Design and Development of a Smart Fire Fighting Robot for Hazardous Environment Applications

Mr. Kambala Vijay Prasad[1] Adduri Mani[2*] Avisetti Himaja[2] Udimudi Devendra Sri[2] Vasamsetti Bharath[2]

[1]Assistant Professor, Bonam Venkata Chalamayya Engineering College, Odalarevu, AP
[2]UG Student, Bonam Venkata Chalamayya Engineering College, Odalarevu, AP
Corresponding MailID: bharathvasamsetti1@gmail.com

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Abstract: Fire accidents can cause severe damage to life and property, especially in industrial, residential, and public areas. To improve safety and reduce risks to firefighters, an autonomous firefighting robot is developed. The robot detects fire using flame and temperature sensors, processes the data through a microcontroller, and moves toward the fire using DC motors. It then activates a water pump or extinguishing system to suppress the fire. Obstacle detection sensors help it navigate safely in hazardous environments. The system is compact, cost-effective, and suitable for various locations, providing quick response while minimizing human exposure. Overall, it showcases the effective use of robotics and embedded systems in fire safety and disaster management.

Keywords: Firefighting robot; Arduino; Flame sensor; IoT; Automation; Embedded system.

1. Introduction

With the ever-increasing technology, the developments are increasing in the face of the situations that cause human life. Every day, the robot industry emerges as a model that is produced as an alternative to the human element in a new branch. Flying, robots, wheeled robots legged robots, humanoid robots, and underwater robots are just some of them. The growing world population is bringing involuntary problems together. Fires are among the most important of these problems. The robot industry has a lot of work in this area. Some of these are fixed mobile robots with different features, which are equipped with different sensors that detect before the fire is out, mobile rescue robots as fire search and rescue equipment, mobile locating robots used for fire detection, fire extinguishing robots in many different models designed to assist firefighters in the fire.

An embedded system is one kind of computer system mainly designed to perform several tasks like accessing, processing, and store, and also controlling the data in various electronics-based systems. Embedded systems are a combination of hardware and software where software is usually known as firmware that is embedded into the hardware. Embedded systems support to make the work more perfect and convenient. The applications of embedded systems mainly involve in our real-life for several devices like microwaves, calculators, TV remote control, home security, neighborhood traffic control systems, etc.

Fire accidents pose a serious threat to human life, property, and the environment. In many situations such as industrial fires, residential fires, or hazardous environments, it becomes extremely dangerous for firefighters to enter and control the fire manually. Traditional firefighting methods often expose humans to high temperatures, toxic gases, and the risk of explosions. Therefore, there is a need to design and develop an automated firefighting robot that can detect fire, navigate towards the source, and extinguish it without human intervention. The robot should be capable of operating in risky and inaccessible areas, reducing human effort and increasing safety. The main challenge is to build a system that is efficient, reliable, and capable of quick response using sensors, control systems, and extinguishing mechanisms.

Fire accidents expose firefighters to extreme heat, smoke, and toxic gases. A firefighting robot helps reduce direct human involvement and minimizes risk to life. Certain fire situations (chemical plants, gas leaks, electrical fires) are too dangerous for humans. Robots can safely operate in such high-risk areas. Early detection of fire using sensors allows the robot to respond quickly, helping to control fires before they spread. With the advancement of automation, robots can perform firefighting tasks efficiently using sensors, microcontrollers, and intelligent control systems. Quick action by robots can prevent the spread of fire, thereby reducing damage to buildings, industries, and valuable assets. Unlike humans, robots can work continuously without fatigue, making them suitable for long-duration firefighting tasks. Although initial setup cost is high, robots reduce long-term expenses related to manpower, safety equipment, and risk management. Firefighting robots can be used in industries, warehouses, homes, and public places.

