School

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Electronics and Communication Engineering

Instutional Research Project Report

on

Lane Detection and Obstacle Avoidance using Q-Car

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CERTIFICATE

This is to certify that the project entitled **Lane Detection and Obstacle Avoidance using Q-Car** is a bonafide work carried out by the student team of **Arihant A (01fe22bei048), Shivani D (01fe22bec293), Radhika M (01fe22bec296)**. The project report has been approved as it satisfies the requirements with respect to the Instutional Research Project work prescribed by the university curriculum for BE (VII semester) in School of Electronics and Communication Engineering of KLE Technological University for the academic year 2025-2026.

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ABSTRACT

The integration of vision-based perception and depth sensing is essential for achieving reliable autonomous navigation in structured environments. This project focuses on the development of a real-time lane detection and obstacle avoidance framework implemented on the Quanser QCar autonomous vehicle platform. The system combines RGB camera-based vision processing with 360° LiDAR sensing to enable accurate lane following and safe navigation in indoor environments. By leveraging complementary sensing modalities, the proposed approach enhances environmental awareness and ensures robust performance under varying operational conditions.

Lane detection is performed using real-time image processing techniques based on color segmentation, enabling precise identification of yellow lane markings and continuous estimation of lane position. The extracted lane information is used to generate steering commands that allow the vehicle to maintain stable and smooth lane tracking. Simultaneously, obstacle detection is achieved using LiDAR data, which provides reliable distance and positional information for identifying obstacles within a predefined safety range. This dual-sensor perception framework ensures timely detection of hazards without interrupting lane-following behavior.

To manage decision-making and motion planning, the system employs a Finite State Machine (FSM)–based control architecture. Under normal conditions, the vehicle operates in a lane-following state. When an obstacle is detected, the FSM transitions through structured states that enable lateral shifting, forward bypassing, and safe re-entry into the original lane. This state-based approach ensures symmetric obstacle handling on both sides of the lane while preventing repetitive or unstable avoidance behavior.

The proposed system was experimentally validated on an indoor test track using the Quanser QCar platform. Results demonstrate reliable lane tracking, smooth obstacle avoidance, and real-time performance with minimal latency. The integration of vision-based lane detection, LiDAR-based obstacle sensing, and FSM-based control provides a stable and effective solution for autonomous navigation. This framework serves as a practical foundation for educational, research, and experimental autonomous driving applications, highlighting the effectiveness of sensor fusion and structured control in small-scale autonomous vehicles.

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Chapter 1

Introduction

The rapid development of autonomous vehicle technologies has increased the need for reliable real-time perception and decision-making systems capable of ensuring safe and efficient navigation. Autonomous vehicles must continuously perceive their surroundings, interpret road structures, detect obstacles, and execute appropriate control actions without human intervention. Among these requirements, accurate lane detection and robust obstacle avoidance are fundamental for maintaining vehicle stability, safety, and compliance with navigation constraints in structured environments.

Traditional autonomous navigation systems often rely on a single sensing modality, such as camera-based vision or range-based sensors alone. Vision-only lane-following systems typically depend on color segmentation or edge detection techniques, which can fail when lanes are partially occluded, interrupted by obstacles, or affected by lighting variations. Similarly, obstacle detection systems operating independently of lane perception may lack contextual awareness of road geometry, leading to inefficient or unsafe avoidance maneuvers. These limitations highlight the necessity of integrating multiple sensing approaches with intelligent decision-making frameworks.

This project focuses on the design and implementation of a real-time lane detection and obstacle avoidance system using the Quanser QCar autonomous vehicle platform. The QCar serves as a compact and versatile research platform for autonomous driving experiments, equipped with an RGB camera, a 360° LiDAR sensor, onboard computation, and real-time control interfaces. Its architecture enables the practical evaluation of perception, planning, and control algorithms in a controlled indoor environment, making it well suited for academic and experimental research.

In the proposed system, lane detection is performed using an RGB camera mounted on the QCar. Real-time image processing techniques based on color segmentation are employed to detect yellow lane markings and estimate the vehicle's relative position within the lane. This information is used to generate steering commands that allow the vehicle to follow the lane smoothly and maintain directional stability. Concurrently, obstacle detection is achieved using LiDAR sensing, which provides accurate distance and angular measurements to identify obstacles located within a predefined safety region ahead of the vehicle.

To coordinate perception and navigation tasks, a Finite State Machine (FSM)–based control strategy is implemented. The FSM governs the vehicle's behavior by transitioning between well-defined states, such as lane following, obstacle detection, lateral shifting, forward bypassing, and lane rejoining. This structured approach ensures systematic and symmetric obstacle avoidance for obstacles appearing on either side of the lane, while preventing repeated or unstable maneuvers. The FSM-based design simplifies decision logic and improves overall system reliability.

The integrated vision–LiDAR perception framework, combined with FSM-based control, enables the QCar to autonomously navigate a predefined path while safely avoiding obstacles in real time. Experimental evaluations conducted on an indoor test track demonstrate stable lane tracking, smooth obstacle avoidance, and minimal latency in control response. The proposed system illustrates an effective approach to sensor fusion and intelligent control for small-scale autonomous vehicles, providing a strong foundation for educational, research, and experimental autonomous driving applications.

1.1 Motivation

The primary motivation for this work arises from the increasing need for safe, reliable, and efficient autonomous navigation systems in modern intelligent transportation and robotic applications. Autonomous vehicles must continuously perceive their environment, maintain lane discipline, and respond appropriately to obstacles in real time. Accurate lane detection and timely obstacle avoidance are fundamental requirements for ensuring vehicle safety, stability, and compliance with navigation constraints, especially in structured environments such as indoor test tracks, campuses, and controlled road networks.

Conventional lane-following systems primarily rely on vision-based techniques such as color segmentation or edge detection. While these methods perform well under ideal conditions, their reliability degrades when obstacles interrupt the lane, lighting conditions vary, or environmental noise is introduced. Similarly, obstacle detection systems operating independently of lane perception may lack contextual understanding of road geometry, leading to inefficient or unsafe avoidance maneuvers. These limitations highlight the need for an integrated perception framework that combines lane awareness with robust obstacle sensing.

Another significant motivation for this project is the growing emphasis on sensor fusion in autonomous vehicle research. Combining complementary sensing modalities, such as RGB cameras for visual lane detection and LiDAR for accurate depth and distance measurement, enhances environmental understanding and system robustness. Such integration allows autonomous systems to compensate for the shortcomings of individual sensors, resulting in more reliable perception and improved decision-making capabilities.

The Quanser QCar platform provides an ideal experimental testbed for exploring these concepts in a realistic yet controlled setting. As a small-scale autonomous vehicle equipped with an RGB camera, a 360° LiDAR sensor, and onboard computation, the QCar enables hands-on implementation and validation of real-time perception and control algorithms. Its modular design supports rapid prototyping and systematic testing of autonomous navigation strategies, making it particularly suitable for academic and research-oriented applications.

Furthermore, the use of a Finite State Machine (FSM)–based control strategy is motivated by the need for structured, predictable, and loop-free decision-making in autonomous systems. FSM-based control simplifies complex navigation tasks by decomposing them into well-defined states, ensuring symmetric obstacle handling and stable vehicle behavior. This approach improves system reliability while maintaining low computational complexity, which is essential for real-time operation on embedded platforms.

