Design and Development of an Autonomous Fire-Fighting Robot Using GSM Communication

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Abstract. Fire accidents are serious life, property, and environmental hazards, and fire-fighting operations tend to put people in risky situations, particularly in hot or confined spots such as factories and narrow corridors of buildings. To address these issues, this paper documents the design and development of an autonomous firefighting robot equipped with GSM communication for remote monitoring and control. The robot runs on 3.7V batteries and is controlled by an Arduino Nano, and a 5.1 development board is used, with mobility provided by DC motors with wheels via an L298N motor driver. Fire detection is provided via various fire sensors, while efficient fire extinguishing is provided via a water tank, a servo motor, and a water pump. Safe high-current component switching is provided via a relay. Real-time feedback to the human driver and remote control of the robot are provided via GSM connectivity, allowing for smartphone or other device control. The novelty of this work lies in the integration of GSM-based communication with a firefighting robot, enabling real-time monitoring, efficient data transmission, and long-distance control beyond the limitations of traditional Wi-Fi or Bluetooth systems. The results of the experiment reveal that the robot will automatically identify and put out indoor fires, save firefighters from injury, and estimate the impacts of operations.

Keywords: GSM, firefighter, Real-time, Arduino Nano, Motor Driver, Relay, Fire sensor.

1 Introduction

Fire hazards continue to pose a significant risk to life, property, and the environment, as fire can spread faster than firefighters can respond. All the conventional fire alarm and fire-extinguishing apparatus, such as smoke detectors, manual extinguishers, and sprinkler systems, are based on human intervention, which will be delayed or risky in a case of emergency. Recent advances in embedded systems, robots, and wireless communication have enabled autonomous solutions that can automatically sense, identify, and extinguish fires in real time. The use of fire detection sensors, self-navigating, and GSM-based communication offers immediate suppression along with remote notification, offering an improved and quicker response to fire accidents. In houses, industries,

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and businesses, early detection alone is insufficient to prevent widespread damage as inaccessible zones and delayed human action give fires time to spread.

To address these needs, this research proposes the design and development of an Autonomous firefighting robot with GSM communication. The system can detect fire, travel to hazardous areas, release suppression via a water pump, and send a real-time alert to engaged personnel. Automating the process is expected to reduce response time, cause less harm, and make it safer for firefighters under unsafe conditions. By and large, the major contributions of this work are as follows. To begin with, the employment of GSM-based communication enables reliable long-distance control and monitoring, which overcomes traditional range limitations of conventional Wi-Fi or Bluetooth systems. Secondly, the system employs IoT-powered sensors for efficient fire detection as well as autonomous navigation, and the robot can move safely in hazardous zones without human interference. Thirdly, the plan is lightweight and cost-effective and thus suitable for home, factory, and business applications. Finally, the proposed framework provides a foundation for future expansion, such as large-scale roaming, power saving, and compatibility with future communication networks such as LoRa or 5G, to render it scalable and flexible for real-world applications in firefighting.