Developed an intelligent firefighting tank robot. Materials like acrylic, plastic, aluminum, and iron are used to make the robot. The tank robot is consisting of components like two servo motors, a thermal array sensor, two DC motors, a flame detector, an ultrasonic sensor, IR and phototransistors, sound activation circuit, and a micro-switch sensor. The goal of the paper is to search the prescribed area find the fire and extinguish it. The robot is activated by using a DTMF transmitter and receiver [1-5]. Developed a firefighting robot. The firefighting robot is integrated with an embedded system. The prototype system is designed to detect and extinguish fire. It aims to reduce air pollution caused due to fire. The robot is designed to detect fire in small floor plans. The task of extinguishing fire is divided into smaller tasks. Each task is carried out in most appropriate way. The robot navigates in every room step by step, finds the fire in a room, approaches fire from fixed distance and then extinguishes fire [6-10].

A firefighting robot which included a project that aims to promote technology innovation to achieve a reliable and efficient outcome. The movement of the robot is controlled by the sensors which are fixed on the mobile platform.is to provide security of home, laboratory, office, factory and buildings is important to human life. They also developed an intelligent multisensory based security system that contains a firefighting system in our daily life. It included the design of the fire detection system using sensors in the system, and program the fire detection and fighting procedure using sensor- based methods [11-15]. Automatic Fire Detection System Using Adaptive Fusion Algorithm for Fire Fighting Robot. Conceptual analysis of firefighting robots' control systems [16-20].

A review of literature on firefighting robots shows that researchers have focused on developing autonomous systems capable of detecting, navigating, and suppressing fires in hazardous environments. Early studies emphasized remote-controlled robots equipped with basic sensors and water sprayers, mainly designed to reduce human exposure to toxic smoke and extreme heat. More recent work highlights the integration of advanced technologies such as infrared cameras, gas sensors, and AI-based navigation systems that allow robots to identify hotspots, detect victims, and adapt to dynamic fire conditions. Several papers discuss mobility solutions—wheeled, tracked, and aerial drones—that enhance deployment in cluttered or collapsed structures.

Scholars also note challenges such as limited battery life, difficulty in navigating smoky or debris-filled environments, and high costs of development. Overall, the literature suggests that firefighting robots are not intended to replace human firefighters but to act as force multipliers, improving safety, efficiency, and effectiveness in fire response operations while paving the way for future innovations in collaborative human–robot firefighting teams.

Smoke, debris, and collapsing structures make it hard for robots to move effectively. Short battery life restricts operation time during prolonged firefighting missions. Sensors, electronics, and mechanical parts may fail under high temperatures. Development, deployment, and maintenance expenses limit widespread adoption. Specialized training is required to control and maintain these robots. Signal loss inside buildings or underground areas reduces effectiveness. Robots cannot match human adaptability in unpredictable fire scenarios. Harsh conditions can cause breakdowns or reduced performance. Difficult to deploy large fleets cost-effectively in diverse environments.

