Intelligent Ground Vehicle Competition 2025

Millersville University of Pennsylvania

ALiEN 6.0

Statement of Integrity

I certify that this report represents the original work of the team and complies with all IGVC rules.

Dr. John R. Wright, Jr., Advisor

5/14/2025
Date Certified & Submitted

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Introduction

The Autonomous Lidar Environment Navigator (ALiEN) 6.0 project represents Millersville University's sixth entry into the Intelligent Ground Vehicle Competition, with a primary focus on the AutoNav challenge. This year, the team chose to move away from traditional and hobbyist approaches. Instead, we pursued an industrial-grade implementation more in line with the current curriculum taught. The core of the system includes elements such as Programmable Logic Controllers (PLCs), DIN-Rail mounted hardware, and a true control cabinet.

This approach prioritized reliability, modularity, and maintainability; all principles drawn from real implementations of automation systems. This decision to switch control schemes from hobbyist electronics to industrial components was driven in large part thanks to generous industry partnerships with Phoenix Contact, SICK AG, SEW Eurodrive, Saginaw Control & Engineering, and The ATMAE Accreditation board.

Team Composition and Organization

Team Members

Name	Department	Class
Zane Weaver	Automation and Robotics, Computer Science	Senior
Joseph LaMontagne	Automation and Robotics	Junior
Sofia Griffiths	Automation and Robotics	Junior
Hecmarys Cintron	Automation and Robotics	Freshman
Tristan Rush	Computer Science	Junior
Ian Troop	Automation and Robotics	Senior
Matthew Way	Automation and Robotics	Junior
John Hershey	Computer Science	Junior
Jacob Garcia	Automation and Robotics	Senior
David Stutzman	Automation and Robotics	Senior
King Igwe	Computer Science	Junior
Khanh Vo	Chemistry	Senior
Benjamin Weaver	Automation and Robotics	Sophomore
Dennis Nguyen	Automation and Robotics	Senior
Mark Hilton	Computer Science	Senior
Gavin Boland	Computer Science	Sophomore
Steven R Cope	Automation and Robotics	Senior

While the team did not employ formal subgroup structure this year, responsibilities were still divided up based on expertise. Members focused on sections such as mechanical design and fabrication, electrical design, software development and integration. Coordination occurred through weekly meetings, and decisions were made by voting as a group. This loose structure allowed members to contribute as they are able, which greatly affected our flexibility.

Design Assumptions and Process

From the beginning, the team made several key assumptions and considerations to ensure the robot could be completed in a timely manner and could properly complete the course. It was assumed that our GPS system would maintain an error margin within two feet, based on consistent past performance. As a result, GPS integration was deprioritized during early development. We assumed that our PLC would have a fast enough scan time to navigate the course. This felt fair to assume due to the speed increase that came from switching away from microcontrollers to a PLC.

The design process was mainly priority driven. Saginaw Control & Engineering provided the team with cabinets and sub-panels for use this year, and while half the team focused on mounting the cabinet to the chassis we stripped from a retired wheelchair, the other half began to lay out DIN rail as well as wire duct. Once these steps were completed, we could install the sub-panel into the cabinet. From there, the next focus was the initial software integration. While some members of the team finalized the GPS tower and LIDAR mount, the rest spent time working on bringing specific sub-systems to life. We brought systems online in the following order: PLC → LIDAR → Safety Circuit → Motors → IPC/Camera → GPS. This allowed the team to isolate and troubleshoot any issues that might arise.

System Architecture

Significant Mechanical Components

The robot’s foundation is built on a repurposed powered wheelchair base, which was fully stripped down and repainted. All original components were removed, except for the casters and wheels. This platform offered a rugged base that had already proven itself.

As in prior years, the team made heavy use of 80/20 aluminum extrusion. This year, it served as the mounting point for all sensors and the panel itself. This aluminum profile continues to prove itself as the best choice for framing, as it is simple to cut to size and allows for unmatched modularity. Sensor adjustment consists of loosening bolts and sliding, which allows for the team to be very flexible based on the needs of the course. The core cabinet of the build, as well as its subpanel, was provided by Saginaw Control and Engineering. This allows ALiEN 6.0 to be innately waterproof, as well as shock resistant.

