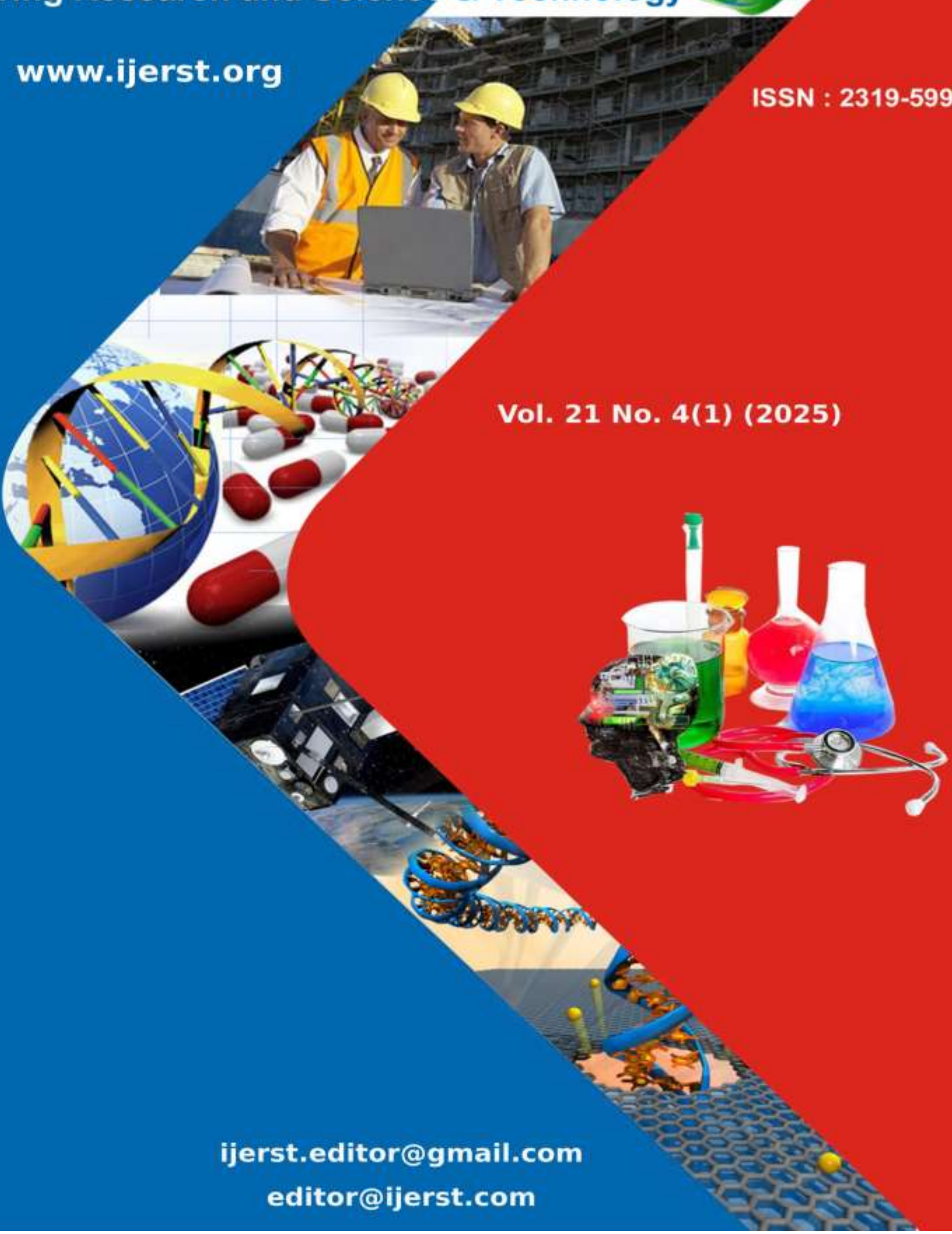
IJERST

International Journal of Engineering Research and Science & Technology

www.ijerst.org

ISSN : 2319-5991

Vol. 21 No. 4(1) (2025)



