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DESIGN AND EXPERIMENTAL EVALUATION OF A DUAL AGENT FIREFIGHTING ROBOT WITH AUTOMATIC FIRE CLASS SELECTION FOR HAZARDOUS INDOOR ENVIRONMENTS

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Abstract
Fire accidents present significant dangers to people's lives and physical assets due to unsafe and high-risk conditions which constrain risk-free and efficient fire suppression efforts. Thus, an intelligent robotic firefighting system is required to operate in high-risk environments without compromising human operators' safety. This paper describes the design, fabrication, and experimental testing of a low-cost dual agent firefighting robot with automatic fire class selection by rule-based sensor fusion. The robot identifies fire, categorizes it and picks a suitable extinguishing agent without the operator intervention. An Arduino Nano is coupled with an infrared flame sensor, a smoke sensor and a camera to carry out real time fire detection and classification. Water based pump is used to suppress Class A fires and CO_2 or foam are used to suppress Non-Class A fires. Controlled indoor experimental results indicated a classification accuracy of 100 percent with Class A fire and 95 percent with Non-Class A fire. Class A fires extinguished in an average of 41 seconds and Non-Class A fires extinguished in an average of 12 seconds with a reduction of flame area of more than 80 percent. The results demonstrate the feasibility of an affordable dual agent robotic system that can be used in confined indoor firefighting.

INTRODUCTION

Fire is a devastating phenomenon that can lead to massive loss of human lives and property [1–16]. Fire emergencies are very common in developing countries because of poor safety infrastructures, lack of awareness, and a high population density in urban and industrial areas [17–23] . In Pakistan, as an example, the frequent explosion of fire in residential buildings, factories, warehouses, and commercial complexes indicates the necessity of improved fire safety practices [24–28]. Conventional firefighting methods rely on human firefighters going into hazardous areas with protective gear, breathing equipment, and water hoses [29–31]. Such methods are however constrained by the accessibility, exposure to heat, inhalation of smoke and structural collapse. Human intervention is not timely or effective in most instances leading to the rising damage and loss of lives [32–38]. Thus, new solutions that minimize human exposure and provide opportunities to suppress fire fast are of utmost significance.

One of the possible solutions to these challenges has been the emergence of robotic systems. The firefighting robots will be able to detect flames, navigate through the dangerous areas, and put out fires without threatening human lives [39–45]. Robotic firefighting study has investigated wheeled and tracked robots, aerial drones, sensor systems and automated suppression systems [46–50]. The majority of robotic platforms however depend solely on one suppression media, typically, water, which can only control Class A fires involving common combustibles. The use of CO_2 or chemical foam is needed during fires on flammable liquids, gases, or energized electrical systems. This mismatch between the suppression techniques and the fire type reduces the efficiency of operations and exposes them to secondary dangers [51,52]. Thus, a system of the firefighting that can automatically identify the fire type and choose the necessary extinguishing medium is very desirable.

The current paper offers a solution to these drawbacks by the design of a small, dual agent firefighting robot featuring an automatic fire class identification. The robot has three infrared flame sensors and a smoke sensor that detect and characterize the fire. Arduino Nano microcontroller assesses sensor measurements to determine whether the fire is Class A (common combustible materials) or Non-Class A (flammable liquids, chemical agents, or energized electrical sources). The system automatically activates either a nozzle driven water pump or a compressed gas cylinder with CO_2 or foam depending on the type of fire to be tackled (Class A fire or Non-Class A fire). The nozzle directs at the flame by a servo motor, and the robot steps to a safe operational zone to carry out suppression. A camera can give the operator live visual feedback to aid in monitoring and decision making. This system combines detection, classification, and dual agent suppression, which allows successful firefighting in restricted, tight corridors, or other hard to reach locations where it would be unsafe to have human operators. The suggested system is focused on safe operation within a limited space indoors and is designed with the focus on low costs, ease of operation, and practical deployability to aid emergency response.

2. System Design and Components

The firefighting robot is designed as a small ground-based platform that could be used within small indoor space. The design was aimed at low price, mechanical stability, safe handling of agents and dependable fire detection and suppression. The system has been designed to incorporate mechanical, sensing, actuation and electrical subsystems into one mobile unit.