The drive system consists of Movimot ELV motors donated to the team from SEW Eurodrive directly powering the main wheels. These motors run off 48 volts with a 24v control setup. These motors provide a simple control scheme and have built in monitoring, as well as fault tracking. ALiEN 6.0 steers by running these motors at different speeds. 2 caster wheels are positioned in the rear to stabilize the build.

Power and Electronic Components

ALiEN 6.0 is powered by a pair of 24V Dakota lithium batteries connected in series. This high voltage is supplied to our motors, as well as to a 48V to 24V converter. The 24V circuit provides power to almost all components, while a 5V system branches off the 24V to power the GPS. All critical circuits are protected by circuit breakers, and distribution is managed by a power distribution module. All electronic equipment was sourced from Phoenix Contact through their partnership with the team.

The control system is built around a Phoenix Contact AXL F 2152 programmable logic controller (PLC), which serves as the logic unit. This PLC is what interfaces with the NAV310 LIDAR, a generous gift from SICK. Additionally, a Phoenix Contact Industrial PC (IPC) handles all vision processing through two Logitech webcams. A teensy 4.0 is utilized in combination with a QMC5883L Compass and a NEO-6M GPS to get real-time position and guidance. A core feature of the Movimot ELV motors from SEW is their built-in motor controllers, so the team did not need to source any extra. A small number of relays were utilized for various functions such as voltage switching and monitoring.

This system architecture would not have been possible without Phoenix Contact, SICK AG, and SEW Eurodrive. By providing the team with the necessary hardware and support to complete this build, they have helped the team build the most robust robot to date.

Significant Software Modules

ALiEN 6.0 is built on a modular software architecture that combines multiple industrial platforms. The core controller, the AXL F 2152 PLC, is programmed using PLCNext Engineer. This development software allows for easy integration of digital I/O, network communications, and the core automation loop. Device-specific configuration software also played a big role in development. SOPAS Engineering Tool is used to configure the SICK NAV310 LiDAR sensor, which enables live object detection and distance measurement. Movisuite, provided by SEW Eurodrive, is used to configure and monitor the ELV motors. This enables hand speed control during testing and fault monitoring. The Teensy 4.0 is programmed using Arduino IDE. High-level vision processing was handled using Python, using libraries like OpenCV and Socket for processing and communication. This program is loaded onto the IPC and effectively serves as the bridge between the cameras and the PLC.

System Integration and Interaction

Subsystems communications within ALiEN 6.0 are handled through a mix of means. The SICK NAV310 LiDAR as well as the Vision system communicate directly with the PLC over a TCP connection. LiDAR broadcasts a high-resolution scan over TCP to the PLC, sending distance values for every scanned angle in its defined view. This is being sent to the PLC over port 2112, which is defined to be the Binary CoLa communications port by SICK. The Python vision script sends a simple byte containing detection data for defined zones around the robot, handling the processing in the background. This is being sent over port 5000, which was chosen arbitrarily as any user-space port would have been functionally equivalent. The GPS module uses a simple 3 wire interface to communicate direction. It handles the processing in the backend and tells us what direction we need to head to hit our next waypoint. The final and most complex protocol integrated is Profinet, which is an industrial communications system embedded between the motors and the PLC. Each device sends and receives 5 words. This enables complex control of speed, acceleration, deceleration, torque, and fault management for the motors.

