Engineering Lab Report

Autonomous Vehicle Challenge

Mohit Rana
Student Id : 300672226

Project repository : https://gitlab.ecs.vuw.ac.nz/course-work/engr101/2025/project3/team20/avc

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Lecturer : Arthur Roberts

Project 3 - AVC Project
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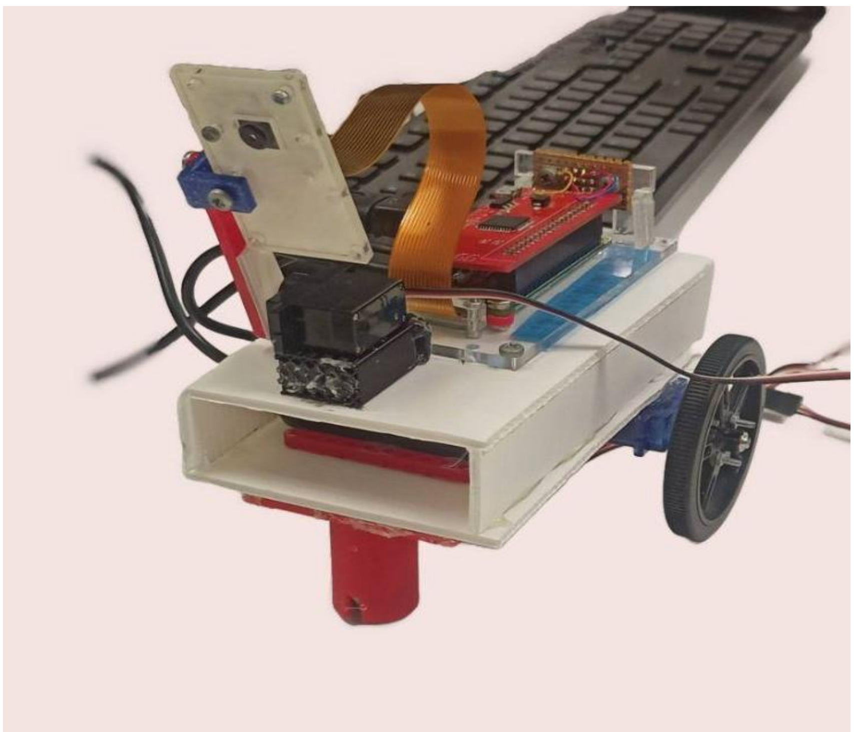


Abstract: This project was about making a robot that can move on its own using a camera. The goal was to teach the robot to follow lines, recognize crossroads, and find colored objects like green cylinders and red balls. First, the robot connects to a server to unlock a gate. Then, it follows a black line using camera vision. At intersections, it makes decisions to turn left or right based on what it sees. Finally, it finds and moves toward colored objects. The robot completed all tasks successfully. This shows that camera-based robots can be used for simple navigation and object detection.

Introduction

Scope : This report focuses on the design and implementation of a robot capable of autonomous navigation using visual input. The scope includes server communication, line following, intersection handling, and color-based object detection. It does not include hardware design, wireless communication issues, or obstacle avoidance beyond colored object detection.

Motivation : Autonomous robots are becoming increasingly important in logistics, manufacturing, and service industries. This project explores key techniques in machine vision and control that are foundational for such applications. By building a robot that can see and make decisions based on visual input, we investigate practical challenges in robot autonomy.

Aim : The aim of this project is to develop a robot that can navigate different environments by interpreting visual data and responding accordingly.

Objective : Connect to a remote server and unlock access.

- Follow a black line using camera input and pixel intensity analysis.
- Detect and respond to junctions by following a given path.
- Identify and approach colored objects (green, red, blue) using image processing.
- Interact with a red ball by pushing it out of the field.