Overall, this work is motivated by the goal of developing an efficient and reliable autonomous navigation framework that integrates vision-based lane detection, LiDAR-based obstacle sensing, and intelligent control. The proposed system contributes to advancing small-scale autonomous vehicle research and serves as a foundation for future developments in autonomous driving, intelligent mobility, and real-world perception-driven navigation systems.

1.2 Objectives

The primary objectives of this project are outlined as follows:

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The primary objectives of this project are outlined as follows:

- To design and develop a real-time 360° panoramic vision system using four wide-angle CSI cameras strategically mounted on the QCar platform to achieve complete environmental coverage and eliminate blind spots.
- To implement an efficient overlap-based image stitching algorithm that seamlessly combines multiple camera views into a single panoramic image, minimizing visual artifacts such as seams, distortions, and illumination inconsistencies.
- To optimize real-time image acquisition, processing, and stitching performance on the NVIDIA® Jetson™ TX2 embedded platform by effectively utilizing GPU acceleration and parallel processing capabilities.
- To integrate a real-time object detection framework with the stitched panoramic output, enabling accurate identification of critical road elements such as traffic signs and traffic lights, with flexibility to extend to additional object classes.
- To evaluate and analyze overall system performance using quantitative metrics including frame rate (FPS), processing latency, detection accuracy, power consumption, and hardware resource utilization, ensuring suitability for embedded autonomous vehicle applications.

1.4 Literature Survey

Lane detection and obstacle avoidance are fundamental components of autonomous navigation systems, as they enable vehicles to maintain structured motion while ensuring safety in dynamic environments. Early research in autonomous driving primarily focused on vision-based lane detection using classical image processing techniques such as edge detection, Hough transform, and vanishing point estimation. These methods provided a computationally efficient means to detect lane boundaries but were highly sensitive to noise, lighting variations, and partial occlusions, limiting their reliability in real-world scenarios.

To improve robustness, color-based lane detection techniques were introduced, particularly using the HSV color space for segmenting lane markings. Several studies demonstrated that HSV-based color segmentation offers improved resilience to illumination changes and is effective for detecting painted lanes in controlled environments. Due to their low computational complexity and ease of implementation, such approaches have been widely adopted in small-scale autonomous vehicle platforms used for educational and experimental purposes, including the Quanser QCar.

Obstacle detection has evolved alongside lane detection to address the safety challenges posed by static and dynamic obstacles. Vision-only obstacle detection methods rely on monocular depth estimation or optical flow, which often lack accuracy in distance measurement. As a result, range-based sensors such as LiDAR have gained prominence due to their ability to provide precise distance and angular information. Research has shown that 360° LiDAR sensors enable reliable obstacle detection across a wide field of view, making them well suited for autonomous navigation in structured and indoor environments.

Several navigation systems combine lane detection with obstacle detection using independent control logic, which can lead to conflicting decisions when obstacles interfere with the lane path. To address this limitation, researchers have proposed structured decision-making frameworks that integrate perception and control. Among these, Finite State Machines (FSMs) have been widely used in mobile robotics and autonomous vehicles due to their simplicity, predictability, and reliability. FSM-based approaches decompose navigation behavior into discrete states such as lane following, obstacle detection, avoidance maneuver, and lane rejoining, ensuring systematic and loop-free vehicle behavior.

Recent literature emphasizes sensor fusion techniques that integrate vision-based perception with LiDAR-based sensing to enhance environmental understanding. Studies conducted on small-scale autonomous platforms demonstrate that combining RGB camera data for lane detection with LiDAR data for obstacle sensing significantly improves navigation reliability. Such integrated systems allow vehicles to maintain lane awareness while safely executing obstacle avoidance maneuvers, even when lane markings are partially occluded.

The Quanser QCar platform has been widely used in academic research to validate autonomous driving algorithms due to its realistic sensor suite, real-time processing capability, and suitability for indoor experimentation. Existing studies using the QCar highlight successful implementations of lane following, obstacle avoidance, and path planning under controlled conditions. These works confirm that real-time performance can be achieved using classical vision techniques combined with structured control strategies, without the need for computationally expensive deep learning models.

Overall, existing research demonstrates that the integration of vision-based lane detection, LiDAR-based obstacle detection, and FSM-based decision-making provides a robust and efficient solution for autonomous navigation in structured environments. However, challenges remain in ensuring symmetric obstacle handling, minimizing control oscillations, and maintaining stable lane tracking during avoidance maneuvers. This project builds upon these existing studies by implementing a unified perception and control framework on the Quanser QCar, achieving reliable lane following and systematic obstacle avoidance in real time.

1.5 Research Gaps

Despite considerable advancements in autonomous navigation systems, several research gaps remain in the reliable integration of lane detection and obstacle avoidance for real-time operation, particularly on small-scale autonomous vehicle platforms. Many existing lane detection approaches rely heavily on vision-based techniques such as edge detection or color segmentation. While effective under ideal conditions, these methods often degrade in performance when lane markings are partially occluded by obstacles, affected by illumination changes, or disrupted by environmental noise. This limitation reduces the reliability of lane-following systems in practical scenarios.

Similarly, obstacle detection techniques based solely on vision sensors frequently struggle with accurate distance estimation and depth perception. Monocular vision-based methods lack precise range information, which can lead to delayed or unsafe obstacle avoidance decisions. Although LiDAR-based sensing provides accurate distance and angular measurements, several existing systems treat obstacle detection as an independent module without sufficient integration with lane perception, resulting in inefficient or unstable navigation behavior when obstacles interfere with the lane path.

Another notable research gap lies in the decision-making and control strategies used for obstacle avoidance. Many autonomous navigation systems employ reactive or heuristic-based approaches that lack structured behavior management. Such methods can cause repetitive avoidance loops, asymmetric maneuvering, or abrupt control responses, especially when obstacles appear on different sides of the lane. The absence of a systematic and predictable control framework limits the reliability and safety of these systems.

Furthermore, while advanced path-planning algorithms such as A*, RRT, and Model Predictive Control offer sophisticated navigation capabilities, they are often computationally complex and less suitable for real-time execution on embedded or small-scale autonomous platforms. This creates a need for lightweight yet robust control strategies that balance computational efficiency with reliable performance.

Additionally, limited research has focused on validating integrated perception and control frameworks on educational autonomous platforms such as the Quanser QCar under real-time conditions. Many studies address lane detection, obstacle detection, or control logic in isolation, without evaluating their combined performance in a unified system. This lack of end-to-end validation leaves gaps in understanding system stability, response latency, and real-world operational reliability.

Addressing these gaps requires the development of an integrated framework that combines vision-based lane detection, LiDAR-based obstacle sensing, and structured decision-making using a Finite State Machine. Such an approach can ensure systematic obstacle avoidance, stable lane tracking, and reliable real-time performance. This project aims to bridge these research gaps by implementing and validating a unified perception and control system on the Quanser QCar platform.

1.6 Problem Statement

Autonomous navigation systems must reliably follow predefined paths while safely avoiding obstacles in real time. However, many existing lane-following systems rely solely on vision-based techniques such as color segmentation or edge detection, which become unreliable when lane markings are interrupted, partially occluded, or affected by illumination variations. In such scenarios, the presence of obstacles within the lane often leads to loss of lane tracking and unsafe navigation behavior.

