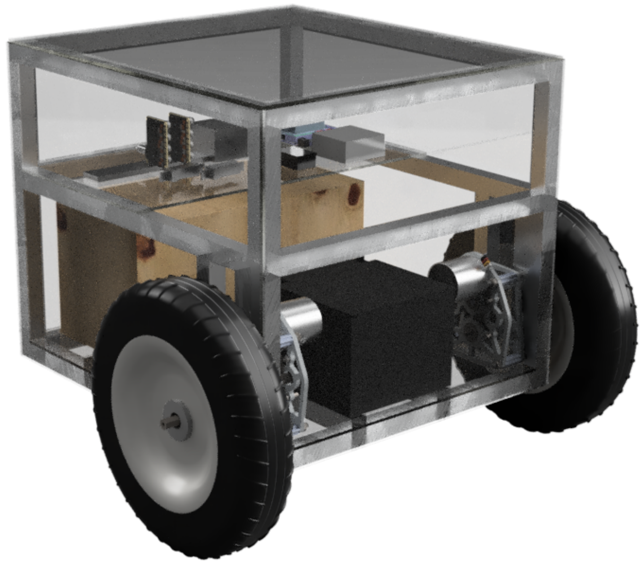
Oakland University IGVC 2025 — Horizon



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Date submitted: May 15, 2025

STATEMENT OF INTEGRITY:
I certify that the design and engineering of __Horizon__ by the current listed student team has been significant and equivalent to what would be awarded credit in a senior design course at Oakland University.

x________________05/15/2025________
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Introduction

The Robotics Association at Oakland University is proud to present Horizon Jr., the latest iteration of our intelligent robotic platform for the 2025 Intelligent Ground Vehicle Competition. The team set out with the goals of improving system reliability, enhancing autonomous navigation, and accomplishing the requirements of IGVC's autonomous waypoint navigation, obstacle avoidance, and lane detection in an outdoor environment.

Team Organization

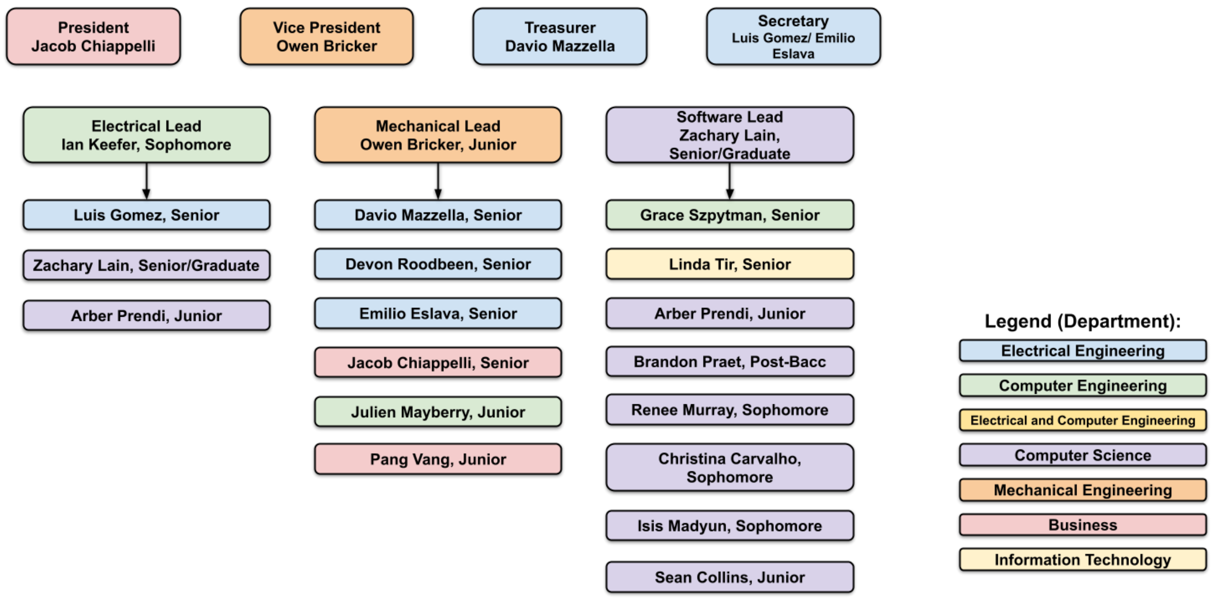

Figure 1: Organization Chart

The Robotics Association at Oakland University is composed of students from various academic disciplines and class levels. The team includes an executive board and leads for electrical, mechanical, and software sub-teams. Executive board members handle administrative responsibilities, allowing team members to focus on the technical development of their respective sub-teams. Members of a given sub-team are encouraged to engage with other sub-teams to create a more comprehensive finished product. General meetings are held regularly to promote cross-team collaboration, while sub-team meetings are scheduled as necessary for key development milestones. Approximately 1722 person-hours were invested in the project.

Subteam	Subteam Hours	Number of Members	Total Hours
Electrical	68	4	272
Mechanical	70	7	490
Software	120	8	960
		Total Team Hours:	1722

Table 1: Breakdown of Person Hours Expended

Design Assumptions & Design Process

This year's design aims to comply with the requirements and objectives laid out in IGVC's 2025 Official Competition Rules, while also integrating previous year judge feedback and insights from returning team members. Using last year's design as a base, changes were made iteratively to improve and complete portions of the robot that were either lacking comprehension, required additional tuning, or required a complete overhaul.

