Autonomous Line-Following and Obstacle-Avoiding Robot

Cyber-Physical Systems Project Report

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Abstract

This report details the design, construction, and implementation of an autonomous mobile robot engineered to follow a designated line and avoid obstacles. The system's architecture is centered on an Arduino Uno platform, featuring a dual-mode perception system that integrates infrared (IR) sensors for line tracking with an active-scanning ultrasonic sensor for obstacle avoidance. Its robust 4WD platform is driven by a state-based control logic, ensuring seamless transitions between navigation modes. This document covers the complete hardware and software architecture, the engineering challenges encountered, and potential future enhancements for the system.

1. Introduction

In the field of logistics and automation, autonomous mobile robots play a crucial role in streamlining operations, from warehouse management to automated delivery. The ability to navigate a predefined path while safely avoiding unexpected obstacles is a fundamental requirement for these systems. This project aims to develop a small-scale prototype that demonstrates these core principles of cyber-physical systems.

Project Objectives:

- To construct a functional robot that can autonomously follow a black line on a white surface.
- To integrate an ultrasonic sensor for real-time obstacle detection and avoidance.
- To implement control logic in the Arduino environment to seamlessly switch between line-following and obstacle-avoidance modes.
- To document the engineering design process from concept to a functional prototype.

2. Methodology

The project was executed through a structured, hands-on engineering design process:

1. **Requirements Analysis:** The project began by defining the core functionalities, establishing the primary goals of autonomous line following and dynamic obstacle avoidance.

2. **Component Selection:** Suitable and cost-effective components were selected. The Arduino Uno was chosen as the main controller for its accessibility, supported by the L293D shield for motor control, and appropriate IR and ultrasonic sensors for perception.

3. **Hardware Assembly:** The robot chassis was assembled, and the electronic components, including the Arduino, motor shield, sensors, and motors, were wired according to the designed circuit diagram.

4. **Custom Fabrication:** A custom mount for the ultrasonic sensor was designed and 3D printed to ensure stability and an optimal viewing angle.

5. **Software Implementation:** The Arduino IDE was used to write and upload the control code, which integrates data from the IR and ultrasonic sensors to command the motors.

6. **Testing and Iteration:** The robot was tested on a designated track. Adjustments were made to the code (sensor thresholds, motor speeds) and hardware (motor wiring) to improve performance and reliability.

3. System Overview

The robot operates as a cohesive system with three primary subsystems:

1. **Control Subsystem:** The Arduino Uno board serves as the central processing unit. It executes the control algorithm, processing inputs from the sensors and sending commands to the L293D motor shield.

2. **Perception Subsystem:** This consists of two IR sensors positioned at the front of the robot to detect the line and an HC-SR04 ultrasonic sensor mounted on a servo motor to detect obstacles and scan for clear paths.

3. **Actuation Subsystem:** Four DC motors, driven by the L293D shield, provide locomotion. The SG90 servo motor actively pans the ultrasonic sensor to give the robot a wider field of view for navigation.

4. Hardware Components

- **Microcontroller:** Arduino Uno R3
- **Motor Driver:** L293D Motor Driver Shield
- **Sensors:**
  - 2 x IR Infrared Line Follower Sensors
  - 1 x HC-SR04 Ultrasonic Distance Sensor
- **Actuators:**
  - 4 x DC Geared Motors with Wheels
  - 1 x SG90 Micro Servo Motor
- **Power:** 9V Battery with a barrel jack connector. (Substituted with 2 3.7v batteries due to a last minute part failure)
- **Chassis:** 4WD Robot Car Chassis Kit and a custom 3D-printed mount.

5. Bill of Materials

Component	Quantity	Purpose
Arduino Uno R3	1	Main controller
L293D Motor Shield	1	Driving DC motors and servo
HC-SR04 Ultrasonic Sensor	1	Obstacle detection
IR Line Follower Sensor	2	Line detection
SG90 Servo Motor	1	Panning the ultrasonic sensor
DC Geared Motor with Wheel	4	Locomotion
4WD Robot Car Chassis	1	Structural frame
9V Battery & Connector	1	Power source
Jumper Wires	Various	Connections
Custom 3D Printed Mount	1	Securely holds the ultrasonic sensor

6. Circuit Wiring

The components were wired according to the provided circuit diagram. The L293D shield simplifies the wiring process by stacking directly onto the Arduino Uno. The IR sensors, ultrasonic sensor, and servo motor are connected to the designated pins on the shield.

During initial testing, we observed minor inconsistencies in motor synchronization. To ensure balanced power distribution and simplify the control logic, we implemented a revised wiring scheme. The two left motors were connected in parallel to the M1 hub of the L293D shield, and the two right motors were connected in parallel to the M3 hub. This design choice guarantees that wheels on the same side receive an identical control signal, leading to more predictable turning and forward motion.