2.1 Mechanical Structure and Chassis

Lightweight aluminum sheets and composite panels were used to make up the chassis to provide structural strength and make the overall mass low. The size of the robot is about 457 mm x 305 mm x 914 mm, and its mass with water tank, CO_2/foam cylinder, battery and electronics is 20 kg. The four-wheel drive design ensures steady movement over smooth indoor surfaces and DC geared motors provide adequate torque to run the two extinguishing systems in a reliable manner. The water tank is positioned centrally to ensure low center of gravity and the CO_2/foam cylinder is mounted securely with the use of a clamp type bracket. Figures 1a-1c show the prototype in an angled, side, and rear view, by displaying the general layout and combination of the mechanical and suppression elements.

2.2 Fire Detecting and Sensing Subsystem.

Fire detection involves three infrared flame sensors which are attached at front (left, center, right) to estimate direction. A smoke detector is a useful addition to flame detection which proves the presence of fire and helps in classifying the kind of fire. A compact camera, mounted directly above the sensor array, enables real-time visual output for monitoring.

(a) (b) (c)

Figure 1. Multiple Views of the Firefighting Robot Prototype: (a) Front Angled View, (b) Side View, and (c) Rear View.

2.3 Suppression Subsystems

The system has two independent fire suppression subsystems for handling different fire classes. The first subsystem is water based and is comprised of a 2.5 L storage tank, a 12 V DC centrifugal pump, and a discharge nozzle. This arrangement supplied a steady and regulated flow of water that is suitable and adequate for the suppression of Class A fires. The second subsystem uses a compressed extinguishing agent and consists of a 0.5kg CO_2 or foam cylinder with solenoid valve and pressure regulator. This subsystem is for Non-Class A fire situations in which the application of water is not appropriate. Separate and dedicated flow paths are provided for each subsystem to offer functional independence and avoid cross contamination of extinguishing agents.

2.4 Nozzle Actuation and Alignment

A servo motor turns the nozzle to the sides in accordance with the infrared sensor feedback. The mounting bracket is strengthened to hold against the reaction forces during the discharge of the agents to ensure accurate and effective suppression.

2.5 Control Electronics and Power System

A microcontroller, the Arduino Nano, is used as the central control unit, where sensor data is processed, and fire classification is done, with motors, actuators, pumps, and valves being controlled. The power system uses a rechargeable 12 V battery, which delivers around 20 minutes of intermittent operation. Logic-level electronics and high current devices are separately controlled. The system maintains reliability via fuses, overcurrent prevention, low-voltage cutoff, and opto-electronic isolation

2.6 Overall System Integration

By integrating all subsystems, the distribution of weight becomes balanced and is easy to maintain. Thermal shielding provides safety to delicate electronics and easily serviceable components, like the water tank, gas cylinder, and battery. Figure 2 represents a labeled diagram of the prototype with all the main components pointed out.