2. Proposed System

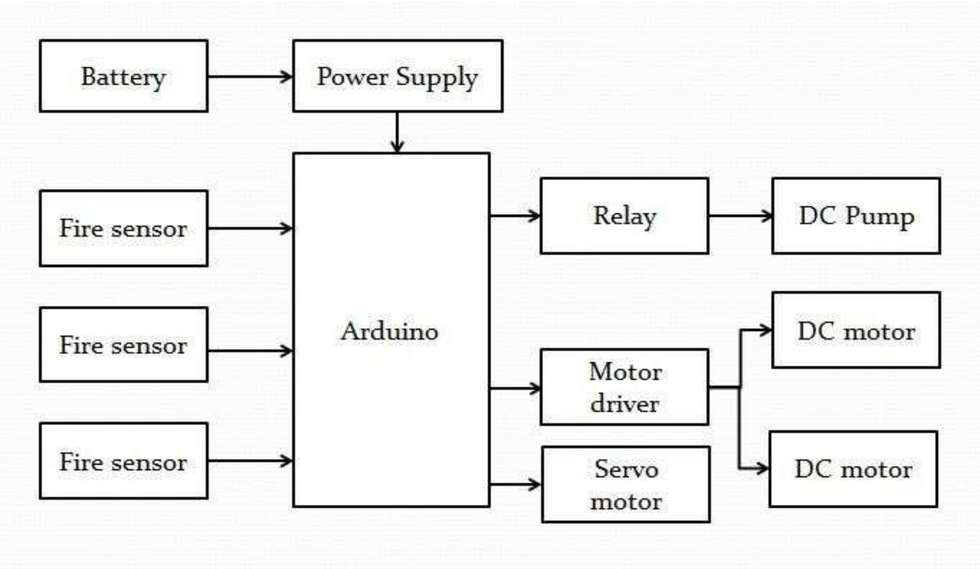

Fig. 1: Block diagram of project

This block diagram shown in figure 1 consists of different parts that are used to make this model and this is the place of alignments of the parts according to the connections. Based on this block diagram we connected every part and made this prototype to a working model this is the short and easy way to check all the parts that are present in the model.

To design and implement an IOT-based firefighting and affected area monitoring robot, the following requirements must be considered:

- Sensing capabilities: The robot must be equipped with sensors to detect fire, smoke, temperature, and other safety hazards present in the affected area. The sensors must be accurate and reliable, with the ability to transmit data in real-time to the central control system.
- Navigation system: The robot must have a navigation system that enables it to navigate through challenging terrain, avoid obstacles, and locate the source of the fire. The navigation system must be accurate, reliable, and efficient, with the ability to adapt to changing environments.
- Communication system: The robot must have a reliable communication system to transmit data to the central control system. The communication system must be able to transmit data in real-time and must be able to operate in environments with poor connectivity.
- Power supply: The robot must have a reliable power supply system that can support its operations for an extended period. The power supply system must be robust enough to withstand high temperatures and other hazards present in firefighting scenarios.

- Safety features: The robot must have safety features that protect it from damage or destruction in case of accidents or hazards. The safety features must also protect firefighters and other personnel from harm during firefighting operations.
- Integration with the central control system: The robot must be integrated with the central control system to enable firefighters to monitor and control its operations remotely. The central control system must be easy to use and must provide real-time data on the robot's operations.
- Durability and maintenance: The robot must be designed to withstand harsh environments and rough handling. Additionally, it must be easy to maintain and repair in case of damage or malfunction.

The proposed system of a firefighting robot is designed to automatically detect and extinguish fire without human intervention, thereby improving safety and reducing the risk to human life and property. This system is especially useful in hazardous environments such as industries, warehouses, and residential areas where fire accidents can cause severe damage. The robot is built using a microcontroller-based system, typically an Arduino Nano, which acts as the brain of the entire operation by processing inputs and controlling outputs. The robot uses flame sensors and temperature sensors to continuously monitor the surroundings for any signs of fire. When a flame is detected, the sensors send signals to the microcontroller, which then analyses the data and determines the direction of the fire source. Based on this information, the robot moves toward the fire using DC motors controlled by a motor driver module. The movement of the robot is fully automated, allowing it to navigate efficiently toward the fire location.

Once the robot reaches close to the fire, it activates a water pump system connected to a water tank. The water is sprayed through a nozzle to extinguish the fire, and a servo motor may be used to adjust the direction of the spray for better accuracy. After successfully extinguishing the fire, the robot either stops or resets itself to continue monitoring the environment for further fire incidents. Overall, the proposed firefighting robot system provides an effective, low-cost, and reliable solution for fire detection and suppression. It minimizes human involvement in dangerous situations and ensures quick response to fire accidents. With further advancements such as the integration of IoT, cameras, and artificial intelligence, the system can be enhanced to provide smarter and more efficient fire safety solutions in the future.

The working principle of the voltage monitoring and tripping system in a fire fighting robot is based on continuously measuring the supply voltage of the battery to ensure safe and reliable operation of the robot. A voltage sensing circuit, typically using a voltage divider or sensor module, is connected to the battery and provides a scaled-down voltage signal to the microcontroller. The microcontroller continuously reads this voltage through its analog input pins and compares it with predefined threshold values for safe operation.

