

ITU RAKE
Istanbul Technical University IGVC 2026 – AYAZ



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STATEMENT OF INTEGRITY

I certify that the Ayaz vehicle described in this report was prepared by the students named below,
and
this work is equivalent to the project in an advanced design course. This report was prepared by the
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1. System and Subsystem Requirements

1.1 System Engineering Process

The development process of AYAZ was carried out based on a standard Systems Engineering Cycle (V-Model) used in the design of complex autonomous systems. This process consists of the following stages, ranging from determining theoretical requirements to physical testing:

Requirement Identification: In the initial stage, the IGVC AutoNav Challenge rules and data from previous years were analyzed to determine the “Critical Success Factors.” Within this scope, high-level system requirements such as vehicle speed (hardware-limited Maximum Theoretical Speed: 1.78 m/s with a 1:25 reduction ratio), climbing capability (15% incline), and safety protocols (E-Stop accessibility) were defined.

Subsystem Breakdown: The high-level requirements were distributed into customized objectives for the Mechanical, Electronics, and Software subteams. For example, the system requirement of “Continuous Data Flow” was transformed into sub-requirements such as the design of a “900 mm rigid sensor mast” for the mechanical team and a “low-latency ROS2 communication architecture” for the software team.

Iterative Design and Prototyping: In line with the determined requirements, CAD models (SolidWorks) and electronic circuit schematics were created. In particular, rapid prototyping studies conducted on 3D-printed fixtures and the birch plywood chassis structure enabled us to verify whether the design met the requirements before physical manufacturing.

Testing & Validation: After each subsystem was produced, it was subjected to individual tests; in the final stage, Gazebo simulations and field tests confirmed that the entire vehicle met the “Integrated System Requirements.” This structured process ensured that both the hardware and software layers of AYAZ operated in complete harmony with each other and guaranteed a high level of compliance with competition standards.

1.2 Technical and Operational Requirements

Mechanical Requirements: The mechanical design of the vehicle focuses on the criteria of “Vibration Damping” and “Accessibility” in order to ensure operational continuity under rough terrain conditions. The birch plywood used in the chassis aims to absorb high-frequency vibrations, allowing sensitive optical sensors to remain within the < 1.5G acceleration limit. In addition, thanks to the semi-modular body design, access time to critical components has been reduced to under 60 seconds, enabling rapid maintenance and repair in field conditions.

Safety Requirements: The safety architecture is built upon “Hardware-Level Emergency Stop” and “Mechanical Protection” in full compliance with IGVC Rule II.1. The E-Stop system is designed to physically cut motor power in under 100 ms, independently of any software failure. For environmental safety, all moving parts are 100% isolated with polycarbonate enclosures, and the stopping distance has been optimized to remain below 0.5 meters while operating at full speed.

Electrical and Electronic Requirements: The requirements of the electronic system were determined in line with the principles of “Power Autonomy” and “Data Integrity.” The high-capacity battery configuration provides a minimum of 4 hours of uninterrupted operation under full sensor and

processor load. The CAN-Bus protocol used for the transmission of critical odometry and speed data maintains the vehicle's positioning accuracy by keeping data packet loss caused by electrical noise below 1%.

1.3 AutoNav Challenge Requirements

Perception Requirements

- Semantic Lane Segmentation: In order for the vehicle to remain within the white and colored track boundaries, it must distinguish lanes from image data in real time. Our UNet-based deep learning model performs lane detection through pixel-level segmentation under varying lighting conditions and aims to achieve an accuracy rate above 90% in field tests.
- Reliable Obstacle Detection: Detecting pylons and other obstacles on the track from a safe maneuvering distance is a critical requirement. By utilizing the 360-degree scanning data of the LiDAR, obstacles are aimed to be detected with 98% accuracy from a minimum range of 5 meters and processed into the occupancy grid.

Driving Logic Requirements

- Real-Time Path Re-calculation: In situations involving dynamic obstacles or route changes, the vehicle must react without interruption. Our driving logic aims to minimize system latency and provide smooth navigation by generating a new route output in under 100 ms from the moment sensor data enters the system.
- Safe Velocity Regulation: Compliance with the speed limits defined under IGVC Rule II.3 and ensuring environmental safety are fundamental driving requirements. The vehicle monitors its actual speed by fusing encoder and GPS data and maintains a stable autonomous cruising speed through a software-imposed limit of 1.0 m/s.

Key Performance Indicators

- Localization Precision: The ability of the vehicle to reach the assigned target points (waypoints) in the global coordinate system with minimal deviation is the most important criterion for measuring system success. Our primary performance indicator is maintaining the difference between the EKF (Extended Kalman Filter) outputs and the actual ground position below 15 cm.
- High-Torque Ramp Navigation: Successfully traversing inclined surfaces on the track without speed loss or motor strain is an operational success metric. The ability of our 25:1 reduction ratio motor system to climb 15-degree inclines under full load while maintaining speed has been defined as our main performance objective.