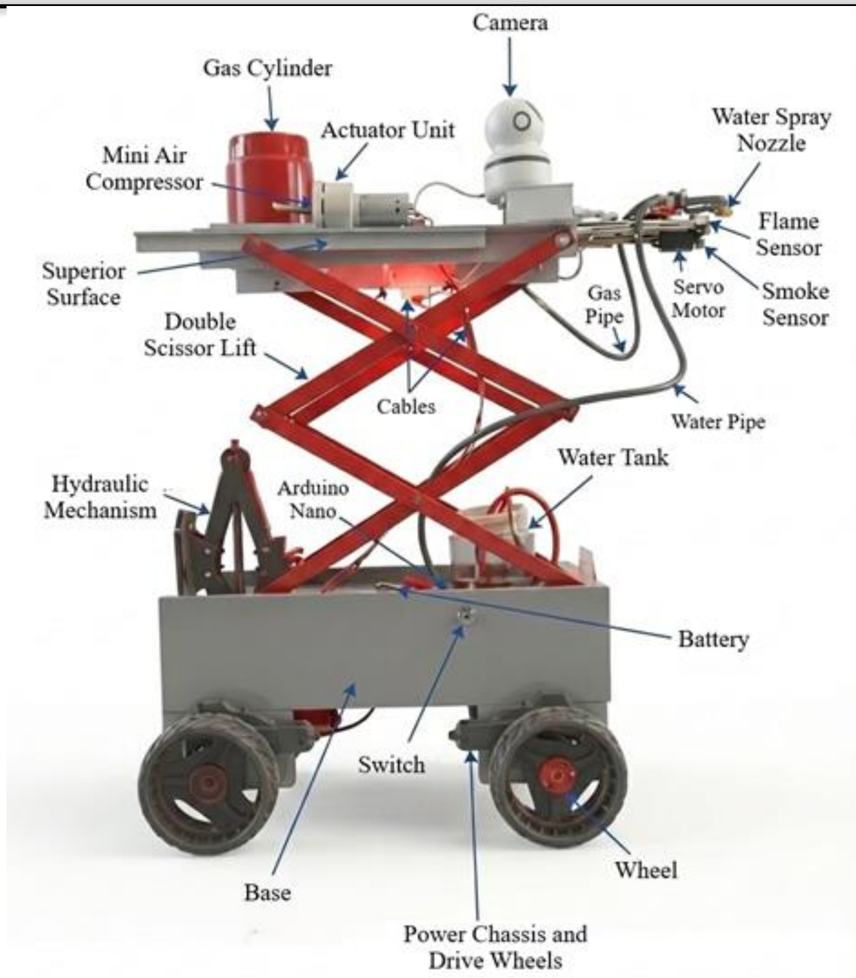

Figure2. Labeled View of the Firefighting Robot Showing all Major Components.

3. Control Logic and Automatic Fire Classification

The robot utilizes a low cost, rule-based decision system for quick and safe fire suppression without the intervention of an operator. The control system is designed with flame intensity monitoring, smoke concentration detection, source direction estimation, and automated fire suppressant selection.

3.1 Fire Detection and Confirmation

IR sensors are used to monitor flame radiations in a continuous manner. The microcontroller, Arduino Nano, measures average intensity at predetermined intervals. Presence of fire is detected when intensity is greater than a detection threshold and the smoke sensor output is greater than that of its activation level. This two-level condition lowers the incidence of false positives due to the surrounding heat sources.

3.2 Logic of Classification of Fire Classes

Classification is a combination of variation in flame intensity and output of smoke sensor. Class A fires are stable and show a steady smoke production while Non-Class A fires are characterized by rapid fluctuations of intensity and non-uniform smoke. Variance and smoke stability have threshold values that allow the classification with low computation and reliability.

3.3 Directional Alignment and Positioning

Following classification, the control unit classifies the primary flame direction by analyzing relative sensor outputs. The nozzle is directed using the servo in the direction of the highest intensity sensor. The robot moves at a regulated pace and automatically halts at a standoff distance of 20 cm to secure effective and safe delivery of the agents.

3.4 Automatic Selection and Suppression of Agents

In case of Class A fires, the water pump is used. The CO_2 or foam solenoid valve is opened in the case of Non-Class A fires. Suppression of the sensor feedback is continued until the flame strength and smoke give a signal of extinguishment.

3.5 Response and System Reliability

Low latency and robustness are considered important in the rule-based logic. Constant sensor surveillance makes sure that agents are not over-discharged and performance does not go down in a confined indoor environment with low-cost hardware.

4. Fabrication and Assembly

Structural integrity, safety, and serviceability were the aspects on which the robot was designed. The subsystems were all made to be interconnected to ensure the balance and compactness.

4.1 Chassis Fabrication

The low-mass rigid chassis is made up of precisely fabricated aluminum sheets and composite panels. Reinforcement of joints is done to resist the dynamic loads either during motion or suppression. Motors, suppression systems, sensors and electronics are mounted using mounting points.

4.2 Mounting of Drive and Suppression Systems

Quad-wheel drive motors are fitted using vibration-absorbing brackets. The water tank is located in the middle, and the CO_2/foam cylinder is fastened with padding. The two suppression subsystems are firmly fixed to avoid misalignment.

4.3 Sensor and Actuator Integration

The smoke sensor and infrared flame sensors are positioned in the best location encompass multiple areas. The nozzle and the servo are mounted on a strengthened platform to ensure proper orientation. The camera is mounted at a high level in order to have an unhindered view.

4.4 Electrical Assembly and Safety Measures

As deemed necessary, wiring is organized by means of insulated conduits equipped with waterproof connectors. The microcontroller is electrically isolated via optical couplers to high-amperage devices. Overcurrent protection circuits and fuses guard against electric current surges.

4.5 Final Assembly and Verification

Subsystems after assembly were subject to functional verification. Weight distribution, stability and accessibility of components were verified. The robot also ensures a secure, reliable, and serviceable platform for successive indoor fire suppression tests.

5. Experimental Setup

To determine the performance, reliability, and safety of the firefighting robot, experimental evaluation was carried out under a controlled indoor environment. The arrangement was meant in such a way that it would be repeatable with limited external disturbances.