System Architecture of Vehicle

The chassis is designed to provide a stable and secure platform for the required electrical and software components. This resulted in the current design that features an easily accessible e-box and top-mounted sensors. The Jetson Orin Nano manages data collection from sensors and drives the motor controllers via communication on the CAN bus. The data the Jetson collects is processed within ROS2 to determine its ideal trajectory during autonomous operation. Sensors the Jetson pulls data from include the Slamtec LiDAR device, ZED 2i Camera, and Sparkfun GPS. The system primarily operates on 12V, with the stack light using 24V supplied from a boost converter. Safety devices include a physical emergency stop button connected to the robot and an RF-triggered latch acting as the remote emergency stop.

Effective Innovations in Vehicle Design

The design of Horizon was decided upon after reviewing last year's performance. Instead of mounting two caster wheels to the front and rear of the vehicle, weight is distributed across three points, minimizing wobble. The components of the electrical box have been overhauled to work with a DIN rail system, allowing for more efficient management and replacement of parts.

Description of Mechanical Design

Overview

Horizon builds on the general principles of the previous iteration, improving on several weaknesses discovered before and during the 2024 competition. With this in mind, the sub-team worked to condense and generally improve the functionality of the chassis and other mechanical systems.

Design on Frame, Enclosure, Interior & Exterior Components, and Wheelbase

Frame and Enclosure. The frame consists of an aluminium beam and steel bracket construction, similar to that of the previous robot. Aluminium was chosen for the beams due to its low weight and relative ease of machining, while steel was chosen for its strength and low ductility. Each face of the frame is covered in an acrylic sheet to protect the interior from debris. The beams were machined using a band saw and a belt grinder. A waterjet was used to cut out the brackets. Improved from last year, the brackets were designed in such a way that no bending would be needed. The chassis includes two openings, one on the side to accommodate the payload and one on the top to access the rest of the internals. Weatherstripping was inserted between the beams and the acrylic panels to increase the reliability of the robot in inclement weather conditions.

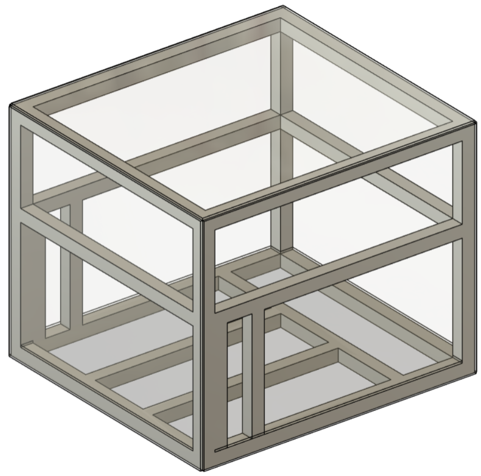

Figure 2: Chassis with Acrylic Panels

Interior Components. The interior of the robot is split into two levels, with one containing the battery, gearboxes, and payload, while the other includes the electrical box and the majority of the electrical components. The interior is designed to be easily accessible to allow for modifications and adjustments to be made without significant effort. The battery and payload are held in place with brackets, making removal simple. The electrical box is raised above the rest of the internals, making it easier to access from the top as well as keeping the more sensitive components sheltered from the larger components.

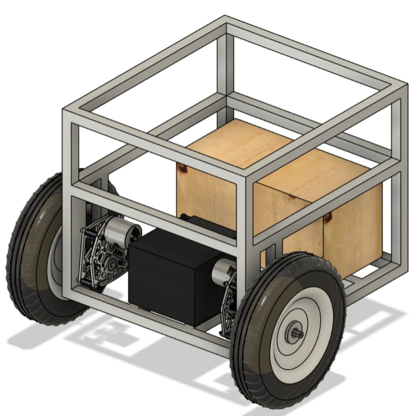

Figure 3: Chassis with Lower Level Components

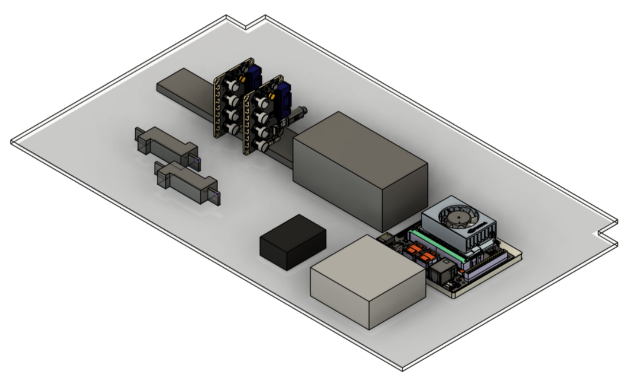

Figure 4: Electrical Box Panel with Used Components

External Components and Wheelbase. Mounted on the outside of the frame are the stack light, LiDAR, and E-stop. The stack light and LiDAR have been attached to the top to improve sightlines to and from the components. The physical E-stop was placed according to the IGVC requirements. The wheelbase for this vehicle consists of 3 wheels: two powered 13.5" wheels, and a 4" caster wheel. The powered wheels are set towards the front of the vehicle on the left and right sides, and the caster wheel is mounted at the rear. The three wheels form a stable surface that includes ample ground clearance. Suspension is limited to the inflation level of the drive wheels.