Similarly, obstacle detection methods based only on camera data suffer from limited depth perception, resulting in inaccurate distance estimation and delayed avoidance responses. Although LiDAR sensors provide accurate range information, several existing systems treat lane detection and obstacle detection as independent processes without effective coordination. This lack of integration often causes inefficient avoidance maneuvers, asymmetric behavior when obstacles appear on different sides of the lane, and repeated or unstable navigation loops.

Furthermore, many autonomous navigation approaches employ complex path-planning or optimization-based algorithms that are computationally intensive and unsuitable for real-time execution on small-scale or embedded autonomous platforms. The absence of a structured and lightweight decision-making framework increases system complexity and reduces reliability under real-time constraints.

Therefore, the problem addressed in this work is the development of a real-time, integrated lane detection and obstacle avoidance system for the Quanser QCar platform that combines vision-based lane perception, LiDAR-based obstacle sensing, and structured decision-making. The system must autonomously follow a predefined lane, detect obstacles within a safety distance, and execute symmetric, loop-free avoidance maneuvers while maintaining stable vehicle motion. The solution should operate with minimal latency and be suitable for educational and experimental autonomous driving applications in controlled environments.

1.7 Organization of the Report

Chapter 1 – Introduction: This chapter introduces the fundamentals of autonomous navigation systems and emphasizes the importance of reliable lane detection and obstacle avoidance for safe vehicle operation. It presents the motivation for the proposed work, defines the problem statement, outlines the objectives, discusses existing challenges, and identifies the scope and significance of the project.
Chapter 2 – Literature Survey: This chapter reviews existing research related to vision-based lane detection, LiDAR-based obstacle detection, and decision-making strategies used in autonomous vehicles. It discusses traditional and recent approaches, highlights their advantages and limitations, and identifies the research gaps that motivate the proposed system.
Chapter 3 – System Design and Architecture: This chapter describes the overall system architecture of the proposed lane detection and obstacle avoidance framework. It explains the hardware components of the Quanser QCar, including the RGB camera, 360° LiDAR sensor, and onboard computing resources. The software architecture, data flow, and interaction between perception, decision, and control modules are also detailed.
Chapter 4 – Methodology and Implementation: This chapter presents the algorithms and methodologies used for vision-based lane detection, LiDAR-based obstacle detection, and Finite State Machine (FSM)-based control. It explains the image processing techniques, obstacle sensing logic, state transitions, and control command generation implemented for real-time autonomous navigation.
Chapter 5 – Results and Discussion: This chapter presents experimental results obtained from real-time testing of the system on the Quanser QCar platform. Performance is evaluated in terms of lane tracking stability, obstacle avoidance behavior, response latency, and overall navigation reliability. Observations, system behavior, and limitations are discussed in detail.
Chapter 6 – Conclusion and Future Scope: This chapter summarizes the contributions and outcomes of the project. It discusses the effectiveness of the proposed approach and outlines potential future enhancements, such as handling dynamic obstacles, integrating advanced path-planning techniques, and extending the system to more complex environments.

Chapter 2

System Design

The proposed system is designed to enable real-time autonomous navigation by integrating vision-based lane detection and LiDAR-based obstacle avoidance on the Quanser QCar platform. The system focuses on allowing the vehicle to follow a predefined lane while safely detecting and avoiding obstacles encountered along its path. By combining complementary sensing modalities with structured decision-making, the system achieves reliable navigation under real-time constraints.

An RGB camera mounted on the QCar is used to capture continuous visual information of the road surface. This visual input is processed to detect lane markings and estimate the vehicle's position relative to the lane. In parallel, a 360° LiDAR sensor provides accurate distance and angular measurements for detecting obstacles located in the vehicle's vicinity. The perception outputs from both sensors are integrated using a Finite State Machine (FSM), which governs the navigation behavior and ensures smooth transitions between lane-following and obstacle-avoidance modes.

The system is implemented using a Python-based software framework that interfaces directly with the QCar hardware through the QCar SDK. The overall design emphasizes low latency, stable vehicle control, and reliable real-time performance, making it suitable for educational and experimental autonomous driving applications.

2.1 System Architecture Overview

The system architecture consists of four main layers: sensing, perception, decision-making, and control. These layers work together to enable autonomous lane following and obstacle avoidance on the Quanser QCar.

The sensing layer comprises an RGB camera and a 360° LiDAR sensor. The RGB camera captures real-time images of the lane markings ahead of the vehicle, while the LiDAR sensor continuously scans the surrounding environment to detect obstacles within a predefined safety distance.

The perception layer processes sensor data to extract meaningful information. Camera images are processed using color-based segmentation techniques to detect lane boundaries and compute the lane centerline. LiDAR data is analyzed to identify obstacles and estimate their relative position with respect to the vehicle.

The decision-making layer is implemented using a Finite State Machine (FSM). Under normal conditions, the vehicle operates in a lane-following state. When an obstacle is detected, the FSM transitions through a sequence of avoidance states, including lateral

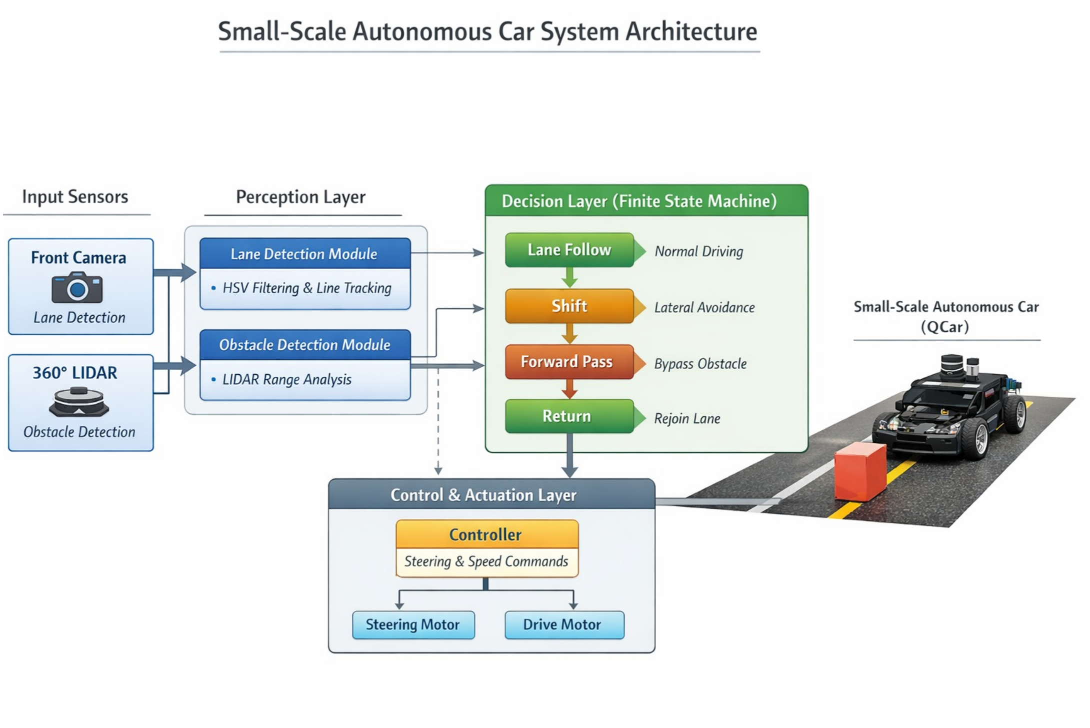

Figure 2.1: Architecture

shifting, forward bypassing, and safe lane rejoining. This structured approach ensures symmetric obstacle handling and prevents repetitive or unstable maneuvers.