5.1 Test Environment and Safety Arrangements

All tests were conducted in an indoor test area that was enclosed and well-ventilated with floors that were fire resistant. There were strict safety measures taken during testing. Fire extinguishers were stored close to the fire line and there were fire blankets and portable fire extinguishers, and emergency shut off controls. All experimental sessions were supervised by certified trained personnel to provide and guarantee reliable operation and rapid response to any unforeseen fire response behavior.

5.2 Fire Scenarios and Test Conditions

Two types of fire scenarios were set up to reflect Class A and Non-Class A fires. The standardized bundles of dry wood and paper were used to create class A fires in order to ensure that there is the same amount of fuel mass in the trials. Flammable liquid fires were simulated by the use of shallow metal pans of a specified amount of liquid fuel. The size of fires and ignition conditions were maintained to be the same so that tests could be compared.

5.3 Testing Procedure

The robot was placed at a specified distance from the fire source prior to each trial. After activation the robot autonomously detected and classified the fire, directed the nozzle, and suppressed fires without operator input. The robot moved towards the fire at a slow pace and automatically halted at a fixed standoff distance of 20 centimeters before beginning discharging an agent. Every experiment was carried out in twenty repetitions to check the reliability and consistency of the results.

5.4 Performance Metrics

The system was analyzed in terms of several performance parameters: flame detection time, accuracy of classifying the type of fire, accuracy of nozzle alignment, extinguishing time, performance in minimizing the flames and mobility stability. The intensity of flames was measured by comparing the area of the flames prior to suppression to the area of the flames following suppression using cameras. The accuracy of nozzle alignment was calculated by counting the angular difference between the direction of the nozzle and flame source.

5.5 Data Collection and Validation

Sensor readings, actuator responses, and time-related data were recorded during each experimental run for evaluation. System-mounted camera provided real-time visual output to monitor and examine the suppression effectiveness and the system performance. The environmental conditions (airflow and lighting) were kept constant as much as possible to minimize variability. All performance indicators were computed as averages of twenty experimental trials for each fire scenario. This experimental design offered a solid foundation of analyzing the efficacy of automatic fire classification selection and dual agent suppressor in indoor settings.

6. Results

The experimental trials indicated consistent performance of firefighting robot in detection, classification, and suppression of fire under controlled indoor environment. Findings are displayed as accuracy of detection, reliability of classification, suppression, nozzle alignment and stability of mobility.

6.1 Fire Detection and Classification Performance

The infrared flame sensors were able to detect the presence of fire in every trial. The control system was also able to find the main direction of the flame using relative sensor intensities. There was a high level of reliability in the fire classes classification among repeated tests. Class A fire scenarios were all identified appropriately leading to 100 percent correct classification. In non-Class A fire cases 19/20 of the trials were correctly identified resulting in 95 percent accuracy. Class A and Non-Class A fires were detected between 2 to 5 seconds and 3 to 5 seconds respectively. Table 1 provides a summary of the performance of fire detection and automatic fire class classification.

Table 1. Fire Detection and Automatic Fire Class Classification Performance across Repeated Indoor Trials

Fire Type	Trials	Correct Classification	Accuracy (%)	Detection Time (s)
Class A	20	20	100	2–5
Non-Class A	20	19	95	3–5

6.2 Extinguishing Effectiveness

In the case of Class A fires, a steady spray of water was used to spray directly at the burning fuel (Figure 3a). The system consistently maintained a stable operational approach and standoff distance with continuous monitoring of real time fire intensity. Class A fires were completely extinguished in all the trials (Figure 3b), with a mean extinguishing time of 41 seconds. In each trial, the complete extinguishing of the flame was not only observed through visual inspection but also verified through automated sensor detection (Table 2).

In the case of Non-Class A fires, the release of CO_2 to the flame surface is shown in Figure 4a. In this case the combustion quenched very fast as shown in Figure 4b. The agent replaced oxygen on the flame interface leading to a substantial decrease in visible flames. Full suppression was observed in every experiment, where the flame area was decreased on average by 85 percent and the extinguishing time was on average 12 s (Table 2).

These findings confirm that both solid and flammable liquid fire can be effectively extinguished with the dual agent configuration. Auto selection of fire classes guaranteed the appropriate extinguishing medium was used in different situations, which reduced chances of misusing an agent and maximized efficiency. Intelligent fire identification system assured appropriate extinguishing agent utilization, decreasing operational errors and optimizing fire mitigation performance.

Table 2. Extinguishing Performance and Nozzle Alignment Indicators for Class A And Non-Class A Fire Scenarios

Fire Type	Average Extinguishing Time (s)	Flame Reduction (%)	Nozzle Alignment Error (°)
Class A	41	100	3
Non-Class A	12	85	2

(a) (b)

Figure 3. Class A fire Suppression using Water: (a) Water Discharge during Active Suppression, and (b) Complete Extinguishment after Suppression.

