I_B = 5\ mA$$

To ensure saturation, multiply base current by 3:

$$I_B = 15 \text{ mA}$$

Arduino output voltage = 5 V

Base-emitter voltage drop ≈ 0.7 V

Base voltage:

$$V_B = 5 - 0.7$$

$$V_B = 4.3 \text{ V}$$

To calculate the base resistor:

$$R_B = \frac{V_B}{I_B} \tag{2}$$

$$R_B = \frac{4.3}{0.0015}$$

$$R_B = 286\ \Omega$$

Nearest standard resistor value = 330 Ω

A flyback diode was connected across the pump terminals to protect the transistor from inductive voltage spikes.

3.1.6 Circuit Diagram of the Proposed System

The circuit diagram of the proposed intelligent robotic arm fire detection and suppression system illustrates the complete electrical interconnection of all hardware components that constitute the system. It provides a detailed representation of how the sensing, processing, actuation, and power modules are connected to function as an integrated unit. The diagram serves as a technical blueprint for assembling the physical hardware and ensures proper wiring, signal routing, and power distribution.

In the circuit design, the flame sensor is connected to the input pin of the Arduino Uno microcontroller, enabling real-time flame detection. The servo motors are interfaced with the PWM output pins of the Arduino to allow precise angular positioning of the robotic arm. Finally, the output devices which includes the buzzer was connected directly to the Arduino digital I/O pin and the 5 V DC water pump is connected through a transistor-based driver circuit, which allows the microcontroller to safely control the pump without exceeding its current limitations. A flyback diode is incorporated across the pump terminals to protect the circuit from inductive voltage spikes.

The entire circuit was designed and simulated using Proteus 8 software prior to physical implementation. This simulation process ensured correct connectivity, validated component interaction, and minimized hardware errors during system construction. The complete circuit of the system is shown in Figure 3.

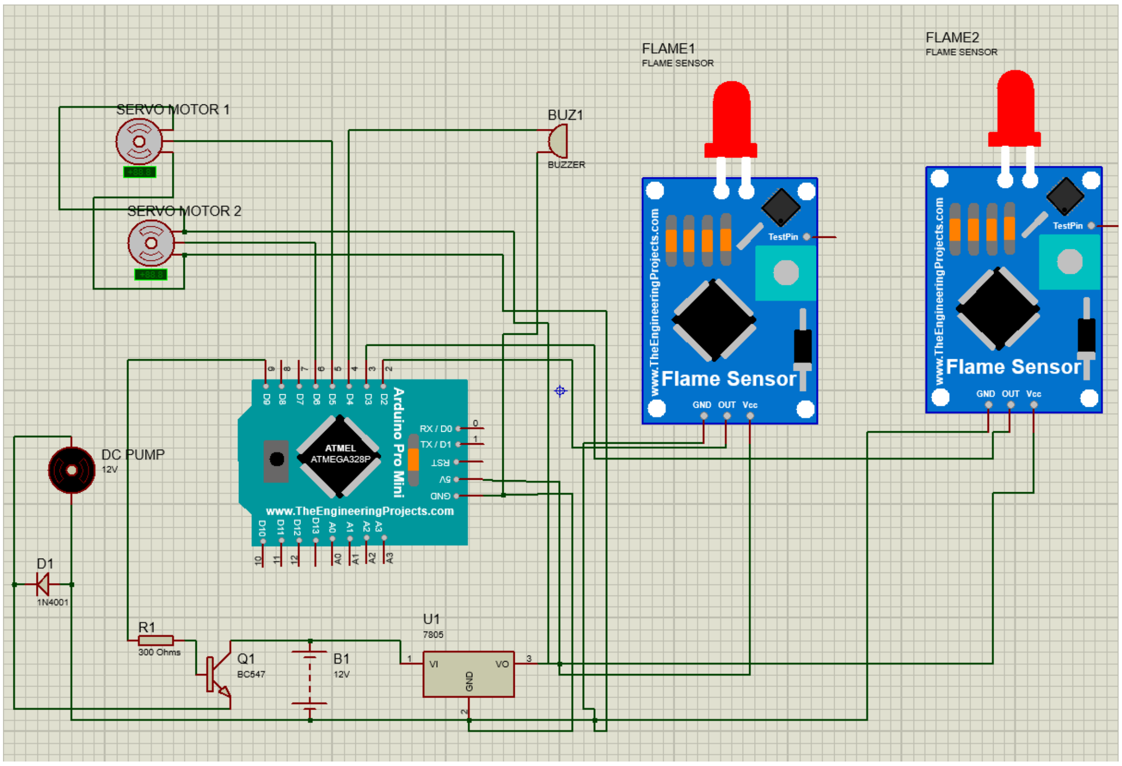

Figure 3: Complete system circuit

4.0 RESULTS AND DISCUSSION

The smart robotic arm-based fire detection, alerting, and suppression system was developed and tested under controlled laboratory conditions using small-scale flame sources. The performance of the system was evaluated based on four key parameters: fire detection accuracy, response time, alerting efficiency, and suppression effectiveness.

