Development of Line Follower and Ultrasonic NodeMCU ESP8266 Motor Shield

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Abstract
This project details the design, implementation, and optimization of a low-cost, autonomous mobile robot that integrates dual functionalities: line-following and ultrasonic obstacle avoidance. The system utilizes a NodeMCU ESP8266 microcontroller as its central processing unit, interfaced with an L298N motor shield for precise bidirectional control of two DC gear motors. For navigation, an array of three TCRT5000 infrared reflectance sensors is employed to track a high-contrast black line on a white surface. Concurrently, an HC-SR04 ultrasonic sensor provides real-time obstacle detection to enable avoidance maneuvers. A primary challenge addressed is the optimization of TCRT5000 sensor performance, where empirical testing revealed that a critical mounting height of 10–12 mm is essential to prevent signal saturation and ensure reliable differential detection between the line and the background.

1. Introduction

The development of autonomous mobile robots has seen significant advancement with the integration of low-cost sensors and microcontrollers, enabling applications ranging from industrial automation to educational robotics. Line-following and obstacle-avoidance represent two fundamental capabilities in autonomous navigation, often implemented using infrared reflectance sensors and ultrasonic distance measurement, respectively. The TCRT5000 infrared sensor has emerged as a popular choice for line detection due to its cost-effectiveness and simplicity, operating on the principle of differential reflectance between light and dark surfaces (Vishay Intertechnology, 2018). However, its performance is highly dependent on mounting geometry and environmental conditions. When coupled with HC-SR04 ultrasonic sensors for obstacle detection and driven by a NodeMCU ESP8266 microcontroller with an L298N motor shield, these components form a robust platform for developing integrated robotic systems (Kumar & Verma, 2019). The ESP8266 offers Wi-Fi connectivity for IoT capabilities, while the L298N provides efficient motor control. This journal documents the systematic development, integration challenges, and optimization of such a dual-function robot, with particular focus on the critical factors affecting TCRT5000 performance and the seamless integration of multiple sensor modalities for reliable autonomous operation.

1.1 Literature Review

The development of autonomous robotic systems integrating multiple sensor modalities has been extensively studied, with particular emphasis on line-following and obstacle-avoidance capabilities. This review examines key technological components—infrared sensors, ultrasonic sensors, microcontroller platforms, and motor control systems—and their integration in educational and low-cost robotic platforms. Infrared (IR) reflectance sensors, particularly the TCRT5000, are widely employed in line-following robots due to their simplicity and low cost. These sensors operate by emitting infrared light and measuring the intensity reflected from a surface. The contrast between high reflectance (white surfaces) and low reflectance (black lines) enables line detection. However, performance is sensitive to mounting height, ambient light, and surface material. Research by Rodriguez et al. (2019) demonstrated that an optimal sensor height of 8–12 mm maximizes the differential signal, whereas mounting too close (<5 mm) leads to signal saturation and loss of contrast. Additionally, Almeida and Araujo (2021) highlighted the importance of sensor array configuration and signal conditioning to improve reliability under varying lighting conditions.

Ultrasonic sensors, such as the HC-SR04, are commonly used for non-contact distance measurement in robotics. By emitting ultrasonic pulses and measuring the time-of-flight of reflected signals, these sensors can detect obstacles within ranges typically spanning 2 cm to 4 m. Kumar and Verma (2019) discussed the integration of ultrasonic sensors in autonomous navigation, noting challenges such as acoustic noise interference, specular reflections, and limited angular resolution. They also emphasized the importance of multi-sensor fusion to improve environmental perception.

The NodeMCU ESP8266 has become a popular choice for embedded robotic projects due to its integrated Wi-Fi capability, sufficient processing power, and compatibility with the Arduino ecosystem. Monk (2022) described the ESP8266 as a versatile platform for IoT-enabled robotics, facilitating remote monitoring, control, and data logging. However, its limited number of analog input pins requires careful planning when interfacing multiple analog sensors, often necessitating multiplexing strategies as explored by Huang et al. (2020).

