# Low-cost multi-sensing fire-fighting robot with obstacle avoidance mechanism

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**ABSTRACT**

Robots are mostly optimized for tasks that require strength exceeding that of humans or for operations in hazardous environments. The fire-fighting robot developed has multiple sensing capabilities with obstacle avoidance mechanisms and is divided into two units: the robot and the static unit. The robot is equipped with three flame sensors to detect flames (infrared radiation) in three directions, an ultrasonic sensor to avoid obstacles, a wireless receiver to receive data from the static unit, a magnetometer giving the robot a sense of direction, and a unit of Arduino Mega microcontroller serving as the central controlling platform. The static unit has four flame sensors and a transmitter that transmits signals to the robot unit, which an Arduino Uno directly controls. A prototype was developed, which helps prevent the escalation of fires in the home as it can detect, navigate and extinguish flames while avoiding obstacles autonomously.



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## 1. INTRODUCTION

Fire is a chemical reaction that produces heat and light as it consumes a fuel source in the presence of oxygen. A firefighter can be simply put as a person who puts out fires, utilizing tools with the capability to extinguish and contain fires, thereby preventing the loss of lives and properties [1]. Firefighting is a physically demanding, critical, and hazardous task that often puts the firefighter's lives at risk [2]–[4]. Advances in technology have made firefighting easier, bridging the gap between firefighting and machines, thereby creating a more efficient and effective method of firefighting [5]–[7].

A robot is an automated intelligent mechanical being, i.e. a machine designed to behave like a human or other elements to carry out complex tasks by moving physically after being programmed [8]–[11]. Oyelami *et al*. [12] discussed the significant rise in robot usage across several fields. Robots can be divided into various groups, with some grouped based on the mode of operation. These include Android robots, which are designed to act like humans and mimic their actions, and autonomous robots, which are capable of acting on their own or independently [13]–[15]. Mobile robots, unlike fixed robots, have a movable base and can navigate using instructions from human beings. Tele-robots and Telepresence robots are quite similar in operation, the technical difference between them is that the latter gives feedback in digital formats like a video, sound clip, and other media data.

The main challenges for the development of autonomous walking robots as summarized by Nonami *et al*. [16] are i) the need for energy-efficient actuators with optimal weight-to-torque and volume-to-torque ratios; ii) the availability of reliable and economical sensors; iii) the use of lightweight but mechanically strong materials for construction; iv) the requirement for small but high computing power in onboard computers; and v) The necessity of lightweight power sources for extended operational duration.

An autonomous firefighting robot is not entirely new, research works have shown progress using different technologies, but also with notable constraints. The development of a firefighting robot by Aliff *et al*. [8] uses Arduino Uno as its microcontroller equipped with a webcam for visual feedback, an ultrasonic sensor for obstacle avoidance, a flame sensor, a water pump, a direct current motor, and also a transmitter and remote control for controlling the robot remotely. The robot has a limited flame sensing range of 40 cm which can be manually monitored by using a camera that connects to a smartphone or remote devices and controls it to the site of the flame. Archana and Suma [5] incorporated an LM35 temperature sensor, with the major limitation to the design being the sensing range. The intelligent wireless fire extinguishing robot by Islam *et al*. [9], however, took advantage of the Internet of Things to make an internet-controlled robot. It uses Arduino Uno to control the robot, and Arduino Yun has built-in Ethernet and Wi-Fi for external communication and video feedback through the webcam. There was also an instance of utilizing a PID controller as opposed to an Arduino microcontroller to achieve more precise control of the robot's movements and responses, as well as more accurate fire extinguishing capabilities [14].

It can be noted that the designs mentioned above featured limited flame sensing range, while others relied on remote control or internet connectivity, which may not be practical in all firefighting scenarios. This project addresses these limitations by developing an autonomous firefighting robot with an extended sensing range and enhanced autonomous capabilities. The proposed solution includes a static sensing unit equipped with multiple flame sensors and a transmitter to relay fire location information to the robot. The robot itself is designed with a proportional motor control system for bi-directional movement, an ultrasonic sensor for obstacle avoidance, and three infrared flame sensors for comprehensive fire detection. These components interact with a microcontroller that operates a water pump to extinguish detected fires [17], aiming to provide an extended range, more effective, and autonomous firefighting solution.

