The 32nd Annual Intelligent Ground Vehicle Competition

Hosei University

Autonomous Robotics Laboratory team

Orange2025

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Faculty Advisor Statement

I hereby certify that the engineering design on Orange2025 was completed by the current student team and that it is significant and equivalent to work that would deserve credit in a senior design course.

Signed Kazuyuki Kobayashi Date May 15, 2025

Prof. Kazuyuki Kobayashi May 15, 2025

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1 DESIGN PROCESS AND TEAM ORGANIZATION

1.1 Introduction

The Hosei University Autonomous Robotics Laboratory (ARL) team is proud to present its newly developed vehicle, Orange2025. In response to the IGVC2025 rules and the eligibility of AutoNav vehicles for the Self-Drive Challenge, the team decided to participate after extensive discussions. Drawing on their past experiences, they conducted a comprehensive evaluation of the previous model's mechanical, electrical, and software aspects, identified issues, and implemented targeted improvements.

1.2 Team Organization

This year's ARL team is composed of four graduate students. To enhance development efficiency, the team was divided into two sub-teams—hardware and software—according to each member's area of expertise. Table 1 presents each member's primary role. Throughout the four-month development period, each member contributed an average of 350 working hours.

Table 1. Each member's primary role

Team Member	Hardware	Software	Hours
Hinata Kasai	Chassis design and Assembly	Path planning	400
Yuhei Takamori	Chassis design and Assembly	Perception and Localization	400
Shun Saito	Chassis design and Assembly / Electrical power design		300
Takuya Yamakawa		Vehicle control	300

1.3 Design Process

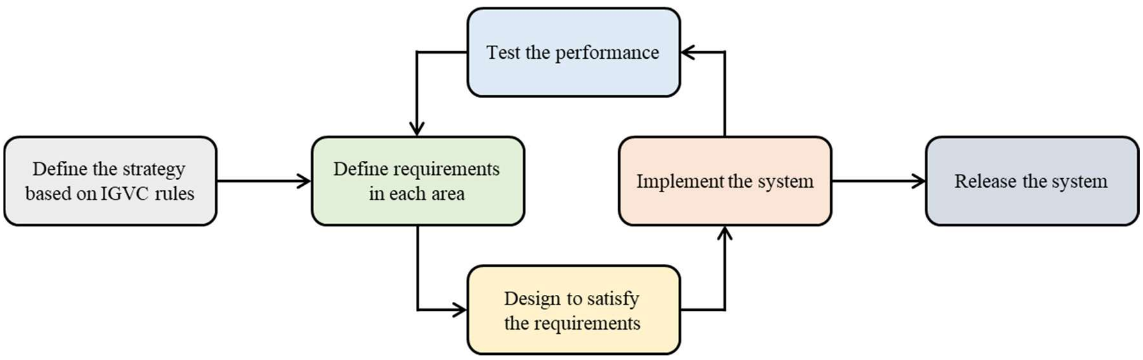


Figure 1. Design process

Figure 1 displays the design process. Previously, we adopted a cautious, waterfall-style development approach, which resulted in a lengthy schedule and delays in responding to changes. To address this, we implemented an agile development methodology with weekly iterations, enabling rapid prototyping and timely feedback. This approach enabled the small team to complete development efficiently within a limited timeframe while remaining adaptable to continuous design improvements.

2 SYSTEM ARCHITECTURE

2.1 Significant Mechanical, Power, and Electronic Components

Figure 2 depicts the key mechanical, power, and electronic components of the developed vehicle. The vehicle utilizes a differential drive system powered by two in-wheel motors. The drive wheels are positioned on either side of the chassis, allowing in situ turning and precise maneuvering. To ensure stability and structural support, caster wheels are mounted at both the front and rear of the chassis.

To improve portability for transportation and facilitate connectivity during testing, we opted to use small, separate batteries to power each essential function this year. The vehicle is fitted with four 18 V batteries that supply power to various components, such as the PC, motor driver, and sensors. Each component is linked via its own dedicated power distribution circuit to maintain stable and safe operation.