When the battery voltage is within the normal range, the system allows the robot to function properly, including movement, fire detection, and water pumping operations. However, if the voltage drops below a specified minimum threshold, indicating a low battery condition, the microcontroller initiates a tripping action. This action may involve stopping the motors, turning off the water pump, and disabling other high-power components to prevent damage to the system and ensure energy conservation. In some cases, the system may also include an alert mechanism such as an LED indicator or buzzer to notify the user about the low voltage condition. Once the voltage returns to a safe level, either by recharging or replacing the battery, the system can be reset and resume normal operation. Thus, the voltage monitoring and tripping system plays a crucial role in protecting the robot’s components, improving efficiency, and ensuring uninterrupted and safe performance during firefighting operations.

The functional block diagram of a firefighting robot represents the overall operation of the system in terms of input, processing, and output units working together in a coordinated manner. In this system, the input block consists of sensors such as flame sensors and temperature sensors, which continuously monitor the environment for the presence of fire. These sensors detect heat or flame and convert it into electrical signals that are sent to the processing unit. The processing block is centred around a microcontroller, such as an Arduino Nano, which acts as the brain of the robot. It receives signals from the sensors, analyses the data, and makes decisions based on programmed instructions. Depending on the input conditions, the microcontroller determines the direction of movement and the required action to be taken for extinguishing the fire.

The output block includes components like the motor driver, DC motors, water pump, and servo motor. The motor driver controls the movement of the DC motors, allowing the robot to navigate toward the fire source. Once the robot reaches the fire, the microcontroller activates the water pump to spray water, while the servo motor helps in adjusting the direction of the spray for effective extinguishing. All these components are powered by a battery supply, which provides the necessary energy for the entire system. Thus, the functional block diagram conceptually shows how input, processing, and output blocks interact to achieve autonomous fire detection and suppression.

3. Hardware Design

The hardware design of the firefighting robot focuses on the selection and integration of physical components required for detecting fire, controlling movement, and extinguishing flames effectively. It forms the backbone of the system, ensuring that all modules work together in a coordinated and reliable manner. The design is centred around a microcontroller, typically an Arduino Nano, which acts as the main control unit and manages all operations based on input signals from sensors. The robot is equipped with flame sensors and temperature sensors that serve as the primary input devices for detecting fire and measuring heat levels in the surroundings. These sensors provide real-time data to the microcontroller, enabling quick and accurate decision-making. For movement, DC motors are used along with a motor driver module, which helps in controlling the direction and speed of the robot. The motor driver acts as an interface between the microcontroller and motors, allowing smooth navigation toward the fire source. To extinguish the fire, a water pump system connected to a small water tank is incorporated into the hardware design. The pump is activated by the microcontroller when fire is detected, and water is sprayed through a nozzle. A servo motor may also be included to adjust the direction of the water flow for better targeting. All components are powered by a battery supply, ensuring portability and independent operation of the robot. Overall, the hardware design plays a crucial role in achieving an efficient, responsive, and autonomous firefighting system.

Arduino is an open-source platform used for building electronics projects. Arduino consists of both a physical programmable circuit board (often referred to as a microcontroller) and a piece of software, or IDE (Integrated Development Environment) that runs on your computer, used to write and upload computer code to the physical board. Arduino is a single-board microcontroller meant to make the application more accessible which are interactive objects and its surroundings. Arduino is an open-source electronics platform based on easy-to-use hardware and software. The hardware features with an open-source hardware board designed around an 8-bit Atmel AVR micro controller or a 32- bit Atmel ARM. The Arduino UNO is a popular microcontroller development board used for building electronics projects. It's based on the ATmega328P microcontroller, and it features an easy-to-use programming environment, making it ideal for both beginners and advanced users shown in fig 2.