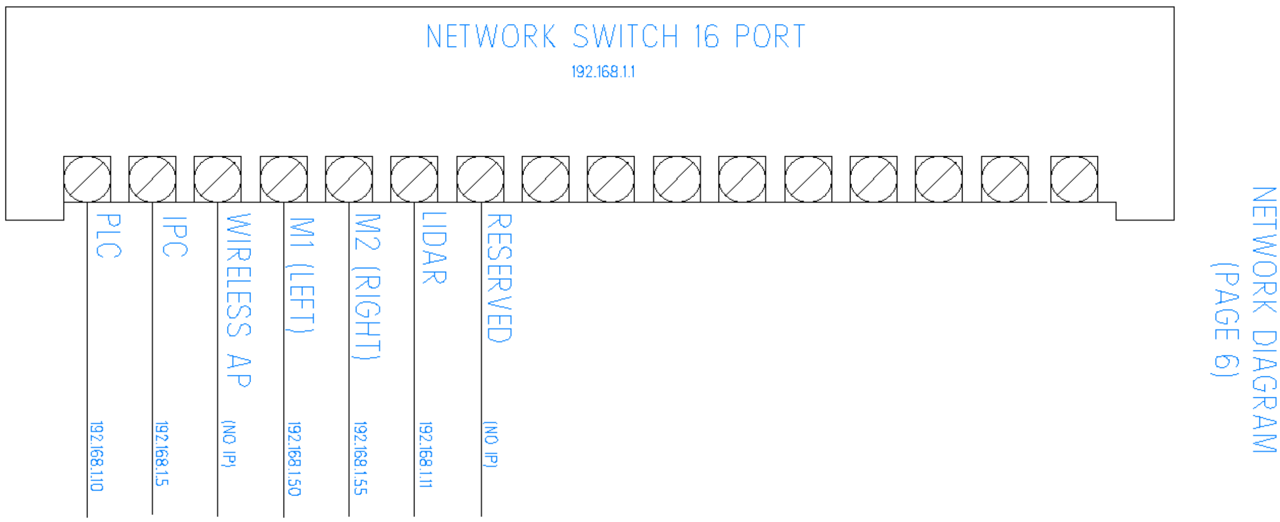

Figure 1: Network Diagram

Safety Devices

ALiEN 6.0 Uses a single-channel safety architecture designed to disable locomotion rapidly and reliably when triggered. The safety system includes two hardwired emergency stop buttons, a remote stop, a safety contactor, and a monitoring relay. The Estops and remote stop are wired so that if any are tripped, power to the motors is immediately cut via the contactor. The system cannot reengage until all estop conditions are cleared. This is in tune with common industrial safety practices, and as such is a well-known robust system.

Effective Innovation in Vehicle Design

Unique Features

The most unique innovation in ALiEN 6.0 is the team's transition to fully industrial control architecture. Past iterations used hobbyist electronics and microcontrollers, which proved harder to scale, debug, and often failed in the field. These systems proved to be unreliable to the team's high expectations, so a new approach was needed.

That new approach was discovered in the form of Phoenix Contact's PLC. The team captain had worked with the AXL F 2152 before and learned how robust it was from that experience. With that knowledge in hand, the team proposed an entirely new kind of robot. This new robot would be fully constructed and automated using strong industrial standards and protocols. Phoenix Contact agreed to donate $25,000 worth of parts, as well as supervise building sessions. The team already received the NAV310 lidar from sick, valued at over $13,000, and began reaching out to other companies to make this dream a reality. SEW agreed to donate 4 motors and support for getting them integrated, totaling

~$15,000. With the help of Phoenix Contact, Saginaw Controls and Engineering agreed to supply a cabinet and panel, as well as backups of both, totaling $510.34.

This architecture required the team to rethink almost all aspects of the robot. Layout, power distribution, and communications all had to be overhauled to meet industrial standards. The safety system had to be completely rethought. While much more complex than hobbyist systems, the modularity and diagnostic capabilities offered far outweighed this cost.

Rather than rely on fragile wiring systems that have proven to be points of failure, all connections were routed through professional grade spring lock terminals. The use of ethernet standards such as TCP and Profinet meant the system was far more robust than simple PWM wires running to motor controllers. The team feels this platform is advanced enough to be pulled off the wheelchair platform and directly mounted onto a car.

Mechanical Design

Chassis and Structural Design

ALiEN 6.0's mechanical design prioritizes modularity over complexity. The core cabinet and sensor frame are mounted atop a repurposed wheelchair chassis via 2 bolts and 4 steel cables. This enables the system to be easily remounted on any other base imaginable with minimal effort. The 80/20 framing allows for highly adjustable and modular attachment points. While mechanically simple, the design has proven to be rugged and intentionally designed for reuse, reflecting the team's emphasis on long-term adaptability.

Suspension and Stability

ALiEN 6.0 uses the existing suspension and caster configuration from the original wheelchair base. The drive wheels are fixed, and the caster wheels provide stabilization. The team chose not to add additional suspension, as the wheelchair functioned suitably without it. Cables were added to help stay the cabinet and absorb any wobbling that might occur.

Weatherproofing

All core electronics were housed in a sealed cabinet provided by Saginaw Control and Engineering, which allows for ALiEN 6.0 to be highly resistant to rain, dust, and debris. Wiring enters through a sealed Cable Entry System, and components are mounted on a raised sub-panel should any water get inside.