## 2. METHOD

The construction of this project utilized several key components, including the Arduino Mega and Arduino Uno microcontrollers, flame sensors, servo motors, L298N motor driver, water pump, water tank, ultrasonic sensors, lithium-ion batteries, 433 MHz transmitter and receiver, and the QMC 5883L magnetometer. These components were meticulously selected based on their reliability, cost-effectiveness, and compatibility with the design specifications of the autonomous firefighting robot. These components were further divided into two separate units: static and mobile (robot).

### 2.1. The static unit

The static unit is made up of an Arduino Uno, four flame sensors, a 433 MHz transmitter, and a power supply. Four flame sensors are positioned at the corners of the structure for this project, and they serve as additional fire-sensing units to aid the robot and can be scaled to any number depending on the range to be covered. When any of these sensors detect fire in this sensing range, the Arduino Uno microcontroller sends a signal to the robot unit to alert it. This signal will contain the location of the sensor that sensed the fire so that the robot can proceed to that location and extinguish the fire. The block diagram of the static unit is shown in Figure 1.

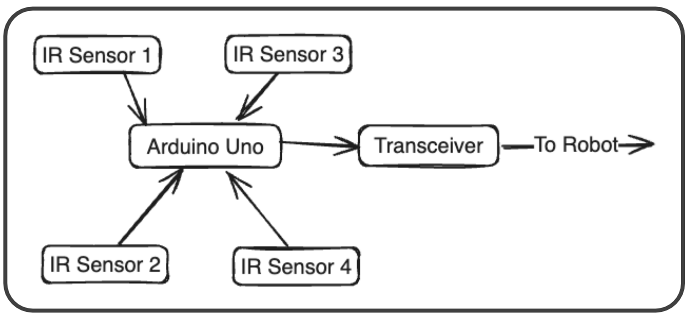


Figure 1. Block diagram of the static unit

**2.2. The main robot**

The robot unit consists of the chassis with motor and wheel, the Arduino Mega, three flame sensors, servo motor, motor driver, extinguisher storage, power supply, water pump, radio frequency receiver, and ultrasonic sensor. The main processing unit of this section is the Arduino Mega microcontroller. It receives signal input from the flame sensors to complete the flame detection system from the ultrasonic sensor to complete the obstacle avoidance system and the radio frequency receiver to adequately process incoming signals and complete the transmission system. Other sub-units include the water pump used to extinguish the flame in its surroundings and the magnetometer to process the sense of the location of the robot. Figure 2 shows a high-level overview of the interconnection of the various components and the direction of the signal.

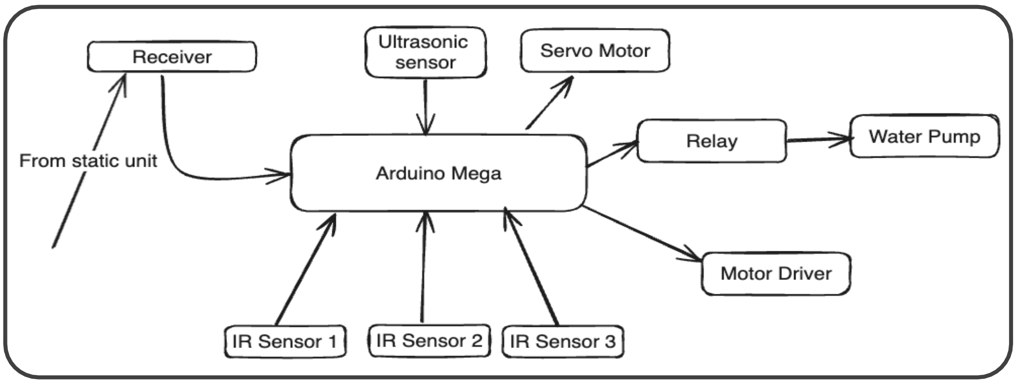


Figure 2. Robot signal pathway

The motion of the robot is controlled based on the Arduino Mega through the L293N module motor driver based on the information received from the flame, ultrasonic sensor, and radio frequency receiver. Flame sensors have a sensing range of about 1 m and an angle of 60° thereby making it possible to combine three flame sensors to give a total coverage angle of 180° [18], [19]. In this way, the sensors not only increase the sensitivity range but also give the robot some sense of direction; left, forward, and right.

