

Design and Development of an ESP32-Based Autonomous Office Logistics Robot

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Abstract: This paper presents the design, development, and implementation of a cost-effective, autonomous indoor mobile robotic platform developed for intra-office logistics and material handling. Built around the high-performance ESP32 microcontroller, the system integrates infrared (IR) reflectance sensors to perform real-time path tracking over a predefined high-contrast indoor track. To ensure operational safety and collision avoidance within a dynamic workplace environment, a front-mounted IR obstacle detection sensor is paired with an active audible buzzer alert framework. The robot features dual-core processing capabilities and establishes stable Wi-Fi connectivity to integrate with the Blynk IoT cloud platform, allowing seamless transitioning between autonomous line-following mode and remote manual override control via a web or mobile application dashboard. Power regulation is managed through an efficient LM2596 step-down buck converter to supply steady voltage levels from a rechargeable lithium-ion battery package. Experimental evaluation demonstrates robust line detection, stable torque control via an L298N motor driver, and reliable hazard mitigation, showcasing a highly viable solution for modern automated office workflows.

Keywords: Autonomous Mobile Robot, ESP32 Microcontroller, Office Automation, Path Tracking, Internet of Things (IoT), Obstacle Avoidance.

I. INTRODUCTION

Automation and robotics play a significant role in improving efficiency, accuracy, and productivity in various environments, especially in indoor service applications [1]. An office BOT is one such intelligent system designed to navigate along a predefined path using color contrast detection [2]. Typically, a black line is laid on a white surface or vice versa, and infrared sensors are used to detect the reflected light from the surface to determine the robot's path [3]. When the robot deviates from the line, corrective steering actions are taken to realign the movement, ensuring continuous and stable navigation [4].

Modern line-following robots incorporate microcontrollers for real-time data processing and decision-making [5]. In this project, an ESP32-based controller manages the sensing and motor control processes, enabling efficient path tracking and mobility [6]. Additionally, an obstacle detection sensor is integrated to stop the robot when an obstruction is found, thereby enhancing safety and operational reliability [7]. The system is further supported by a buzzer that provides audible alerts during obstacle encounters or for status indication [8]. This autonomous platform is designed as a cost-effective and practical solution for office tasks such as material transport, guided movement, and automated services, contributing to smart indoor assistance and workflow optimization [9].

II. LITERATURE SURVEY

Office BOTs have gained considerable attention in both academic research and industrial automation due to their simplicity, efficiency, and wide applicability in navigation-based robotic systems [10]. Many researchers have explored

the use of infrared (IR) reflectance sensors for detecting black-and-white path contrasts, as black surfaces absorb IR light while white surfaces reflect it [11]. This principle enables precise path tracking when the sensors are positioned close to the ground surface [12]. Reliable sensor placement, spacing, and height are crucial for improving line detection accuracy, especially in curved or narrow track conditions [13].

Microcontrollers are commonly used for processing sensor data and controlling motor actions based on the detected

path [14]. Early systems often relied on basic logic gate circuits, which were limited in accuracy and speed [15]. Modern advancements have introduced efficient embedded controllers such as AVR, Arduino, and ESP-based systems to enhance real-time control, decision-making, and system performance [16]. Motor driver modules like L298N are widely used to interface low-power control signals with higher-power DC motors, enabling smooth bidirectional motion control [17]. Several existing designs focus on optimizing sensor configuration, motor control strategies, and algorithm performance to ensure smooth turns, reduced error, and stable movement [18]. Recent studies have also incorporated additional features such as obstacle detection, speed control using PWM, and IoT connectivity for monitoring and automation [19]. These developments highlight the increasing necessity of cost-effective, reliable, and smart navigation robots for applications in logistics, education, security, and smart office environments [20].

III. PROJECT NEED ANALYSIS

A. Background

With the growing demand for automation in workplaces, the role of intelligent robots has expanded to improve efficiency and reduce human workload [1]. Line-following robots are widely used in indoor environments due to their ability to navigate predefined routes autonomously [2]. By using infrared sensors to detect contrasting lines and motor drivers to control movement, such robots can effectively move along corridors and pathways without human intervention [3]. Recent advancements in microcontrollers and IoT connectivity have enhanced the functionality, accuracy, and practical usability of these systems in real-time operations [4].