Electronic and Power Design

Overview

ALiEN 6.0 uses a 48V system supplied by 2 24V Dakota Lithium batteries in series. Power is stepped down to 24V for control systems and 5V for the GPS system. All wiring is done through terminals and protected by circuit breakers, allowing for a robust and industry grade circuit.

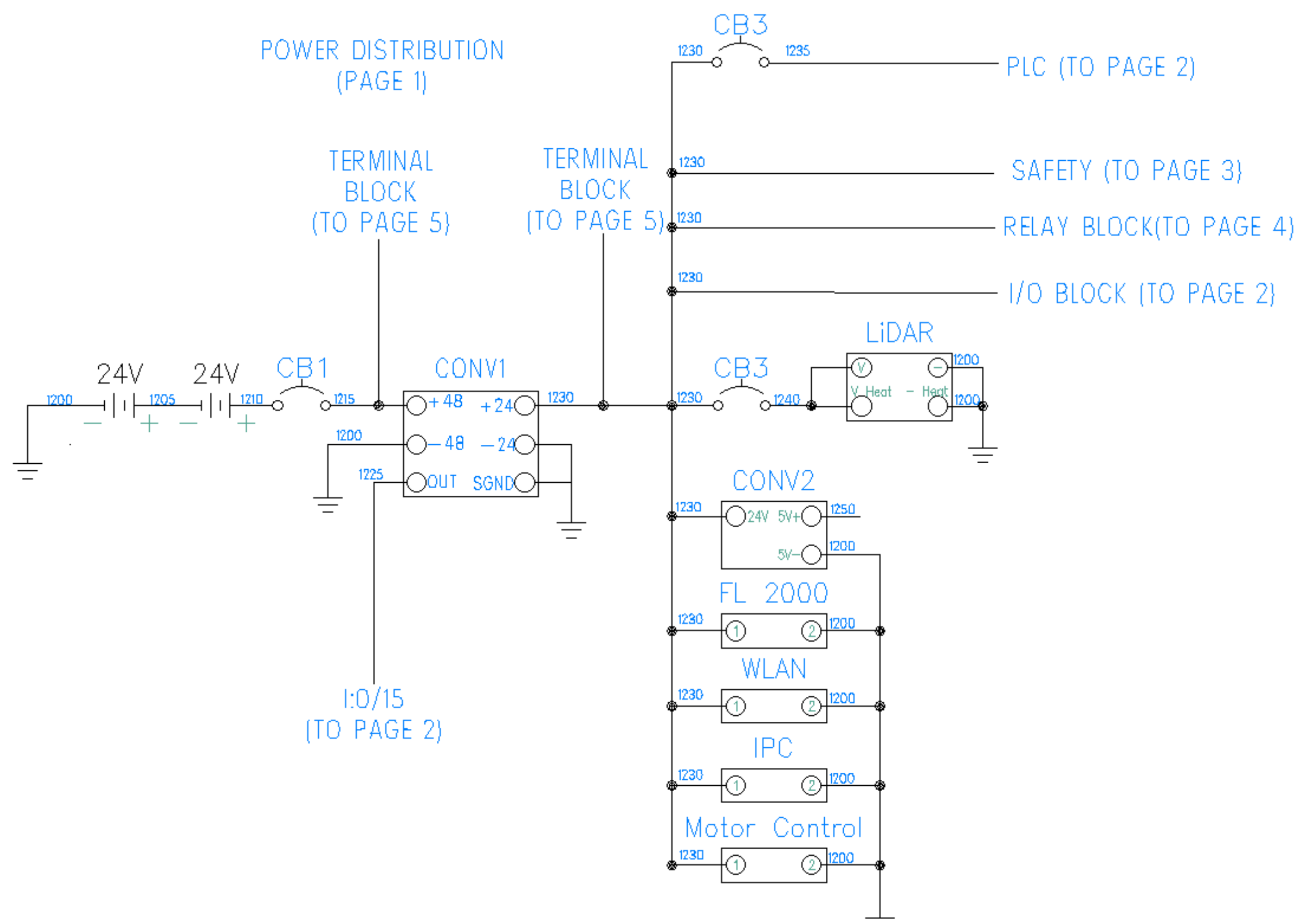

Figure 2: Power Distribution

Power System and Distribution

24V power is distributed to various electronics systems via a DIN rail mounted Power Distribution Module. The 5V power is brought directly up the GPS tower and distributed to all major components. This system has run for over 24 hours without needing a charge and is recharged via the supplied Dakota Lithium chargers.