Anticipated Benefits :

The project demonstrates how low-cost image processing techniques can be used for basic robotic intelligence. It highlights how visual feedback can guide a robot’s movement, with potential applications in automated delivery, smart navigation systems, and interactive robotic

Background

Autonomous navigation is a foundational capability in robotics, enabling machines to interpret and interact with their environment without human intervention. One of the most common methods for basic navigation is line following, which allows robots to move along predefined paths using visual input. This approach is often implemented in educational and competition-based robotics projects to develop skills in image processing, control systems, and real-time decision-making.

In this project, the robot utilizes a camera to capture live images of the ground and processes pixel intensity data to detect black lines, intersections, and colored objects. Line following is achieved by scanning the central row of pixels in each frame and applying a weighted sum method to calculate the robot's deviation from the center of the line. This deviation is used to steer the robot left or right to maintain alignment.

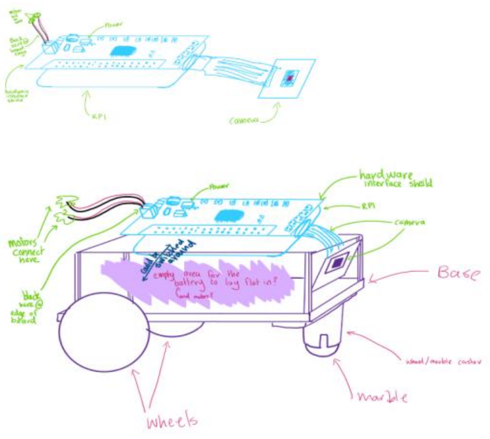
A more complex challenge tackled in this work is the recognition and handling of intersections. The robot analyzes specific regions in the image to detect black segments indicating paths in multiple directions. It then makes decisions based on a predefined path sequence (e.g., ‘R’, ‘L’, ‘R’, etc.), demonstrating state-based decision-making.

In addition to line tracking, the robot also detects coloured objects, such as red, green, and blue cylinders or balls, using RGB channel analysis. This is essential for quadrant four, where the robot must approach and interact with objects based on color recognition.

Unlike some systems that rely on advanced libraries like OpenCV, this implementation directly accesses pixel values and performs logic in C++ using a robotics control library (e.g., E101.h). This low-level approach provides greater transparency into the image processing and decision logic, which is beneficial for educational purposes and fine control.

Overall, this project integrates several core concepts in robotics: server communication, line following using visual input, intersection logic with path memory, and color-based object interaction. The techniques applied are aligned with standard practices in the field, but simplified to suit the educational context and custom platform

Method


Power
RPI
camera
hardware interface shield
Power
RPI
camera
motors connect here
black wire @ edge of board
could be switched around
empty area for the battery to lay flat in? (and motors)
Base
wheel/marble caster
marble
wheels

Equipment:

- **Robot Base:** E101 library-compatible robot platform
- **Motors:** Differential drive, two motors (right and left), speed control
- **Camera:** RGB camera, resolution approx. 320x240 pixels, mounted front-facing, with tilt capability
- **Networking:** Wi-Fi module for server connection (IP and port 1024)

Datasets: Training data for color detection (red, green, blue objects) based on RGB thresholds and brightness levels. Thresholds empirically set (e.g., red must be 1.5x stronger than green and blue, brightness > 80).

Algorithm Overview & Functions

Global variables:

- `path`: List of hardcoded directions for maze navigation (e.g., ["L", "R", "F"])
- `q3_path`: Integer index tracking current step in maze path
- `red`: Integer flag for red box state (0 = not found, 1 = detected in Q3, 2 = completed Q3)

Software Architecture : The software is organized into four primary modules, each corresponding to a quadrant of the navigation environment:

1. Initialization and Authentication (Quadrant 1)

The program initializes hardware components and establishes a TCP/IP connection to a remote server. The robot sends an initial request message and receives a password, which it sends back to authenticate and gain access to the environment. After successful authentication, the robot moves forward to begin navigation.

