

Firefighting Robot for Tunnel Environment

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Abstract – Tunnel environments are among the most hazardous industrial and infrastructural settings, where the confined geometry, limited ventilation, and dense accumulation of toxic fumes create life-threatening conditions during fire incidents. Conventional fire suppression systems installed in tunnels are expensive, require manual intervention, and often fail to reach inaccessible zones. This paper presents the design and implementation of an autonomous firefighting robot specifically engineered for tunnel environments. The proposed system integrates a flame sensor for fire detection, an MQ-2 gas sensor for smoke and combustible gas monitoring, and an ultrasonic sensor for real-time obstacle avoidance within the confined tunnel pathway. A NodeMCU (ESP8266) microcontroller acts as the central processing unit and provides Wi-Fi-based wireless control and data transmission. An ESP32-CAM module enables live video streaming to a remote monitoring station, facilitating situational awareness for emergency responders. Upon fire detection, a relay module activates a DC water pump that discharges water to suppress the flames. The robot chassis employs four DC gear motors driven by an L298N motor driver, enabling reliable navigation over uneven tunnel surfaces. Experimental results confirm that the system reliably detects fire and gas leakage, avoids obstacles, and suppresses small-scale fires within an average response time of 4.2 seconds. The platform offers a scalable, cost-effective solution for smart tunnel safety.

Key Words: *firefighting robot, tunnel fire safety, flame sensor, MQ-2 gas sensor, ultrasonic sensor, NodeMCU, ESP32-CAM, obstacle avoidance, smoke detection, remote monitoring.*

1. INTRODUCTION

Tunnels form critical nodes in modern transportation and utility infrastructure, including road, rail, metro, and mining networks. Fire incidents inside tunnels are disproportionately catastrophic compared to open environments due to the chimney-effect convection of heat and smoke, restricted egress pathways, and the inherent difficulty of deploying conventional firefighting personnel under such extreme conditions. Historical tunnel fire events, such as the Mont Blanc Tunnel fire (1999) and the Kaprun funicular fire (2000),

resulted in heavy casualties and reinforced the urgent need for autonomous fire management systems.

Traditional sprinkler-based fixed suppression systems offer a first line of defence but are limited in their spatial coverage, cannot navigate to the fire source, and rely entirely on fixed sensor nodes that may be damaged in an explosion or structurally weak section of the tunnel. Mobile robotic platforms bridge this gap by offering dynamic deployment, adaptable navigation, and sensor-rich real-time feedback to remote operators.

Advances in low-cost embedded platforms such as the NodeMCU ESP8266, ESP32-CAM, and compact sensor modules have made it feasible to develop capable firefighting robots at a fraction of the cost of industrial alternatives. This work leverages these components to present a functional prototype that autonomously detects fire, identifies gas hazards, avoids structural obstacles, streams live video, and activates a water-based suppression mechanism without human presence in the danger zone.

The remainder of this paper is organized as follows: Section 2.1 reviews related literature; Section 2.2 describes the system architecture; Section 2.3 details the methodology; Section 2.4 presents results and discussion; Section 3 draws conclusions.

2. BODY OF PAPER

2.1 Literature Survey

Chen et al. [1] proposed a wheeled firefighting robot for indoor environments using an Arduino Mega and infrared flame sensors. While effective indoors, the platform did not address the gas detection or live-streaming requirements specific to tunnel scenarios. Sinha and Kumar [2] developed a gas-leak detection robot using MQ-2 and MQ-7 sensors mounted on a differential drive chassis, demonstrating accurate detection of LPG and CO concentrations. Their work, however, lacked any fire suppression capability.

Rao et al. [3] integrated an ESP32 microcontroller with an OV2640 camera to build a remote surveillance robot capable of Wi-Fi streaming. The authors validated real-time video quality over a 30-metre indoor corridor, analogous in communication challenges to a short tunnel segment.

Fernandez and Torres [4] examined obstacle avoidance strategies for confined-space robots using HC-SR04 ultrasonic sensors and a PID-based wall-following algorithm. Their results highlighted that ultrasonic sensing performs reliably in acoustically reflective environments such as concrete tunnels.

Waqas et al. [5] designed a fully autonomous firefighting robot using NodeMCU with MQTT-based telemetry, showing that low-bandwidth IoT protocols can sustain reliable command and sensor data exchange in Wi-Fi-shadowed areas. Collectively, the reviewed works establish the feasibility of the individual subsystems proposed in this paper, but none combines all of them into a unified tunnel-specific firefighting platform. The present work addresses this gap.

2.2 System Architecture

The proposed firefighting robot is built around a four-wheeled mobile chassis equipped with a two-tier aluminium frame. The lower tier houses the motor driver, battery, and water reservoir, while the upper tier carries the sensing and computing modules. Figure 1 presents the overall system block diagram.



Fig. 1: Tunnel Firefighting Robot Block Diagram

The NodeMCU ESP8266 serves as the primary microcontroller and network hub. It interfaces with the flame sensor, MQ-2 gas sensor, and ultrasonic sensor through its analogue and digital input/output pins. On detection of a hazard, it energises the appropriate relay channels to actuate the water pump and trigger an alert over Wi-Fi. The ESP32-CAM module is connected to the NodeMCU via a serial UART link and streams MJPEG video to a local access-point-hosted web server accessible from any browser-enabled device outside the tunnel.

Four 12V DC gear motors are controlled in pairs by an L298N dual H-bridge motor driver, receiving PWM signals from the NodeMCU to regulate speed and direction. Power is supplied by an 11.1 V, 2200 mAh LiPo pack through a 5 V buck converter for the logic circuitry and a direct 12 V rail for motors and the water pump. Table 1 lists all major hardware components and their specifications.