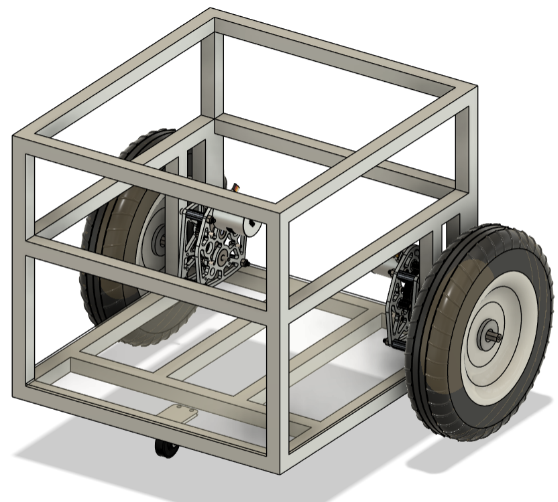

Figure 5: Frame with Wheels

Description of Electronic and Power Design

Overview

Horizon's electrical design builds upon the main design goals of the previous iteration for safety, reliability, and efficiency, while making necessary changes in light of its previous final state. Components have been picked for their compatibility with a DIN rail system, allowing for the quick replacement and maintenance of parts. High and low-level control of the robot is unified onto the Jetson Orin Nano, and communication between electrical components is handled through the Controller Area Network (CAN). The Slamtec RPLIDAR LiDAR system has been added to improve the acquisition of locational data, complementing the ZED 2i Camera and Sparkfun-RTK Global Positioning System (GPS). The ODrive D5065 270k Dual Shaft motors are employed due to their compatibility with the ODrive S1 motor controllers and the ability to install RS485 Absolute encoders, improving the accuracy of recording position and speed information. The Xbox Controller, connected to the Jetson Orin Nano through Bluetooth, can manually control the robot, initiate autonomous driving, and trigger a software emergency stop. Circuit breakers have been implemented across the electrical system to limit current to safe levels, and motor controllers have been configured to trip the system during unwanted current spikes as an added level of redundancy. Finally, the stack light indicates Horizon's current operating mode and an indication of emergency stop.

Power Distribution System

Horizon continues to have a majority of its components operate off of 12V, except for the stack light, which uses a boost converter to operate at 24V. The NERMAX 12V 30Ah Lithium LiFePO4 battery acts as the power source of the robot and was chosen based on the power requirements of the components. Continuous current draw from the motors is limited to below 20A, enforced by circuit breakers. The D5065 270k motors have also been configured to draw no more than 18A continuously at a given time. While this causes a tradeoff in maximum speed, the reduced overhead of the current draw allows the system to handle the additional positioning components and added current draw of operating a boost converter. Horizon is expected to maintain its continuous operation time of 45 minutes.

Electronics Suite Description

While the form of Horizon's electrical box has been vastly updated, the underlying connections remain the same due to the continued usage of 12V. The two ODrive D5065 270k dual-shaft motors are powered and controlled by a pair of ODrive S1 motor controllers. The ZED 2i camera, Absolute RS485 Encoders, Sparkfun-RTK GPS, and Slamtec RPLIDAR are used to track locational, positional, and speed information of the platform at a given moment.