2 Literature Review

Firefighting is a risky operation, per se, that requires prompt response to minimize loss of life and property. Conventional firefighting operations expose individuals to hazardous environments, which necessitate the development of robotic platforms with autonomous or semi-autonomous fire detection and extinguishing capabilities. Early applications, e.g., Aliff et al. [1] QRob, Arduino rover robots [5,10], and proof-of-concept implementations [11,16], have predominantly employed flame and temperature sensors for fire localization. Although such systems provided the foundation for automated firefighting, they were hampered by restricted mobility, limited operational time, and a lack of real-time remote monitoring. Emerging technologies have tapped into IoT and wireless communication technology to increase availability and control operations. Hossain et al. [2] and Jadhav et al. [14] presented robots empowered by IoT and operated through mobile apps with remote monitoring and feedback. However, such systems were still founded on Wi-Fi or Bluetooth, restricting operational distance and network reliability. Vasanthkumar et al. [18] integrated GSM communication with fuzzy logic, proving cellular networks' capability of offering extended control distance and localized network autonomy. Similarly, Wasu et al. [10] implemented wireless Arduino-based control for home firefighting systems, illustrating real-world applicability. Environmental adaptability and sensor fusion were also explored to achieve maximum performance. Perumal et al. [3] utilized night vision cameras for enhanced low-light observation, while Dhiman et al. [9] employed machine vision and deep learning for intelligent fire detection. Legged robots with PID control have been implemented for traversing rugged landscapes [8], and video streaming has also been incorporated to provide situational awareness [21]. Other studies focused on particular sectors, e.g., industrial environments [12], indoor firefighting [4], and multi-room environments [5], demonstrating the adaptability of robotic systems across different operational environments. Several designs centered on autonomous mobility, energy management, and control protocols. Murad et al. [5] and Chaudhari et al. [11] used Arduino-based control in indoor mobility, whereas Jawad and Jawad [15] investigated solar-powered mobile robots enhanced with artificial intelligence to enhance their function for longer periods. Latif et al. [8] optimized legged robot movement using PID control, and Singh et al. [13,19] presented miniaturized robots maintaining cost, size, and efficiency equilibrium. Kareem et al. [20] developed a multi-sensor smart firefighting robot using Arduino, highlighting the advantages of low-cost and modular approaches. Wu et al. [17] implemented STM32 microcontrollers for precise control in smart firefighting systems, reflecting the tendency to incorporate embedded systems for improved performance. Despite these advancements, most of the existing systems remain plagued by recurring limitations like restricted range of communication, reliance on local networks, restricted operating time due to energy limitations, reduced flexibility for multi-level or complicated environments, and poor integration of autonomous navigation and remote control. Environmental conditions such as chemical makeup in smoke, high temperature, and uneven ground still affect sensors' performance and the mobility of robots. Cybersecurity problems have also been reported for networked robotics systems [7], emphasizing the necessity of secure and dependable communication in mission-critical settings. Bridging these gaps, this research proposes an autonomous fire-fighting robot with GSM-based communication, IoT-based sensors, and autonomous navigation. In contrast to the past work, the system is designed to maintain real-time monitoring and remote control over long distances with operational efficiency and safety in different environments. Its low-cost and compact size assures scalability to residential, industrial, and commercial environments. Besides, the proposed framework is also extensible to future evolution, like multi-level navigation, power efficiency, and compatibility for next-generation communication protocols like LoRa or 5G, with a strong foundation for advanced firefighting applications.

3 Proposed Methodology

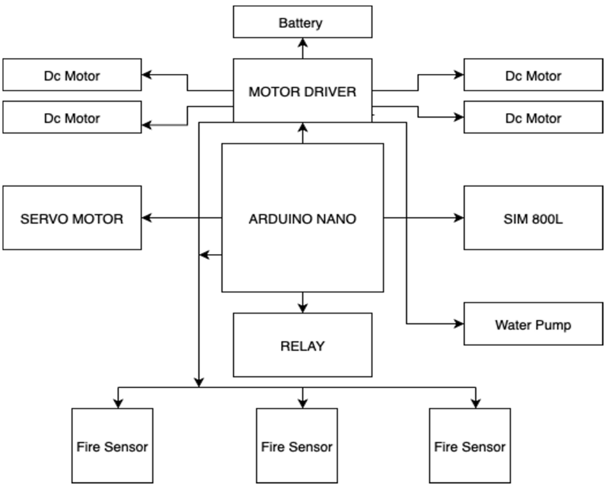

Fig. 1. Block diagram of the Proposed System

3.1 System Overview

The autonomous firefighting robot is designed to have various subsystems to achieve effective fire detection and extinguishment in a hazardous environment. Movement is enabled by DC motors, controlled by a motor driver, with a servo motor employed for precise directional management. Fire sensors continuously monitor the environment and provide feedback to an Arduino Nano microcontroller, which controls the activation of a relay for managing a water pump when a fire has been identified. Also, a SIM800L GSM module offers remote control and monitoring with support for timely human intervention where necessary.