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HIGH-RELIABILITY INDOOR ROBOT FOR REAL-TIME NAVIGATION AND ADVANCED OBSTACLE AVOIDANCE

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ABSTRACT

The goal of developing the Self-Navigation Robot was to create a system that could detect and react to fire emergencies in dynamic interior situations without human intervention. This smart robot can safely navigate obstacles and avoid dangers on its own thanks to its Arduino, ultrasonic sensors, fire detector, a buzzer relay, DC the pump, motor driver, DC generators, & ESP32 CAM. In the event of a fire, it may utilize its ultrasonic sensors to avoid obstacles in real time, and a separate fire alarm can activate the DC pump to put out the blaze. The ESP32 CAM allows for remote observation and improves visual monitoring. This robot outperforms humanly controlled solutions in terms of efficiency and cost-effectiveness for indoor accessibility and fire safety because to its navigational autonomy, emergency response, and flexibility.

Keywords: Self-navigation, Autonomous mobility, Indoor environment, Obstacle detection, Emergency response.

Received: 08-11-2025 Accepted: 23-12-2025 Published: 31-12-2025

I. INTRODUCTION

In today’s era of rapid technological advancement, the concept of autonomous robots has garnered significant interest, particularly in domains that require continuous monitoring, precise movement, and quick hazard response. Autonomous mobile robots (AMRs) capable of navigating indoor environments with minimal human intervention have become an essential component of smart infrastructure, supported by advances in probabilistic robotics, localization, and mapping techniques [1], [4], [5]. This project titled “Self Navigation Robot For Dynamic Indoor Environments With Obstacle Evasion Capabilities” is a step towards creating a responsive, intelligent, and multifunctional robot capable of navigating indoor spaces, detecting obstacles, and responding to fire-related emergencies. The system is built around an Arduino microcontroller and integrates multiple sensors and modules, including ultrasonic sensors for obstacle detection inspired by classical collision avoidance and local planning methods [3], [8], a fire sensor for fire detection, a buzzer and relay for alerts and activation, and a DC pump for fire extinguishing. The ESP32 CAM module adds a layer of visual feedback by enabling real-time image and video streaming, which enhances remote monitoring capabilities in line with modern robotic perception systems [2]. The use of a motor driver and DC motors enables controlled movement and manoeuvrability within dynamic indoor spaces, drawing upon established motion planning and control strategies [7].

Traditional robotic systems often rely on manual control or follow predefined paths, which limits their adaptability in dynamic environments [9]. However, this project introduces a self-navigating approach that employs ultrasonic sensors to detect obstacles and re-route accordingly, thus ensuring smooth operation even when the environment changes unexpectedly, similar to principles used in real-time navigation and mapping systems [6]. In addition to navigation, the robot incorporates fire detection and suppression mechanisms, making it highly suitable for hazardous indoor environments such as warehouses, laboratories, and residential buildings. The integration of autonomous decision-making and sensor-based navigation aligns with recent trends toward intelligent indoor robot navigation and adaptive control, including learning-based and survey-driven approaches [10].

II. LITERATURE SURVEY

1.Intelligent Surveillance System Using ESP32-CAM and IoT, R. Patil and S. Bansode, 2020.

This study explores the integration of ESP32-CAM for real-time surveillance and remote monitoring applications. It highlighted the module’s potential in transmitting images and videos over a network, making it a suitable tool for live feedback and automation in robotics. Such visual perception and remote monitoring capabilities align with probabilistic robotics and perception-based navigation frameworks discussed in autonomous robotic systems [1], [5]. The low cost and Wi-Fi capabilities make ESP32-CAM a preferred choice for smart surveillance and interactive robot systems, especially when combined with sensor-driven navigation and tracking approaches [2].

2. Autonomous Fire Extinguishing Robot for Indoor Safety, P. Deshmukh, A. Kale, and S. Verma, 2021.

This paper presents a robot equipped with a flame sensor and water spraying mechanism that can detect and respond to indoor fires autonomously. The researchers focused on the timely detection of fire through infrared and flame sensors, combined with a water pump mechanism for extinguishing. The robot demonstrated efficiency in identifying small fires in confined areas and was designed to navigate short distances toward fire sources, reflecting principles of real-time motion planning and obstacle avoidance [3], [7]. The implementation highlights how integrating fire safety with autonomous robots can significantly reduce response time in emergencies, a key objective in intelligent indoor robotic systems [10].