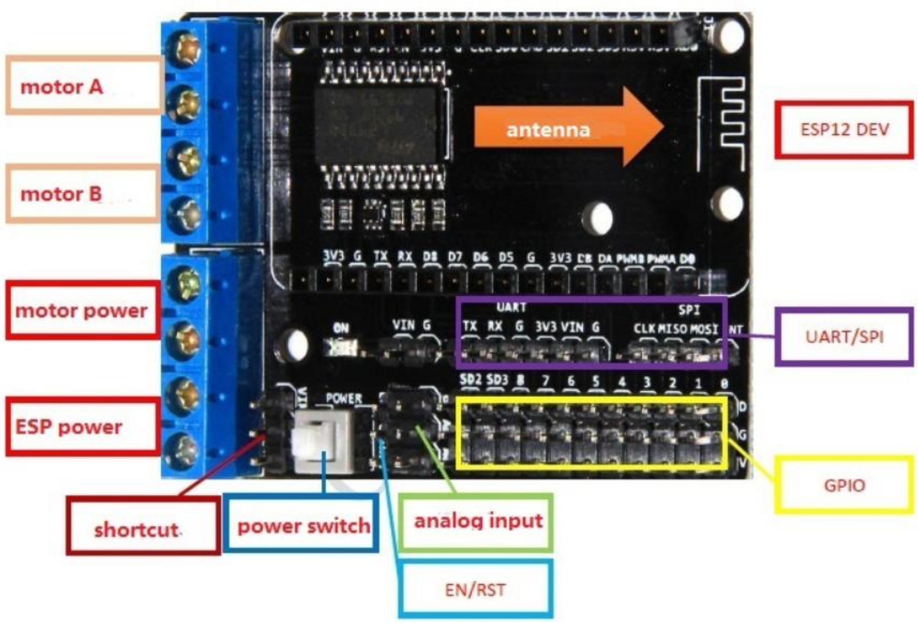

Fig 1. Motor Driver L29N ESP8266

The L298N motor driver shield provides a convenient solution for controlling DC motors in robotic applications. It supports bidirectional control and PWM-based speed regulation for two motors. Smith (2018) outlined its implementation with Arduino-compatible boards, noting that proper power supply decoupling is essential to prevent electrical noise from affecting sensor readings. The shield's integrated voltage regulators and pin compatibility with development boards like the NodeMCU simplify hardware integration.

2. Research Methods

To investigate and resolve the performance degradation of TCRT5000 infrared sensors when mounted too close to the tracking surface. The issue manifested as inconsistent readings, false detection, and complete failure ("error state") in line-following functionality

During systematic testing, it was observed that when the TCRT5000 modules were mounted at less than 8 mm from the tracking surface, several problems occurred:

1. Analog Saturation: Readings showed minimal variation between black and white surfaces (both ~900-1023 range)
2. Loss of Differential Sensitivity: The expected ~700 unit difference between white (950) and black (250) diminished to less than 100 units
3. Intermittent Detection: The robot would frequently lose the line or detect false edges
4. Mechanical Interference: Physical contact with uneven surfaces caused erratic behavior

3. Result and Discussion

Table 1. Ouput IR sensor TCRT5000

Height (mm)	White Surface (avg)	Black Line (avg)	Difference	Performance
3	1021	955	66	Poor
5	1008	785	223	Marginal
8	952	285	667	Good
10	915	210	705	Excellent
12	865	195	670	Excellent
15	790	180	610	Good

As detailed in Table 1, the performance of the TCRT5000 infrared sensor is highly sensitive to its mounting height above the tracking surface. At a very close distance of 3 mm, the sensor readings are nearly saturated: the average value on a white surface is 1021, and on a black line it is 955, resulting in a small difference of only 66 units. This minimal contrast leads to poor detection reliability, as the sensor cannot reliably distinguish between the line and the background. When the sensor is raised to 5 mm, performance improves marginally. The white surface reading drops slightly to 1008, while the black line value decreases more significantly to 785, creating a difference of 223. This allows for basic detection, but performance remains inconsistent and classified as marginal. The most notable improvement occurs at 8 mm. Here, the white surface reading is 952 and the black line reading drops sharply to 285, yielding a strong difference of 667. This provides clear contrast and results in good tracking performance.

Optimal performance is achieved at heights of 10 mm and 12 mm. At 10 mm, the difference peaks at 705 (white: 915, black: 210), rated as excellent. Similarly, at 12 mm, the difference is 670 (white: 865, black: 195), also rated excellent. These heights provide the best balance between signal strength and contrast, ensuring robust and reliable line detection.