B. Problem Statement

In many office and industrial spaces, routine tasks such as document handling, item delivery, and basic material transportation still rely on human effort, leading to reduced productivity and time inefficiency [1]. Commercial robotic solutions are often expensive and complex for small-scale environments [2]. Therefore, there is a need for a cost-efficient and reliable robotic system capable of autonomously following a predefined path while detecting and avoiding obstacles [3]. The proposed system addresses this need by integrating real-time line detection, safety alert mechanisms, and IoT monitoring for improved indoor automation [4].

C. Objectives

The primary objective of this project is to design and develop a smart autonomous line-following robot equipped with obstacle detection and IoT connectivity for indoor navigation [1].

The detailed objectives for each major component are as follows [2]:

- **Infrared Sensors (Line Detection):** To accurately detect the black line path based on reflectivity differences between black and white surfaces, and to continuously monitor the robot's position relative to the track to provide real-time data for path correction [3].
- **ESP32 Microcontroller (Control and Processing Unit):** To process sensor inputs and execute the control logic for smooth navigation [4]; to manage switching between AUTO mode (line following) and MANUAL mode (IoT remote control) [5]; and to establish Wi-Fi connectivity and interface with Blynk IoT for monitoring and control [6].
- **L298N Motor Driver (Motion Control):** To drive the DC motors in forward, reverse, left, and right directions based on microcontroller commands while enabling reliable and safe distribution of motor power with isolation from control circuits [7].
- **DC Gear Motors & Wheels (Mobility System):** To provide efficient locomotion with stable speed and maneuverability on indoor surfaces, enabling smooth directional control while turning on curves or sharp corners [8].
- **Obstacle Detection Sensor:** To detect obstacles in the robot's path and stop the movement automatically to prevent collision, thereby enhancing safety and reliability during autonomous navigation [3].
- **Buzzer Alert System:** To provide an audible alert during obstacle detection and operational warnings, and to indicate robot status visually/audibly for debugging and user awareness [4].
- **Power Supply System (Li-ion Battery + DC-DC Converter):** To supply stable and regulated power to both motors and control circuits, ensuring long operational time and safe power management for portable use [5].
- **Blynk IoT Dashboard (Monitoring & Control):** To remotely monitor sensor status and robot state from a mobile or web application, allowing manual override control via Wi-Fi for improved usability and automation flexibility [6].

D. Scope

This project focuses on the design, development, and testing of a line-following robot that operates on a predefined path within indoor environments [1]. The scope includes hardware integration of sensors, motors, battery supply, and microcontroller, along with software implementation for automatic control and IoT features [2]. The project does not involve dynamic path planning, outdoor navigation, heavy load carrying, or advanced artificial vision-based tracking [3]. However, the system can be upgraded in the future with additional sensors and communication features [4].

E. Applications

The developed robotic system can be deployed in a wide range of areas where repetitive path-based movement is needed [1]. Potential applications include [2]:

- Office document and stationery delivery system [3].
- Hospital assistance for distributing medicines and supplies [4].
- Automated guidance system in public buildings [5].
- Warehouse material handling and inventory support [6].
- Smart home automation and educational robotics learning [7].
- Autonomous service robot for malls and institutions [8].

IV. SYSTEM DESIGN METHODOLOGY

A. Block Diagram Explanation

The overall system integrates multiple sensing, control, and actuation components to achieve autonomous navigation [1]. The infrared sensors continuously scan the surface to detect the black line by identifying changes in reflectivity [2]. The sensed signals are given to the ESP32 microcontroller, which processes the input and generates appropriate control signals to the L298N motor driver [3]. The motor driver controls the speed and direction of the DC motors for forward, left, right, and stop movements [4]. An obstacle detection sensor is placed at the front to ensure collision prevention by stopping the robot and activating the buzzer when an object is detected [5]. The ESP32 also connects to the Blynk IoT platform for remote monitoring and manual override control via Wi-Fi, enabling control through a web or mobile dashboard [6]. The robot is battery-powered and regulated through a DC-DC converter for stable operation [7].