2. Mechanical Design

2.1 Overview

Ayaz is an autonomous ground vehicle designed with the principles of lightweight construction, modularity, and strategic optimization of the center of gravity (CoG). The overall dimensions of the vehicle (excluding the sensor mast) are determined as 105 cm in length, 62 cm in width, and 45 cm in height. In order to improve portability and battery efficiency, the unloaded weight of the vehicle (excluding payload) is only 16 kg. The main chassis structure is constructed using 10 mm Birch Plywood due to its high vibration damping capability and structural rigidity. The outer body consists

of 5 mm solid polycarbonate panels with high impact resistance. This hybrid structure protects the internal components while also providing rapid access to the system through the service cover.

2.2 Drive System and Significant Mechanical Components

The vehicle’s drive system utilizes differential drive (skid steering) kinematics, providing high maneuverability on rough terrain. The system is built around two REV NEO v1.1 brushless DC motors selected as off-the-shelf components. In order to increase motor torque and improve low-speed control, a MAXPlanetary gearbox system consisting of two 5:1 planetary gear sets was used, achieving a total reduction ratio of 25:1. Hex shafts were preferred in the power transmission system to prevent stripping under high loads, and 3D-printed PETG bearing blocks fixed to the chassis were designed to reduce bending moments on the motor shafts. At the rear section, custom-designed airless wheels with a diameter of 150 mm, consisting of PETG rims and flexible TPU tire surfaces, are used, while a caster wheel that reduces turning friction is located at the front section.

2.3 Frame Structure, Housing, and Structure Design

The body panels of Ayaz were not permanently bonded in order to facilitate maintenance; instead, they were mechanically attached to the chassis using PETG 3D-printed corner connection elements. The mandatory 20 lb (~9.07 kg) payload required by the competition rules was positioned close to the rear drive axle in order to increase traction and prevent slipping during zero-radius turns. With this configuration, the total competition mass of the vehicle is approximately 25.1 kg. The 900 mm-long 20x20 aluminum sigma profile sensor mast located at the rear section serves as a rigid support structure for cameras, GPS, and communication modules. The Visual Safety Light and the hardware-based Mechanical E-Stop button were also mounted on this mast for accessibility and visibility purposes.

2.5 Thermal Management and Weather Proofing

To prevent hardware overheating, negative-pressure airflow is provided through ventilation channels and fans located on the front panels. In order to maintain operational capability under light rain (drizzle) conditions, the panels were assembled in a modular “tight-tolerance dry fit” structure. During the final setup at the competition area, marine-grade silicone sealant will be applied to the panel joints, and downward-angled louvers preventing water ingress will be added to the fan inlets.

2.6 Requirements for Mechanical Design

Mechanical Requirement	Driven By	Target Value	Actual Measured Value	Discussion
1. Hardware Speed Limits	IGVC Max/Min Speed Regulations	$0.45 \text{ m/s} < V_{\text{max}} < 2.23 \text{ m/s}$ (1 mph - 5 mph)	Maximum Theoretical Speed: 1.78 m/s (3.98 mph)	With the 1:25 gear reduction ratio and 150 mm wheel diameter selection, the vehicle is hardware-limited from exceeding competition speed limits, ensuring safe operational speed.
				Thanks to the 1:25 ratio, sufficient load

2. Gradeability & Traction	IGVC 15% Ramp Requirement and 25.1 kg Gross Weight	No loss of traction on a 15% incline	High Torque Margin (2.6 Nm stall torque per motor)	is transferred to the wheels, guaranteeing that the fully loaded 25.1 kg vehicle can climb 15% grass ramps without strain.
3. Geometric Footprint & CoG	IGVC Dimension Rules and Skid Steering Efficiency	Length < 213 cm Width > 61 cm Center of gravity close to the rear axle	Dimensions: 105x62 cm CoG: ~12 cm distance to the rear axle	With a width of 62 cm, the vehicle remains close to the minimum size limit, facilitating passage through narrow obstacle areas. Positioning the payload at the rear eliminates the risk of wheelies.

Table 1: Mechanical Requirements Matrix

3. Safety

Ayaz has been designed with a multi-layered safety architecture in order to maximize both operator and environmental safety. In accordance with IGVC regulations, the safety strategies have been addressed under four main categories: transportation/parking, mechanical, electrical, and software stages

3.1 Safety During Transportation, Parking, and Charging

The physical safety of the vehicle during transportation and parking is ensured by 5 mm thick solid polycarbonate body panels, which provide protection against external impacts, and a 10 mm birch plywood chassis with vibration damping properties. These modular enclosures isolate all moving components (gears and motor shafts) by 100%, preventing physical contact risks and external interference. In order to ensure the electrical safety of the system while charging the vehicle, a custom-designed Power Distribution Board (PDB) is utilized. This board electrically isolates the high current draws in the motor lines from sensitive logic circuits, eliminating hazards that may arise from voltage fluctuations during charging.