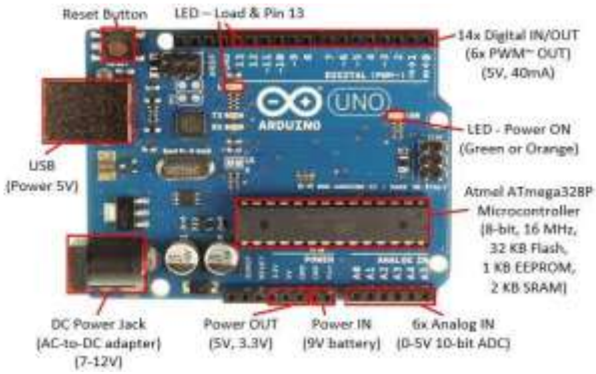

Fig:2: Arduino UNO

Fig. 3. Flame sensor

Fig 3 shows is a Flame sensor. Usually, in the infrared spectrum, all objects radiate some form of thermal radiation. These types of radiation are invisible to our eyes, and can be detected by an infrared sensor. The emitter is simply an IR LED (Light Emitting Diode) and the detector is simply an IR photodiode that is sensitive to IR light of the same wavelength as that emitted by the IR LED. When IR light falls on the photodiode, the resistances, and these output voltages, change in proportion to the magnitude of the IR light received.

4. Software Design

STEP-1: ARDUINO IDE

Once the software has been installed on your computer, go ahead and open it up. This is the Arduino IDE and is the place where all the programming will happen. Take some time to look around and get comfortable with it.

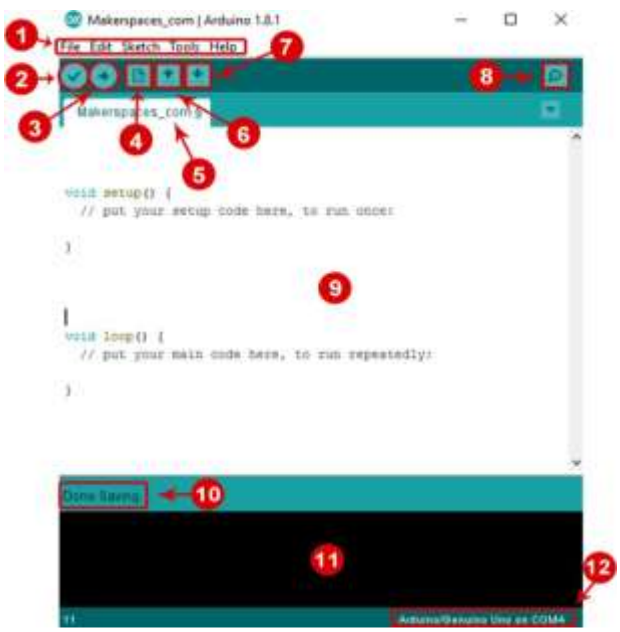

Fig: 4. Arduino tools

STEP-2: CONFIGURATION TOOLS

- Menu Bar: Gives you access to the tools needed for creating and saving Arduino sketches.
- Verify Button: Compiles your code and checks for errors in spelling or syntax.
- Upload Button: Sends the code to the board that's connected such as Arduino Uno in this case. Lights on the board will blink rapidly when uploading.

- New Sketch: Opens a new window containing a blank sketch.
- Sketch Name: When the sketch is saved, the name of the sketch is displayed here.
- Open Existing Sketch: Allows you to open a saved sketch or one from the stored examples.
- Save Sketch: This saves the sketch you currently have open.
- Serial Monitor: When the board is connected, this will display the serial information of your Arduino
- Code Area: This area is where you compose the code of the sketch that tells the board what to do.
- Message Area: This area tells you the status on saving, code compiling, errors and more.
- Text Console: Shows the details of an error messages, size of the program that was compiled and additional info.
- Board and Serial Port: Tells you what board is being used and what serial port it is connected to.