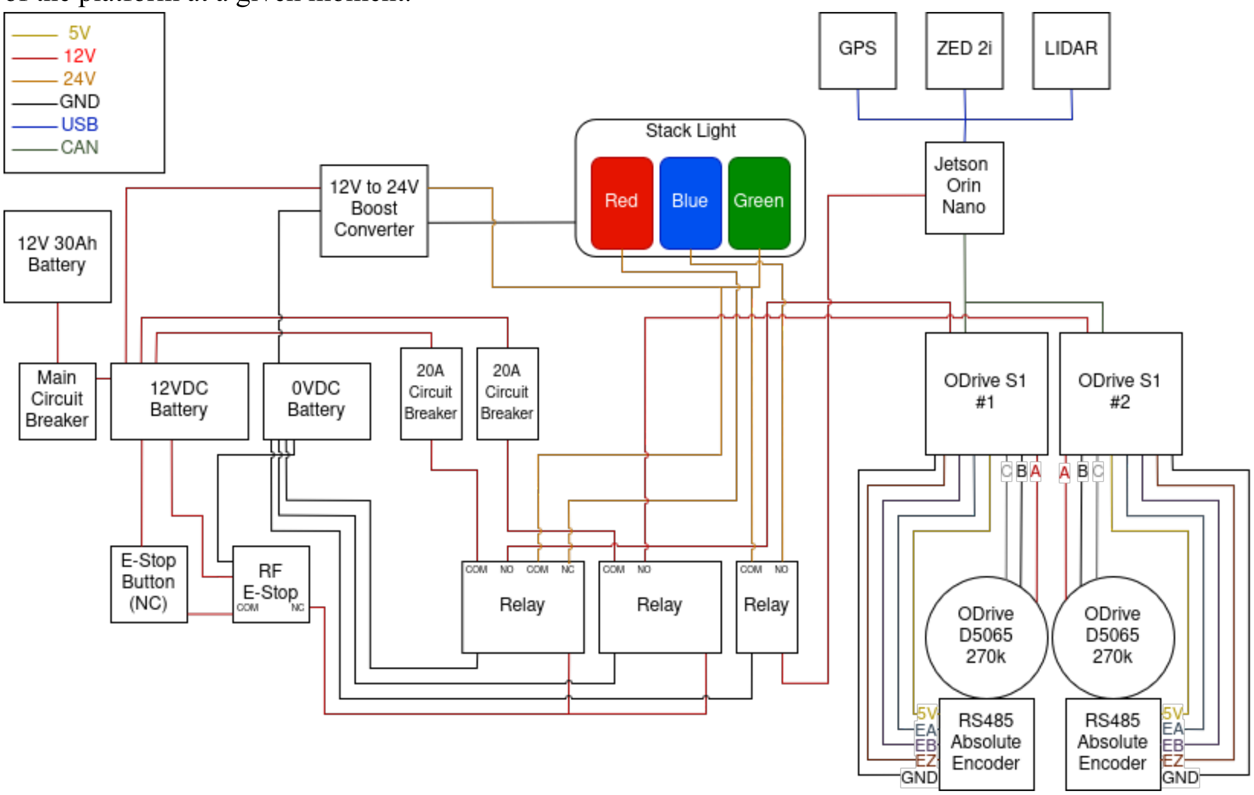

Figure 6: Electrical Box Diagram

The following components were used on Horizon to collect and interpret data from the surroundings and make decisions during auto-navigation:

Main Computer. The Jetson Orin Nano is powered by an NVIDIA Orin system-on-chip design, equipped with an ARM Cortex CPU and an integrated Ampere architecture GPU. Connectivity options consist of USB 3.0, HDMI, Ethernet, and GPIO pins. The Jetson mainly uses the USB ports, GPIO, and CAN TX and RX pins for connectivity to the rest of the devices. The Jetson was chosen for its image processing capabilities, strong community support, and documentation.

GPS. The Sparkfun-RTK GPS module, a breakout board for the uBlox ZED-F9R, was selected for its high precision and reliability, along with its ability to calibrate for low-speed ground robotics. Operating at 20Hz, it offers an accuracy of up to 10mm. This performance allows Horizon to navigate with exceptional precision.

Camera. The ZED 2i is a stereo depth camera capable of capturing images at a maximum resolution of 4416 x 1242 (2208 x 1242 per camera) at 15 frames per second. The resolution has been configured to provide a 30 frames per second video feed at 2560 x 720 (1280 x 720 per camera). The Jetson Orin Nano provides power to the camera through USB, and communication is facilitated between it and the camera.

External encoders. The AMT212B-V-OD absolute encoders can be configured to produce either 12 or 14 bits of resolution per revolution at an update rate of 25 or 100 microseconds. They provide position and speed values for the D5065 270k motors with an accuracy of 0.2 degrees, and are attached to the second shaft.

LiDAR. The Slamtec RPLIDAR A1M8 is a 360-degree infrared LiDAR sensor with a range of 12 meters, a scan rate configurable between 2 and 10 Hz, and a maximum sample rate of 8000 samples per second. The Jetson Orin Nano provides power to the LiDAR sensor through USB, and communication is facilitated between it and the sensor.

Safety Devices and Integration

Safety Light. The safety light is a multi-color Stack Light consisting of three colors. The Jetson Orin Nano controls the safety light, with signals sent to keep the safety light updated to the current operating state of the robot. When Horizon is in E-Stop, the safety light will be set to red. Otherwise, the safety light will have its red LED off.

E-Stop. E-Stop is implemented wholly with hardware components, a physical button, and an RF latch. As shown in Figure 6, power to the relays is controlled by the physical button and RF latch in series. When the button is pressed, the connection opens and stops the current from traveling to the relays, which opens the connection between the circuit breakers and motor controllers, stopping current flow to the motor controllers and stopping the robot. The RF latch is wired between the physical button and relays, and is triggered when its corresponding RF signal is received from an RF remote, turning the latch on and off. When the latch is off, current is let through, triggering the relays to shut off, stopping current flow to the motor controllers, and stopping the robot. Finally, a software e-stop is configured on the controller, sending a CAN message to the motor controllers to stop the motors and place the controllers into E-Stop mode.