6.3 Nozzle Alignment and Positioning Accuracy

The nozzle alignment system that was driven by a servo was very accurate in every suppression experiment. The nozzle always pointed to the fire source with an average angular error of about 3° in Class A fire and 2° in non-Class A fire as indicated in Table 2. Throughout the fire suppression, the robot stood a constant distance of 20 centimeters to the fire source, which guaranteed proper delivery of agents without being too close.

6.4 Mobility and Operational Stability

The robot was steady in its movement during all the experiments with an average speed of 0.25 meters per second. Movement and suppression did not reveal any loss of balance or traction. The pre-programmed standoff distance was accurate to a high degree and the robot halted successfully before taking extinguishing measures. The onboard camera provided continuous visual feedback which ensured that the automatic detection, classification, alignment and suppression sequence were executed correctly in all test scenarios.

(a) (b)

Figure 4. Non-Class A Fire Suppression using CO_2: (a) CO_2 Discharge during Active Suppression, and (b) Complete Extinguishment after Suppression.

6.5 Overall System Performance

The findings validated that the consolidated control framework and dual-agent deployment setup facilitated enhanced suppression performance in compact indoor settings. The system exhibited steady operational behavior in repeated experimental evaluations, confirming reliability of automated fire type classification and extinguishing agent deployment.

7. Discussion

The results of trials confirm that the proposed dual agent firefighting robot is a reliable tool in detecting, classifying, and suppression of fires in constrained indoor settings. Automatic classification of the type of fire used allows safe and efficient use of the correct extinguishing agent, with no water being used on Non-Class A fires.

Water suppression to Class A fires was found to be fully effective in the elimination of flames, but it took a longer time to extinguish because of the smoldering ability of wood and paper. Conversely, CO_2 quickly minimized visible flame area in Non-Class A fires with an average flame minimization of 85 percent and extinguishing time of about 12 seconds as indicated by Table 2. The results prove the efficiency of the dual agent setup and confirm the automatic agent choice approach.

Directional sensing and servo-acted nozzle alignment were also helpful in suppress efficiency. The noticed low nozzle alignment errors (3° in Class A and 2° in Non-Class A, Table 2) were considered to achieve focused agent delivery and reduce wastage. Constant stability and predictable positioning enabled the robot to have a safe standoff distance of 20 centimeters, which is crucial in suppression and hardware safety.

The proposed system offers greater operational flexibility than the single-agent firefighting robots recorded in the past. Handling multiple fire classes without operator intervention reduces cognitive load and improves response reliability in mixed-hazard environments. The small size also facilitates its use along narrow corridors and constrained indoor areas that have low human access.

Main constraints include finite water capacity and limited onboard compressed agent, constraining sustained operation, and the absence of self-navigation functionality or obstacle detection and maneuvering, which could impact system performance in intricate operational environments. Surrounding environmental influences e.g., airflow, high-opacity smoke and high-reflectivity surfaces could impact sensor-detected parameters.

Overall, the findings show that the system attains a viable trade-off between performance, cost, and complexity. The rule-based fire classification and dual agent configuration offer high-quality indoor firefighting support and creates a groundwork towards increased autonomy and operational durability.

8. Conclusion

A low-cost, dual agent, firefighting robot that automatically selects the fire class was developed, manufactured and tested experimentally in confined indoor settings. The system incorporates infrared flame detection, smoke detection, servo-controlled directional alignment, and rule-based control logic to differentiate between fire types and dispense the appropriate fire extinguishing agent without operator involvement. Experiment results proved a high degree of consistency in fire detection, correct classification of Class A and Non-Class A fires, and efficient suppression with both water and CO_2. All trials of the robot were characterized by stable mobility, accurate nozzle positioning, and a safe standoff distance. Table 2 and Figures 3-4 confirm that dual agent capability is far more flexible in terms of operational range, and less prone to risks related to inappropriate application of agents, than single-agent systems.

These results show that it is possible to do effective fire class discrimination and suppression with low-cost sensors and simple control logic on low resource hardware. The small platform is suitable in tight spaces with indoors and can be used as auxiliary equipment by emergency response teams. Future developments will consider the enhancement of extinguishing agent capacity, the incorporation of advanced sensing, including thermal imaging, autonomous navigation and obstacle avoidance, and thermal protection to allow operating in a more challenging fire environment.

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