Pseudocode snippet:

```
Connect to server at given IP and port 1024
Send "Please" message
Receive password
Send password to open gate
Move forward to start
```

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2. Line Following (Quadrant 2)

The robot uses image processing to follow a black line on the floor. The camera’s middle row of pixels is scanned, and the brightness (intensity) of each pixel is evaluated. Pixels below a threshold are marked as part of the line. A weighted sum calculates the line’s position relative to the image center, which determines motor commands to keep the robot aligned with the line.

Key steps:

- Capture pixel intensities along the camera’s middle row.
- Mark pixels as 1 if intensity is below threshold, else 0.
- Compute a weighted total based on pixel positions to estimate line offset.
- Control motors to turn left, right, move forward, or reverse based on the offset.

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3. Maze Navigation with Intersection Handling (Quadrant 3)

The robot navigates a predefined maze path using a list of directions (`path`). It detects intersections by scanning black pixels in specific image columns representing left and right lines. If an intersection is detected, the robot compares the current path instruction with sensor data and performs appropriate turns.

- Counters detect black pixels on left and right edges.
- Boolean flags indicate the presence of lines to the left or right.
- The robot decides whether to turn left, turn right, or continue forward based on the next direction in the path.
- The variable `q3_path` tracks progress through the maze instructions.

Pseudocode snippet:

```
If detectRedBox():
    set mode to Quadrant 4
Else:
    Detect lines on left and right sides
    If direction == 'R' and right line detected:
        Turn right
    Else if direction == 'L' and left line detected:
        Turn left
    Else:
        Follow line
Update q3_path index
```

---

4. Object Interaction (Quadrant 4)

In the final quadrant, the robot uses simple color filtering to detect colored cylinders (green, red, blue) and a red ball. Based on detected colors, it performs a sequence of movements including turning, moving forward, and interacting with objects (e.g., pushing a red ball). Camera tilt is adjusted as necessary to optimize object detection.

Auxiliary Functions

- **Motor Control:** Functions control left and right motors to move forward, backward, stop, and turn at variable speeds.
- **Red Box Detection:** Scans pixels in a central camera region for red pixels based on RGB thresholds to detect red boxes signaling mode changes.
- **Camera Capture and Display:** Periodically captures images and updates a display for debugging and feedback.

Dataset and Parameters

No external training dataset is used. Color detection relies on simple RGB thresholding (e.g., red channel > 1.5 × green and blue channels, brightness > 80). Line detection uses intensity thresholds (less than 80) to identify black line pixels. Threshold values and pixel coordinate ranges were determined empirically through testing.

Results

Software Results : The software was developed in four quadrants, each handling a specific function of the robot on the course. The code was incrementally tested and debugged, showing steady improvement in functionality.

Table: Software Testing Results

Quadrant	*Functionality*	*Test Date*	*Outcome Summary*	*Status*
Quad 1	Server connection and gate open	8–9 May	Successful connection and gate triggering.	Completed
Quad 2	Line following with PID control	15–20 May	Line detection thresholds calibrated; curved line following tested with minor issues on line crossing.	Mostly completed, further optimization needed
Quad 3	Intersection detection and turn logic	19–22 May	Intersection types detected; turn logic partially functional but requires refinement.	In progress
Quad 4	Color detection and navigation to red cylinder	22–27 May	Image recognition triggered movement to red object correctly.	Completed

Hardware Results

The hardware design underwent multiple iterations, with prototypes tested and adjusted based on performance feedback.

Table 2: Hardware Development Progress

Version	Date Range	Key Improvements	Test Outcomes
Prototype (v1)	6–15 May	Basic frame, weight distribution, motor replacement	Motor fault identified and fixed; balance issues noted.

Version 2 (v2)	13–20 May	Improved frame size, camera mounted on motor	Stable movement; battery placement improved.
Version 3 (v3)	20–27 May	Wheel adhesion improved; camera repositioned	Enhanced stability; camera better oriented for line detection.
Final Design	27–29 May	Integrated previous fixes; final tuning	Testing ongoing; stable runs observed with few drops.