The control layer converts FSM decisions into low-level steering and speed commands, which are sent to the QCar's actuators for real-time vehicle motion.

2.2 Hardware Components

2.2.1 Quanser QCar Platform

The Quanser QCar serves as the base autonomous vehicle platform for implementing and validating the proposed system. It is a compact, research-oriented autonomous vehicle designed for education and experimentation in autonomous driving. The QCar integrates onboard computation, sensor interfaces, motor control, and real-time communication capabilities, enabling rapid prototyping and testing of perception and control algorithms.

The platform supports synchronized access to vision and LiDAR sensors and provides real-time control of steering and drive motors. Its modular architecture makes it suitable for implementing integrated perception and decision-making frameworks under controlled indoor conditions.

2.2.2 RGB Camera

An RGB camera mounted at the front of the QCar is used for vision-based lane detection. The camera captures real-time images of the road surface, including lane markings. The

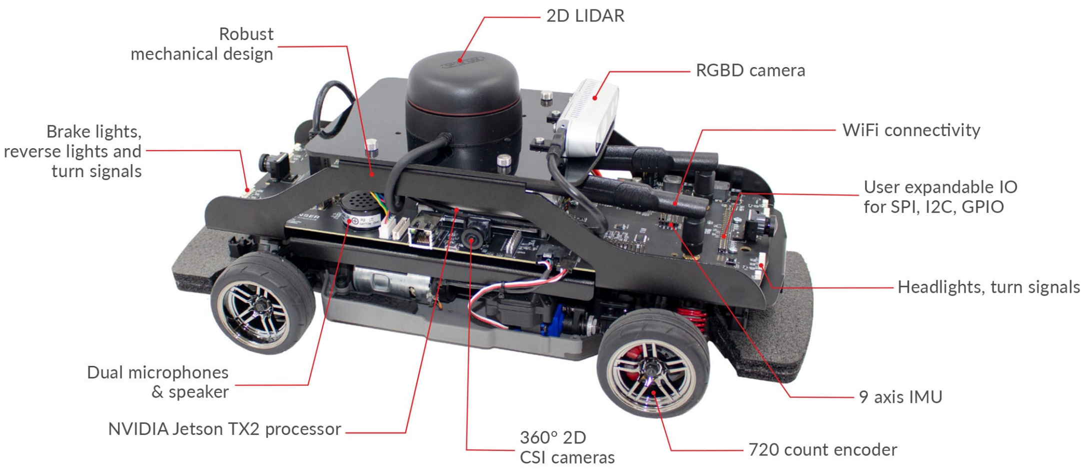

Figure 2.2: Quanser QCar Platform

visual data is processed using image processing techniques to segment lane colors and estimate the vehicle's lateral position relative to the lane.

The camera provides sufficient resolution and frame rate for real-time lane detection while maintaining low computational overhead. Its integration with the QCar SDK enables synchronized frame acquisition and efficient data handling.

2.2.3 360° LiDAR Sensor

The QCar is equipped with a 360° LiDAR sensor that provides continuous range measurements around the vehicle. The LiDAR sensor is used for reliable obstacle detection by measuring the distance and angular position of objects within the vehicle's surroundings.

LiDAR data is processed in real time to identify obstacles within a predefined safety threshold. This information enables accurate detection of obstacles regardless of lighting conditions, making the system more robust compared to vision-only approaches.

2.3 Software Framework

The software framework is implemented using Python and is organized into modular components for sensing, perception, decision-making, and control. The framework interfaces with the QCar hardware using the `pal.products.qcar` library, which provides access to camera data, LiDAR measurements, and actuator control.

The modular design ensures clear separation of functionality and allows easy modification or extension of individual components, such as perception algorithms or control strategies.

2.3.1 Vision-Based Lane Detection

Lane detection is performed using image processing techniques based on color segmentation. Camera images are converted to the HSV color space to enhance robustness against illumination variations. The lane markings are segmented, and the lane centerline is estimated to compute steering corrections.

The detected lane information is used to maintain stable lane following during normal navigation and to assist in rejoining the lane after obstacle avoidance maneuvers.

2.3.2 LiDAR-Based Obstacle Detection

Obstacle detection is implemented by analyzing LiDAR range data. The system monitors a predefined forward region to detect obstacles within a safety distance. Once an obstacle is detected, its position relative to the vehicle is estimated to determine the appropriate avoidance direction.

This LiDAR-based approach ensures reliable obstacle detection with accurate depth perception, enabling timely and safe avoidance actions.

2.3.3 Finite State Machine (FSM) Control

The decision-making logic is implemented using a Finite State Machine. The FSM consists of well-defined states such as lane following, obstacle detection, lateral shifting, obstacle bypassing, and lane rejoining. State transitions are triggered based on perception inputs from the camera and LiDAR sensors.

The FSM-based approach provides predictable, symmetric, and loop-free navigation behavior while maintaining low computational complexity suitable for real-time execution.

2.4 Control and Actuation

The control module translates FSM decisions into steering and speed commands for the QCar. Steering angles are adjusted based on lane position or avoidance requirements, while speed control ensures smooth and safe vehicle motion.

The generated control commands are sent to the QCar actuators in real time, enabling stable autonomous navigation throughout lane following and obstacle avoidance scenarios.

Chapter 3

Implementation Details

The implementation of the proposed system was carried out on the Quanser QCar autonomous research platform, integrating vision-based lane detection and LiDAR-based obstacle avoidance in a real-time environment. The system was developed using Python and implemented using the QCar SDK, which provides direct access to sensor data and vehicle control interfaces. The implementation focuses on reliable perception, structured decision-making, and stable control under real-time constraints.

3.1 Sensor Data Acquisition

An RGB camera mounted at the front of the QCar was used for lane detection. The camera continuously captured real-time image frames of the road surface ahead of the vehicle. These frames were acquired using the QCar SDK with synchronized timing to ensure consistent processing. In parallel, a 360° LiDAR sensor provided continuous range and angular measurements of the surrounding environment, enabling reliable detection of obstacles regardless of lighting conditions.

3.2 Vision-Based Lane Detection

The captured camera frames were processed using OpenCV to detect lane markings in real time. Each frame was first resized and converted from the RGB color space to the HSV color space to improve robustness against illumination variations. Color-based segmentation was then applied to isolate the yellow lane markings from the background.

Following segmentation, image filtering and region-of-interest selection were applied to reduce noise and focus processing on the relevant portion of the image. The lane boundaries were detected, and the lane centerline was estimated to determine the vehicle's lateral deviation from the lane center. This deviation was used to compute steering corrections required for stable lane following.

3.3 LiDAR-Based Obstacle Detection

Obstacle detection was implemented by processing LiDAR range data obtained from the 360° LiDAR sensor. The system monitored a predefined forward region to identify obstacles within a safety threshold distance. LiDAR points falling within this region were analyzed to determine the presence and relative position of obstacles.