Description of Software System

Overview

The software stack used to control Horizon runs on an NVIDIA Jetson Orin Nano with Jetpack 6.2 and is built on the Robot Operating System 2 (ROS 2) Humble Hawksbill distribution. The system is designed as a collection of modular ROS 2 packages, enabling independent development, testing, and replacement of system components. This modularity allows team members to work concurrently on distinct systems and supports simulation by seamlessly swapping real-world components with Gazebo-compatible alternatives. The core autonomy of Horizon is provided by Nav2, a navigation framework in ROS 2, which integrates mapping, localization, path planning, and obstacle avoidance. Nav2 produces motion commands in the form of linear and angular velocity (Twist) messages that guide the robot towards its goals. To support testing and development, a teleoperation node was added. This allows a user to control the robot for testing of the electrical systems and basic movement for easy transport. The teleoperation node is controlled by an Xbox controller and uses the position of the joysticks to send a Twist message. The system for teleoperation also includes a "live-man" switch – Horizon will only respond to joystick commands when either the left or right bumper is held down. This helps prevent unintended motion from accidental input or a stop of movement if the user controlling the teleoperated robot lets go of the trigger for any reason. Both the autonomous and teleoperation motion commands are passed through a multiplexer that sends the commands to a single topic. The multiplexer prioritizes teleoperation commands by default, but the teleoperation mode can be disabled via a button on the controller to enable fully autonomous control. The resulting motion commands are transmitted over the CAN bus to the ODrive S1 motor controllers, providing reliable, low-latency control of the differential control system.

Obstacle Detection and Avoidance

Horizon uses a combination of LiDAR and stereo vision to detect and avoid obstacles in its environment. For above-ground obstacle detection (cones, barrels, etc.), the RPLIDAR A1M8, a 2D 360° LiDAR with a range of 12 meters, is used. This sensor publishes range data as a standard ROS 2 LaserScan message. These scan messages are utilized by the Simultaneous Mapping and Localization (SLAM) toolbox for mapping and localization, providing the robot with a better understanding of its surroundings and location. For ground-level perception, such as lane lines, the ZED 2i stereo camera is used. The camera is integrated through the ZED SDK ROS wrapper, which exposes RGB and depth images as ROS topics. A custom vision pipeline, implemented using OpenCV and the ZED SDK, processes the raw color image to detect lane lines using filtering and edge detection techniques. The resulting mask is applied to the ZED's depth image to extract the 3D positions of the lane lines. These filtered 3D points are then published as a point cloud and incorporated into the costmap for avoidance.

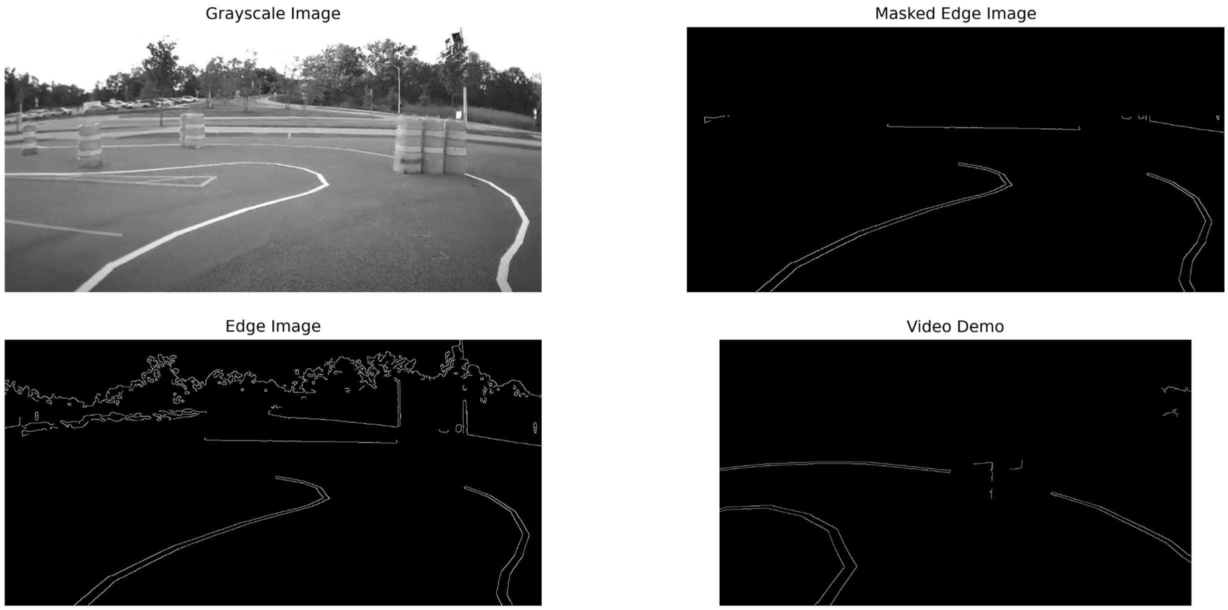

Figure 7: OpenCV Pipeline for Lane Lines

Mapping

Horizon uses the SLAM Toolbox to create and continuously update both a local and global occupancy grid, or costmap, based on LiDAR scan data. The global costmap holds obstacle data from previously visited areas, allowing the robot to plan paths through known environments. In contrast, the local costmap represents a short-range view of the robot's immediate surroundings and is updated at a higher rate for real-time navigation and collision avoidance. As SLAM-based global mapping can suffer from drift over time, particularly as the robot moves further from its starting point, and the course is unknown, the local costmap is used as the main source for nearby obstacle data. This approach provides long-term awareness with short-term reactivity. The costmaps also have an inflation layer, which deters the path planner from getting too close to the obstacle. In addition to the LiDAR data, the costmap is provided with the 3D lane line detections obtained from the ZED 2i. These features are added to the costmap as obstacles, allowing the path planner to avoid driving over the lane boundaries.