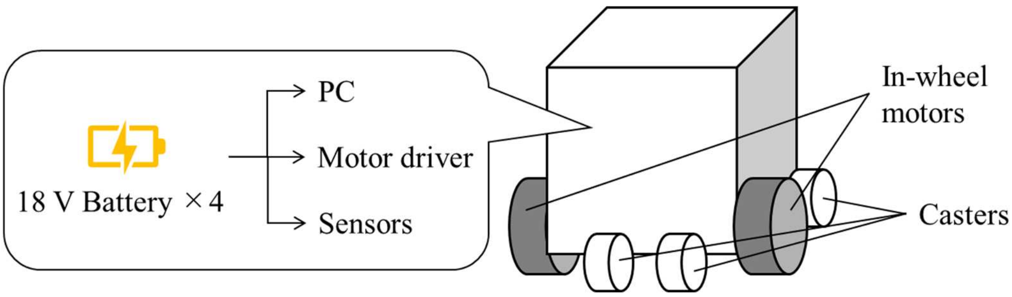


Figure 2. System architecture

2.2 Safety Devices

The vehicle features both a physical emergency stop (E-Stop) button and a wireless E-Stop system. Activating either system immediately cuts power to the motor, bringing the vehicle to a complete stop for safety.

To clearly indicate the vehicle's status, color LED indicators are installed on its top. These indicators display the following statuses:

- Off: Power is turned off.
- Red (solid): Manual mode is active or stopped by E-Stop.
- Green (blinking): Autonomous driving mode is active.

2.3 Significant Software Modules

Following in-depth team discussions, we decided to use ROS2 as the base operating system for the vehicle. This decision was based on the platform's robust open-source ecosystem for vehicle sensing and control, along with its flexibility for making rapid modifications. The following are the significant ROS2 software modules we have developed:

- 3D LiDAR-Based Detection Module: This module processes point cloud data and reflection intensity to robustly detect ground-level obstacles and lane markings.
- A*based Path Generation Module: Utilizing a custom-developed A* algorithm enhanced with potential field methods, this model generates safe navigation paths.
- Control Module: This module implements a suitable pure pursuit algorithm for our differential drive vehicle.

3 EFFECTIVE INNOVATIONS

Table 2 presents the innovations in our vehicles. The team's discussions led to updates in the mechanical, electrical, and software aspects of the vehicle.

Table 2. Innovations in our vehicle

Field	Innovation
Mechanical	To improve stability, operability, and maintainability, we have considered the total balance of the vehicle's center of gravity, including essential components, while accommodating the placement of the IGVC payload.
Electrical	To enhance experimental test continuity, we employ separate battery supplies for each component, including the 3D-LiDAR, motor drive, and PC, among others.
Software	We use ROS2 as the base operating system, which enables rapid prototyping of suitable modules for each of the IGVC AutoNav Challenge and the Self-Drive Challenge.

3.1 Mechanical Innovations

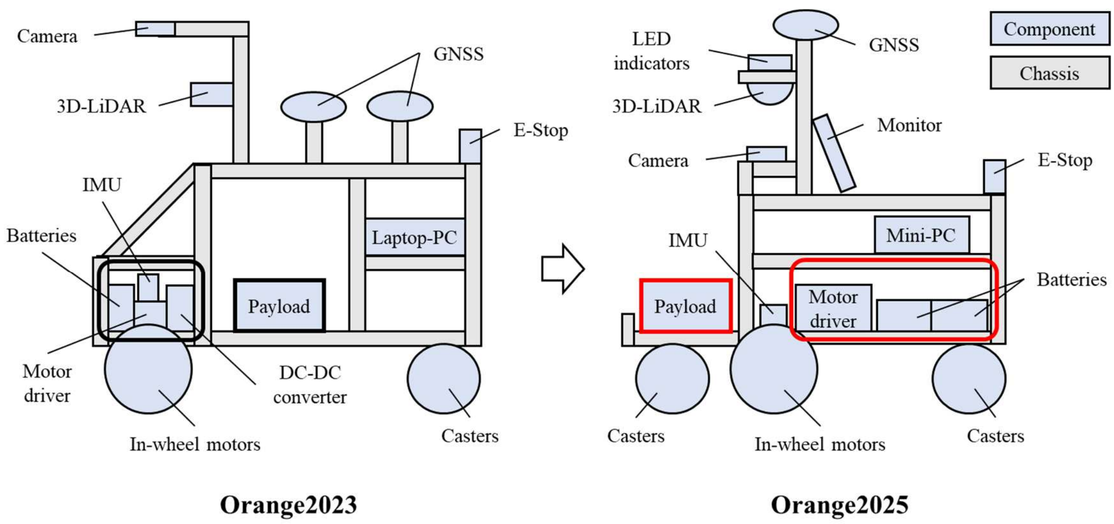


Figure 3. Mechanical layout differences between Orange 2023 and Orange2025

Figure 3 displays the mechanical layout differences between Orange2023 and the new Orange2025. In the previous layout design of Orange2023, portability for transport to the U.S. was prioritized, which led to a layout where each component was concentrated near the wheels. In contrast, the new design focuses on achieving a balanced center of gravity and improved maintainability, particularly when the IGVC payload is present. To achieve both maintainability and overall balance, we implemented a three-layered frame arrangement, improving accessibility to each component, including the loading and unloading of the IGVC payload. This design contrasts with the single-layer, more congested component layout of Orange2023.