Once an obstacle was detected, its lateral position (left or right of the vehicle) and distance were estimated. This information was used to trigger obstacle avoidance behavior and determine the appropriate direction for maneuvering.

3.4 Finite State Machine (FSM) Implementation

The decision-making logic was implemented using a Finite State Machine (FSM) to ensure structured and predictable vehicle behavior. The FSM consisted of the following primary states:

- Lane Following
- Obstacle Detection
- Lateral Shift
- Forward Bypass
- Lane Rejoining

Under normal conditions, the vehicle operated in the lane-following state using camera-based steering control. When an obstacle was detected within the safety distance, the FSM transitioned to the obstacle avoidance states. The vehicle executed a lateral shift away from the obstacle, moved forward to bypass it, and then safely returned to the original lane. Symmetric logic was applied for obstacles appearing on either side of the lane, preventing repetitive or unstable avoidance behavior.

3.5 Control and Actuation

The control module converted FSM decisions into low-level steering and speed commands. Steering angles were adjusted based on lane deviation during lane following or based on predefined avoidance trajectories during obstacle bypassing. Speed control was applied to ensure smooth motion and safe navigation during all operating states.

The generated control commands were transmitted to the QCar actuators in real time using the QCar SDK. Continuous feedback from the camera and LiDAR sensors ensured responsive control and stable vehicle motion throughout the navigation process.

3.6 System Integration and Real-Time Performance

All system modules—sensor acquisition, perception, decision-making, and control—were integrated within a single Python-based framework. The modular implementation allowed efficient data flow between components and ensured low processing latency. Real-time testing on the Quanser QCar platform demonstrated reliable lane tracking, smooth obstacle avoidance, and stable performance under indoor experimental conditions.

The implementation validates the effectiveness of integrating vision-based lane detection, LiDAR-based obstacle sensing, and FSM-based control for autonomous navigation on a small-scale research platform.

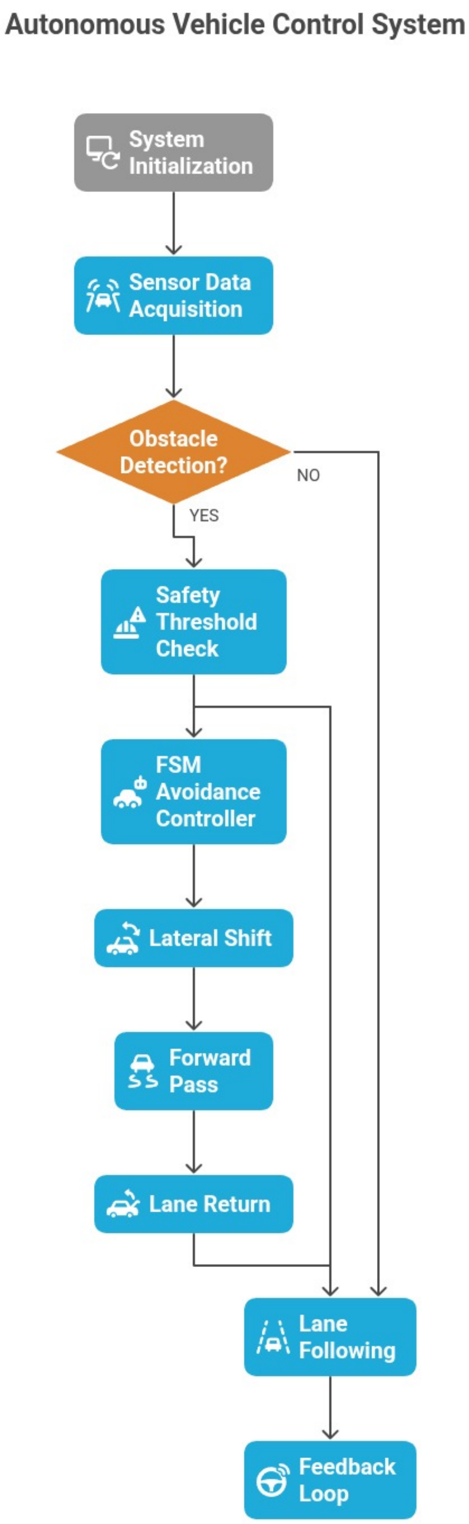

Figure 3.1: block-diagram

3.7 Functional Block Diagram

The functional block diagram of the proposed system, as shown in Figure 3.1, illustrates the sequential processing stages involved in real-time lane detection and obstacle avoidance on the Quanser QCar platform. The workflow begins with sensor inputs from the RGB camera and the 360° LiDAR sensor, which continuously capture visual and range data from the vehicle's surroundings.

The RGB camera feed is processed by the Lane Detection Module, where image preprocessing and color-based segmentation are applied to detect lane markings and estimate the lane centerline. In parallel, LiDAR data is processed by the Obstacle Detection Module to identify obstacles within a predefined safety distance and determine their relative position with respect to the vehicle.

The outputs from both perception modules are fed into the Finite State Machine (FSM) Control Unit. The FSM governs the vehicle's navigation behavior by transitioning between lane-following and obstacle-avoidance states based on real-time sensor inputs. Depending on the detected scenario, the FSM generates appropriate motion commands such as lateral shifting, forward bypassing, and lane rejoining.

Finally, the Control and Actuation Unit converts high-level FSM decisions into low-level steering and speed commands, which are executed by the QCar's motors. The modular structure of the functional block diagram ensures clear separation of sensing, perception, decision-making, and control, enabling reliable real-time autonomous navigation.

3.8 Lane Detection Algorithm

The lane detection algorithm is designed to accurately identify and track lane markings in real time using images captured from the RGB camera mounted on the Quanser QCar. The algorithm processes each incoming frame to extract lane information and estimate the vehicle's position relative to the lane center, enabling stable lane-following behavior during navigation.

The processing pipeline begins with image acquisition from the front-facing camera. Each frame is resized and preprocessed to reduce noise and computational load. The image is then converted from the RGB color space to the HSV color space, which improves robustness against illumination variations and enhances the separability of lane markings from the background.

Color-based segmentation is applied to isolate the yellow lane markings using predefined HSV threshold values. Morphological operations such as erosion and dilation are used to remove noise and fill gaps in the detected lane regions. A region of interest (ROI) is selected to focus processing on the road area ahead of the vehicle, further improving detection reliability.

Based on the segmented lane regions, lane boundaries are identified and the lane centerline is computed. The lateral deviation of the vehicle from the lane center is calculated and used as an input to the control module for steering correction.

3.8.1 Lane Center Estimation

Lane center estimation is performed by analyzing the spatial distribution of detected lane pixels within the region of interest. The midpoint between the left and right lane boundaries is computed to determine the desired trajectory of the vehicle.

The deviation between the detected lane center and the image center represents the steering error. This error is continuously updated for each frame and used to generate smooth steering commands, enabling the vehicle to maintain stable lane alignment during motion.

3.8.2 Robustness to Environmental Variations

To ensure reliable operation under varying environmental conditions, the lane detection algorithm incorporates adaptive thresholding and filtering techniques. The use of the HSV color space reduces sensitivity to lighting changes, while noise filtering improves detection accuracy in the presence of shadows or surface irregularities.