Path Planning

Horizon utilizes two techniques for path planning. The first approach includes “behavior trees,” a conditional list of tasks for the robot to attempt to accomplish. That means, for the robot, there is an overarching task of navigating to its goals; in this case, the GPS waypoints and its original starting point. The process of navigating to a goal begins with computing a navigation path to the selected goal. If the robot finds no valid path, the behavior tree can trigger a different action to help the robot compute a new valid path. Behaviors include backing up, spinning, or clearing the costmap to remap the environment with the latest data. The tree can also dynamically switch between different path planners based on certain conditions being met, such as the goal being changed and/or reached, or an amount of time passing. For the process of planning the robot's path to the next goal, the second approach was used. NavFn planner, a built-in algorithm from Nav2, takes the global costmap and, using Dijkstra’s algorithm, plans a path to the goal. Finally, Nav2’s controller is used to follow the path and take action to dynamically navigate around any obstacles that may appear in the robot’s local costmap.

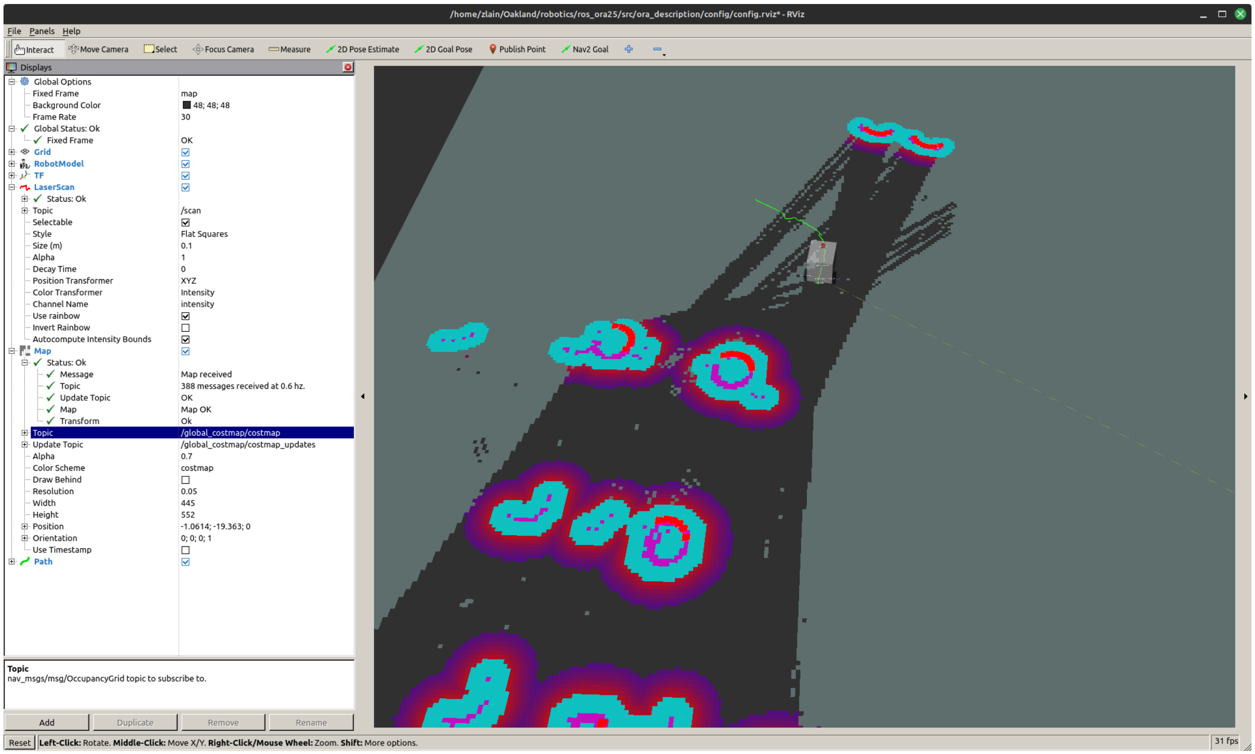

Figure 8: Robot Costmap and Path Planning

Localization

Dual-EKF (Extended Kalman Filter) is used as the primary localization process. Data from several sources, such as the GPS, IMU, VIO (Visual-Inertial Odometry), and wheel encoders, are combined to better estimate the robot's location. The first EKF localizes the robot globally, while the second computes the odometry locally from its starting position. Additionally, a node converts the GPS coordinates to Cartesian coordinates for NAV2 to read them. The SLAM Toolbox also has a role in localization. It fuses LiDAR scans, IMU readings, and wheel odometry to estimate the robot's pose in the map. This estimated pose is published as a ROS 2 Transform, which is used by the navigation stack to ensure consistent world-frame alignment across the path planning, control, and obstacle avoidance components.

Cybersecurity Analysis using RMF

The NIST RMF is a 7-step procedure that can be applied by an organization to cost-effectively apply and continuously monitor their security policies. The 7 steps are:

1. ***Prepare:*** Prepare the group to carry out the needed activities that help manage the security and privacy risks using RMF.
2. ***Categorize:*** The system is undergone within a set of categories and their impacts on the system. This includes confidentiality, integrity, and availability of the systems and what information is stored and transmitted with these systems.
3. ***Select:*** Because of the risk and impact, we designed the system and controls to protect against specific intrusions of those categories.