Table 1: Hardware Components and Specifications

Component	Function
Flame Sensor (IR)	Detects infrared radiation from open fire
MQ-2 Gas Sensor	Detects smoke, LPG, CO, combustible gases
Ultrasonic Sensor	Obstacle detection and distance measurement
NodeMCU (ESP8266)	Main controller; Wi-Fi enabled IoT module
ESP32-CAM	Live video streaming in tunnel environment
Relay Module (5V)	Switches water pump and motor power
DC Water Pump	Sprays water upon fire detection
L298N Motor Driver	Controls differential drive DC motors
DC Gear Motors (×4)	Robot chassis locomotion in tunnel
LiPo Battery Pack	Portable power supply for all modules

2.3 Methodology

The operational workflow of the robot follows a continuous sensing-decision-actuation loop executed by the NodeMCU firmware. During normal navigation, the ultrasonic sensor samples the forward distance at 10 Hz. If the measured distance falls below a configurable threshold (default: 25 cm), the motor driver is commanded to halt and reverse before re-routing around the obstacle, implementing a simple reactive collision avoidance behaviour suitable for the corridor-like geometry of a tunnel.

The flame sensor outputs a logic LOW when infrared radiation characteristic of an open flame is detected within its 60° field of view. Simultaneously, the MQ-2 sensor provides an analogue voltage proportional to the ambient concentration of combustible gases. The NodeMCU's ADC samples this voltage at 5 Hz and applies a moving-average filter to reject transient noise. If the filtered reading exceeds a calibrated threshold corresponding to 300 ppm of smoke or LPG equivalent, the system issues a gas hazard alert over the Wi-Fi serial stream and reduces robot speed to approach the hazard cautiously.

illustrates the firmware state machine. The robot operates in one of four states: NAVIGATE, AVOID_OBSTACLE, APPROACH_FIRE, and SUPPRESS. Transitions are governed by sensor readings and a priority hierarchy in which fire detection overrides obstacle avoidance, and gas detection triggers speed reduction regardless of current state. Upon entering SUPPRESS state, the NodeMCU asserts the relay control pin HIGH, energising the water pump relay coil and opening the solenoid valve on the pump output line. The pump continues to operate until the flame sensor reports no detection for a sustained 3-second window, after which the system reverts to NAVIGATE state.

The ESP32-CAM operates an autonomous MJPEG streaming server on port 80. The NodeMCU wakes the camera module via a GPIO signal upon entering APPROACH_FIRE state, allowing remote operators to confirm fire conditions visually before committing suppression resources. All sensor data, robot state, and GPS-tagged timestamps are published to an MQTT broker running on a local Raspberry Pi acting as the tunnel edge server, providing a persistent log for post-incident analysis.

2.4 Results and Discussions

The prototype was evaluated in a controlled tunnel mock-up of 6 m length and 1.2 m width, constructed from hollow concrete blocks to replicate realistic acoustic and electromagnetic reflectivity. Candle-based test flames and commercially available smoke cartridges were used as controlled fire and smoke sources, respectively, in compliance with laboratory safety regulations.

Flame detection tests conducted at distances ranging from 20 cm to 80 cm showed a 100% detection rate up to 60 cm with zero false positives. Beyond 60 cm, detection rate dropped to 78% due to the diverging cone of the sensor and ambient IR noise from the fluorescent lighting used in the test corridor. MQ-2 smoke detection achieved an average response time of 2.1 seconds from cartridge actuation to relay trigger at a 400 ppm equivalent setting. The suppression loop (flame detection to pump activation) showed an end-to-end latency of 4.2 ± 0.6 seconds across ten repeated trials.

Obstacle avoidance performance was quantified by navigating the robot through a 6 m corridor containing three randomly placed 30 cm $\times$ 30 cm cardboard box obstacles. Across twenty runs, the robot successfully avoided all obstacles in 18 runs (90% success rate), with the two failures attributable to obstacles placed at acute angles outside the 15° beam half-angle of the HC-SR04 sensor. The ESP32-CAM delivered a stable MJPEG stream at 640 $\times$ 480 resolution and approximately 8 frames per second over a 10 m Wi-Fi link,

confirmed sufficient for operator situational awareness. Figure illustrates the assembled robot deployed in the test tunnel.

Fig. 3: Prototype Robot Inside Test Tunnel Mock-up

Power consumption analysis showed an average draw of 1.8 A at 11.1 V during combined navigation and streaming, yielding an estimated operational endurance of approximately 68 minutes on the 2200 mAh battery pack before suppression actuation. When the water pump was active, peak current rose to 4.1 A, reducing the operational window to roughly 28 minutes under continuous pumping. These figures are consistent with practical deployment requirements for sub-kilometre tunnel segments.

3. CONCLUSIONS

This paper presented the design, implementation, and experimental validation of an autonomous firefighting robot tailored for tunnel environments. The system successfully integrates flame sensing, MQ-2-based smoke and gas detection, ultrasonic obstacle avoidance, NodeMCU-driven wireless control, ESP32-CAM live video streaming, and relay-actuated water pump suppression into a single compact mobile platform. Key performance metrics — an average end-to-end suppression response time of 4.2 seconds, 100% flame detection up to 60 cm, 90% obstacle avoidance success, and stable 8 fps video streaming — confirm the practical utility of the platform.

The proposed robot reduces the need for human entry into hazardous tunnel fire zones, thereby safeguarding emergency personnel. Future enhancements will explore the integration of LiDAR-based mapping for autonomous long-range tunnel navigation, incorporation of a CO sensor (MQ-7) for improved gas classification, deployment of a mesh Wi-Fi backbone to extend operational range beyond single access-point coverage, and the use of thermal imaging to locate fire zones through dense smoke where optical flame sensors become unreliable.

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