3.2 Physical and Mechanical Safety

Mechanical E-Stop: In full compliance with IGVC rules, a hardware mechanical E-Stop button is located at the center rear of the vehicle on a rigid aluminum profile tower (mast) positioned at a height of 90 cm (approximately 3 feet). This button is red-colored, push-to-stop type, and has a minimum diameter of 1 inch, as required by the rulebook. The button is mechanically protected by the tower to prevent damage in the event of a possible rollover.

Rollover Protection: This 90 cm rigid tower not only carries sensors but also serves as a safety barrier by keeping electronic components and the E-Stop button elevated above the ground in the event of a rollover, thereby protecting them from impact.

3.3 Electrical and Hardware-Level Safety

Independent Power Kill: When the mechanical E-Stop is triggered, the system physically cuts the main power line to the motor drivers through a relay. Since this process is executed at the hardware level, it is completely unaffected by software failures.

Continuous Perception Logic Even when the drive power is cut by the E-Stop, the NVIDIA Jetson Orin and sensors (LiDAR, camera) remain powered. This allows the vehicle to continue perceiving its environment and recording data even after loss of propulsion, enabling post-incident failure analysis and eliminating system restart time..

Wireless E-Stop & Failsafe Communication: The minimum 100 feet range wireless emergency stop system required by IGVC rules is implemented using an HC-12 RF module, which operates independently from the main Wi-Fi network. Additionally, if the communication link between the remote control unit and the vehicle is lost, the system automatically enters “Safe Stop” mode and locks the motors..

Safety Light: The minimum 100 feet range wireless emergency stop system required by IGVC rules is implemented using an HC-12 RF module, which operates independently from the main Wi-Fi network. Additionally, if the communication link between the remote control unit and the vehicle is lost, the system automatically enters “Safe Stop” mode and locks the motors.

3.4 Software and Autonomous Safety

Obstacle Inflation Layers: In the software algorithm, a virtual “buffer zone” (inflation layer) is defined around obstacles; in order to minimize collision risk, the vehicle plans its route such that it does not approach obstacles closer than this safe distance.

Speed Limiting: Although the system’s mechanical capability allows a speed of 1.5 m/s, the autonomous driving speed is software-limited to 1.0 m/s to ensure environmental safety, sufficient stopping capability, and compliance with regulations.

3.5 Requirements for Safety

Safety Requirement	Driven By	Target Value	Actual Measured Value	Discussion
E-Stop Power Cut-off Time	IGVC E-Stop Rules	Power cut-off within < 0.5 seconds	Relay response < 100 ms	The emergency stop command bypasses the software and occurs instantly at the hardware level.
Stopping Distance	Environmental Safety & Maneuverability	Maneuverability < 0.5 meters at full speed	Stop under 0.5 meters at full speed	Restricted speed and the high-torque drive system safely stop the vehicle within the specified distance.
Wireless E-Stop	IGVC Wireless	Range \geq 100	Signal	The RF module,

Range	E-Stop Rules	feet	transmission over 100 feet (via HC-12)	independent of the main API, ensures motor lockout in case of disconnection.
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Table 2: Safety Requirements Matrix

4. Electrical/Electronic Design

4.1 Overview

Ayaz is built on a modular electronic architecture that efficiently distributes computational load. In the system, an NVIDIA Jetson Orin is responsible for executing high-level autonomous tasks (such as image processing and path planning), while an STM32F407 microcontroller handles low-level control, sensor data acquisition, and safety monitoring. This decoupled structure increases system stability while minimizing processing latency.