3.2 Mechanical and Electrical Design Structure

The robotic design for autonomous firefighting involves mechanical and electrical components to ensure stable motion, efficient detection of the fire, and GSM communication-based remote control. The robot is equipped with four wheels on two DC motors per side to ensure stability and enable easy motion and rotation. A servo motor is installed to control the water pump for fire extinguishing.

The chassis consists of acrylic sheets that protect the electronic circuitry. The acrylic is also fire-resistant up to 200 °C and features easy mounting of sensors, motors, and other mechanical components. The fire sensors are placed on the front of the robot for the identification of fire sources, and an ultrasonic sensor can be interfaced for the detection of obstacles. A miniature camera can also be fitted for real-time monitoring via a smartphone. The electronic circuit is centered around an Arduino Nano microcontroller, which controls the DC motors through an L298N motor driver, and powers the servo motor and water pump through a relay module. AA 3.7V batteries power the robot. Remote communication is provided by the GSM module (SIM800L), with the facility to send notifications to the operator and see the robot in real time. The whole integration and wiring of robot components are shown in Fig. 1, where all the sensors, motors, water pump, relay, and GSM module are interfaced to Arduino Nano. It ensures synchronized operation of the navigation, fire detection, suppression, and communication.

3.3 Hardware Implementation

The electronic section is one of the critical portions in the development of the firefighting robot. It contains several components like sensors, a microcontroller, DC motors and drivers, a water pump, and a GSM module. Fig. 2 Circuit diagram of the Proposed System shows the block diagram of the robot operation, which includes flame and temperature sensors for fire detection, and ultrasonic sensors for obstacle avoidance as the system inputs.

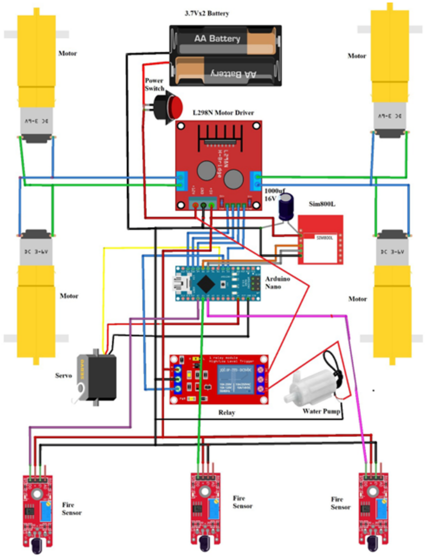

Fig. 2. Circuit diagram of the Proposed System

An Arduino Nano microcontroller board is utilized to manage and control the operation of the robot. DC motors powered through L298N motor drivers enable the mobility of the robot. A water pump is utilized as the fire extinguisher system, which is activated based on sensor input and operator command. For remote notification, a SIM800L GSM module is provided for sending SMS and call alerts when there is a fire detection. The overall system flow is controlled by the Arduino Nano, which receives feedback from sensors and regulates the motors and the pump in sequence.

1) Fire Sensor: The fire detection system of the robot employs a flame sensor and a temperature sensor. The fire sensor employs detection of infrared radiation from flames to sense fire, while the thermal sensor employs detection of heat in the vicinity of the sensors to confirm that there is fire. The sensors provide real-time feedback to the microcontroller as Arduino Nano, to assist the robot in ensuring safe detection and reaction to the source of the fire.
Upon fire detection, the sensors directly notify Arduino, which instantly activates the water pump to extinguish the fire and the GSM module to send an SMS alert to the operator, informing him of the event. Such coordination provides immediate fire detection and response and security in the environment.

***2)* Servo motor:** The robot uses a servo motor to control the precise movement of components such as the water pump nozzle or sensor alignment. It allows the robot to point the water stream directly at the fire source. The Arduino Nano microcontroller controls the servo motor and gives it PWM signals, which determine its rotation angle.
This is an accurate control that ensures the fire suppression system has the ability to respond best to fires, and this makes it an upgrade to the general capability of the robot to fight fires.