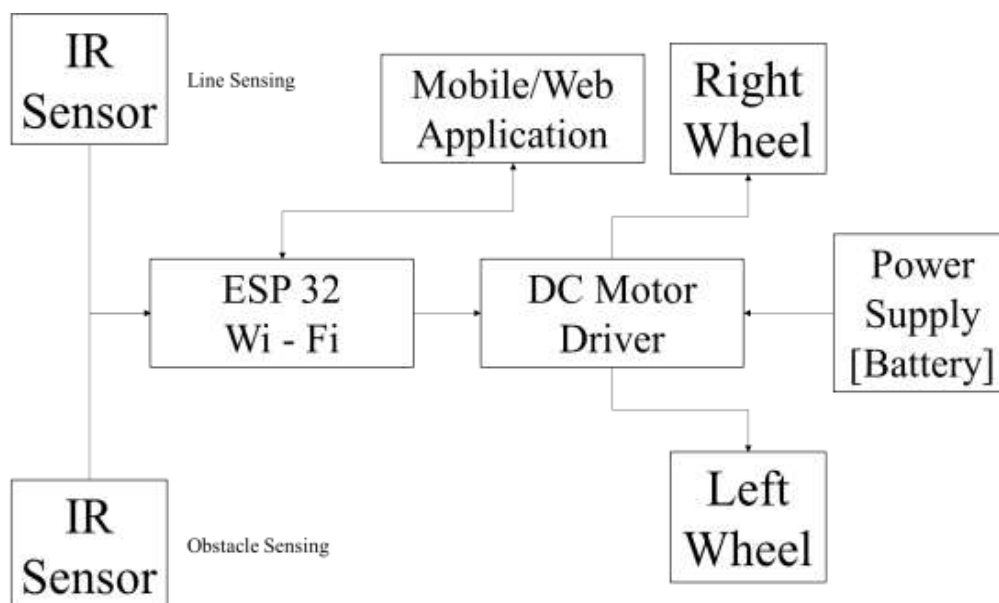


Figure 1 Block Diagram Architecture.

B. Working Principle

The robot follows a black path on a white surface using IR reflectance principles: black absorbs infrared light while white reflects it [1]. Each IR sensor outputs a digital signal indicating whether it is over black (LOW) or white (HIGH) [2]. When both sensors detect black, the robot moves forward; when only one sensor detects black, the robot takes corrective turns to align itself back to the track [3]. If both sensors detect white, the robot stops momentarily assuming the line is lost [4]. The obstacle sensor ensures safety by stopping the robot and triggering an alert via buzzer [5]. In manual mode, commands from the Blynk Dashboard override automatic navigation and control the robot remotely [6].

C. Hardware Architecture

The hardware architecture consists of the following integrated modules [1]:

ESP32 Microcontroller: Serves as the central processing unit. It receives input from sensors, processes logic for automatic navigation, controls motor actions, and manages Wi-Fi-based IoT communication [1]. It features dual-core processing, integrated WLAN, multiple GPIO pins, and low power consumption [2].



Figure 2 ESP32 Module

IR Sensors: Mounted at the bottom of the chassis near the track [3]. They detect the difference between black and white surfaces based on infrared reflection [4]. Black color absorbs IR resulting in a LOW output, whereas a white surface reflects IR resulting in a HIGH output [5].



Figure 3 IR Module

L298N Motor Driver Module: The dual H-bridge motor driver provides the required current and voltage to the DC motors based on the control signals from the ESP32 [6]. It supports forward, reverse, and turning operations while isolating the microcontroller from high-power circuits [7].



Figure 4 L298N Driver Module

LM2596 DC-DC Buck Converter (HW-411): Used to convert a higher DC voltage into a stable lower DC voltage with high efficiency [8]. It reduces the lithium-ion battery voltage (typically 7.4V-8.4V from two 18650 cells) to a regulated 5V output required for powering the ESP32 microcontroller and sensors [9]. It supplies continuous output current up to 3A [10].



Figure 5 LM2596 DC-DC Buck Converter Module

DC Motors and Wheels: Provide the required torque and movement for robot mobility [11]. The geared mechanism helps maintain constant speed, smooth turns, and stability during tracking [12].



Figure 6 DC Motor

Buzzer: Integrated for alert and status indication. It produces audible warnings during obstacle detection and can also be manually controlled from the IoT dashboard for testing purposes [13].