STEP 3: LINK ARDUINO UNO TO PC

- At this point you are ready to connect your Arduino to your computer. Plug one end of the USB cable to the Arduino Uno and then the other end of the USB to your computer's USB port.
- Once the board is connected, you will need to go to Tools then Board then finally select Arduino Uno
- Next, you must tell the Arduino which port you are using on your computer.
- To select the port, go to Tools then Port then selects the port that says
- Arduino

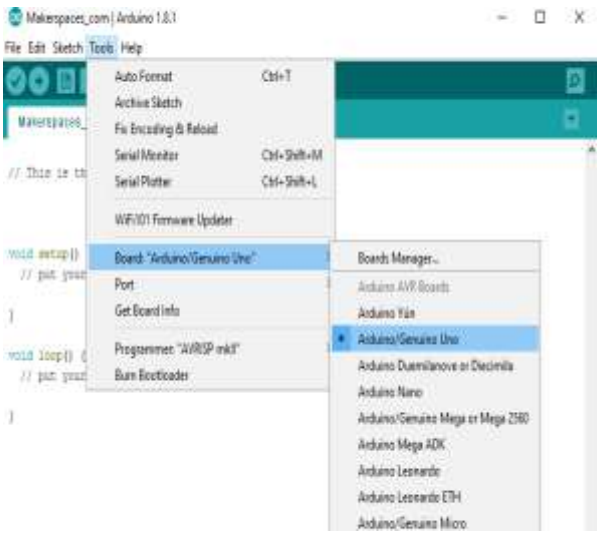

Fig:5. Board linking tool

STEP 4: COMPILE AND UPLOAD

You need to click on the verify button (check mark) that is in the top left of the IDE box. This will compile the sketch and look for errors. Once it says "Done Compiling" you are ready to upload it. Click the upload button (forward arrow) to send the program to the Arduino board.

Fig:6. Code verification & upload

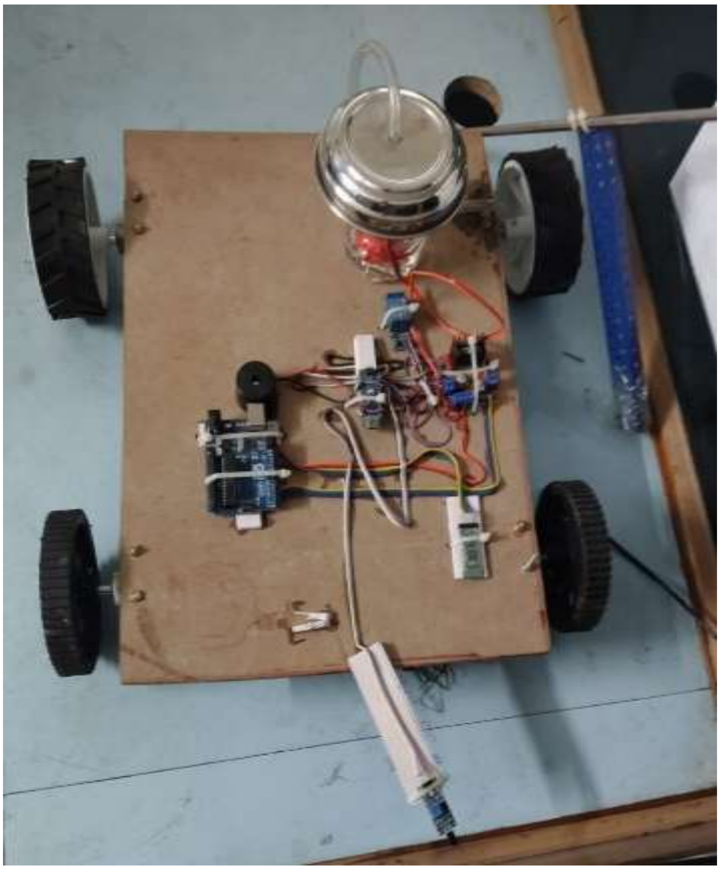

Fig: 7. Working Model of Proposed Method

a. Results and Discussion

The results of the implementation showed that the robot was able to detect fires using temperature and smoke sensors and spray water to extinguish the flames. Additionally, the robot was able to monitor the area for changes in temperature, humidity, and gas levels, providing real-time data that could be used to improve the firefighting process.The results also showed that the robot was able to navigate through different types of terrain and obstacles to reach the affected area. The use of motor drivers and motors allowed the robot to move smoothly and avoid obstacles.