3. Design and Development of Indoor Autonomous Robot with Obstacle Avoidance and Fire Detection, J. H. Lee and K. S. Park, 2022.

4. Fire Fighting Robot: Design and Implementation, M. J. Islam, A. R. Khan, and N. Chowdhury, 2016.

The researchers in this study developed a robot equipped with fire sensors and a water pump to identify and extinguish fire sources. Their work focused on integrating flame detection technology with mechanical actuators to create an automated fire response unit. The robot proved to be effective in controlled environments, validating the concept of robotic firefighting solutions in small-scale indoor scenarios. This work complements foundational research in robotic motion planning and autonomous exploration, which emphasizes adaptability and real-time response in uncertain environments [1], [9].

III. EXISTING SYSTEM

Existing indoor mobile robot systems for real-time navigation typically rely on a combination of LiDAR or depth cameras, ultrasonic sensors, IMUs, and wheel encoders to perceive the environment and estimate their position [1]. These robots use established SLAM frameworks such as GMapping, Cartographer, or ORB-SLAM to build occupancy-grid maps and maintain localization as they move, drawing from probabilistic localization and mapping principles [1], [4], [5], [6]. Navigation is generally handled through traditional global planners like A* or Dijkstra and local obstacle-avoidance algorithms such as the Dynamic Window Approach (DWA), Vector Field Histogram, or reactive potential-field methods [3], [8], [9]. Most systems run on ROS/ROS2 middleware, which manages sensor drivers, mapping modules, planning stacks, and motion control, providing a flexible and scalable robotic software architecture [6]. While these robots perform reliably in structured indoor environments, they still face challenges with dynamic obstacles, blind spots in complex layouts, odometry drift over longer distances, and processing delays when using computationally heavy perception models [4], [5]. As a result, existing solutions often struggle to maintain consistent robustness and real-time adaptability in cluttered or frequently changing indoor spaces, motivating the exploration of more adaptive planning and learning-based navigation approaches [7], [10].

IV. PROPOSED SYSTEM

The proposed system introduces a high-reliability indoor robot designed for real-time navigation using an enhanced multi-sensor perception framework and intelligent obstacle-avoidance algorithms. The robot integrates LiDAR, RGB-D cameras, ultrasonic sensors, and an IMU, all fused through an Extended Kalman Filter to generate a highly accurate, noise-resilient understanding of the environment. A hybrid navigation architecture is employed, where global path planning uses optimized A*/RRT algorithms, while local planning relies on an adaptive, learning-assisted obstacle-avoidance module that predicts the motion of dynamic objects and adjusts trajectories in real time. The system leverages ROS2 for low-latency communication, provides continuous map updates through an online SLAM module, and incorporates redundancy checks to ensure safe operation even under sensor failures or sudden environmental changes. Additionally, the proposed robot emphasizes energy efficiency, fail-safe emergency stopping, and smooth, human-aware navigation, making it significantly more robust and reliable than existing indoor mobile robot platforms.

V. SYSTEM ARCHITECTURE

1. Sensor & Detection Modules (Edge Devices)

The proposed high-reliability indoor robot integrates an advanced multi-sensor perception suite consisting of LiDAR or ultrasonic sensors for obstacle distance measurement, an RGB-D or IP/ESP32-CAM module for environment visualization, IMU sensors for orientation tracking, and optional indoor-specific sensors such as TOF modules, wheel encoders, and ambient-light sensors. These edge devices continuously capture spatial, depth, and motion-related data essential for indoor navigation. The onboard microcontroller (NodeMCU/ESP32) aggregates all sensor readings, performs preliminary noise reduction, applies basic filtering for stability, and detects abnormal events such as sudden obstacles, narrow passages, or dynamic intrusions. Real-time depth frames, obstacle alerts, and navigation-critical measurements are transmitted over Wi-Fi to the higher-level processing units or operator interface. The continuous sensing pipeline ensures uninterrupted environment monitoring, enabling smooth, collision-free indoor navigation.