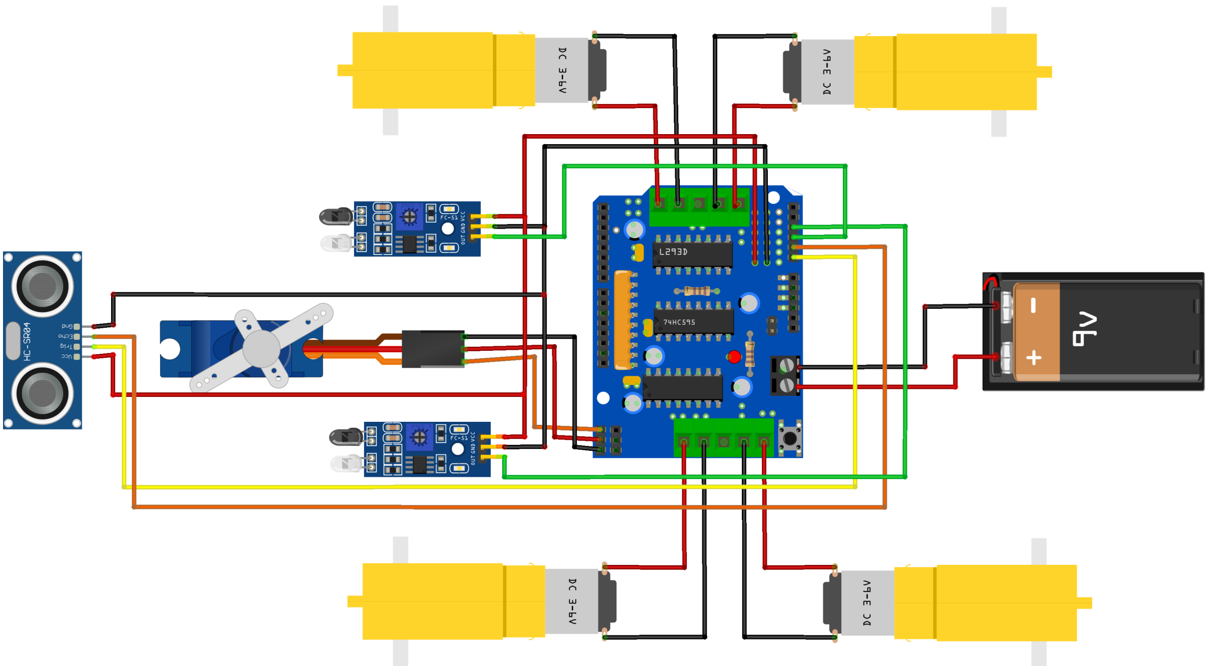

Figure 1: The circuit diagram of the project.

7. Software Architecture

The robot's logic is implemented in C++ using the Arduino IDE as a state-based system. The main loop determines the robot's current state (line following or avoiding obstacle) and executes the corresponding logic.

- **Default State (Line Following):**
  - The code reads the digital output from the two IR sensors.
  - If both sensors are on the white surface (off the line), the robot moves forward.
  - If the right sensor detects the black line, the robot corrects its course by turning right.
  - If the left sensor detects the black line, it turns left.
- **Obstacle Avoidance State:**
  - This state is triggered when the ultrasonic sensor detects an object within a predefined threshold (e.g., 20 cm).
  - Upon entry, all forward motion ceases. The control logic then initiates an active scanning sequence using the servo motor to pan the ultrasonic sensor left and right.
  - By comparing the distance measurements from these scans, the robot determines the clearest path, turns in that direction, and proceeds for a set duration before attempting to reacquire the line and return to the default state.

8. Design Iteration and Refinements

The final design was the result of an iterative prototyping process. Initial tests with a standard assembly revealed two key areas for improvement: mechanical stability of the primary sensor and motor control synchronization.

1. **Mechanical Stability:** The original mounting for the HC-SR04 ultrasonic sensor was found to be prone to vibration, which compromised the accuracy of distance readings, especially while the robot was in motion. To address this, we designed and fabricated a custom sensor mount using a 3D printer. This bespoke component provides a secure, vibration-resistant housing, leading to significantly more reliable and consistent sensor data.

2. **Motor Synchronization:** As noted in the wiring section, achieving perfectly synchronized movement across four independently controlled motors was challenging. The consolidated wiring strategy was a direct response to this issue. By driving each pair of motors (left and right) from a single output, we simplified the software control and ensured uniform power delivery, which proved highly effective for the robot's required maneuvers.