3) **Arduino Nano:** The Arduino Nano microcontroller has been utilized as the robot's processor, managing all the hardware and managing the robot's operations. It receives input from sensors such as flame, temperature, and ultrasonic sensors, processes the input, and provides control signals to actuators such as DC motors, servo motors, and the water pump.
The compactness of the Arduino Nano is ideal for snugly fitting into the robot chassis for component mounting and easy wiring. The module's adaptability and flexibility to interface with various modules and sensors, like the SIM800L GSM module, enable smooth control and communication to facilitate the robot's autonomous fire detection, navigation, and suppression efficiently.

4) **L298N Motor Driver:** The L298N motor driver manages the movement of the DC motors of the robot. It acts as a link between the Arduino Nano microcontroller and motors in order to allow the microcontroller to efficiently control motor speed and direction. Taking the Arduino's control signals, the L298N driver provides the necessary voltage and current to the DC motors to achieve precise and smooth robotic movements. Applying the L298N driver ensures robust navigation and collision avoidance during firefighting.

5) SIM800L GSM: The SIM800L GSM module is implemented inside the robot for remote communication. The robot can send an SMS alert and a Call alert to the operator in the event of a fire, thus issuing early notifications even when the operator is not near the robot. Its small size and low power consumption make it suitable for mobile robot applications. The incorporation of the SIM800L GSM module incorporates safety and responsiveness into the fire-fighting robot via real-time remote monitoring and alarming in the event of a fire attack.

*6***) DC motors:** The DC motors are employed to enable the mobility of the robot so that it can move forward, backward, and turn as and when required. They are powered by the Arduino Nano through the L298N motor driver, which regulates the speed and direction of the motors.
The motors are placed on wheels to produce a differential drive system, such that the robot can move around objects detected by the ultrasonic sensors with great accuracy. The smooth and interactive movement is needed by the robot to move to fire points

7) Relay: The relay is an electromechanical relay used by the robot to switch on/off high-voltage devices such as the water pump, which cannot be driven directly from the Arduino Nano. It allows the pump to be switched on and off by the microcontroller from a low-voltage control signal. The relay offers electrical isolation between the low-power control circuit and high-power load for secure and reliable operation of the fire extinguishing system.

3.4 Performance Metrics Evaluation

Evaluation of the robot's performance was done through four main metrics: detection accuracy, response time, detection range, and operational reliability. A series of tests was conducted with various flame types (candle, paper, alcohol) through several trials. Measurements involved the timing of sensor activation, the start of movement, the triggering of the GSM alert, and the success of extinguishing.

Table 1. Required Component List

SN	Components	Quantity
01	Servo motor	1 Piece
02	Water pump	1 Piece
03	5.1 dev board	1 Piece
04	Arduino Nano	1 Piece
05	L298N Motor Driver	1 Piece
06	DC motor	4 Piece
07	Wheel	4 Piece
08	Relay	1 Piece
09	Fire sensor	3 Piece
10	AA 3.7v battery	2 Piece
11	GSM _ SIM800L	1 Piece
12	Water Tank	1 Piece
13	Connection wire	10 Pare

4 System Design and Implementation

The robot travels on a two-dimensional plane. The robot takes place on the (0,0) position, which serves as the reference for movement and navigation. The world coordinate system (Xm, Ym) is referenced to the plane of two dimensions and is the map frame of reference. All robot paths and locations are specified with respect to the plane. The local coordinate system (Xc, Yc) is attached to the body of the robot and moves with the robot across the plane. The global to local coordinate transformation, as shown in Fig. 4, is described by the rotation angle θ and the translation vector (nx, ny) (x,y), specifying the position and orientation of the robot on the surface. Thus, the surface plane is the common ground for both frames: The global frame defines absolute positions on the surface. The local frame defines relative measurements of the motion of wheels, sensor values. and maps them back onto the main plane through coordinate transformations. This mapping guarantees that actuator outputs (nozzle direction, wheel speeds) and sensor inputs (obstacle ranges, fire locations) are always referenced relative to the robot's physical surface.