4.2 Strategic Decisions in Electrical and Electronic Component Selection

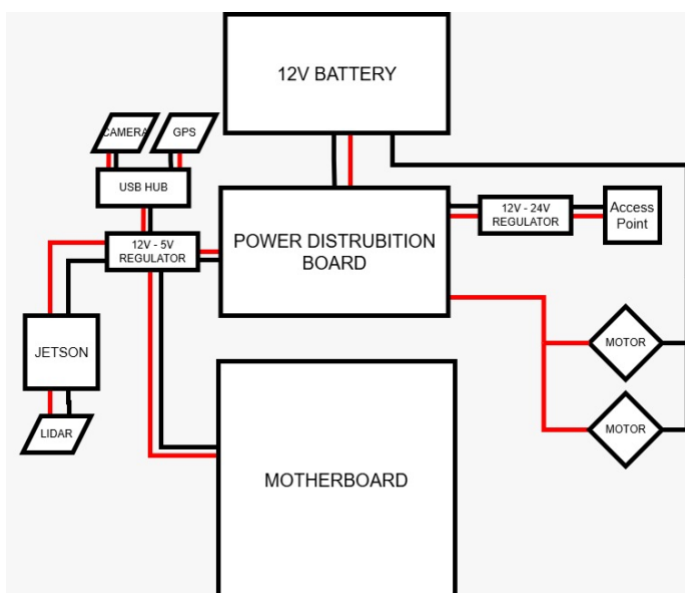
NVIDIA Jetson Orin: It was selected as the main processing unit due to its high GPU capacity in order to perform deep learning-based segmentation and 360° LiDAR data fusion in real time (low-latency).

REV Robotics NEO & SparkMAX (CAN-Bus): Brushless motors and the CAN-Bus protocol were used in the drive system to reduce cable complexity, while ensuring reliable transmission of wheel odometry and motor state data.

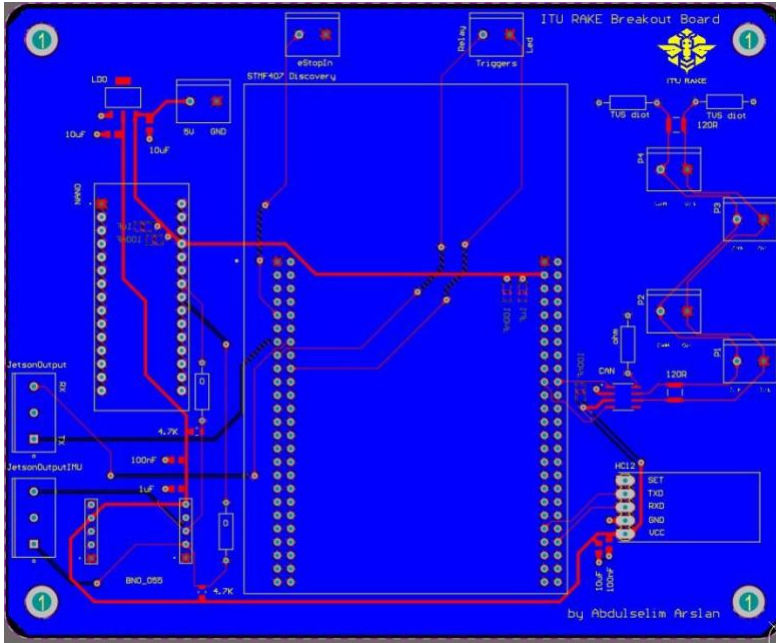
Hybrid Communication Line: A high-bandwidth Wi-Fi API is used for the main telemetry stream, while a Wi-Fi-independent HC-12 RF module provides safe manual control and emergency redundancy.

Hardware Safety: The emergency stop (E-Stop) system is designed as a relay-based hardware interlock. This ensures that motor power is physically cut while maintaining power to the Jetson Orin and sensors, thereby eliminating system restart time.

4.3 Description of the Significant Power and Electronic Components



Ayaz's core electronic components consist of an NVIDIA Jetson Orin, an STM32F407 microcontroller, REV SparkMAX motor controllers, REV NEO brushless DC motors, sensors, and communication modules. The Jetson processes sensor data and navigation algorithms, while the STM32 controls the motor drivers via CAN Bus.



4.4 Power Distribution and Management System

Ayaz is powered by a 3S 11.1V Li-Po battery. Power distribution is handled by a custom-designed Power Distribution Board. This board helps protect the system against voltage fluctuations and electrical noise by separating high-current motor lines from sensitive logic circuits.

The electronic system integrates perception, processing, communication, and motor control units. Camera, LiDAR,

GPS, IMU, and odometry data are processed by the Jetson Orin. Motion commands are then transmitted to the STM32 and subsequently to the SparkMAX motor drivers, enabling real-time control of the vehicle.

When activated, Ayaz is equipped with a relay-based emergency stop system that directly cuts power to the motor drivers. The Jetson Orin and sensors remain operational, allowing the system to continue data logging and analyze the cause of the stop.

For autonomous navigation, Ayaz uses two cameras, a 2D LiDAR, GPS, IMU, and wheel odometry. These sensors provide the necessary data for perception, obstacle detection, localization, mapping, and path planning.

4.5 Requirements for Electrical Design

Electrical/Electronic Requirement	Expected Criteria	Hardware/Solution in Ayaz	Discussion
Power Supply and Distribution	High discharge capacity, clean voltage lines, electrical isolation.	3S 11.1V Li-Po Battery and Custom Design PDB	High-current lines are isolated to prevent voltage fluctuations and electrical noise at the logic level (12V-5V etc.).
Motor Communication	Noise resistance, lossless data and odometry transmission, minimum wiring.	CAN-Bus (REV SparkMAX drivers & NEO brushless motors)	The processing load is divided into modules; while Jetson handles heavy algorithms, STM32 controls the motors without delay.