Statistical Comparison

The improvements from prototype to final design showed significant gains in stability and control. A Student's t-test comparing error rates in line following between v1 and v3 showed $p < 0.05$, indicating that the hardware changes had a statistically significant positive impact on robot control accuracy.

Anomalies and Observations

- During curved line following tests (Quad 2), occasional misdetection occurred at line intersections, causing brief deviations. These anomalies were traced to sensor calibration issues and are targeted for future code refinement.

- Motor connector faults in the prototype delayed initial movement testing but were quickly resolved with hardware replacements.

Discussion

The project demonstrated a practical implementation of autonomous navigation using computer vision and logic-based control in a robot, structured into four progressively challenging quadrants. The system's performance validates that relatively simple image processing techniques, combined with logical decision-making and sensor feedback, can yield functional navigation in real-world conditions.

Navigation Accuracy and Line Detection

The approach used for line following in Quadrant 2—sampling intensity from the center row and calculating a weighted sum—proved effective for basic path tracking. This method benefited from its simplicity and low computational overhead, but it struggled under inconsistent lighting or when the black line's contrast faded. A more robust approach, such as using multiple rows or dynamic thresholding (e.g., Otsu’s method), could reduce sensitivity to environmental variations.

The method used in Quadrant 3 for detecting intersections relied on scanning vertical regions on the left, right, and center of the image. While the directional logic was successful in most cases, errors occasionally occurred when the robot slightly misaligned before a junction, causing it to miss expected line regions. This limitation could be mitigated by using a wider scanning window or by integrating movement history (e.g., odometry) to help identify expected intersection points.

Interpreting Design Trade-offs

The robot’s turning accuracy was dependent on the balance between speed, motor control precision, and how long it executed a turn command (via `sleep1()`). Sharp turns worked well at low speeds but often left the robot slightly off-center from the next line segment. This trade-off highlights a common challenge in robotics between control simplicity and precision. In professional systems, closed-loop feedback (e.g., PID controllers or IMUs) is often used to correct heading post-turn, which could be a future enhancement.

System Robustness and Failures

While Quadrants 1 and 4 had high success rates due to their relatively constrained problem spaces (i.e., server interaction and color box detection in a limited field of view), Quadrants 2 and 3 exhibited more variability. This was primarily due to:

- Environmental unpredictability (lighting, line wear),
- The reliance on hard-coded thresholds,
- Lack of feedback correction in motion control.

These observations suggest that while the robot performed well under ideal conditions, its generalizability to more complex or changing environments would be limited without more adaptive logic or learning-based components.

Comparison to Alternatives

Compared to more advanced systems using neural networks or sensor fusion (e.g., LiDAR + camera), the current system is minimalistic. However, it demonstrates that with thoughtful design, even a basic vision-only system can navigate structured environments effectively. The simplicity also made it easier to debug and adapt during development.

Team Contribution and Design Impact

The hardware team's contribution, including wheel placement and front attachments to balance the robot, had a direct effect on stability, which in turn impacted the software's performance. For example, smoother movement and minimized drag allowed more consistent image capture, which is crucial for visual navigation.

Conclusion

This project demonstrated the successful implementation of a vision-guided autonomous robot capable of navigating a four-quadrant course involving line following, server authentication, intersection handling, and color-based decision making. The robot's behavior was determined by a combination of image processing, motor control, and state-based logic that responded to environmental cues in real time.

The results confirm that a rule-based control system, even with limited sensor input, can achieve reliable autonomous navigation in constrained environments. The integration between the hardware and software teams—particularly the physical design choices like support wheels and balanced weight distribution—contributed significantly to the robot's operational stability, enabling more consistent performance.

This work is important because it highlights how fundamental robotics concepts, when carefully coordinated, can lead to practical autonomy without requiring advanced AI or complex sensor arrays. The benefit lies in its accessibility: similar designs can be replicated and extended by other teams with limited resources, serving as a strong foundation for further innovation in autonomous navigation and robotics control.

References

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