$$\begin{bmatrix} \dot{x}' \\ \dot{y}' \\ \theta' \end{bmatrix} = \begin{bmatrix} cos\theta & 0 \\ sin\theta & 0 \\ 0 & 1 \end{bmatrix} * \begin{bmatrix} v \\ \omega \end{bmatrix} \qquad (i)$$

Equation (1) captures the kinematic model of the differential-drive robot, where the state vector $[x' y' \theta']$ describes the instantaneous position change and orientation. The first component $[\cos\theta \sin\theta 0]v$ accounts for the contribution of the linear velocity v, mapping the robot's forward motion from its local reference frame into the global coordinate space according to the heading angle θ. The second component [0 0 1]ω, which restores the orientation of the robot. These two terms combined describe how translational and rotational velocities of the robot define its trajectory on the surface plane.

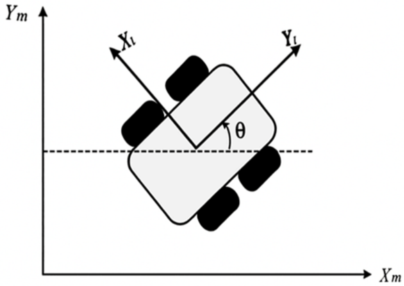

Fig. 3. Relationship between Robot Coordinate Plane with Main Surface.

The robot's motion is depicted in Fig. 3, Relationship between Robot Coordinate Plane with Main Surface, where (Xm, Ym) is the global (map) reference frame and (Xc, Yc) is the local (robot) reference frame. The robot's orientation with respect to the global frame is determined by the angle θ. A point represented at the robot frame , Pc=[XcYc]^T, can be transformed into the global frame as:

$$P_m = R(\theta) P_c + t. \qquad (ii)$$

$$R(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}, \ t = \begin{bmatrix} x \\ y \end{bmatrix} \qquad (iii)$$

This mapping is utilized for extrapolating measurements from the sensor (e.g., obstacle distances) from the local frame to the map in the global frame. The robot's movement is based on the basis of a differential-drive platform. If v_r and v_l are the velocities of the right wheel and left wheel, respectively, and b is the wheelbase, then the linear and angular velocities are:

$$v = \frac{v_r + v_l}{2} \qquad (iv)$$

$$\omega = \frac{v_r - v_l}{b} \qquad (v)$$

Here, r is the radius of the wheel, and d is the distance from the wheel to the center of rotation of the robot. The robot's pose (x,y,θ) is updated through: $\dot{x} = v \cos\theta$, $\dot{y} = v \sin\theta$, $\dot{\theta} = \omega$.

The control structure integrates actuation and sensor inputs hierarchically. Temperature and flame sensors provide fire detection, and ultrasonic sensors provide obstacle avoidance through a refresh of the robot's navigation instructions.

4.1 Experimental Setup

Using controlled flame sources, the experiments were done inside a 2×2 m test arena.
Distances tested: 10-120 cm.
Trials: 50 for accuracy, and 30 for reliability.
Tools: stopwatch, distance meter, multimeter, and GSM module verification.

Listing 1. Arduino pin configuration for motor and sensor: This code defines the Arduino pins for motor, sensor, servo, and water pump.

```
#define leftMotor1 11
#define leftMotor2 10
#define rightMotor1 9
#define rightMotor2 3
#define leftSensor A0
#define frontSensor A1
```

Listing 2. Arduino setup function: Initializes the sensor and actuator as outputs and sets up serial communication.

```
void setup() {
  Serial.begin(9600);
  pinMode(leftSensor, INPUT);
  pinMode(frontSensor, INPUT);
  pinMode(rightSensor, INPUT);
  pinMode(pumpMotor, OUTPUT);
  digitalWrite(pumpMotor, HIGH);
  pinMode(servo, OUTPUT);
```

Listing 3. Forward Motion Function: Control different driver motors using PWM to move the robot forward.

```
void forward(int leftmotor1, int leftmotor2, int rightmotor1, int rightmotor2) {
  analogWrite(leftMotor1, leftmotor1);
  analogWrite(leftMotor2, leftmotor2);
  analogWrite(rightMotor1, rightmotor1);
  analogWrite(rightMotor2, rightmotor2);
```