D. Program Code Logic and Explanation

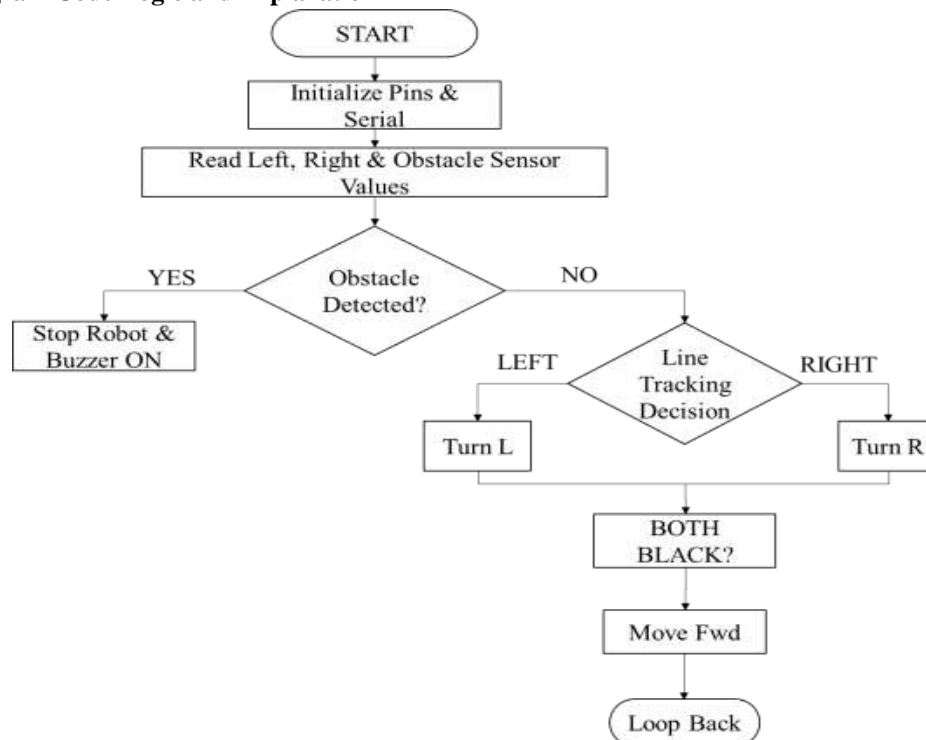


Figure 7 Flow chart

The software is developed using the Arduino IDE with Blynk IoT integration [1]. The flow begins with the initialization of pins, Wi-Fi connection, and sensor calibration [2]. Based on the selected mode, the operations execute as follows [3]:

- **AUTO Mode:** Robot performs real-time line detection, executes movement logic, monitors obstacles, and stops if a hazard is detected [4].
- **MANUAL Mode:** Receives user input commands from Blynk dashboard, prioritizes manual control, and executes motor actions accordingly [5].

The control firmware continuously reads data from the left, right, and front IR sensors to determine the position of the line and detect any obstacles in the robot's path [1]. Based on the sensor inputs, the program compares the readings and decides the robot's movement direction [2]. When both sensors detect the black line, the robot moves forward [3]; if

only one sensor detects the line, it performs a corrective turn toward that side [4]; and if the line is completely lost, the robot stops to avoid moving off the track [5].

The system also includes an obstacle detection feature where the robot immediately halts and activates the buzzer when an object is detected by the front IR sensor [6]. Additionally, the hardware parameters and real-time sensor values are piped to the serial output for debugging and monitoring purposes [7]. The executive loop ensures that all these operations are executed repeatedly, enabling continuous line following and smooth autonomous navigation [8].

E. Mechanical Design

The robot is built on a lightweight chassis to reduce energy consumption and improve speed [1]. A three-wheel configuration is used: two rear wheels directly driven by DC motors and a front caster wheel for better maneuverability [2]. Sensors are mounted close to the ground (2-10 mm) for accurate detection [3]. Proper component placement ensures weight balancing and minimizes vibration for smooth tracking [4].

F. Control Algorithm

The algorithmic implementation for Line Following and Obstacle Avoidance operates through the following sequence [1]:

1. Start the system [2].
2. Initialize sensors, motors, and Wi-Fi connectivity [3].
3. Read IR sensor and obstacle sensor signals continuously [4].
4. If obstacle is detected: halt vehicle execution, activate buzzer alert [5].
5. If AUTO mode is selected [6]:
 - If both sensors detect black: Move forward [7].
 - If left sensor is black & right sensor is white: Turn left [8].
 - If right sensor is black & left sensor is white: Turn right [9].
 - If both sensors detect white: Stop temporarily [10].
6. If MANUAL mode is selected [11]:
 - Execute movement based on Blynk switch dashboard commands [12].
7. Repeat steps continuously [13].