3.2 Electrical Innovations

3.2.1 Change in Electric Power Supply Arrangement for Each component

Orange2025 utilizes compact lithium-ion batteries instead of the nickel-hydride batteries used in Orange2023. Owing to transportation limitations, we were unable to bring large-capacity lithium-ion batteries. To address this, we combined several smaller lithium-ion batteries to match the power supply capacity of the previous nickel-hydride battery system. Moreover, the use of multiple smaller batteries allows for independent connections to each component, improving overall availability.

In addition to reducing battery weight, this change freed up internal space within the vehicle, thus allowing for better wiring flexibility and improving cooling to prevent overheating problems. Figure 4 and Table 3 show the specifications of the previous and current battery systems.

Orange2023 Orange2025

Figure 4. Comparison of battery specifications

Table 3. Previous and current battery specifications

Specification	Orange2023	Orange2025
Model	YAMAHA JWB2	Makita BL1860B
Type	Nickel-hydride	Lithium-ion
Rated Voltage	24 V	18 V
Capacity	6.7 Ah	6.0 Ah
Weight per Unit	2.9 kg	0.7 kg
Number of Units	2 units	4 units
Total Weight	5.8 kg	2.8 kg

3.2.2 Employment of mini-PC

When mounted on Orange 2023, the laptop computer occasionally experiences USB connection issues due to vibrations caused by the vehicle’s movement. The laptop PC’s design also posed challenges for cable management, as the USB connectors were often positioned at both ends or on the back. To improve the stability of the USB connection and enhance cable management, we replaced the laptop PC with a new, compact mini-PC. This change not only minimizes the risk of disconnections during operation but also offers a more robust and reliable computing platform that can better withstand the demands of mobile environments.

3.2.3 Employing a New 3D-LiDAR

In the case of Orange2025, we utilized a new compact 3D-LiDAR system. The major differences between the two systems are size and vertical fields of view. Figure 5 compares the VLP-16 used in Orange2023 with the Mid-360 for Orange2025. The VLP-16 has a limited vertical field of view, ranging from +15° to −15° (totaling 30°). Conversely, the Mid-360 provides a much wider vertical field of view, ranging from +52° to −7° (totaling 59°). To improve the effective vertical field of view of the Mid-360, we installed it upside down, allowing the robot to observe the ground from above. This optimization improves downward visibility, facilitating better detection of ground-level features by ensuring sufficient observation of point clouds.

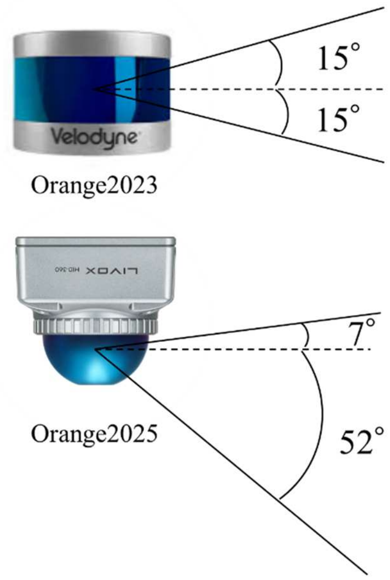


Figure 5. Comparison of VLP-16 (Orange2023) with Mid-360 (Orange2025)

3.3 Software Innovations

3.3.1 Enhanced Heuristic Path Planning Module

To enable more intelligent movement, we developed an advanced heuristic path planning module for the Orange 2025. This module processes global obstacle coordinates and ground white-line information while performing short-term simultaneous localization and mapping (SLAM) to intelligently determine the next movement direction. The developed module is capable of detecting detour situations based on the short-term SLAM map, allowing the vehicle to adapt and correct its course accordingly.