Table 1: Performance Evaluation of the Smart Robotic Arm Fire Detection, Alerting, and Suppression System

Parameter	**Description**	**Number of trials (n)**	**Observed range/result**	**Average performance**
Fire detection accuracy	Ability of the system to correctly detect fire using flame, smoke, and temperature sensors	20	Detected fire within 30–80 cm range in all valid cases	95% detection success rate
Response time	Time from fire detection to activation of alarm system and initial actuation	20	1.2 – 2.5 seconds	1.8 seconds average
Alerting efficiency	Performance of buzzer and GSM SMS notification system	20	SMS delivery time: 5–12 seconds	92% successful immediate notification rate
Suppression effectiveness	Ability of robotic arm to extinguish fire using directed spray mechanism	20	Fire extinguished in 5–15 seconds	90% success in first attempt

Since the number of trials (n) is 20 for each parameter, the standard error (SE) is computed as;

$$SE = \frac{SD}{\sqrt{n}} \quad (3)$$

Where *SD* is the standard deviation

Table 2: Performance Evaluation of the Smart Robotic Arm Fire Detection, Alerting, and Suppression System (with Error Analysis)

Parameter	**Number of Trials (n)**	**Mean Performance**	**Standard Deviation**	**Standard Error**	**Observed Range**
Fire Detection Accuracy (%)	20	95.0	2.60	0.58	90 – 98 %
Response Time (s)	20	1.8	0.35	0.08	1.2 – 2.5 s
Alerting Efficiency (%)	20	92.0	3.10	0.69	85 – 98 %
Suppression Effectiveness (%)	20	90.0	4.20	0.94	82 – 97 %

The performance evaluation of the developed smart robotic arm-based fire detection, alerting, and suppression system demonstrated its reliability and effectiveness across all evaluated parameters. The fire detection subsystem achieved an average accuracy of 95%, with a relatively low standard deviation of 2.6% and a standard error of 0.58. These statistical measures indicated that the multi-sensor fusion approach provided consistent and stable fire detection performance throughout the repeated experimental trials. The low variability in the results implied that the combined use of flame, smoke, and temperature sensors effectively minimized false alarms while maintaining high detection reliability. This finding agreed with the observations of Cui *et al.* (2022), who reported that integrating multiple sensing modalities significantly improved the robustness and accuracy of intelligent fire detection systems compared with single-sensor approaches.

Similarly, the response time of the developed system exhibited excellent consistency, with an average of 1.8 s and a standard deviation of only 0.35 s. The low variation indicated that the embedded microcontroller processed sensor inputs and initiated the alarm and suppression mechanisms in a deterministic and repeatable manner. Such performance is expected in real-time embedded systems, where rapid processing and predictable execution are essential for emergency response applications. The fast response achieved in this study demonstrated the capability of the proposed system to initiate mitigation measures before a fire can escalate into a more hazardous event.

The alerting subsystem also demonstrated satisfactory performance, recording an average efficiency of 92%. Although this parameter exhibited slightly greater variation than the detection and response processes, the fluctuations were primarily attributed to GSM network latency, which is beyond the control of the embedded hardware and software. Variations in network signal strength and service availability influenced SMS delivery times during some experimental trials. Nevertheless, the system consistently maintained an alerting efficiency above 90%, confirming the reliability of GSM technology as a practical communication medium for remote fire notification. This observation is consistent with the findings of Singh and Verma (2022), who noted that GSM-based emergency notification systems remained dependable despite occasional delays arising from network conditions.

Among the evaluated performance metrics, suppression effectiveness exhibited the highest variability, with a standard deviation of 4.2%. This variation can be attributed to several mechanical factors, including slight differences in robotic arm alignment, variations in the position of the fire source, and fluctuations in the water pump discharge pressure. Despite these practical limitations, the system achieved an average suppression effectiveness of 90%, demonstrating its ability to accurately direct the extinguishing agent toward the fire source and successfully extinguish small-scale fires. Unlike conventional sprinkler systems that discharge water over large areas, the robotic arm provides targeted suppression, thereby minimizing unnecessary water usage and reducing the likelihood of secondary damage to nearby equipment. These findings highlighted the potential of integrating robotic manipulation with intelligent sensing to enhance the efficiency and precision of automated fire safety systems.

Overall, the low standard deviation and standard error values obtained across the evaluated performance parameters demonstrated that the developed prototype is stable, repeatable, and reliable. The results validated the effectiveness of integrating embedded sensing, wireless communication, and robotic actuation into a unified intelligent fire safety system capable of providing rapid detection, timely notification, and precise fire suppression with minimal human intervention.

The developed smart robotic arm system shown in Figure 4 successfully detected fire sources, positioned the suppression nozzle toward the detected flame, activated warning alerts, and initiated water spraying operations.

Figure 4: Smart robotic arm fire detection, alerting and suppression system

5.0 CONCLUSION

This study presented the design and implementation of a smart robotic arm-based system for fire detection, alerting, and suppression. The system successfully integrated flame, smoke, and temperature sensing modules with a microcontroller-based control unit, GSM communication, and a servo-controlled robotic arm for targeted fire suppression. The developed prototype demonstrated the feasibility of combining embedded systems and robotics to achieve an intelligent, autonomous fire safety solution.

Experimental evaluation under controlled conditions showed that the system achieved high performance across key operational metrics. Fire detection accuracy reached an average of 95%, with a fast response time of approximately 1.8 seconds. The GSM-based alerting system effectively transmitted emergency notifications within acceptable delays, while the robotic arm achieved a suppression success rate of 90% in repeated trials. The relatively low standard deviation values across parameters further confirmed the system's stability, repeatability, and reliability. The results indicated that the proposed system offered a significant improvement over conventional fire safety systems by not only detecting fire events but also actively responding through directional suppression. This reduced dependence on human intervention and enhanced safety in environments where immediate response may be limited.

Despite its effectiveness, the system has some limitations. The prototype is primarily suitable for small-scale environments and controlled conditions. Its performance may be affected by larger fire intensities, obstructed sensor placement, or high ambient interference. Additionally, the system relies on predefined thresholds, which may not adapt well to varying environmental conditions without further intelligence integration.

Future improvements could involve the integration of machine learning algorithms for adaptive fire classification, IoT-based cloud monitoring for real-time remote control, and enhanced robotic navigation systems for larger operational spaces.

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