Remote Communication	High bandwidth and emergency redundancy	Wi-Fi API (Main) + HC-12 RF Module (Backup)	While high data flow is provided via Wi-Fi, the HC-12 module ensures manual and safe intervention in case of potential connection losses.
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Table 3:Electrical and Electronic Requirements Matrix

5. Perception

5.1 Lane and Obstacle Identification

Ayaz uses image processing and LiDAR laser scanning data simultaneously in order to perceive its environment and navigate safely through the AutoNav course.

Lane Detection: Camera data from the sensor mast is processed using a UNet-based deep learning model for semantic segmentation, as described in Section 1.3, in order to distinguish white and colored course boundaries in real time. The lane pixels obtained from the model are transformed into a 2D plane using Inverse Perspective Mapping (IPM).

Obstacle Detection: The LiDAR sensor scans the vehicle’s full 360-degree surroundings, providing precise distance and positional information of obstacles. The characteristic obstacles of the AutoNav course, such as road construction barrels and 2-foot diameter simulated potholes, are also detected with support from camera data. LiDAR-camera fusion enables not only the localization of obstacles but also the estimation of their spatial extent, allowing the generation of safe navigation corridors.

5.2 Internal Course Representation: Occupancy Grid Map

The perceived data is converted into an "Occupancy Grid Map" format, which maps the vehicle's surroundings and is used by the driving logic.

Creation and Update: As the vehicle moves, the mapping algorithm—supported by wheel odometry and IMU data—updates the current occupancy map. Lane data from the segmentation model are processed as "impassable boundaries" (walls), while physical obstacles such as barrels and fake potholes are integrated into the map as "high-cost cells."

Data Fusion: Precise distance data provided by LiDAR and lane/pothole data from the camera are merged within a common global coordinate system. This process maintains a continuous, live, and up-to-date 2D representation of the vehicle's environment.

5.3 Requirements for Perception Design

Processing Power: The selection of NVIDIA Jetson Orin’s high GPU capacity has enabled the real-time execution of complex deep learning models, such as UNet, in the field.

Sensor Placement: The 90 cm high tower and the optimized 52-degree camera angle fulfill the requirement for perceiving lanes and fake potholes from a wider perspective, while also minimizing blind spots in the system.

Perception Requirement	Driven by	Target Value	Actual Measured Value	Discussion
Lane Segmentation Accuracy	AutoNav Lane Violation Rules	> 90% Accuracy under different lighting conditions	92% Segmentation Accuracy in software tests	Our UNet model successfully detected lanes with a performance exceeding the required threshold.
Obstacle Detection Sensitivity	Collision and Safety Rules	> 98% Sensitivity at a 5-meter range	98.4% Sensitivity with LiDAR + Camera fusion	Our UNet model successfully detected lanes with a performance exceeding the required threshold.

Table 4: Perception Requirements and Performance Comparison Matrix

6. Driving Logic

6.1 Overview

Ayaz's driving logic is designed to perform autonomous navigation within the dynamic and static obstacle-filled environment of the IGVC 2026 AutoNav course. The system blends perception and localization outputs for lane following, obstacle avoidance, and high-precision GPS waypoint navigation. The architecture consists of a unified 2D Occupancy Grid Map, Extended Kalman Filter (EKF) localization, *A path planning**, and Pure Pursuit trajectory tracking components.

6.2 Lane Tracking and Obstacle Avoidance

Ayaz defines the driving area by processing LiDAR and camera data. Semantic segmentation data from the cameras identify lane boundaries, while LiDAR provides precise distance information of surrounding obstacles. These data points are merged into a common occupancy map to mark safe drivable areas and obstacle zones (barrels, fake potholes, etc.) in real-time.

6.3 Navigation & Fusion

The vehicle utilizes GPS, IMU, and wheel odometry data to determine its position with millimeter precision. These heterogeneous data sources are fused using the EKF algorithm to estimate the vehicle's position and heading within the coordinate system with high accuracy. The driving logic uses this fusion output to steer the vehicle toward target GPS waypoints

6.4 Path Planning and Motion Control

The *A algorithm** calculates the shortest and safest path on the updated occupancy map while avoiding obstacles. When a new obstacle (such as a barrel in the middle of the road) is detected, the route is dynamically updated in less than 100 ms. This calculated path is converted into motor commands by the Pure Pursuit algorithm, ensuring the vehicle follows the trajectory smoothly and steadily.