3.3.2 YOLO-Based Stop Signs, Pedestrians, and Tires Recognition Module

To detect stop signs, pedestrians, and tires, we developed a ROS2 module using the YOLOv8 algorithm. This module takes advantage of the YOLOv8 algorithm to accurately detect and classify these objects in real time, significantly improving the vehicle's situational awareness and navigation safety.

4 MECHANICAL DESIGN

4.1 Overview

Figure 6 shows Orange2025, and Table 4 presents the overall dimensions of the developed vehicle. The dimensions were determined based on transportation baggage size limitations and the IGVC vehicle dimension requirements. With the drive wheels centrally located on the vehicle, caster wheels are positioned at the front and rear edges to stabilize the vehicle.

Figure 6. Overall dimensions of the developed vehicle

Table 4. Vehicle specifications

Specification	value
Length	3.2 ft
Width	2.1 ft
Height	3.4 ft
Weight	35 kg

4.2 Structure and Components

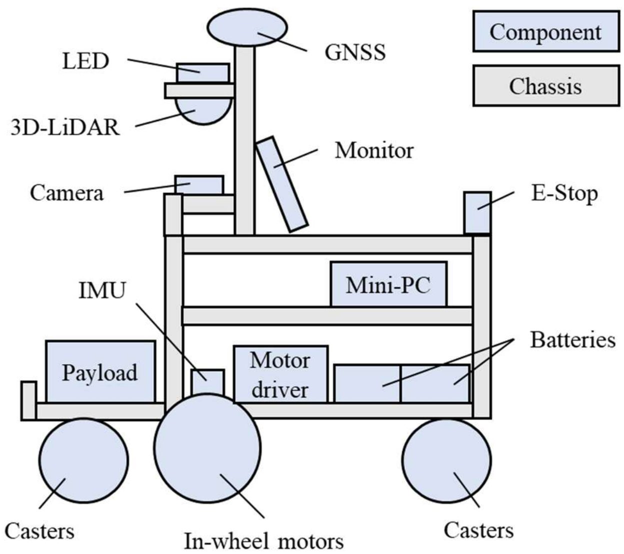


Figure 7. Structure and components

As illustrated in Figure 7, Orange2025 adopts a three-layer structure to improve modularity and optimize the use of space within the vehicle, while also enhancing stability and ease of maintenance. The bottom layer houses heavy components such as the batteries and motor driver, helping to achieve a low center of gravity. The middle layer accommodates the mini-PC, ensuring secure mounting and effective heat dissipation. The top layer is designated for sensors, including the camera and GNSS antennas, providing clear fields of view. This layered arrangement prevents cable congestion by providing dedicated space for each component module, thus improving both system reliability and maintainability.

4.3 Employment of a Waterproof Cloth as an Exterior

We used waterproof cloth as the outer covering of Orange2025. This material ensures effective weatherproofing, especially in rainy conditions, while allowing easy access to each module for maintenance. This design choice contributes to both weight reduction and improved maintainability.

5 ELECTRONICS AND POWER DESIGN

5.1 Overview

Figure 8 displays the power and signal flow of Orange2025. The vehicle uses four separate power battery cartridge systems, allowing the mini-PC, motor driver, and 3D-LiDAR to be powered individually. The camera, GNSS, IMU, and LED indicators are connected to the mini-PC via USB, which provides both 5 V power and data communication. For real-time processing, point cloud data from the 3D-LiDAR is transmitted via Ethernet.