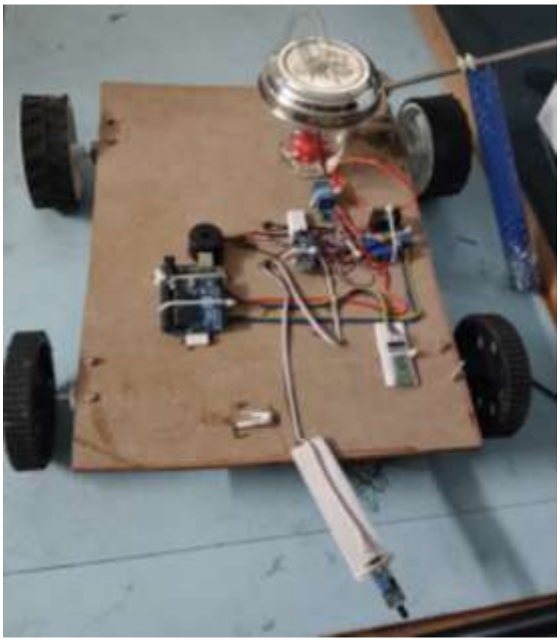

Fig. 8: Power Supply of the Project

However, one of the challenges encountered during the implementation was ensuring the reliability of the sensors in detecting fires and environmental changes. The sensitivity of the sensors needed to be adjusted to prevent false alarms while also ensuring that fires were detected quickly and accurately. Finally, the IOT-based firefighting and affected area monitoring robot provides an automated and efficient solution for firefighting and environmental monitoring. The real-time data collected by the robot can be used to improve firefighting techniques and prevent future fires. With further research and development, this technology has the potential to revolutionize firefighting and disaster response.

The response time analysis of a firefighting robot is an important performance parameter that measures how quickly the system reacts to the presence of fire and takes appropriate action to extinguish it. It represents the total time taken from the moment a fire is detected by the sensors to the activation of the extinguishing mechanism, such as the water pump. A faster response time indicates a more efficient and reliable system, which is critical in minimizing fire damage and ensuring safety. The response time is influenced by several factors, including the sensitivity and placement of flame sensors, the speed of signal processing by the microcontroller, and the movement speed of the robot. Initially, when the flame sensor detects fire, it sends a signal to the microcontroller, which processes the input and generates control signals for the motors. The robot then moves toward the fire source, and once it reaches an optimal distance, the water pump is activated to extinguish the fire. The total response time includes detection time, decision-making time, movement time, and action time. To analyze the response time, multiple experiments are conducted by placing the robot at different distances and directions from the fire source. The time taken for each stage is measured using timers or observation methods, and the results are recorded for comparison. Any delay in detection, slow movement, or inefficient control logic can increase the response time. By analyzing these factors, improvements can be made in sensor accuracy, programming efficiency, and motor performance to achieve a faster and more effective firefighting robot system.

Conclusion

The Proposed approach of modular design strategy was a good solution in implementing the firefighting robot to help people at the critical condition. The proposed robot can move in forward, backward, left, right and can stop also. It reduces human efforts and protects their property. Robot detects fire and extinguishes the fire with the help of a sprinkler pump. A firefighting and affected area monitoring robot is proposed based on the Internet of Things environment, which can take instant steps during fire accidents. This robot can be used to reduce the risk of human firefighters in area which is out of reach for human beings. Industries with a higher risk of fire accidents can use this robot to avoid huge damage. In the future re, Machine Learning and AI systems can be implemented to improve the performance of the robot.

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