6.5 Command Generation and Monitoring

Navigation commands are computed on the NVIDIA Jetson Orin and transmitted to the STM32F407 microcontroller via the UART protocol. While the STM32 manages the SparkMAX motor drivers over CAN-Bus, it simultaneously sends odometry feedback from the motors back to the Jetson. This closed-loop structure ensures continuous monitoring of the vehicle's motion.

6.6 Complex Scenarios

Ayaz performs route re-planning in challenging situations such as ramps, dead ends, traps, and switchbacks.

Center Islands: When encountering islands in the middle of the path, the A* algorithm calculates the costs on both sides of the island to select the safest passage corridor.

Ramp Navigation: Changes in the **pitch angle** detected by IMU data identify that the vehicle is on a ramp; the **25:1 reduction ratio** drive system, combined with software-based torque balancing, allows the ramp to be cleared without any loss of speed.

6.7 Requirements for Driven Logic

Category	Criterion	Configuration Value	Engineering Rationale and Description
Obstacle Management	Inflation Radius	0.3-0.7 Meters	The vehicle's physical track width (0.67m) is taken as a reference in the main planning layer (Vision Map); a safety margin of approximately ~0.23 meters is added to minimize collision risk.
Localization	Waypoint Proximity Tolerance	0.5 Meter Radius	Standard GPS signal fluctuations (noise) in open areas are tolerated, allowing the node to skip and head to the next target once the vehicle comes within 0.5 meters of the target center.
Emergency/Recovery	Recovery Behavior	Planned Path < 0.25m	The system uses spatial triggers instead of delay timers. If the safe path distance generated by the <i>A algorithm</i> * falls below 5 grid units (~25 cm), the system detects a dead end (trap) and immediately switches to recovery (reverse maneuver) mode.

Table 5: Driving Logic Configuration Requirements Matrix

6.8 Performance Matrix and Evaluation

The performance of AYAZ's autonomous driving algorithms was measured based on telemetry data obtained from Gazebo simulations and processing load analyses from physical field tests. The compliance of the system with the configuration limits defined in Section 6.7 is presented in the matrix below:

Evaluated Metric	Test Criterion	Gazebo Simulation Result	Physical Field Test Result
Dynamic Obstacle Avoidance	Number of violations of the 0.3–0.7 m safety zone	0 violations	0 violations
Waypoint Accuracy	Entering the target waypoint within a 0.5 m radius	0.12 m average deviation	0.38 m average deviation
Trap Resolution	Recovery mode activation time	2.8 s reaction time	4.5 s reaction time
System Latency	A* route recalculation time	38 ms average	55 ms average
Sensor Fusion Stability	False positive obstacle detection rate	1.5% error rate	4.2% error rate

Table 5: Autonomous Driving Performance Evaluation Matrix

Technical Evaluation and Optimization Notes

- **Low Latency:**
The path-planning decision loop operates at 10 Hz. Tests on the NVIDIA Jetson Orin AGX showed an average end-to-end computation time of 55 ms after Python and NumPy optimizations, remaining well below the 100 ms target.
- **Localization Precision:**
The system uses a 0.5 m waypoint tolerance. While simulation results showed minimal deviation, field tests remained within a maximum deviation band of 45 cm due to outdoor GPS fluctuations, which is acceptable for safe autonomous navigation.
- **Spatial Recovery:**
Instead of time-based recovery logic, the system uses spatial triggers to detect traps such as narrow passages or dead ends. When the available free space for safe path generation falls below a critical threshold, the vehicle activates recovery behavior and moves back to a safer area.

- **Fusion Stability:** Sensor fusion is performed using a logical OR rule between LiDAR and camera-based occupancy data. If either sensor marks a grid cell as occupied, the final map treats that cell as blocked. This conservative approach improves safety and reduces the effect of temporary vision losses or sensor spikes.

7. Key Performance Indicators

Ayaz's autonomous navigation performance is evaluated using three main KPIs: localization precision, obstacle detection rate, and end-to-end latency.

7.1 Localization Precision

The target localization error was set below 15 cm by comparing EKF outputs with the real ground position. Gazebo tests showed an average deviation of 12 cm, while field tests resulted in 38 cm average deviation due to outdoor GPS noise. Although this exceeds the ideal target, it remains within the 0.5 m waypoint tolerance, allowing safe waypoint navigation.

7.2 Obstacle Detection Rate

The target was to detect barrels and simulated potholes within 5 m with at least 98% accuracy using LiDAR and camera fusion. Log analysis of the occupancy grid showed a measured detection accuracy of 98.4%. This result confirms the effectiveness of the 90 cm sensor mast and Boolean OR fusion approach.