Electronics Suite

The major electronics onboard consist of the AXL F 2152 PLC, Phoenix Contact IPC, and Teensy 4.0 Module. Sensors include the SICK NAV310 LiDAR, QMC5883L compass, NEO-6M GPS module, and 2 webcams.

Safety Systems

The robot includes 2 hardwired E-stop buttons, a remote stop, a safety contactor, and a monitoring relay. Crucially, this system is negative edge triggering, meaning the wire always has 24V passing through it. If that circuit is ever interrupted at any point, the e-stop system will trigger.

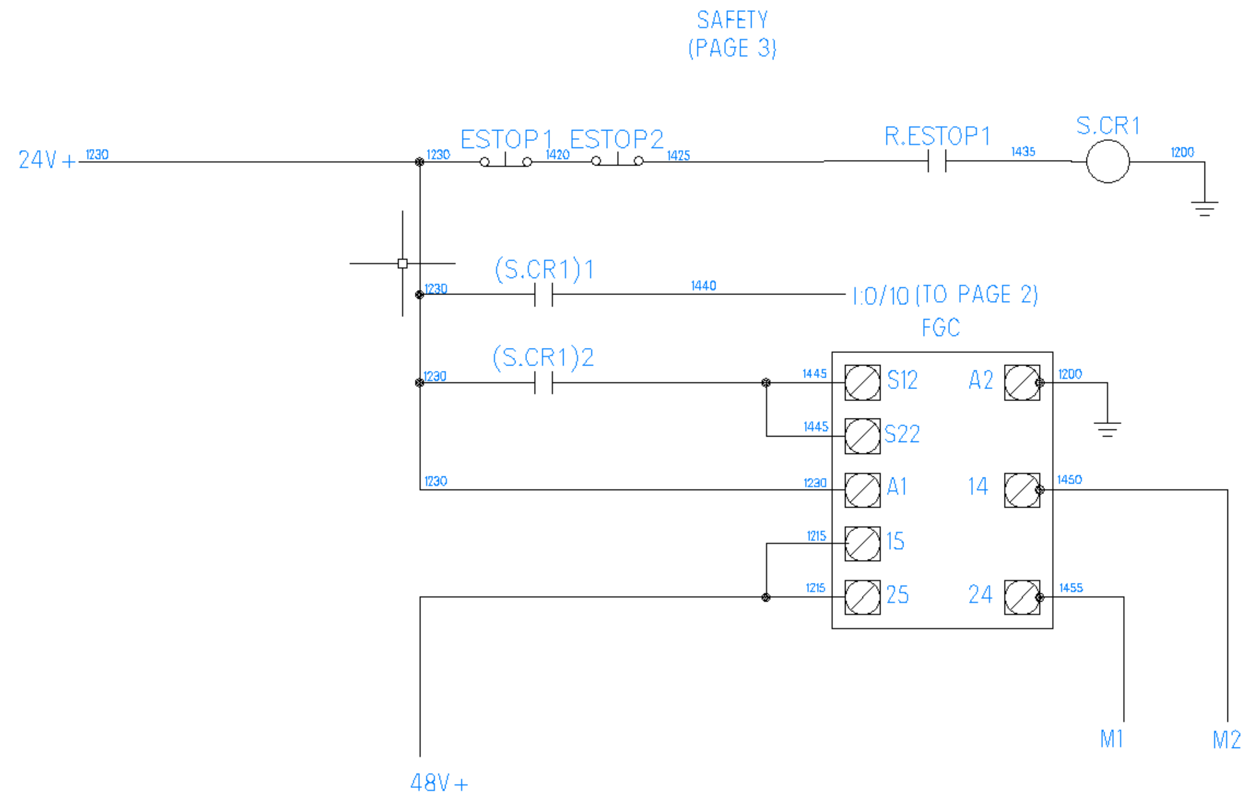

Figure 3: Safety Circuit

Software System

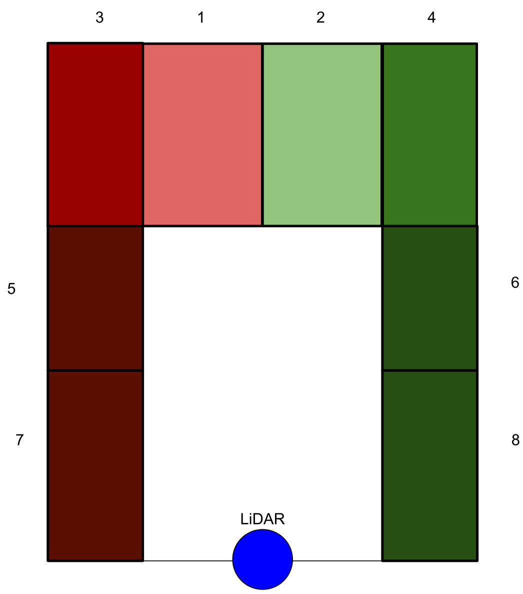

Figure 4: Zone Distribution of ALiEN 6.0

Overall Architecture

The software architecture of ALiEN 6.0 is layered across 3 primary systems. These are the Phoenix Contact PLC, Phoenix Contact IPC, and the Teensy 4.0 microcontroller. The PLC handles the main decision making, motor control, navigation logic, and motion execution. It is also responsible for decoding the LiDAR data from raw bytes to a cartesian point cloud, where it can then identify zone occupancy. It is also responsible for stack light management and the selector switch.

The IPC is primarily used for onboard development, as well as handling vision systems. It processes the camera feeds using OpenCV, interprets any lane lines or potholes it might detect, and transmits that data via a single byte to the PLC. The Teensy 4.0 handles the GPS and compass modules, interpreting and processing their signals down to a simple octal telling the PLC the desired direction.

All communication is routed to the PLC, which acts as the system's brain. It receives all input from various sensors and makes the final decision on behavior. Inputs are primarily received through TCP, and control occurs through Profinet. The PLC also hosts a Web-based HMI which is utilized for manual control, diagnostics, and monitoring.

Perception and Sensor Processing

ALiEN 6.0 uses two primary sensors to interpret its surroundings. It uses a dual camera vision system for Line and Pothole detection, as well as the LiDAR to detect obstacles. Both systems analyze the same zones, and the PLC merges them to identify if an object that needs avoided exists in that zone.

The vision system, running on the Phoenix Contact IPC, is designed to identify large sections of white color. This will enable the camera to identify the lines and markers, while not detecting the ramp as an object to be avoided. The LiDAR scans the surroundings ahead and reports back to the PLC what it sees. The PLC then turns this data into zones, letting us know where we detect obstacles.