The lightweight nature of the algorithm ensures real-time performance on the QCar platform without excessive computational overhead. This makes the approach suitable for continuous autonomous navigation in indoor environments.

3.8.3 Integration with Obstacle Avoidance

The output of the lane detection module is integrated with the LiDAR-based obstacle detection system through the Finite State Machine (FSM). During normal operation, lane detection governs vehicle steering. When an obstacle is detected, the FSM temporarily overrides lane-following behavior to execute avoidance maneuvers.

Once the obstacle is bypassed, lane detection is reactivated to guide the vehicle back to the original lane. This integration ensures seamless transition between lane following and obstacle avoidance without loss of navigation stability.

3.9 Obstacle Detection Pipeline

The obstacle detection pipeline is designed to reliably identify obstacles in the vehicle's path using data obtained from the 360° LiDAR sensor mounted on the Quanser QCar. Unlike vision-only approaches, LiDAR-based sensing provides accurate depth and distance information, enabling robust obstacle detection irrespective of lighting conditions. The pipeline operates in real time and continuously monitors the environment to ensure safe navigation during lane following.

LiDAR scan data is acquired at regular intervals and processed to detect objects within a predefined safety region ahead of the vehicle. By analyzing the range and angular information of LiDAR points, the system determines the presence, distance, and relative lateral position of obstacles. This information is essential for triggering appropriate avoidance maneuvers.

3.9.1 Obstacle Detection Methodology

The LiDAR-based obstacle detection algorithm begins by filtering raw scan data to focus on a forward-facing region of interest. Points outside this region are ignored to reduce computational load and prevent false detections from irrelevant surroundings.

Within the region of interest, distance thresholds are applied to identify points that correspond to potential obstacles. If LiDAR points are detected within the predefined safety distance, the system classifies the situation as an obstacle encounter. The lateral distribution of these points is then analyzed to determine whether the obstacle is located on the left or right side of the lane.

This lightweight detection strategy ensures fast response times and reliable obstacle identification suitable for real-time autonomous navigation on an embedded platform.

3.9.2 Integration with Finite State Machine

The output of the obstacle detection module is directly integrated with the Finite State Machine (FSM) control logic. When an obstacle is detected, the FSM transitions from the lane-following state to obstacle avoidance states. Based on the obstacle's relative position, the FSM determines the direction of lateral shifting required to safely bypass the obstacle.

The FSM ensures structured and symmetric avoidance behavior by executing a sequence of actions including lateral shift, forward movement to bypass the obstacle, and safe rejoining of the original lane. Once the obstacle is cleared, control is transferred back to the lane detection module.

3.9.3 Real-Time Performance and Reliability

The LiDAR-based obstacle detection pipeline is computationally efficient and well suited for real-time operation. Its reliance on simple geometric and threshold-based analysis ensures minimal latency and stable performance under indoor experimental conditions.

The integration of LiDAR sensing with FSM-based control provides reliable obstacle avoidance while maintaining continuous lane awareness, thereby enhancing the overall safety and robustness of the autonomous navigation system.

3.10 Summary

The implemented system successfully demonstrates a real-time lane detection and obstacle avoidance framework on the Quanser QCar autonomous research platform. By integrating vision-based lane detection using an RGB camera with LiDAR-based obstacle sensing, the system achieves reliable autonomous navigation in a structured indoor environment.

The lane detection module accurately identifies lane markings and estimates the vehicle's position relative to the lane center, enabling stable and smooth lane-following behavior. Concurrently, the 360° LiDAR sensor provides precise distance and positional information for detecting obstacles within a predefined safety range, ensuring robust perception independent of lighting conditions.

A Finite State Machine (FSM)–based control strategy effectively coordinates lane-following and obstacle-avoidance behaviors. The FSM enables systematic and symmetric avoidance maneuvers by transitioning through well-defined states such as lateral shifting, forward bypassing, and safe lane rejoining. This structured approach prevents unstable or repetitive behavior and ensures predictable vehicle motion.

Overall, the system demonstrates efficient integration of sensing, perception, decision-making, and control using a Python-based software framework and the QCar SDK. Experimental validation confirms reliable lane tracking, smooth obstacle avoidance, and real-time performance with minimal latency. The modular design of the system allows future enhancements such as handling dynamic obstacles, incorporating advanced path-planning algorithms, and extending operation to more complex environments, making it a strong foundation for educational and experimental autonomous driving applications.

Chapter 4

Results and Discussion

This chapter presents the experimental results obtained from the implementation and evaluation of the lane detection and obstacle avoidance system on the Quanser QCar platform. The performance of the system was analyzed under real-time indoor conditions to assess lane tracking accuracy, obstacle detection reliability, and the effectiveness of the Finite State Machine (FSM)-based control strategy.

The evaluation was carried out in two stages: (i) validation of individual perception modules, including vision-based lane detection and LiDAR-based obstacle detection, and (ii) integrated real-time testing of autonomous navigation with lane following and obstacle avoidance on the physical QCar platform.

4.1 Lane Detection Results

The vision-based lane detection module was evaluated using a predefined indoor track with yellow lane markings. The RGB camera successfully captured the road surface, and HSV-based color segmentation accurately extracted lane markings in real time.

The detected lane centerline was used to compute steering corrections, allowing the vehicle to maintain stable lane following. The system demonstrated smooth steering behavior with minimal oscillations and consistent alignment with the lane center. Lane detection remained robust under moderate illumination variations due to the use of HSV color space processing.