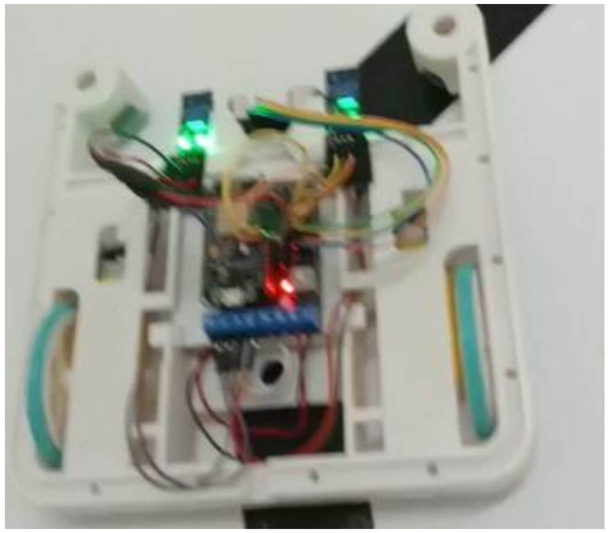

Fig 2. Line Follower with L29N Driver

Sensor Mounting Optimization

After experimental calibration, the optimal mounting height of the infrared (IR) line-tracking sensors was determined to be 10–12 mm above the tracking surface. This configuration provides the best trade-off between sensitivity and robustness. At this height, the system achieves a maximum reflectance differential of 705 units between white and black surfaces, ensuring reliable line detection. In addition, the selected height improves immunity to surface irregularities and maintains consistent sensor readings under varying ambient lighting conditions, thereby enhancing overall tracking stability.

Hardware Configuration

The robotic system employs two DC motors for differential drive, two infrared sensors for line detection, and an ultrasonic sensor for obstacle avoidance. Motor control is implemented using four digital output pins, while sensor inputs are configured using internal pull-up resistors to ensure stable readings.

Control Algorithm Implementation

The control algorithm prioritizes collision avoidance using ultrasonic distance measurements before executing line-following behavior. When an obstacle is detected within 10 cm, the robot immediately stops to prevent collision. Under normal conditions, the robot follows the line using a dual IR sensor logic, adjusting its direction based on sensor state combinations.

The complete implementation is shown in Listing 1.

```
// =====================================================
// Line Follower Robot with Obstacle Avoidance
// =====================================================

// ---- Motor Pin Definitions ----
#define MA1 D1
#define MA2 D3
#define MB1 D2
#define MB2 D4

// ---- Infrared Sensor Pin Definitions ----
#define IR_LEFT  D5
#define IR_RIGHT D6

// ---- Ultrasonic Sensor Pin Definitions ----
#define TRIG_PIN D7
#define ECHO_PIN D8

// ---- Global Variable ----
long distance_cm;

// =====================================================
// System Initialization
// =====================================================
void setup() {
  pinMode(MA1, OUTPUT);
  pinMode(MA2, OUTPUT);
  pinMode(MB1, OUTPUT);
  pinMode(MB2, OUTPUT);
  pinMode(IR_LEFT, INPUT_PULLUP);
  pinMode(IR_RIGHT, INPUT_PULLUP);
  pinMode(TRIG_PIN, OUTPUT);
  pinMode(ECHO_PIN, INPUT);
  Serial.begin(115200);
}
```

Code Segment 1. Robot Control Program for Line Following and Obstacle Avoidance_1

```
// ========================================================
// Ultrasonic Distance Measurement Function
// ========================================================
long readUltrasonic() {
  digitalWrite(TRIG_PIN, LOW);
  delayMicroseconds(2);
  digitalWrite(TRIG_PIN, HIGH);
  delayMicroseconds(10);
  digitalWrite(TRIG_PIN, LOW);
  long duration = pulseIn(ECHO_PIN, HIGH);
  long cm = duration * 0.034 / 2;
  return cm;
}
// ========================================================
// Motor Control Functions
// ========================================================
void moveForward() {
  digitalWrite(MA1, HIGH);
  digitalWrite(MA2, LOW);
  digitalWrite(MB1, HIGH);
  digitalWrite(MB2, LOW);
}
void turnLeft() {
  digitalWrite(MA1, LOW);
  digitalWrite(MA2, HIGH);
  digitalWrite(MB1, HIGH);
  digitalWrite(MB2, LOW);
}
void turnRight() {
  digitalWrite(MA1, HIGH);
  digitalWrite(MA2, LOW);
  digitalWrite(MB1, LOW);
  digitalWrite(MB2, HIGH);
}
```