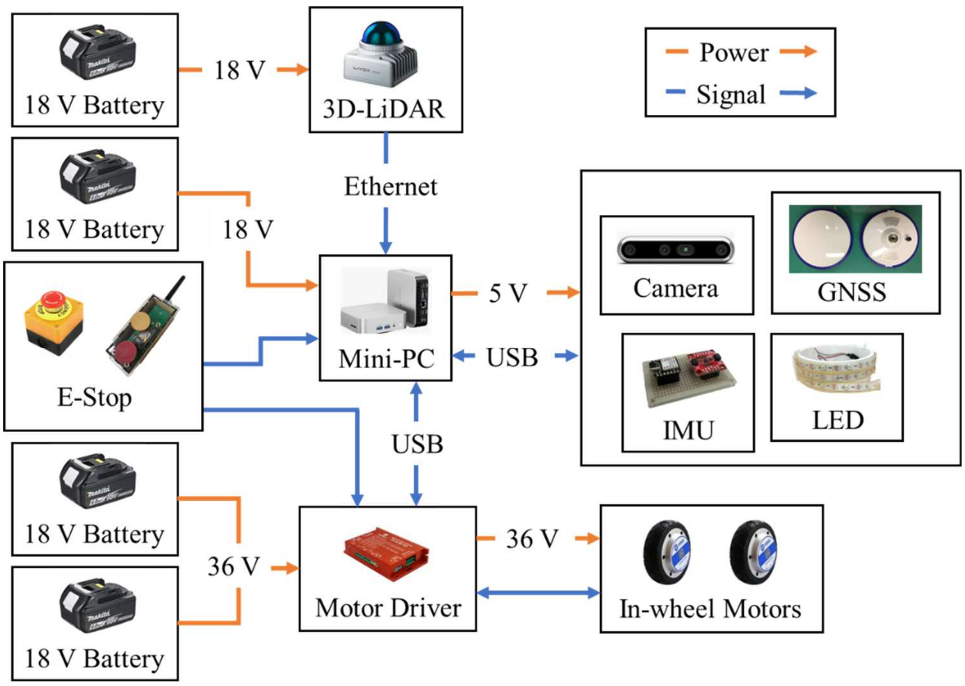


Figure 8. Power and signal flow

5.2 Significant Power and Electronic Components

Table 5. Battery specifications

Specification	Value
Model	Makita BL1860B
Type	Lithium-ion
Rated Voltage	18 V
Capacity	6.0 Ah
Charging Time	40 min

For Orange2025, we redesigned the system to include four independent small lithium-ion batteries, each assigned to the powering sensors, PC, or motor driver, thereby enhancing power reliability. Orange2025 is powered by a Makita 18 V lithium-ion battery (BL1860B), equipped with a charge level indicator and built-in self-diagnostic functions. Detailed specifications are listed in Table 5. Conversely, Orange2023 used two nickel-hydride batteries to power all modules via voltage-regulated DC–DC converters, which resulted in inefficiencies and limited reliability.

5.3 Electronics Suite

Orange2025 is equipped with a diverse range of sensor components and vehicle actuators, including a motor driver that supports key autonomous driving functions. These components are integrated through the ROS 2 framework and communicate via USB and Ethernet. The main devices are as follows:

- Mini-PC (GEEKOM A7): Equipped with an AMD Ryzen R9-7940HS running at 4 GHz and 32 GB of RAM, this mini-PC gathers and processes all sensor signals and controls the vehicle's motor driver.
- Motor Driver (ZLAC8015D): Connected to a differential drive system, it controls the rotation speed of the in-wheel motors.
- IMU (ICM-20948): The IMU sensor comprises three types of sensors, including a three-dimensional accelerometer, gyroscope, and magnetometer.
- GNSS (u-blox F9P + BT-200 antenna) ×2: Featuring two antennas, this GNSS system delivers real-time self-positioning with centimeter-level accuracy and supports heading estimation.
- 3D-LiDAR (Livox Mid-360): This sensor offers point cloud data with a full 360° horizontal field of view and a vertical field of view from +7° to −52°.
- Camera (RealSense D435): The front-facing RGB-D camera offers an RGB field of view of 69.4° × 42.5° × 77° and a depth field of view of 91.2° × 65.5° × 100.6°.

5.4 Mechanical and Wireless E-Stop Systems

Orange2025 features both a physical E-stop button and a wireless E-stop system. The wireless E-stop utilizes the IEEE 802.15.4 protocol (2.4GHz), enabling low-latency, low-power communication. Upon activation, the motor power is immediately cut off—bypassing the PC—ensuring a safe stop of the vehicle.

6 DESCRIPTION OF THE SOFTWARE SYSTEM

Figure 9 presents the software architecture for Orange2025. For the AutoNav Challenge, the system uses GNSS, wheel odometry, and IMU data to determine its position. Simultaneously, a 3D-LiDAR sensor detects obstacles in the surrounding environment and analyzes the ground surface. The resulting point clouds data generated by the LiDAR, along with the reflection intensity, are processed to identify white lines on the ground.

In the Self-Drive Challenge, image data from the camera are integrated to detect tires, potholes, pedestrians, and stop signs.

Using the environmental recognition results, a potential field map is generated. The A* algorithm is then applied incorporating the short-term SLAM map and self-positioning data, to generate commands for controlling the motor driver.