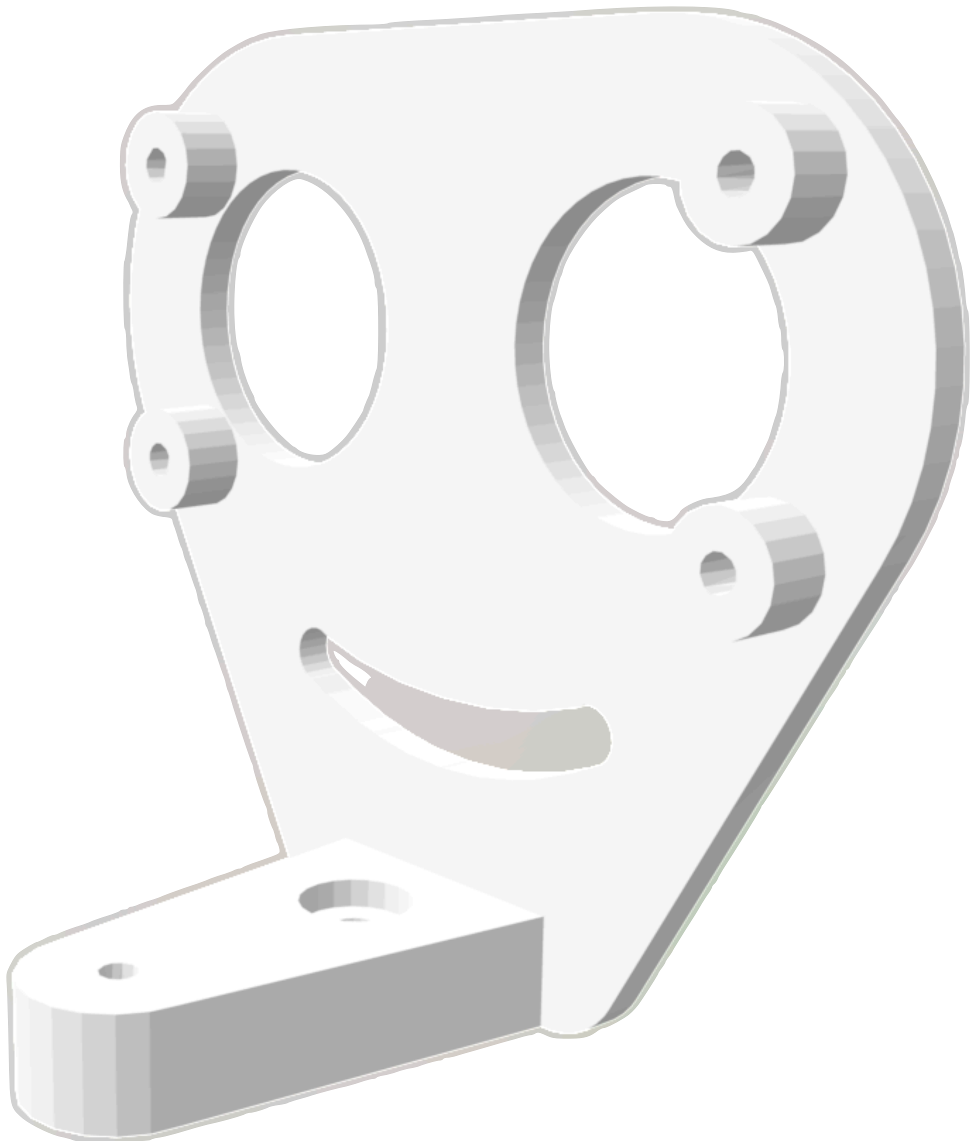

Figure 2: The custom 3D-printed mount for the HC-SR04 sensor.

9. Problems Faced

- **IR Sensor Calibration:** The IR sensors were sensitive to ambient lighting conditions, requiring frequent recalibration of the detection threshold in the code.
- **Power Source Failure:** During late-stage testing, the initial 9V battery overheated and failed completely. We resolved this by by doing a last-minute re-engineering of the power system to use two 3.7V Li-ion batteries in series.
- **Traction and Turning:** Achieving smooth and precise turns was challenging, as the motors sometimes had slightly different speeds, and the wheels could slip on smooth surfaces.

10. Limitations and Constraints

- **Surface Dependency:** The robot's performance is highly dependent on a high-contrast line (e.g., black on white) and is not suitable for complex or reflective surfaces.
- **Basic Avoidance Algorithm:** The obstacle avoidance logic is rudimentary and may fail in cluttered environments or with complex obstacle shapes.
- **Open-Loop Control:** The system lacks any feedback mechanisms, such as wheel encoders, to ensure precise control over distance and speed.

11. Future Improvements

- **PID Control:** Implementing a Proportional-Integral-Derivative (PID) controller for line following would result in much smoother and more accurate navigation.
- **Upgraded Power Source:** Replacing the battery with a rechargeable LiPo battery pack and a voltage regulator would provide more stable and longer-lasting power.
- **Sensor Fusion:** Adding more sensors, such as a gyroscope or accelerometer (IMU), could provide better data for navigation and turning.

12. Conclusion

This project successfully achieved its goal of building an autonomous line-following robot with obstacle avoidance capabilities. The successful integration of its perception, control, and actuation subsystems into a cohesive unit demonstrates a practical application of core cyber-physical systems principles. The project culminated in a robust and reliable prototype, providing valuable hands-on experience in designing and troubleshooting a complete autonomous system from the ground up.