Listing 4. Direct Phone Call function: Sends an emergency call via the SIM800L module when fire is detected.

```
void callNumber() {
  gsmSerial.println("AT+CMGS=\"" + number + "\"\r");
  delay (1000);
  gsmSerial.print(F("ATD"));
  gsmSerial.print(number);
  gsmSerial.print(F(";\r\n"));
```

Listing 5. Message sending function: Sends an emergency SMS alert via the SIM800L module.

```
void SendMessage() {
```

```
gsmSerial.println("AT+CMGF=1");
delay(1000);
gsmSerial.println("AT+CMGS=\"" + number + "\"\r");
delay(1000);
gsmSerial.println(SMS);
delay(100);
gsmSerial.write (26);}
```

Arduino code listings presented exhibit the overall control structure of the fire-fighting robot. Listing 1 defines the pin configuration for motor, sensor, pump, and servo interfacing. Listing 2 initializes the system by defining sensor inputs, actuator outputs, and serial communication configurations. Listing 3 provides the forward motion function, where PWM signals are provided to motor driver pins for moving the wheels. On the other hand, Listing 4 gives the GSM-based message and call sending process through which the robot can send SMS to a mobile device to alert when it detects a fire.

4.2 Internal Circuit of the Prototype model.

The prototype autonomous firefighting robot works on a four-wheeled base, providing stable mobility and an Arduino Nano as a controlling unit, shown in Fig. 4, *Internal Circuit of the Prototype model.* It consists of a motor driver, a fire sensor, a servo motor, a relay module, a water pump, and a SIM800L GSM module.

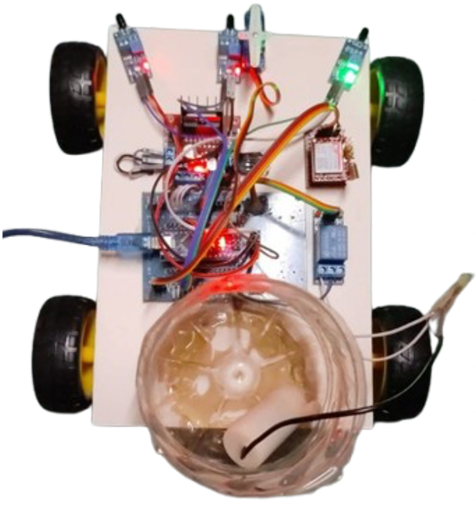

Fig. 4. Internal Circuit of the Prototype model.

The water pump, which is connected to the water tank located on the robot's chassis, is turned on by a relay when the fire sensors detect fire, and at the same time, the servo motor is directed towards the fire. The GSM module allows for the monitoring and control to be done remotely.

5 Control Programming

The control system of the firefighting robot built using Arduino has integrated three major functions, which are sensor reading, decision-making, and actuator control. The entire system is initialized with motor drivers, sensors, a servo motor, a water pump, and a GSM communication module.

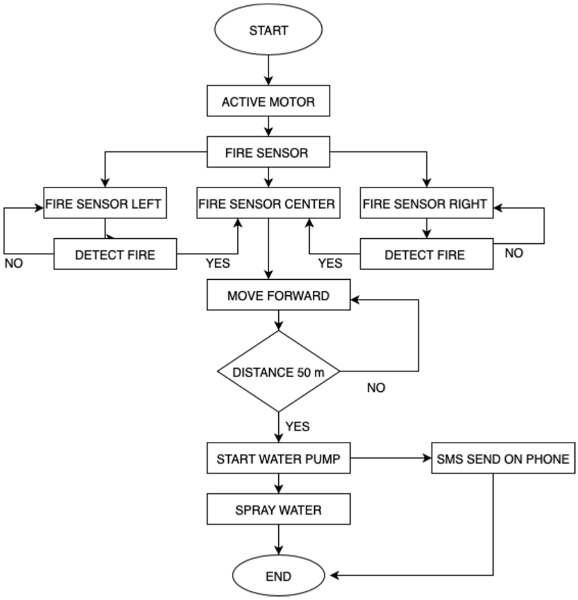

Fig. 5. Operational flowchart.