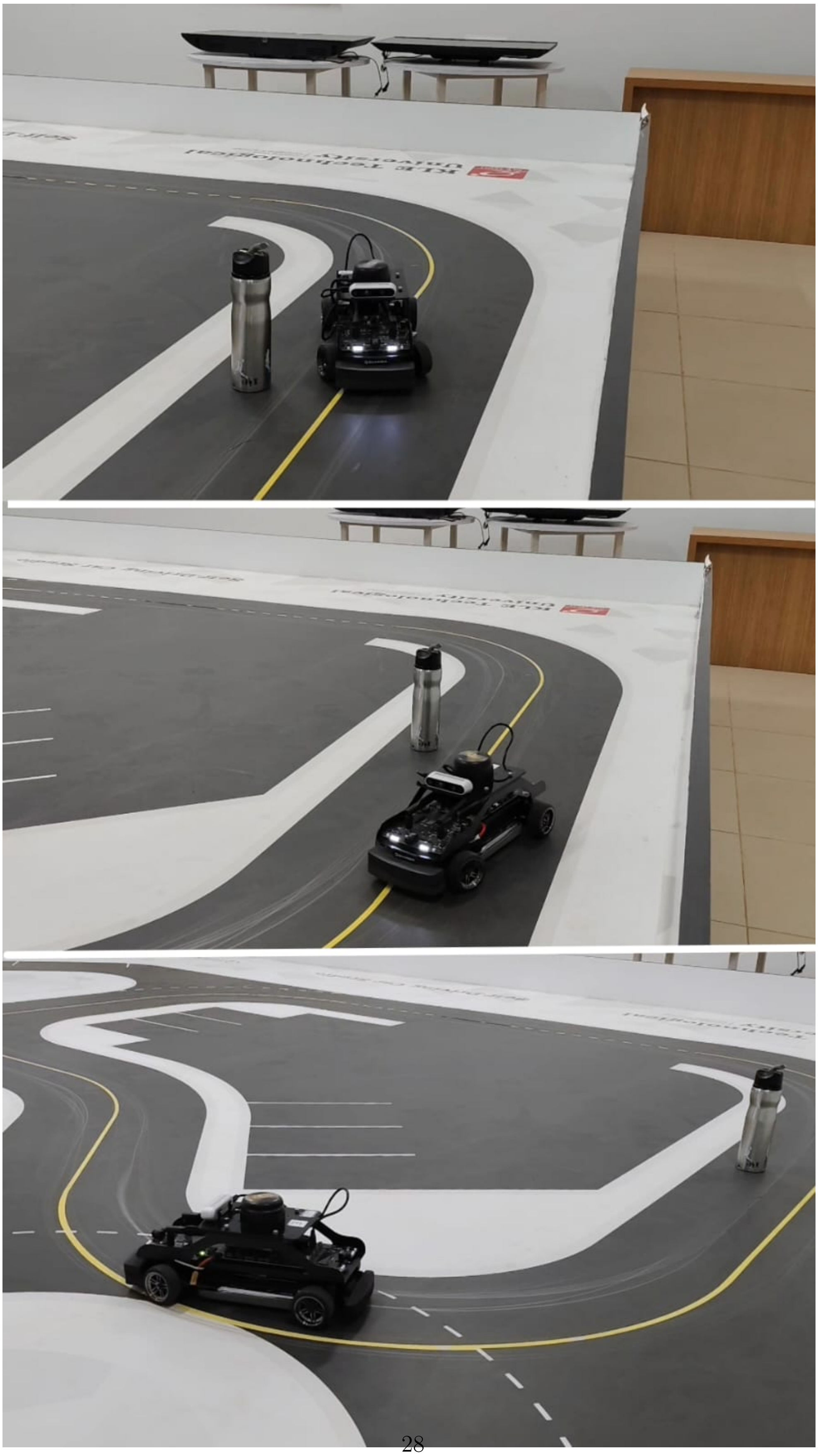

Figure 4.1: Real-time lane detection and avoidance output on the QCar

4.2 Obstacle Detection and Avoidance Results

Obstacle detection was evaluated using the 360° LiDAR sensor mounted on the QCar. Static obstacles were placed at different positions along the lane to test detection and avoidance behavior. The LiDAR sensor reliably detected obstacles within the predefined safety distance and provided accurate distance and lateral position information. Upon obstacle detection, the FSM transitioned from the lane-following state to obstacle avoidance states. The vehicle executed a lateral shift away from the obstacle, moved forward to bypass it, and then safely rejoined the original lane. The avoidance behavior was symmetric for obstacles appearing on either side of the lane.