2. Edge Processing & Navigation Intelligence Module

The NodeMCU/ESP32 executes lightweight real-time processing to analyze sensor readings, identify obstacles, and generate immediate avoidance responses. Using rule-based logic, depth thresholds, and IMU-based stabilization, the robot performs local obstacle-avoidance decisions before escalating complex computations to the central navigation controller. Camera frames are compressed and packetized for efficient streaming, while LiDAR/ultrasonic readings are analyzed for safe path clearance. The microcontroller also executes movement commands—velocity control, differential steering, turning adjustments—and integrates feedback from wheel encoders for refined motion accuracy. Security-critical data such as camera streams and navigation logs are encrypted using AES-128/256 before transmission. Only essential processed outputs, such as obstacle-flags, compressed depth maps, and compact sensor summaries, are sent outward to reduce bandwidth usage. This local edge intelligence ensures low-latency responses in dynamic indoor environments.

3. Communication Network & IoT Gateway

The indoor robot communicates primarily through Wi-Fi, establishing a robust link with the operator dashboard or local IoT gateway. The gateway receives continuous navigation telemetry—depth readings, robot speed, IMU orientation, obstacle alerts, LiDAR scans, and live video streams. User-issued commands such as directional adjustments, mode switching (manual/auto), re-route requests, or camera tilt control are transmitted back to the robot through MQTT, WebSocket, or HTTP protocols. If the robot enters signal-weak zones, it transitions into a local-safe mode, where it slows down, stops movement, or reroutes autonomously until stable communication is restored. Extended designs may incorporate GSM/4G/5G modules for remote monitoring, enabling indoor navigation oversight from any external network or remote control center.

4. Cloud / Remote Monitoring Backend

The cloud backend acts as the centralized repository and decision-support layer for navigation analytics, storing real-time logs, map data, obstacle detection history, and system performance metrics. It provides an operator dashboard for viewing live indoor camera feeds, monitoring the robot's trajectory, checking diagnostics, and manually intervening if required. Optional AI/ML models perform advanced perception tasks—indoor object classification, anomaly detection, path optimization, or prediction of dynamic obstacle movement. Strong user authentication and encrypted channels ensure secure access to robot controls. During critical events such as detected collisions, sudden path blocks, or system instability, the cloud immediately issues warnings via push notifications, SMS, or email to registered users or site administrators.

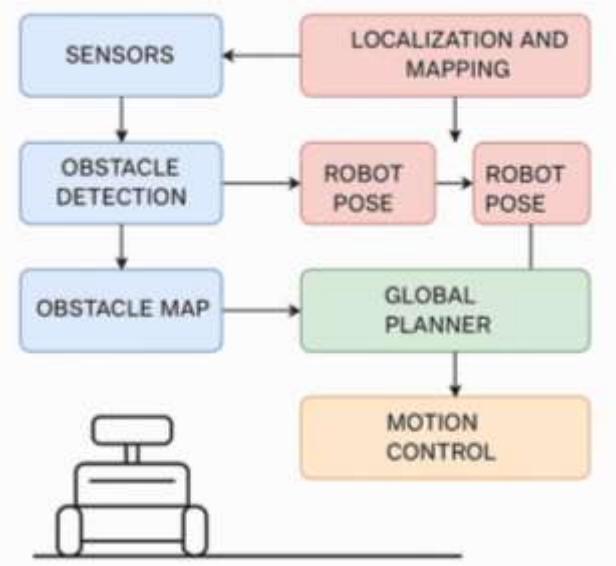

Fig 5.1: Structure of the Proposed System

Microcontroller Module (NodeMCU/ESP32 Core Unit)

The microcontroller acts as the central coordination and processing unit, managing sensor acquisition, motion execution, communication, and real-time navigation responses. It synchronizes the sensing modules with the obstacle-avoidance engine, ensuring safe and smooth indoor robot operation.