The flowchart illustrates the functioning of the fire-fighting robot from activation to suppression of fire, show*n i*n Fig. 5, Operational flowchart. The robot, after starting up, sets the motors and the three flame sensors (on the left, in the middle, and on the right) for continuous checking. When a flame is detected, the robot goes to the flame and, at a distance of 50 cm, triggers the water pump and simultaneously sends an SMS alert through the GSM module to terminate the operation.

6 Result Analysis

The robot was tested in a controlled setup to confirm sensing, navigation, suppression, and communication functionality. The flame sensors consistently detected fire sources at various positions in the robot's field of view. The left, center, and right sensors provided directional orientation to the flame. Motor control based on Arduino successfully propelled the differential-drive mechanism, and ultrasonic sensors guaranteed safe movement through obstacle avoidance. At a distance of approximately 50 cm from the origin of the fire, the relay module activated the water pump, and the servo motor changed direction to rotate the nozzle to spray water over the flame. This resulted in successful fire extinguishing in seconds of activation. At the same time, the GSM SIM800L module gave an SMS alert to a pre-programmed mobile number, indicating the detection and extinguishing process. These tests verified that the system is capable of being utilized to automatically detect, drive towards, and extinguish small fire hazards and provide remote alarms to the operator. Out of 50 trials, the system reached a detection precision of 97%, with an average response time of 1.32 seconds. Flames were detected accurately in the range of 10–95 cm. The total operational reliability was 95% (27 successful cycles out of 30), with small percentages of failures occurring due to GSM delays or wheel slip.

7 Discussion

The main contribution of our work is a small and cheap GSM-based firefighting robot intended for indoor places with small dimensions, and this is backed up with quantifiable performance results.[18] Handling a similar topic has made the robot more complex with kinematics, real-time response evaluation, and a heavy extinguishing mechanism that are decidedly not meant for deployment at the low-cost and practical level. The combination of flame detection, automatic navigation, suppression, and GSM communication creates an inexpensive robotic option for fire occurrences. The system worked well during the experiments under controlled indoor conditions, proving its hardware and control logic. Limited pump capacity kept the system to small fire areas, but performance was reduced in the presence of strong light and uneven terrain. Nevertheless, the design is promising for unsafe areas.

8 Limitations and Feature Work

The robot designed to fight against fire without human intervention is good at what it does, but is nonetheless restricted by smoke, heat, and rugged ground, which impact sensor performance and the robot's ability to move around. Communication via GSM might cause a delay in response, and one of the issues that has yet to be solved is the short battery life. In the coming years, improvements will be made with a focus on combining sensors, speeding up communication (LoRa or 5G), improving power management, and increasing mobility of the robot to make it capable of firefighting in real life with reliability.

9 Conclusion

The paper presents the design and development of a GSM-based autonomous firefighting robot with remote monitoring and control. The system has been observed to detect and suppress fire efficiently with repetitive performance under controlled conditions. The robot, through autonomous navigation in conjunction with real-time communication, reduces human risk in hazardous firefighting operations. Through the support of IoT-enabled sensors, the system instantly detects fire and reacts correspondingly, while the modular methodology facilitates future upgrades. Despite environmental and operational constraints, the proposed system establishes a solid groundwork for intelligent fire management. Future improvements in the form of improved mobility, energy optimization, and improved communication protocols can be anticipated to further increase efficiency and applicability, contributing valuably towards the evolution of automated firefighting technologies. This study successfully delineates the design and development of an autonomous fire-fighting robot with GSM-based communication, combining IoT-enabled sensors and autonomous navigation for enhanced safety and operational effectiveness. The system redefines firefighting by overcoming the limits of the conventional method with real-time monitoring, remote control, and low-cost deployment, which in turn opens up the future to longer range, less power consumption, and superior communication for increased efficiency

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