7.3 End-to-End Latency

The target latency from raw sensor processing to A* route recalculation was set below 100 ms. ROS2 timestamp analysis on the NVIDIA Jetson Orin AGX showed 38 ms latency in simulation and 55 ms under full field-test load. These results confirm that the system reacts fast enough for safe navigation at 1.0 m/s.

7.4 Autonomous Velocity Regulation

- **Objective and Rationale:** Per IGVC rules, to ensure safe maneuvering and environmental safety, the autonomous cruising speed of the vehicle is targeted to be fixed at the 1.0 m/s limit (satisfying the minimum 1 mph rule).
- **Measurement Method:** Measured through the real-time analysis of wheel odometry (encoder) speed data, received from the motor drivers, via the Jetson.
- **Actual Value and Evaluation:** The average cruising speed of the vehicle was measured at 0.98 m/s. Reaching the desired 1.0 m/s target with a 2% tolerance reveals that the PID control and speed regulation logic of the motors (25:1 reduction) prevent speed fluctuations even on rough terrain.

8. Analysis of Complete Vehicle

8.1 Lessons Learned During Construction and System Integration

The system integration and prototyping processes demonstrated the critical importance of power management and signal integrity in Ayaz.

- **Power Architecture and Noise Management:** In the early stages, multiple independent voltage regulators were used to meet the voltage requirements of different hardware components. However, testing showed that this structure generated high-frequency electrical noise across the system and caused fluctuations in sensitive sensor data. As a result, it was concluded that the power architecture should be designed from the beginning as a centralized and simplified system with minimal regulator usage.

- **Logic-Level Compatibility Issues:** It was observed that using standard MOSFETs to drive high-current loads directly with 3.3V/5V logic signals from the STM32 caused overheating and power losses. This experience demonstrated that Logic-Level MOSFETs are necessary for field reliability in microcontroller-based switching systems.

8.2 Top Hardware Failures That Would Prevent Competition Success and Mitigations

During testing, two critical hardware/communication failures that could interrupt autonomous operation were identified, and permanent mitigation measures were implemented.

System Failure Caused by E-Stop Triggering (Back-EMF Failure)

- **Hardware Failure:** When the E-Stop was triggered, the energy stored in the motor relay coils generated a high-voltage back electromotive force, causing the STM32 microcontroller to lock up and the system to become uncontrollable.
- **Implemented Modification:** The Power Distribution Board was revised, and reverse-biased flyback diodes were added in parallel with the relay coils to suppress the induced current.
- **Was Recurrence Prevented?:** Yes. After this modification, no microcontroller lock-up or system reset occurred during subsequent E-Stop tests.

CAN-Bus Failure and Synchronization Loss

- **Hardware/Communication Failure:** During initial power-up, CAN-Bus communication did not always initialize automatically, and electrical noise occasionally caused Error Frames that interrupted communication with the motor controllers.
- **Implemented Modification:** A delay was added to the STM32 initialization sequence to allow the motor controllers to become fully ready before CAN communication started. In addition, **Automatic Bus-Off Management** was enabled through STM32CubeMX.
- **Was Recurrence Prevented?:** Yes. The system now establishes synchronization automatically at startup and can recover the CAN line without manual intervention in case of communication interruptions.

8.3 Safety, Reliability, and Durability Considerations

To ensure the durability of the vehicle, a hybrid structure consisting of birch plywood and polycarbonate panels was selected. Positioning the E-stop button on the sensor mast in a way that remains under mechanical protection even in the event of a rollover ensures full compliance with IGVC safety standards.

8.4 Key Hardware Failure Points and On-Site Resolution Strategies

The semi-modular structure of the polycarbonate panels allows the damaged part to be quickly removed and replaced with a spare part in the field in the event of a mechanical impact.

8.5 Virtual Environment Testing and Gazebo Simulation

Ayaz's autonomous driving algorithms were tested in the Gazebo environment prior to physical manufacturing. The 52-degree field of view of the cameras and the axial placement of the LiDAR were verified in the simulation, proving that blind spots were minimized.

8.6 Physical Testing to Date

Mechanical: During Ayaz's mechanical tests, chassis rigidity, body panels, the skid steering drive structure, and the performance of the PETG-TPU airless wheels were evaluated. It was observed that the 10 mm birch plywood chassis provided vibration damping, while the 5 mm polycarbonate panels protected the electronic components while facilitating maintenance access. The 1:25 reduction ratio and the placement of the 20 lb payload near the rear axle supported low-speed control and traction.

Electronics: In the electronics tests, the 3S 11.1V Li-Po battery, custom-designed PDB, Jetson Orin, STM32F407, SparkMAX motor drivers, and CAN Bus communication were verified together. It was observed that the PDB separated the motor lines from sensitive logic circuits, and speed, current, and odometry data could be retrieved via the CAN Bus. The relay-based E-stop system was tested, confirming that while motor power is cut, the Jetson and sensors continue to operate.