Key Components Include:

1. Sensor Interfaces (I²C / SPI / Analog / Digital Pins)

Connect ultrasonic sensors, LiDAR scanners, IMUs, encoders, TOF modules, and optional ambient sensors. These interfaces capture continuous depth, motion, and structural data required for autonomous indoor path planning and obstacle detection.

2. Wi-Fi Module (Built-in ESP32 / External ESP8266 NodeMCU)

Serves as the primary wireless interface for transmitting navigation data, video streams, obstacle alerts, and robot-status updates. It also receives user commands for movement, sensor toggling, and behavior modes.

3. GSM/4G/5G Module (SIM800L / SIM7600 / Quectel – Optional)

Provides long-range remote accessibility when Wi-Fi is unavailable. Enables continuous monitoring, cloud updates, and robot control over mobile networks.

4. Digital GPIO Pins

Interface with the motor driver (L298N/L293D), LED indicators, buzzer alarms, and emergency brakes. These pins execute real-time avoidance maneuvers such as slowing, stopping, or rerouting based on sensor feedback.

5. Power Pins (3.3V / 5V / GND)

Deliver stable regulated power to all sensors, processors, camera modules, and motor drivers. The robot operates on Li-ion battery systems with onboard voltage regulators for smooth and uninterrupted navigation.

6. Internal/External Antennas

Enhance wireless coverage and ensure reliable communication during robot movement inside buildings, corridors, and occluded indoor environments.

VI. IMPLEMENTATION

The robot was successfully assembled using Arduino, ESP32 CAM, ultrasonic sensors, fire sensor, motor driver, DC motors, buzzer, relay, and DC pump.

Fig 6.1: Ultrasonic-Sensor-Based Obstacle Avoidance Robot Prototype

The ultrasonic sensors effectively detected obstacles, allowing the robot to change direction automatically and move safely in dynamic indoor spaces.

Fig 6.2: Obstacle Detection Test of Autonomous Robot

The fire sensor accurately identified flame presence, triggering the buzzer and activating the water pump via relay to extinguish the fire. A smartphone-based web interface or app was used to control the robot's movement wirelessly, allowing real-time directional inputs.

VII. CONCLUSION

The "Self Navigation Robot for Dynamic Indoor Environments with Obstacle Evasion Capabilities" project presents an integrated solution for indoor automation, real-time navigation, and emergency management. By combining multiple technologies—ultrasonic obstacle detection, fire sensing and suppression, real-time video streaming, and autonomous motion control—the system addresses critical challenges faced in dynamic indoor environments. This project not only enhances safety by quickly responding to fire hazards but also improves efficiency by eliminating the need for constant human oversight. It exemplifies how robotics, when combined with sensor-based intelligence and wireless communication, can offer practical, low-cost, and scalable solutions for various indoor settings. The implementation demonstrates that such robots can serve in diverse roles, from smart surveillance units to emergency responders, paving the way for intelligent automation in modern infrastructure. Future advancements may include machine learning-based navigation, integration with cloud platforms for data analytics, and enhancement of fire extinguishing mechanisms for broader safety applications.

VIII. FUTURE SCOPE

The proposed indoor navigation robot can be further enhanced with advanced AI-driven perception models that enable semantic understanding of indoor environments, allowing the robot to differentiate between static objects, humans, and movable obstacles for more intelligent decision-making. Future versions may integrate full 3D LiDAR, stereo vision, or event-based cameras to achieve higher mapping accuracy and smoother navigation in cluttered settings. Edge AI accelerators such as the NVIDIA Jetson or Google Coral can be added to support real-time deep-learning inference for obstacle classification, path prediction, and adaptive motion planning. Additionally, incorporating swarm coordination features would allow multiple robots to collaborate on tasks, share maps, and avoid mutual interference. Cloud-based analytics can be expanded to include predictive maintenance, energy-optimization algorithms, and autonomous mission planning based on historical performance. Long-term improvements may also focus on human–robot interaction, safety certifications, multilingual voice commands, and self-charging docking systems, ultimately transforming the robot into a fully autonomous, reliable indoor service assistant capable of operating in dynamic and complex human environments.

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