Research of Autonomous Driving Capabilities Utilizing Computer Vision in a Formula SAE Vehicle

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1 Abstract

The primary goal of this project is to research and develop an autonomous 1:10 scale car, the GRmini. GRmini serves as a small-scale vehicle prototype for developing and testing driverless software. Using the open-source Formula Student Objects in Context (FSOCO) dataset, which is specifically for the cones used in competition, the project will develop a path-planning algorithm that integrates object detection with speed control to navigate corners and the course. This work will allow Gaucho Racing to later integrate our software and hardware findings into the full-sized Formula SAE racecar.

2 Overview

2.1 Background

In autonomous vehicle design, the ability to detect and navigate around obstacles in real time is critical for reliable and safe operation. Many autonomous systems, including Formula SAE teams, use LiDAR (Light Detecting and Ranging) and GPS-INS (Global Positioning System–Inertial Navigation System). High-resolution LiDAR units are extremely expensive, often costing thousands of dollars per sensor. Stereo camera systems, by contrast, provide real-time depth perception at a fraction of the cost. While this can reduce accuracy compared to full LiDAR + camera setups, it offers a lower-cost, easier-to-use alternative. Developing software for a camera-only system is simpler than integrating multiple sensor inputs. GRmini's camera-only approach allows testing its effectiveness against LiDAR and sensor-based driverless cars without risking the full-size FSAE vehicle, providing a practical pathway for low-cost autonomous navigation. Formula SAE's Driverless Supplement offers a controlled environment for testing, with full implementation expected by 2030.

GRmini provides UCSB's FSAE team a platform to study perception, path planning, and control affordably. While LiDAR and GPS-INS deliver high-accuracy localization, research on reliable navigation using only stereo vision on low-power embedded hardware is limited. This project investigates whether a stereo-camera system can achieve sufficient detection accuracy and real-time responsiveness to autonomously navigate a Formula SAE–style course.

2.2 Objectives

Our primary objective is to develop and implement a camera-only system for live autonomous navigation of a small-scale vehicle, GRmini. This prototype will serve as a test bench for object detection and path-planning software development. It will be deemed a success if GRmini can navigate one lap of a cone-lined course fully autonomously by May of 2026. This course should be about 0.5 to 0.8 kilometers in length, similar to a real Formula SAE course, and GRmini should be able to complete it in under 2 minutes at about 25 kilometers per hour. The above objective serves the longer-term goal of improving the Gaucho Racing team's competitiveness in the upcoming driverless section of the Formula SAE competition. To transfer code from GRmini to the full-sized racecar, there are only minor tweaks necessary, such as camera location and integration with the existing firmware. Essentially, most of the legwork, which includes object detection, path-planning, and their integration, will be completed through this prototype. This strategy will avoid tying up the rest of the Gaucho Racing subteams by working on a prototype instead of the constantly evolving full-scale car. In the end, research aims to facilitate a reliable prototype for a cost-effective, camera-only driverless system that can be integrated into a full-sized Formula SAE car.

3 Methodology

3.1 SOFTWARE DEVELOPMENT

The software development process will begin with implementing algorithms for cone detection, path planning, and real-time control using Python and OpenCV. The Robot Operating System (ROS) will serve as the middleware that connects these modules, manages communication between them, and provides the tools needed for sensor integration and testing. To train our cone-detection model, we will use an open-source dataset specifically designed for traffic-cone recognition. Through iterative testing and integration within the ROS environment, we will verify that our path-planning and object detection software modules work reliably as part of the full autonomous driving stack. To improve overall performance, we will tune system parameters such as PID gains to ensure smooth and responsive vehicle motion under different operating conditions. All computer-vision and path-planning processes will run on an Nvidia Jetson Nano, an onboard computer capable of handling real-time camera input and computation.

3.2 SIMULATION TESTING

This project will use the community-built Formula Student Driverless Simulator, which models vehicle dynamics and track layouts, to safely test algorithms before deploying them onto a physical prototype. In simulation, we will evaluate performance under controlled variations such as cone spacing, lighting conditions, and vehicle speed to measure whether the system meets expected outcomes, such as maintaining lane centering within a set tolerance, detecting cones with high precision, and completing a full track without collisions. We will also create edge cases that test system limits, including missing cones, sudden obstacles, irregular cone placements, and very tight turns that challenge the path planning and control algorithms. These scenarios allow us to assess boundary conditions such as maximum steering responsiveness, perception reliability in noisy settings, and how well the system recovers when detection fails. By comparing simulated results with these objective performance targets, we can refine GRmini's control strategy and increase confidence that the system will behave reliably in real-world conditions.

3.3 PROTOTYPE CONSTRUCTION

The prototype will be constructed from a simple 1:10 RC car chassis with drivetrain motors, a steering servo, and a frame with wheels, while components such as the Jetson Nano, Zed 2i Stereo Camera, and mounting hardware will either be external or custom-built. Custom mounts for the Jetson Nano, the Zed 2i stereo camera, and the electronic speed controller will be designed in CAD and fabricated through machining and 3D printing to ensure proper alignment, vibration resistance, and secure cable routing. For the computational power needed for the algorithms that will be running on GRmini, we will use the Jetson Nano.