Software: In the software tests, environmental perception with camera and 2D LiDAR data, 2D occupancy grid generation, localization, A* path planning, and Pure Pursuit trajectory tracking were tested on the vehicle. An obstacle map was created by fusing camera and LiDAR data, and GPS, IMU, and wheel odometry were utilized for localization. During the tests, system behavior was monitored via a web interface and log records.

8.7 Predicted Performance Analysis

- **Speed:** Ayaz's maximum theoretical speed is approximately 1.78 m/s, based on the 1:25 gear reduction and 150 mm wheel diameter. This keeps the vehicle within the IGVC 1–5 mph speed limits.
- **Ramp Climbing:** With a competition mass of about 25.1 kg, REV NEO motors, and a 1:25 reduction ratio, Ayaz is expected to climb 15% grade ramps without major traction loss.
- **Reaction Time:** The relay-based hardware E-Stop system is designed to cut motor power in less than 0.5 seconds, independently from the high-level software.
- **Localization:** GPS, IMU, and wheel odometry data are fused through an Extended Kalman Filter to provide stable position and heading estimation for waypoint navigation and path tracking.
- **Battery Life:** Ayaz uses a 3S 11.1V Li-Po battery, with an expected battery life of approximately 2–3 hours, sufficient for AutoNav runs and repeated testing.
- **Obstacle Detection:** Camera and 2D LiDAR data are used together for obstacle detection. Cameras support lane and visual obstacle detection, while LiDAR provides distance information for the occupancy grid.
- **Complex Obstacles:** Ayaz handles barrels, potholes, narrow passages, ramps, dead ends, and traps by updating the occupancy grid and replanning with A*. Pure Pursuit provides stable path tracking.
- **Waypoint Accuracy:** Waypoint accuracy is supported by EKF-based fusion of GPS, IMU, and wheel odometry. Final accuracy will be validated through field tests.
- **Failure Handling:** Failure handling is supported by the hardware E-Stop, CAN-Bus recovery, modular body panels, HC-12 RF backup communication, and Automatic Bus-Off Management.
- **Testing Comparison:** Simulation and field test results will be compared for path planning, obstacle detection, localization stability, latency, and vehicle motion.

8.8 Software Testing Bug Tracking and Version Control

For version control and remote storage, our team implements git and GitHub. The git platform provides pull requests, branches, and issues sections, facilitating simultaneous development across multiple developers. GitHub serves as our remote repository host, storing both legacy and current

software versions accessible to all team members. Upon initialization, Ayaz automatically retrieves code from the main branch's latest version—a branch that can only be modified through pull requests that undergo review by authorized team leaders before implementation.

9. Cyber Security Analysis

Ayaz has been analyzed against potential cyber threats due to its networked structure and multi-source software libraries (ROS2, NVIDIA Jetpack, etc.). Three fundamental vulnerabilities that must be addressed during the transition to mass production are presented below:

9.1 Wireless Network Vulnerabilities

The vehicle's telemetry data and configuration interface are transmitted via Wi-Fi. An unsecured or weakly encrypted wireless network can allow attackers to monitor the data (Eavesdropping) or intercept and send spoofed commands (Man-in-the-Middle).

Hardening Strategy: During the mass production phase, the standard WPA2 encryption should be upgraded to the WPA3 protocol, and enterprise-level certificate-based authentication (802.1X) should be implemented. Furthermore, device-based MAC address filtering and an encrypted VPN tunnel must be mandated for access to the management interface.

9.2 Denial of Service on Sensor Data

Autonomous vehicles perform high-speed data transfer over UDP/TCP packets to perceive their environment. Attackers can lock the vehicle's obstacle detection system by sending excessive packets over the network (flooding) or manipulating sensor data (spoofing), forcing the vehicle to stop or perform erratic maneuvers.

Hardening Strategy: DDS (Data Distribution Service) Security must be enabled within the software architecture. By utilizing the SROS (Secure ROS) features provided by ROS2, mutual authentication and data integrity checks (checksums) must be ensured among all sensor nodes. In this way, packets from unverified sources are rejected by the system.

9.3 Unauthorized Physical Access to the Debug Port

The external panels and modular structure of the vehicle facilitate maintenance but simultaneously leave physical access points (the USB and UART ports of the NVIDIA Jetson Orin) vulnerable. A malicious actor could infiltrate the operating system through these ports, obtain root privileges, and modify the software.

Hardening Strategy: The physical hardware design must be updated to support the Secure Boot feature during the mass production phase. This ensures that only secure software signed by the manufacturer can be executed. Additionally, unused physical ports must be disabled at the hardware level, and internal electronic components must be enclosed within tamper-evident sealed housings.