V. HARDWARE IMPLEMENTATION

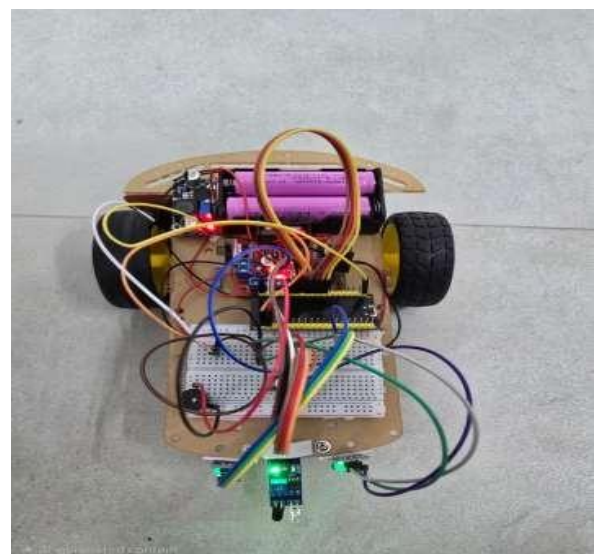
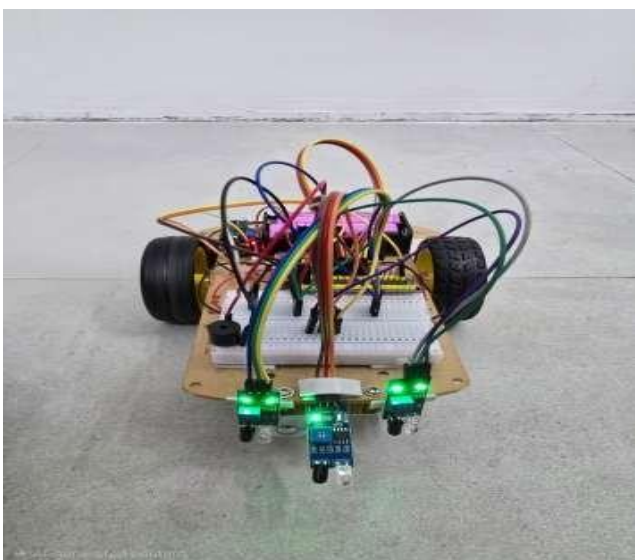


Figure 8 Hardware Setup

The proposed hardware implementation consists of an autonomous obstacle avoidance robotic system integrated with a microcontroller, IR sensors, motor driver module, DC geared motors, and a rechargeable battery unit. The front-

mounted IR sensors continuously monitor the surrounding environment and detect obstacles in real time. Based on the sensor feedback, the microcontroller processes the input signals and generates appropriate control commands to the motor driver for directional movement. The dual DC motors enable smooth forward, reverse, left, and right navigation of the robot. A compact chassis structure securely accommodates all hardware components, ensuring stability and efficient operation. This implementation provides a reliable and cost-effective solution for intelligent robotic navigation and automation applications.

VI. RESULTS AND DISCUSSION

The developed line-following robot successfully performs autonomous navigation along a predefined black line path using IR sensors [1]. During testing, the robot demonstrated accurate line detection and quick correction when deviating from the track [2]. When both sensors detected the line, the robot moved smoothly in the forward direction, while individual sensor activation resulted in precise left or right turning actions [3].

The obstacle detection feature worked effectively, stopping the robot immediately when an object was placed in front and activating the buzzer as an alert mechanism [4]. The internal registers and runtime flags confirmed that real-time sensor readings and control decisions were executed correctly [5]. The system remained stable during long-duration operation and maintained consistent movement even on curved paths, provided the track contrast was clear [6]. The power supply system delivered a reliable voltage level to the ESP32 and sensors, ensuring uninterrupted performance [7]. Overall, the robot met the expected design outcomes by successfully integrating sensing, processing, control, and safety functionalities to achieve autonomous line following with obstacle avoidance [8].

VII. CONCLUSION

The design and development of the autonomous line-following robot with obstacle detection were successfully completed [1]. The system integrated IR sensors, an ESP32 microcontroller, a motor driver, and a buzzer to achieve efficient path tracking and safe navigation [2]. The robot accurately followed a predefined black line and demonstrated quick correction when deviating from the track [3]. The obstacle detection mechanism ensured safety by stopping the robot and providing an alert when any object obstructed its path [4]. The implementation proved to be reliable, cost-effective, and well-suited for indoor environments such as offices and institutions where repetitive path-based movement is required [5].

Through experimental evaluation, the robot exhibited stable performance, real-time responsiveness, and efficient power usage [6]. The project objectives were met by successfully achieving autonomous navigation and safety enhancement [7]. This work contributes toward the development of low-cost service robots and establishes a foundation for future enhancements in smart automation systems [8].

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