3.4 FINAL TESTING

After the prototype has been constructed and programmed, a half-kilometer cone-lined track will be built to test the driving capabilities of the prototype in real-world conditions, as well as the software algorithms that enable the live pathfinding and object detection of GRmini.

4 Addendum

Hrithik Mereddy – Object Detection

I will be in charge of the development and testing of the object detection system, and this is an important part of the vehicle's autonomous driving software. I will mainly be focusing on developing the algorithms needed to track and identify objects in the vehicle's environment that are scanned by the stereo camera. I will also be optimizing the performance of the object detection algorithm on the vehicle's onboard computer, the Jetson Nano. Another important role I will take on in the development of GRmini's software is the testing and validation of the software once it is integrated with the vehicle. First, I will test the object detection software by uploading a video feed and specific frames to check its accuracy. This will allow me to see how effective the machine learning model is in the detection and tracking of objects in different scenarios, such as cone configurations for the track, light levels, and obstacle configurations. Testing will allow me to quickly debug and update my code, which will improve the accuracy and reliability of the vehicle's object detection system. Once the software has been tested successfully in simulation, I will be able to apply it to the GRmini vehicle and test the car's object detection in the real world. Through object detection, I will make sure that the autonomous driving software possesses a proper and accurate perception of its environment. By utilizing simulation and real-world testing, I will be able to tune the object detection capabilities of GRmini in order to enable safe and effective autonomous navigation.

Aditya – Path Planning and PID Control

I will work on creating a path-planning algorithm and integrating it with the object detection software. I will begin this by researching different ways that vision-based autonomous cars behave in the real world. This algorithm will adjust the speed and direction of GRmini depending on the obstacles and curves ahead. An important part of my work would be processing the object detection software that Hrithik writes, which allows the data to be read and analyzed by the path-planning algorithm so that it can safely avoid obstacles. To accomplish this processing, I will work with Hrithik to research and learn computer vision techniques like depth estimation and feature tracking. In order to create a proper path-planning algorithm, I will be using Proportional-Integral-Derivative (PID) controls, which constantly adjust and distribute power to each of the motors based on real-time environment conditions. Once the path is identified, I will compute optimal steering angles and speed targets. PID control is essential for producing smooth, stable motion, and I will tune the gains through experimental testing to ensure that the car can react appropriately to sudden changes in spacing, unexpected obstacles, or tight corners. I will also integrate sensor feedback loops into GRmini. These loops allow the car to constantly compare its current trajectory with the intended trajectory as given by the code. This way, our software can solve errors it faces in real time, such as speed deviation, heading, and cross-track errors. These errors would feed into the PID controls, which allow the car to minimize drift and maintain a proper trajectory line.

Tanay – Hardware Integration

I will be in charge of the GRmini autonomous vehicle's hardware integration and design. Assembling the actual vehicle and connecting the electrical and mechanical components will be my responsibility in order to make sure they work reliably with the autonomous software. I will start by designing the vehicle's layout and figuring out the best locations for the motor, steering servos, speed controller, and power system to make sure the vehicle is stable and organized. Additionally, I'll install the Jetson Nano and stereo camera so that the computing hardware and camera have a good field of view. Along with the assembly of the mechanical components, I will also be installing the vehicle's electronics, including the high-current buck converter, power distribution board, and motor controller. I'll make sure the car's power system provides enough voltage and current to the onboard computer as well. In order to guarantee that the sensors, motor, and control electronics are all in sync for seamless operation, I will also be communicating with Juno, who is in charge of the firmware. To make sure the car responds in accordance with the commands from the autonomous driving software, I will test the electrical and mechanical systems after the vehicle is constructed. The job involves diagnosing issues and implementing modifications to the vehicle that boost its dependability. By integrating the hardware, I will have created a solid foundation for Hrithik and Aditya to concentrate on developing the algorithms needed for detection and path finding. My role involves ensuring GRmini is a ready and stable platform for researching and developing autonomous driving capabilities for FSAE.

Juno – Embedded Firmware and Testing

I will be responsible for integrating and testing the entirety of the system produced by my team members. My role centers on bringing together each subsystem into a functional and reliable autonomous pipeline. I will work to connect Hrithik's object detection software to Aditya's path-finding algorithm, verifying that the outputs of one module become clean, interpretable inputs for the next. I will test this system end-to-end, ensuring it is both interpretable and interoperable so that the GRmini behaves predictably in real-world conditions. A major part of my responsibility involves connecting Aditya's PID controls to the hardware and software components that make up the vehicle. I will ensure the Jetson Nano and other physical components receive the correct signals generated by the computer vision system, and that these signals translate into stable steering and throttle adjustments. I will run structured test suites to uncover edge cases and error scenarios, especially those that emerge from interactions between Tanay's hardware work and the software-driven modules. This includes identifying unexpected latencies, sensor-to-actuator mismatches, or behaviors that differ from simulation results. Final integration and confirming congruency with predicted simulation outcomes will be an important contribution of mine. I will verify the full loop of functionality from data input to object identification, path plotting, and ultimately reliable following of the computed path. I will handle much of the final testing, both simulation and real-life, including diagnosing root causes of failed behaviors during physical track tests. These findings will guide the team in refining and improving individual subsystems to create a cohesive and dependable autonomous platform.