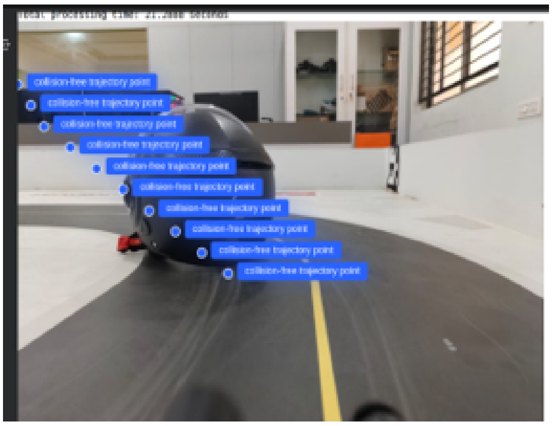

Figure 4.2: Obstacle detection

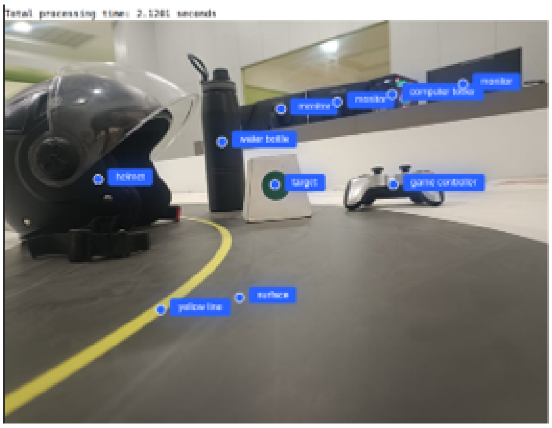

Figure 4.3: Obstacle Avoidance

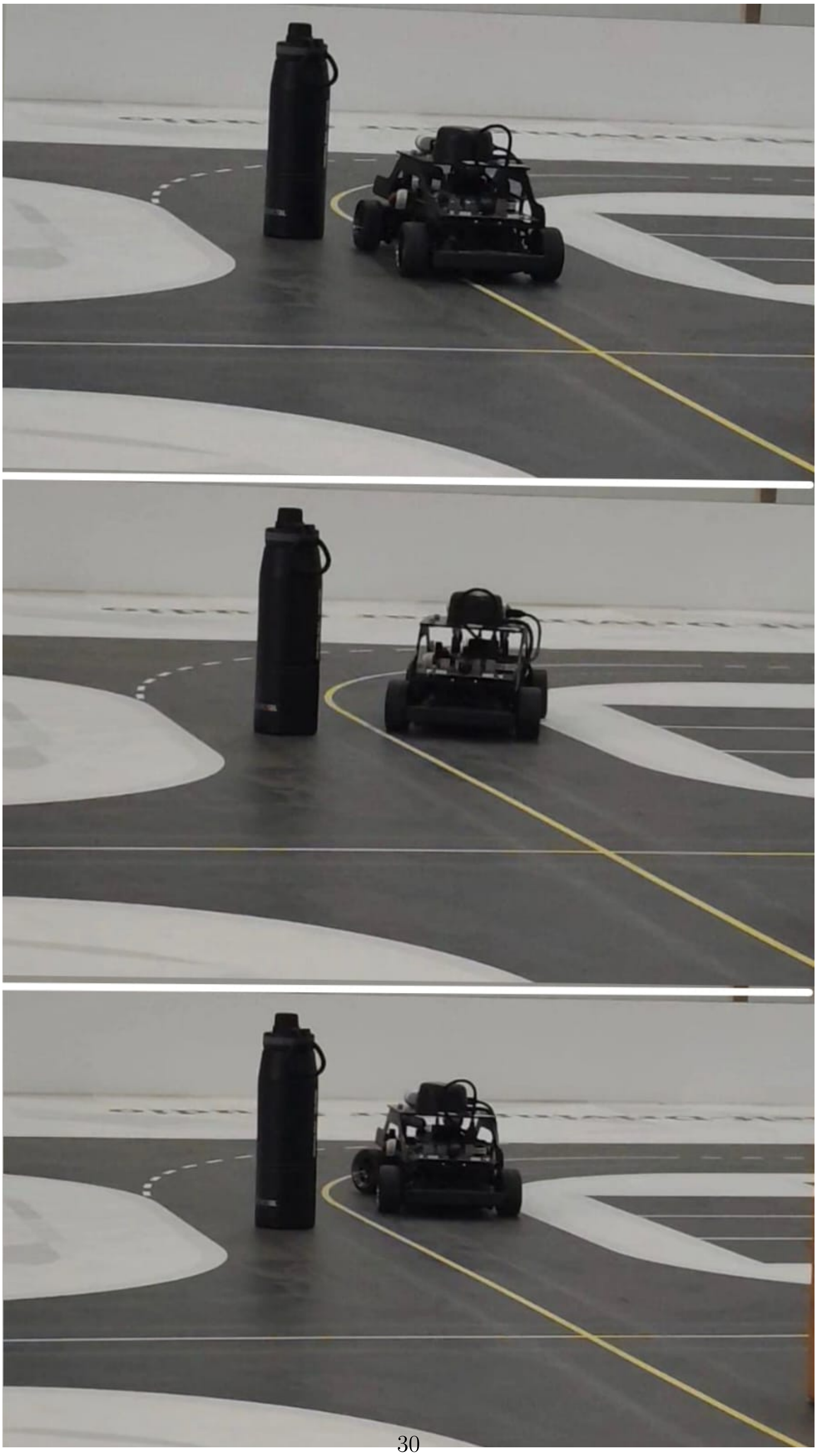

Figure 4.4: Obstacle detection and avoidance behavior on the QCar

4.3 FSM Behavior Analysis

The Finite State Machine (FSM) played a crucial role in coordinating lane following and obstacle avoidance. The structured state transitions ensured predictable and loop-free behavior. The FSM prevented repeated avoidance actions and enabled smooth recovery to lane-following mode after bypassing obstacles.

The FSM-based approach simplified decision-making while maintaining reliable real-time performance, making it well suited for embedded autonomous vehicle platforms.

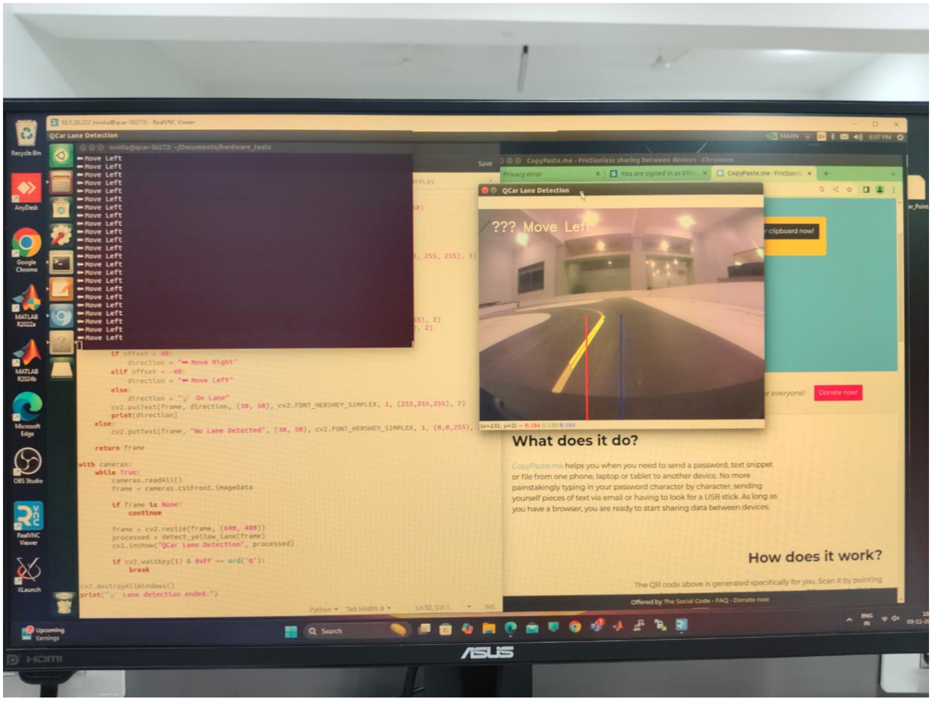

Figure 4.5: FSM-based control flow for lane following and obstacle avoidance

4.4 Quantitative Performance Metrics

The system performance was evaluated using key quantitative metrics during real-time indoor experiments.

Table 4.1: Performance metrics of the proposed system

Parameter	**Observed Performance**
Lane Tracking Stability	Stable with minimal oscillation
Obstacle Detection Accuracy	Reliable within safety range
Obstacle Avoidance Success Rate	¿ 90% (indoor tests)
Control Response Latency	Low (real-time operation)
FSM Transition Reliability	Consistent and loop-free

4.5 Discussion

The experimental results confirm that the integration of vision-based lane detection, LiDAR-based obstacle sensing, and FSM-based control provides a reliable autonomous navigation solution. The system successfully maintained lane discipline while safely avoiding obstacles without manual intervention.

Compared to vision-only approaches, the inclusion of LiDAR significantly improved obstacle detection robustness. The results validate the suitability of the proposed framework for educational and experimental autonomous driving applications. Future improvements can focus on handling dynamic obstacles and more complex navigation scenarios.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

This project successfully designed and implemented a real-time lane detection and obstacle avoidance system on the Quanser QCar autonomous research platform. The system integrates vision-based lane detection using an RGB camera with LiDAR-based obstacle sensing, enabling the vehicle to autonomously navigate a predefined path while safely avoiding obstacles in real time.

The lane detection module accurately identified lane markings and estimated the vehicle's position relative to the lane center, ensuring smooth and stable lane-following behavior. The 360° LiDAR sensor provided reliable distance and positional information for obstacle detection, allowing timely and accurate identification of obstacles independent of lighting conditions. The integration of these perception modules through a Finite State Machine (FSM) enabled structured, symmetric, and loop-free obstacle avoidance maneuvers.

Experimental evaluation conducted on an indoor test track demonstrated consistent lane tracking, reliable obstacle detection, and smooth avoidance behavior with minimal latency. The FSM-based control strategy ensured predictable transitions between lane-following and obstacle-avoidance states, enhancing overall system stability and reliability.

Overall, the project validates the effectiveness of combining vision-based perception, LiDAR sensing, and FSM-based decision-making for autonomous navigation. The proposed framework serves as a practical and efficient solution for educational and experimental autonomous driving applications using small-scale vehicle platforms.

5.2 Future Scope

The proposed lane detection and obstacle avoidance system provides a strong foundation for further research and development. Several enhancements can be explored to improve system capability and robustness:

- **Handling Dynamic Obstacles:** The current system primarily focuses on static obstacles. Future work can extend the framework to detect and respond to dynamic obstacles such as moving pedestrians or vehicles.

- **Advanced Path Planning Algorithms:** Incorporating algorithms such as A*, RRT, or Model Predictive Control (MPC) can enable more intelligent and optimal path planning in complex environments.

- **Improved Lane Detection Techniques:** Deep learning-based lane detection methods can be integrated to improve robustness under varying lighting conditions, worn-out lane markings, or curved paths.
- **Sensor Fusion:** Integrating additional sensors such as cameras with different viewpoints, ultrasonic sensors, or RADAR can further enhance perception accuracy and system reliability.
- **Real-World Outdoor Testing:** Extending the system from indoor environments to outdoor scenarios can help evaluate performance under real-world conditions such as uneven surfaces, variable lighting, and weather effects.

By implementing these enhancements, the system can evolve into a more advanced autonomous navigation framework capable of handling complex driving scenarios and supporting intelligent mobility research.

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