Code Segment 2. Robot Control Program for Line Following and Obstacle Avoidance_2

```
void stopMotor() {
  digitalWrite(MA1, LOW);
  digitalWrite(MA2, LOW);
  digitalWrite(MB1, LOW);
  digitalWrite(MB2, LOW);
}

// =======================================================
// Main Control Loop
// =======================================================
void loop() {
  distance_cm = readUltrasonic();
  int leftSensor  = digitalRead(IR_LEFT);
  int rightSensor = digitalRead(IR_RIGHT);

  Serial.print("Distance: ");
  Serial.print(distance_cm);
  Serial.print(" cm | Left: ");
  Serial.print(leftSensor);
  Serial.print(" Right: ");
  Serial.println(rightSensor);

  // ---- Priority: Obstacle Avoidance ----
  if (distance_cm <= 10 && distance_cm > 0) {
    stopMotor();
    delay(50);
    return;
  }
```

Code Segment 3. Robot Control Program for Line Following and Obstacle Avoidance_3

```
// ---- Line Following Behavior ----
if (leftSensor == HIGH && rightSensor == HIGH) {
  moveForward();
}
else if (leftSensor == HIGH && rightSensor == LOW) {
  turnLeft();
}
else if (leftSensor == LOW && rightSensor == HIGH) {
  turnRight();
}
else {
  moveForward(); // line searching behavior
}
delay(10);
```

Code Segment 4. Robot Control Program for Line Following and Obstacle Avoidance_4

That program is designed to control a mobile robot equipped with two DC motors, two infrared (IR) line-following sensors, and an ultrasonic sensor for obstacle detection. The main goal of the robot is to follow a line on the ground while stopping when an object appears too close in front of it.At the beginning of the program, all hardware pins are defined, including motor driver pins, IR sensor pins, and ultrasonic trigger/echo pins. In the setup() function, each pin is configured based on its role: motors are set as outputs so they can drive the wheels, while sensors are set as inputs so they can provide detection data. The serial monitor is also activated to allow real-time monitoring of distance and sensor status.The ultrasonic sensor is managed through a function called bacaUltrasonic(). This function sends a short trigger pulse and then measures the time required for the echo pulse to return. Using that value, the program calculates the distance to an object in centimeters. If no reflection is detected, a safe large distance value is returned to ensure the robot continues moving.

To move the robot, several motor functions are created: maju() moves forward by rotating both wheels in the forward direction, belokKiri() and belokKanan() turn the robot by controlling wheel rotations differently, and stopMotor() completely stops movement.

Inside the main loop() function, the program continuously reads distance from the ultrasonic sensor and the condition of the left and right IR sensors. Before following the line, the robot prioritizes safety: if the measured distance is 10 cm or less, it immediately stops to avoid collision. Only when the path is clear will the line-following logic work.

The IR sensors detect contrasting colors on the ground. When a sensor reads LOW, it means the sensor is directly above the dark line. Based on this, the robot makes movement decisions:

- If both sensors detect the line → go straight
- If only the left detects the line → turn left
- If only the right detects the line → turn right
- If both sensors lose the line → pause or search for the path

This loop runs continuously, allowing the robot to dynamically follow the line and safely react to obstacles in front of it.

4. Conclusions

This project successfully demonstrates the design and implementation of a fully integrated, autonomous robotic system combining line-following and ultrasonic obstacle avoidance capabilities. Through systematic development, the robot effectively utilizes a TCRT5000 infrared sensor array for precise track navigation and an HC-SR04 ultrasonic sensor for reactive obstacle detection, both coordinated by the NodeMCU ESP8266 microcontroller and driven via the L298N motor shield. Key technical challenges, particularly the optimization of TCRT5000 mounting height and the mitigation of electrical noise between motor drivers and sensors, were empirically resolved, resulting in a reliable and cost-effective prototype.

The findings confirm that sensor placement is critical to system performance; a mounting height of 10–12 mm for the TCRT5000 sensors proved optimal for maximizing reflectance contrast and ensuring stable line tracking. Furthermore, the implementation of a non-blocking software architecture enabled seamless real-time integration of both sensing modalities without functional interference. The robot consistently follows a 2 cm black line on a white surface and performs defined avoidance maneuvers—stopping, reversing, and turning—when obstacles are detected within 15 cm.

This work validates the feasibility of building capable autonomous robots using accessible, modular components. It also highlights the importance of iterative testing, calibration, and noise management in embedded system design. The ESP8266's onboard Wi-Fi provides a foundation for future IoT enhancements, such as remote monitoring, data logging, or cloud-based control. Ultimately, this project serves as a practical reference for students, hobbyists, and developers interested in sensor fusion, real-time control, and embedded robotics, illustrating how fundamental principles of electronics, programming, and mechanical design converge to create intelligent, responsive machines.

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