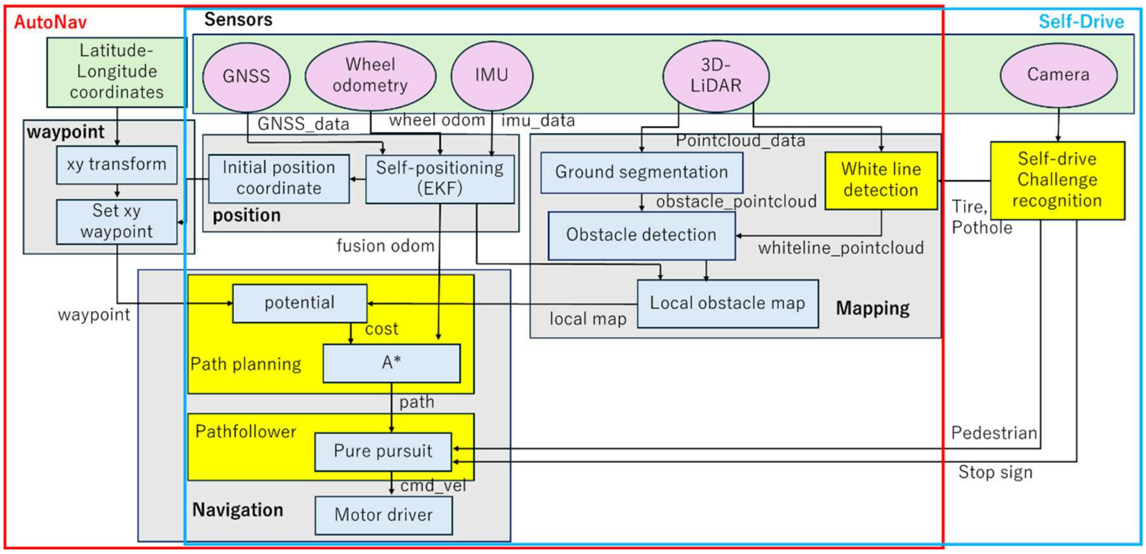


Figure 9. Overview of software

6.1 Path Planning

The path planning algorithm used in this system integrates a potential field map with the A* search algorithm. A* search was selected for its ability to always find a valid path when one exists.

First, a cost map is created using predefined waypoints and environmental data based on the potential field method. The total cost is determined by combining two components:

- **Positional cost**: Decreases as the robot approaches the target.
- **Environmental cost**: Increases as the robot moves closer to obstacles.

Using this cost map, the final path is generated through the A* search algorithm. The search process follows these steps:

1. Evaluate the cost of each 30 cm × 30-cm grid cell around the vehicle's current position.

2. Choose the grid cell with the lowest cost from the evaluated options.
3. Move the evaluation center to the selected cell and assess the costs of its neighboring grid cells.
4. Expand the search grid by repeating this process, always selecting the grid cell with the lowest cost.
5. Mark the selected cells as visited and exclude them from further evaluations, then return to step 2.

This iterative process continues until one of the following conditions is met:

- The selected grid cell’s cost drops below a predefined threshold, signifying that the goal has been reached.
- The process exceeds the maximum number of iterations, indicating a search failure.

Once the search is complete, the system detects the valid cell nearest to the goal and designates it as the endpoint of the final path.

6.2 Path Following

We chose the Pure Pursuit algorithm because both AutoNav and self-driving navigation require high levels of accuracy and speed. The Pure Pursuit algorithm enables smooth and stable path following, even at high speeds. Due to its effectiveness in minimizing tracking errors and ensuring consistent trajectory adherence, we determined that this approach would improve lap times, leading us to implement it.

6.3 Recognizing White Lines and Distinguishing Between White and Dashed Lines

In IGVC 2023, we found that the reflection intensity from 3D LiDAR effectively detects white lines on the ground. Building on this insight for Orange 2025, we decided to use 3D LiDAR for white line detection instead of cameras, which can be unreliable in varying weather conditions. This decision guarantees that detection accuracy remains unaffected by weather variations.

Figure 10 depicts the overall processing flow for detecting while lines on the ground.