4. ***Implementation:*** Applied the controls and securities within said systems to prevent such unauthorized actions.
5. ***Assess:*** Once the implementation of security measures is complete, we then determine the effectiveness and efficiency of said controls to ensure confidence in the correct setup.
6. ***Authorize:*** A senior official will then determine if the security controls are of proper organizational requirements.
7. ***Monitor:*** The system is then continuously monitored during operation to ensure only necessary operations occur.

The NIST RMF (Risk Management Framework), as described above, are tools to simplify controlling and taking into account risks that can be detrimental to the operation of the robot. It summarizes the necessary security measures to reduce or eliminate potential threats. If a user with malicious intentions were able to gain access to the robot, their attacks would be at most minimal or nonexistent. Because the robot's design is that of a series of simple solutions for an overall non-complicated operation, the real main threat would be the software portion of the Jetson Orin Nano. To prepare for such an attack, all members of the software team are familiar with and have an understanding of the Jetson, the OS running it, and its capabilities. This event would fall under the categories of having low confidentiality, high integrity, and availability since there is not much sensitive information available within the Orion Nano. However, having the integrity of the software as well as its low-effort access could present a threat to the intended operation of the robot. To mitigate this, the SP 800-53 Control Enhancement that can be implemented is IA-05(01), which pertains to passwords. The Oakland Robotics Association does have access to the passwords for all accounts within the club, along with the passwords for multiple computing devices in our possession. Each password has strict requirements and is unique and complex to guarantee at a 99% CI that they are difficult to guess and are then secure against unauthorized access. We continually ensure that all assets are secured, and if it becomes apparent that they are no longer, we take the appropriate steps to rectify the situation.

System	Threat Description	Conf.	Avail.	Integ.	Overall
Jetson Orin Nano	Malicious user gains access and tampers with the software on the Jetson Orin Nano.	low	high	high	high

Table 1: Threat Analysis

Analysis of Complete Vehicle

Mechanical Analysis

During the design and construction of the mechanical portion, several lessons were learned. Firstly, an overreliance on the tools in the machine shop spells disaster when said tools fail. Secondly, the process of ordering materials often consumes more time than necessary. Mechanical failure is most likely to occur where the hubs attach to the wheels, which has been mitigated by increasing the number of screws holding the hub on to reduce the load on each bolt. All the sharp edges were sanded down to make the robot safer, and the construction materials were chosen with reliability and durability in mind. The lessons learned stemmed from the key issues encountered, and those issues were solved through the adaptation of lab tools and increased lead times on purchases.

Electrical Analysis

During the creation of the electrical box, substantial focus was placed on increasing the quality of the components. Moving to the DIN rail system allowed for the workflow of adding, managing, and removing components to be more efficient. Since the electrical box's design was largely a completion of last year's design with new components and enhanced safety features, the remaining portions, such as power distribution to the Jetson Orin Nano and stack light, required extra time to design. An unexpected challenge came from revisions of the same component having slightly different dimensions. When a component was replaced with a later revision that exhibits this quirk, not recognizing or communicating these differences to the mechanical team in time would cause delays in their work. One of the key safety features of the electrical box was the standardization of crimping wires across all connections, decreasing the chance for a short to occur due to a frayed stranded wire. The most likely key failure modes of the electrical box will come from managing the current draw of the motors. Using 20A circuit breakers means that tripping due to a large current draw will only occur after seconds of continued draw. Our contingency plan includes employing the software configuration of the ODrive S1 motor controllers to add an extra trip level based on expected conditions.

Software Testing and Version Control

The development process of the software system involved many iterations as the system developed and changed. GitHub Projects were used to plan the timeline, and a shared GitHub repository was created for version control, issues, and bug tracking. The repository contained multiple branches used for development and production code. This allowed us to test the robot with the production branch while working on updates in the development branches. The code can be found at https://github.com/oaklandrobotics/ros_ora25.

Software Simulation

To simulate our robot, the Gazebo ROS package was used. Gazebo is a powerful physics simulator that allows us to replicate the IGVC course and test the software used on the real robot. The IGVC course we created included obstacles from previous years, such as lane lines, barrels, and a ramp. Gazebo includes multiple plugins that allow for easy testing of simulated hardware. To define the robot's physical properties and sensors in Gazebo, a Unified Robot Description Format (URDF) file was created. This URDF was then placed into the Gazebo world to test the robot's overall functionality, including motion controls, sensor functions, path planning, and autonomous navigation. All code was tested in simulation before moving to the real robot to ensure correct functionality and safety.