The ultrasonic sensor is positioned on the chassis at the front of the robot. The main function of the ultrasonic sensor is to sense the presence of obstacles in the robot paths [20]–[23]. Obstacles may include a wall or a solid object that throws the robot out of balance. If the static unit senses the fire, the robot proceeds towards it in the direction of the sensing sensor using its ultrasonic sensor to avoid obstacles. It extinguishes it by powering the water pump and servo motor that spray water in a sweep motion.

The environment for implementation was carefully mapped out into five key locations: 0, the initial starting point, and 1, 2, 3, and 4, which correspond to the four corners of the environment and the positions of the flame sensors connected to the static unit. This strategic arrangement ensures comprehensive coverage and accurate fire detection throughout the entire area. The precise bearings and coordinates of all locations relative to each other were carefully encoded into the robot's navigation system, allowing it to autonomously and efficiently travel to any specified location within the mapped area [24]–[26]. This setup not only enhances the robot's operational efficiency but also maximizes its ability to respond quickly and effectively to fire incidents. A visual representation of this mapping can be seen in the accompanying Figure 3 and the robot prototype in Figure 4.

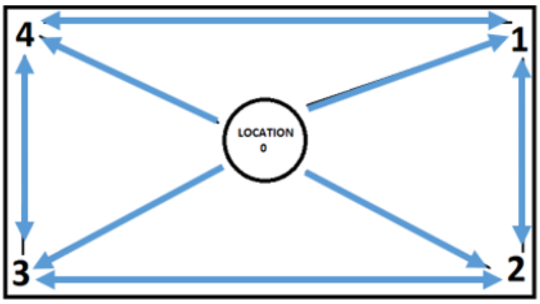


Figure 3. Robot pathway

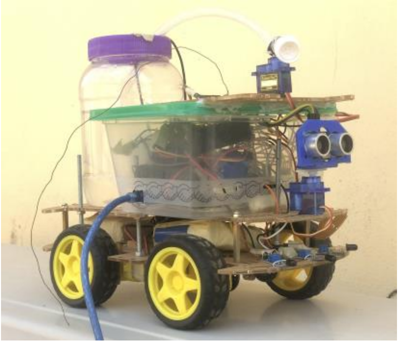

Figure 4. Robot prototype

## 3. RESULTS AND DISCUSSION

This design was implemented on a four-wheel drive chassis. The chassis houses all the components which include the motor, batteries, motor shields, sensors, magnetometer, transceiver, and servo motors. It protects them from any damage from the fire source. The robot successfully detected multiple flames from around it and also received signals from the transceiver at the static units, thereafter, navigating toward the flame with the directional aid of the compass and extinguishing the flame from a safe distance.

Analysis of the results obtained is divided into the following subsystems: i) the flame detection system, ii) the obstacle avoidance system, and iii) the navigation and transmission system.

### 3.1. Flame detection system

This test conducted was to determine the coverage distance and the angle of the three analog flame sensors installed on the robot. According to the datasheet, each flame sensor has a coverage angle of 60° and can sense flame up to 100 cm away and this test was carried out to ensure the obtained data was accurate. This robot uses three flame sensors and is arranged in such a way as to provide it with 180° of flame detection. The angle was measured from the leftmost sensor and the test sought to confirm the flame detection angle and range. The result at 100 cm is shown in Table 1.

Table 1. Sensorics analysis at different flame detection angles

| S/N | Angle (°) | Response Time (s) | Sensor Sensitivity (s/cm) | Sensor Reading | Test Result |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0.00 | 1024 | FAILED |
| 2 | 20 | 10 | 0.10 | 250 | PASS |
| 3 | 40 | 8 | 0.08 | 200 | PASS |
| 4 | 60 | 2 | 0.02 | 150 | PASS |
| 5 | 80 | 1 | 0.01 | 137 | PASS |
| 6 | 100 | 1 | 0.01 | 136 | PASS |
| 7 | 120 | 4 | 0.04 | 138 | PASS |
| 8 | 140 | 6 | 0.06 | 151 | PASS |
| 9 | 160 | 8 | 0.08 | 200 | PASS |
| 10 | 180 | 0 | 0.00 | 1024 | FAILED |

### 3.2. Obstacle avoidance system response

This test was conducted by placing obstacles on the robot’s path and analyzing the response. The programmed response of the robot is to halt if it is 30 cm away from an obstacle, check if the left path is free by rotating the servo motor that holds the ultrasonic sensor towards the left, and then read and record the distance, before rotating the ultrasonic sensor to the right to also check the distance towards the right. It then compares the two values and takes the path with a clearer path and the result obtained from this test is shown in Table 2.