The captured point cloud data and corresponding reflection intensity from the 3D LiDAR are first acquired, followed by edge extraction. Next, the Hough Transform is applied to detect line segments. Rather than processing

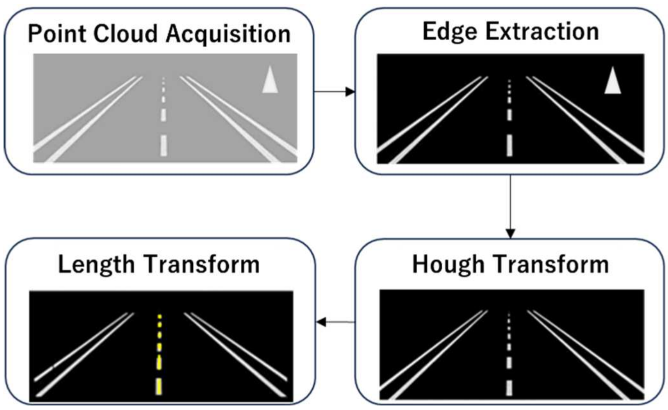


Figure 10 Flow of white line detection

the point cloud data directly, it is converted into an image format allowing us to leverage OpenCV's high-precision edge detection and Hough Transform algorithms. To reduce computational load, a threshold based on line segment length was introduced, with line segments shorter than the threshold classified as dashed lines. This method ensures accurate identification of solid lines on both sides of the road and dashed lines in the center.

6.4 Recognition of Stop Signs, Pedestrians, Tires and Potholes

In the Self-Drive Challenge, the camera was utilized exclusively to recognize stop signs, pedestrians, tires, and potholes. The YOLOv8 model was used to detect and identify stop signs, pedestrians, and tires. To improve detection accuracy, transfer learning was performed for each target category. For pothole detection, a white ellipse-shaped region was extracted from the camera image, and an ellipse shape was then fitted to the region's contour to identify potholes based on their shape and position. The detection results for each target are shown in Figure 11.

Figure 11. Examples of detection: stop signs, pedestrians, tires, and potholes

7 CYBERSECURITY ANALYSIS USING RMF

In accordance with the IGVC2025 rules, the Cyber Challenge must address the risk of unauthorized access and cyberattacks from other teams in the pit area. To protect our vehicles from such threats, we implemented information security measures based on the NIST risk management framework (RMF). Specifically, we followed the RMF process to identify and assess potential threats during the competition and to select and apply appropriate security measures. Table 6 presents typical threats and their classifications—confidentiality, integrity, and availability—based on the summary outcomes of our team discussions.

Table 6. Typical threats and classification

Security Category	Confidentiality	Integnity	Availability
Communication Interference	Low	Low	High
Unauthorized Access	Moderate	Moderate	Moderate
Data Falsification	Low	Moderate	High
Vehicle Hijack	Moderate	Moderate	High
Physical Attacks	Low	Low	High

Through several discussions among team members, Table 7 lists some of the corresponding control measures and their implementation methods. After implementation, these measures were evaluated by the team and subsequently operated and monitored following confirmation by the faculty advisor.

Table 7. Corresponding control measures and their implementation methods

Security Control	Tailoring
AC-2	Only people on the team can use accounts with administrative privileges.
AC-3	Change password after a certain period of time.
CA-4	Use iptables and ufw as firewall, do not allow anything not on whitelist.
SC-7	Use iptables and ufw as firewall.
SC-8	Use iptabels and ufw as firewall.
SC-12	Use OpenVPN and change settings every six months.
SC-13	Use iptables and ufw as firewall.
IA-2	Identification using a password known only to those on the team.
PE-10	Introduction of emergency stop switch.
CM-6	System design such that the system will not boot if devices are not configured correctly.

8 ANALYSIS OF THE COMPLETE VEHICLE

8.1 Hardware Failure Points and Their Solutions

Table 8. Hardware failure points and their solutions

Failire Points	Solution
Wheels detaches from the vehicle	Resecure the connection points
Wheels spinning on the hill	Adjusted caster height
Unable to acquire GNSS data	Firmware reconfigured

8.2 Software Testing and Version Control

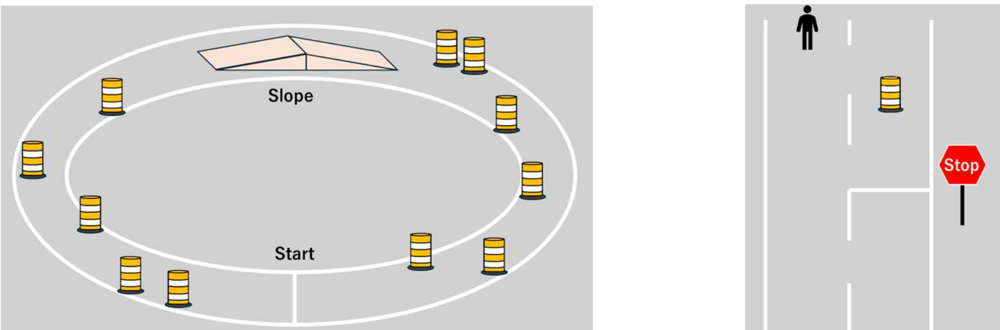
The development of Orange2025 followed a structured agile process with four key phases: defining requirements for each area, designing solutions to satisfy those requirements, implementing the system, and testing its performance. These phases were executed iteratively to ensure both quality and flexibility throughout development.