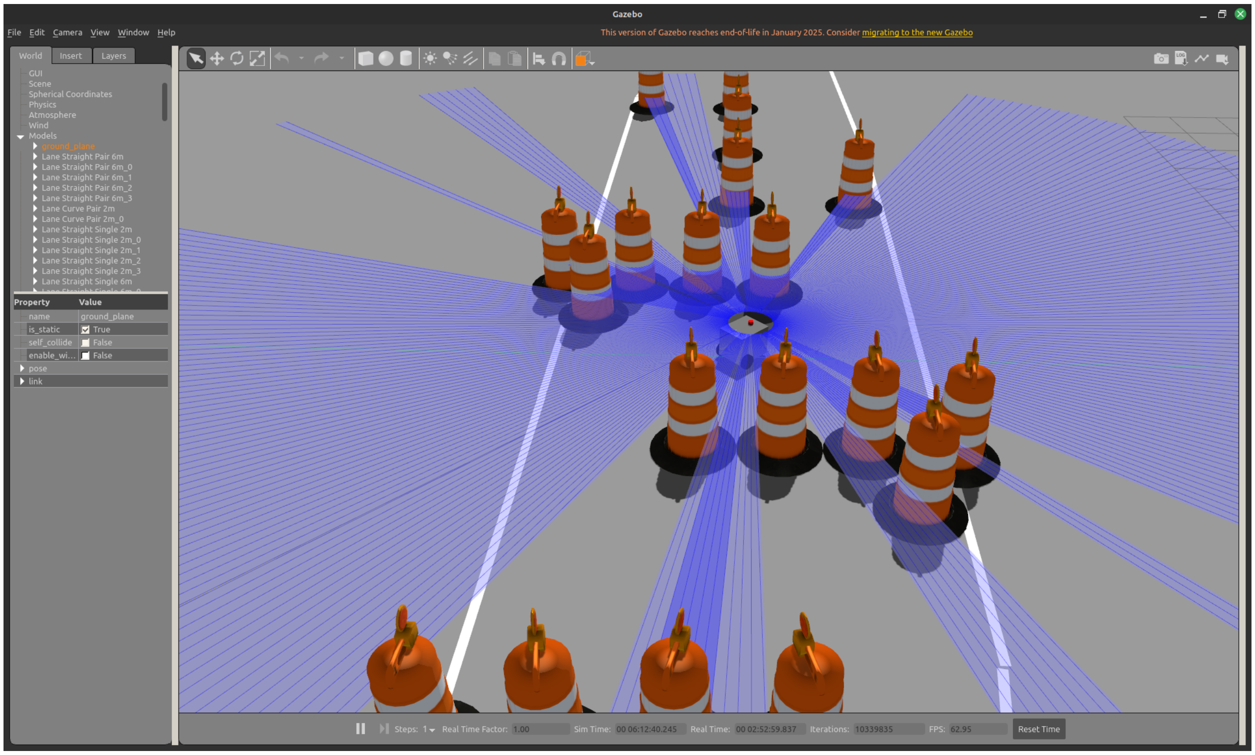

Figure 9: Gazebo Simulation

Description of AutoNav

The robot features an upgraded system of sensors, adding onto last year's system with a 360° LiDAR. This creates a 2D point cloud, which allows for the use of SLAM. This builds a 3D map of the environment to be used with the path planning software. The software now also controls both the autonomous and mechanical movement through the use of a Bluetooth Xbox controller. With the inclusion of dual shaft motors on the robot, absolute encoders can be installed, allowing us to more accurately collect the motor and movement data.

Performance Testing to Date

Testing of the performance has primarily been completed on the subteam level to ensure that each subteam's system is operating at an acceptable level before integration. The results show that the subteams can perform what is required for the completion of the IGVC course with relative ease. In simulation, the software subsystem on Horizon can perceive and map obstacles, plan a path to a selected goal, and output the desired wheel velocities to physically navigate the robot to the goal. The electrical system has been tested to ensure consistent, successful performance of the E-stop circuit, motor controllers, control PCB, and safety components. They are currently all functioning well together and are expected to perform correctly when integrated with other systems.

Initial Performance Assessments

Each subsystem appears to be performing as intended, based on the extensive testing completed by each subteam. There is, however, room for improvement in each subsystem, and new adjustments made to each system are currently being thoroughly tested. It is anticipated that these adjustments will improve the overall performance of the robot as one complete system.

Part	Model	Date Ordered	Quantity	Price / Unit	Cost Total	Cost to Team
Motors	ODrive D5065 270k Dual Shaft Motor	5/2025	4	$65	$260	$0
Motor Controllers	ODrive S1	5/2025	2	$168	$336	$336
Lidar	Slamtec RPLIDAR A1M8	2/2025	1	$100	$100	$0
Controller	Xbox One Controller	—	1	$70	$70	$0
Computer	NVIDIA Jetson Orin Nano	5/2025	1	$250	$250	$250
Stack Light	855T-BCB Stack Light	4/2025	1	$444	$444	$0
Encoders	16384 CPR Absolute RS485 Encoder	4/2025	2	$59	$118	$0
GPS	SparkFun GPS-RTK-SMA	—	1	$350	$350	$0
Camera	ZED 2i	—	1	$550	$550	$0
Batteries	Nermak LIFEPO4 12V 30Ah	—	2	$187	$374	$0
Gearboxes	AndyMark EVO Slim	—	2	$150	$300	$0
Mechanical	Raw Materials*	—	—	—	$300	$300
Electrical	Assorted Materials**	—	—	—	$100	$30
				Total Cost	**$3,552**	**$916**

Cost Report

* Includes aluminum beams, steel sheets, polycarbonate sheets, clamps, and wheels.

** Includes wires, crimps, solder, flux, resistors, capacitors, terminals, and other electrical components.--

Table 2: Cost Breakdown of Horizon to Date