Table 2. Response analysis based on obstacles on the robot’s path

| S/N | Obstacle Distance (cm) | Distance Robot Halted (cm) | Left Path Obstacle Distance | Right Path Obstacle Distance (cm) | Correct Path to take | Path Robot took | Is the robot correct? |
|---|---|---|---|---|---|---|---|
| 1 | 100 | 28 | 70 | 80 | Right | Right | Yes |
| 2 | 50 | 25 | 50 | 20 | Left | Left | Yes |
| 3 | 30 | 30 | 60 | 65 | Right | Right | Yes |
| 4 | 15 | 15 | 0 | 60 | Right | Right | Yes |

### 3.3. Navigation and transmission system

This test was carried out by triggering the flame sensors connected to the static unit and measuring the time taken for the robot to respond. There are five different locations as stated in the methodology. The robot was placed at one each time and the static unit sends a signal for the remaining four locations. The distance between locations was also measured. For the obtained results, one can obtain the signal response speed and also the robot's navigation speed. The complete results obtained from this test are shown in Table 3.

Table 3. Robot response time to flame sensing

| S/N | Current Location | Static Unit Signal | Distance between location (cm) | Response Time (sec) | Response Speed (cm/sec) | Travel Time (sec) | Robot Navigation Speed (cm/sec) |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 250 | 5 | 50.00 | 15 | 16.7 |
| 2 | | 2 | 250 | 6 | 41.70 | 13 | 20.8 |
| 3 | | 3 | 250 | 5 | 50.00 | 14 | 17.9 |
| 4 | | 4 | 250 | 8 | 31.30 | 17 | 14.7 |
| 5 | 1 | 2 | 265 | 10 | 26.50 | 25 | 10.6 |
| 6 | | 3 | 500 | 15 | 33.30 | 30 | 16.7 |
| 7 | | 4 | 400 | 17 | 23.50 | 25 | 16.0 |
| 9 | 2 | 1 | 265 | 9 | 29.44 | 22 | 12.1 |
| 10 | | 3 | 400 | 15 | 26.70 | 27 | 14.8 |
| 11 | | 4 | 500 | 16 | 31.25 | 31 | 16.1 |
| 12 | 3 | 1 | 500 | 17 | 29.40 | 33 | 15.2 |
| 13 | | 2 | 400 | 16 | 25.00 | 28 | 14.3 |
| 14 | | 4 | 265 | 10 | 26.50 | 27 | 9.8 |
| 15 | 4 | 1 | 400 | 17 | 23.50 | 30 | 13.3 |
| 16 | | 2 | 500 | 20 | 25.00 | 32 | 15.6 |
| 17 | | 3 | 265 | 10 | 26.50 | 30 | 8.3 |

## 4. CONCLUSION

The developed robot is a prototype of a semi-advanced firefighting robot created on a limited budget. Despite financial constraints, the robot demonstrates accurate and efficient obstacle avoidance and fire detection capabilities. It can detect fire within a wavelength range of 760 to 1100 nm and a distance from 10 cm to 100 cm on the main. The range extension from the static units also provided an extended 100 cm sensing range, marking a significant improvement and an additional advantage compared to other similar setups.

Building an autonomous mobile robot navigation system is challenging, particularly in unknown or unmapped environments. The system successfully integrates multiple sensors to gather comprehensive environmental data, enabling it to generate appropriate behaviors and achieve its objectives autonomously. This integration is crucial for the robot to operate effectively in environments that are out of human reach or too dangerous for human intervention.

In conclusion, the successful development and testing of this autonomous firefighting robot prototype demonstrates its potential as a practical and innovative solution for fire disaster management. By addressing key challenges in fire detection and navigation, this research paves the way for future advancements in autonomous firefighting technology, promising safer and more efficient operations. The project's outcomes suggest a transformative impact on firefighting practices, significantly reducing the risks faced by human firefighters and enhancing overall fire management strategies.

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