In agile development, software is frequently and flexibly updated in response to changing conditions. Therefore, streamlining the development cycle, thoroughly tracking bugs, and maintaining robust version control are crucial. To meet these needs, ROS2 was selected as the base operating system, and its logging functionality was leveraged to capture sensor data during real-world experiments. This facilitated efficient and consistent execution of the entire process—from implementation based on design to performance testing.

GitHub was utilized for version control to support the iterative nature of agile development. Separate branches were created for each task, corresponding to key phases: defining requirements, designing features, implementing adjustments, and applying performance fixes. Following review and validation, these branches were merged into the main branch. This process minimizes the risk of bugs, clarified the change history, and simplified track differences from earlier versions.

8.3 Environment of the Driving Test

Figure 12 depicts a test course built in a real-world setting. A white-lined course was marked on an asphalt surface, and various elements—such as obstacles, slopes, mannequins, stop signs, and potholes—were included to replicate realistic driving conditions for testing purposes.



(a) AutoNav course (b) Self-drive course

Figure 12. Test environment for the AutoNav and Self drive

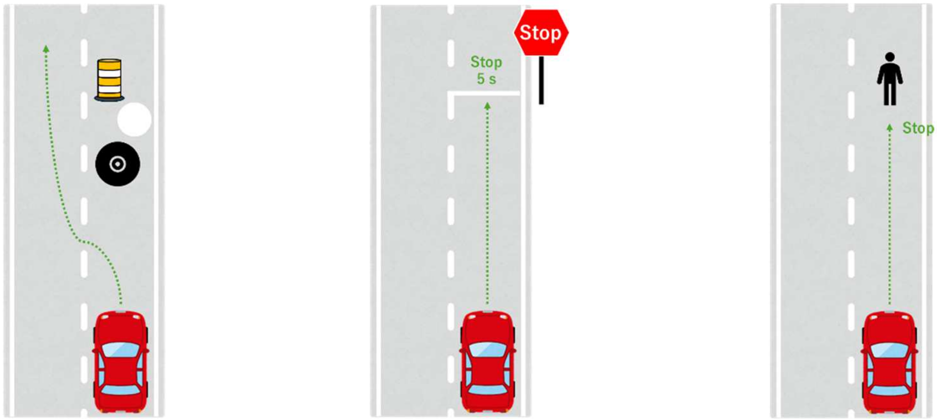
9 UNIQUE SOFTWARE, SENSORS, AND CONTROLS TAILORED FOR AUTONAV OR SELF-DRIVE

9.1 AutoNav

The distinction between the white line following the autonomous navigation area and the preassigned waypoint navigation area was determined using the GNSS positioning data.

9.2 Self-Drive

As with AutoNav, the primary task is lane following. Additionally, the vehicle is designed to respond appropriately upon detecting specific objects, such as tires, potholes, stop signs, and pedestrians. Figure 13 depicts the vehicle's behavior in response to each recognized object.



(a) When a tire or pothole is recognized, the vehicle deviates from the dashed line to avoid the obstacle.

(b) When a stop sign is detected, the vehicle stops for 5 s before automatically resuming movement.

(c) When a pedestrian is recognized, the vehicle stops and waits until the pedestrian has safely passed before resuming movement.

Figure 13. Vehicle behavior in response to recognized objects

10 INITIAL PERFORMANCE ASSESSMENT

Table 9 presents the performance of Orange2025. The following performance was verified in the experimental environment described previously.

Table 9. Performance of Orange2025

Measurement	Performance Result
Speed	4.00mph(6.44km/h)
Ramp climbing abirity	15.0%incline
Reaction times	0.16s
Battery life	4h
Obstacle detection distance	0.7-33ft(0.2-10m)
Waypoint navigation	±0.27ft(±0.08m)