While the sensors are tuned to look for different features, they are tuned to look at the same regions. This allows the system to treat lines and physical obstacles equivalently, simplifying the robot's control logic.

Object Detection and Avoidance

ALiEN 6.0 uses the SICK NAV310 LiDAR to perform object detection and avoidance. The sensor scans all points ahead and beside the robot. This data is transmitted over TCP to the PLC. Here, the data is decoded into a cartesian point cloud and eventually boiled down to presence absence bits within

8 distinct zones. These zones are arranged so that half exist in front of the robot in a row, and half exist on either side alongside the robot. If any zone gets marked as occupied, the robot adjusts its trajectory to avoid the occupied zone. This system allows ALiEN 6.0 to react dynamically to both static and dynamic conditions, making it very adaptable and requiring no human intervention.

Lane Following

Lane following is performed in a similar manner to object avoidance, but the bulk of the processing is performed on the IPC rather than on the PLC. The IPC uses 2 cameras and OpenCV to detect large white regions in the camera feeds, which are interpreted to be lane lines or potholes. These areas are flagged and transmitted to the PLC, which treats them equally to obstacles.

The biggest distinction between the cameras and LiDAR is that the camera system only checks six zones. Throughout our testing phases, the team learned the presence of a line in the rear two zones made very little difference in our navigation system. Instead, the team chose to reposition the cameras to give better views in front.

By treating lines and obstacles equally, ALiEN 6.0 can avoid giving accidental precedence to either lane avoidance or obstacle avoidance.

GPS Waypoint Navigation

GPS waypoint navigation is handled by a Teensy 4.0 microcontroller. This controller is connected to both a NEO-6M GPS module and a QMC5883L digital compass. The teensy continuously compares the robot’s current coordinates and heading to the desired waypoint, and transmits a simple octal code representing the directional intent. This code is sent via 3 wires. The PLC receives these signals to determine which direction the robot should head in. Each number received corresponds to an approximate cardinal direction, with 0 being on point. The robot listens to these only when it is safe to do so, meaning there are no objects near the robot.

Motion Control Loop

In autonomous mode, the motion control loop is handled entirely within the PLC. First, the PLC receives zone occupancy data from the LiDAR and vision system. If the system detects anything around it, the vehicle adjusts motor speeds to turn away from obstacles. Otherwise, the motors are adjusted to steer in the direction the GPS is guiding. This steering is handled by differential speed control.

The PLC also has another mode of operation, manual mode. In this mode, all sensor data is disregarded. When a user is connected to the web-based HMI, they can control the robot using 4 buttons, one for each motion possible.

Cybersecurity Analysis Using RMF

Supposing a rival team attempted to disrupt our robot's software, ALiEN 6.0 will be fully capable of defending itself. Following the NIST Risk Management Framework, the team categorized system functions, identified all access points, and selected appropriate controls. All networked devices are isolated on a WPA3 protected network system and require passwords to access any device for configuration or code changes. No unsecured devices are accessible on the network, and the onboard switch has security built in for port monitoring. Even if physical network access is compromised, an attacker would not gain authorization to modify anything on the robot. Testing was performed by a group of team members attempting to red team. They were not successful in gaining unauthorized access to any system embedded.

Analysis of Complete Vehicle

Performance Evaluation

The following performance metrics were observed:

- Top **speed**: governed to 5mph
- **Obstacle detection range**: LiDAR reliably detects obstacles up to 100 meters
- **Reaction time**: Average reaction time (from detection to motor adjustment) is under 10 ms
- **Battery life**: Estimated runtime of 8 hours under full system load
- **GPS accuracy**: Functional with an error margin of approximately 2 feet
- **Waypoint arrival accuracy**: Waypoints are generally reached within 1–2 feet of center
- **Potholes and painted lines**: Detected visually up to 10 feet in front of the robot
- **Complex obstacles (switchbacks, center islands)**: Navigated by combining zone clearance logic with GPS directional intent
- **Traps and dead ends**: Detected before entering typically, and properly avoided
- **Software version control**: Files were stamped with time and date, as well as revision notes.
- **Bug tracking**: Issues logged informally during team meetings and test runs
- **Simulation testing**: No SIL simulation environment was used; all testing performed on physical hardware for
- **Physical testing**: Conducted both indoors and outdoors; results were consistent with predictions, with minor deviations due to lighting and terrain variability

Trade-off Decisions

Several key trade-offs were made during the development process of ALiEN 6.0. The shift to industrial hardware introduced complexity in terms of wiring and development, but greatly improved reliability and maintainability. Vision processing was isolated to simple zone management for the sake of development speed. The team also opted not to do full GPS path planning, instead choosing to use the octal system described above to simplify hardware and communications. Suspension and mechanical complexity were minimized in favor of a modular frame that could be easily remounted elsewhere.

Limitations and Improvements

While ALiEN 6.0 demonstrated strong systems integration and robustness, a few limitations were observed during testing. The GPS tower exhibits some minor wobbling during movement, which could theoretically impact it and the lidar's ability to detect. To date, this has not been observed as an issue. Additionally, the SEW motors produce so much torque that the wheels lose traction and spin. Future iterations will stabilize the tower and select better tires to ensure traction during high torque.

Unique Software, Sensors, and Controls Tailored for AutoNav

The entire platform was developed specifically to complete the AutoNav challenge. The software architecture focuses solely on obstacle avoidance and GPS-based waypoint navigation, allowing the system to operate efficiently without extra logic for Self-Drive elements like cones or signs. The LiDAR is positioned at just the right height to detect the barrels, and the cameras are tuned to specifically look for white lines. The PLC's decision making and control logic are bound to this architecture, built to efficiently complete the course.

Initial Performance Assessments

All core systems have passed bench testing without issue. Individual subsystems were verified before integration, and few hardware failures have occurred. In real-world testing, ALiEN 6.0 has been able to solve even the hardest switchback we could throw at it. Vision systems regularly pick up the lines, LiDAR has never missed detection of an obstacle, and the GPS is always able to pinpoint the exact location. The greatest weakness the team has observed to date has been driving at high speeds (over 3mph). At those speeds, ALiEN 6.0 begins to experience traction loss. Additional testing is planned to refine acceleration and deceleration to avoid this loss.