IGVC 2024 – ALiEN 5.0

Ville Robotics AutoNav Design Report

Millersville University of Pennsylvania

Figure 1. Autonomous LiDAR-Based Environment Navigator 5.0

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I certify that the design and engineering of the ALiEN 5.0 robot has been undertaken by the team members listed below and that the efforts have met the demands of a senior level design course.

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1. Conduct of Design Process, Team Identification & Team Organization

1.1 Team Identification

The Millersville Mobile Robotics Research Team ("Ville Robotics") has a long history of developing competition-grade robots. Since 2001, the team has won 50 individual first-, second-, and third-place awards in numerous national/international competitions, including seven national championships. In 2018 the team began developing self-driving autonomous applications using LiDAR (Light Detection and Ranging), Machine Vision, GPS, and other technologies organized via a distributed control system architecture. Specifically, the team has used SICK LiDAR products due to their industrial grade, local programmability, and intuitive graphical user interface (GUI). This is Millersville University's fourth year entering the annual Intelligent Ground Vehicle Competition (IGVC). To meet the demands of this challenge, we organized ourselves into three main areas of research and development (R&D): Electrical, Mechanical, and Control. We focused on improving our use of technology to complement a robust strategy of navigating the course autonomously while considering each other's perspectives for effective problem solving. To execute this within the given project period, we relied heavily on concurrent engineering.

1.2 Team Organization

Each area of R&D had a student assume the lead on that area of the project. The remaining students then chose their team based on their personal preferences, strengths, and ability levels. Tables 1 and 2 illustrate each team member's name, academic standing, role, time contribution, and club position when applicable, and advisory faculty and staff.

Table 1. Team Member Contribution Catalog

Name	Year	Mechanical	Electrical	Controls	Club Position or Role	Hours
Konrad Bernardino	Senior		X		Electrical Engineer	10 +
Joseph Favoroso	Senior			X	Controls Engineer, Public Relations Chair	30 +
Sofia Griffiths	Sophomore	X	X		Mechanical & Electrical Engineer	40 +
Kenneth Jones	Freshman	X	X		Mechanical & Electrical Engineer	30 +
Joseph LaMontange	Sophomore	X			Mechanical Engineer	200 +
Elizabeth Maschke	Junior	X	Lead		Mechanical Engineer, Senior Electrical Engineer, President	900 +
Dennis Nguyen	Junior			Lead	Senior Controls Engineer	650 +
Griffin Raber	Sophomore	X	X		Mechanical & Electrical Engineer	20 +
Ian Troop	Junior			X	Controls Engineer	100 +
Aiden Ward	Senior	X	X	X	Testing Assistant	10 +
Matthew Way	Sophomore	X	X		Mechanical & Electrical Engineer	200 +
Benjamin Weaver	Freshman			X	Controls Engineer, Secretary	200 +
Zane Weaver	Junior	X	X	X	Project Manager, Vice President	1,000 +
Benjamin Wright	Junior	Lead			Senior Mechanical Engineer, Treasurer	650 +

Table 2. Advisor Catalog

Name	Position	Role
Dr. John Haughery	Faculty	Team Advisor, Millersville University
Jeff Pinegar	Volunteer	Industry Advisor, Phoenix Contact, USA
Ermias Wogari	Volunteer	Industry Advisor, Precision Cobotics, LLC
Kritsada Wongsa	Graduate Student	Lab Supervisor, Millersville University
Dr. John Wright	Faculty	Team Advisor, Millersville University

Mechanical team members produced models, CADD drawings, fixtures, and helped with the robot's overall construction. Electrical team members generated control and power distribution schematics for all electronic systems and wired and integrated all the systems. Members of the Controls team developed code algorithms, programmed sensors, finalized device integration, and iteratively tested to automate ALiEN 5.0.

1.3 Design Assumptions & Design Process

Our team followed The Welding Institute (TWI) 12-step cyclical engineering design process to fabricate the systems of ALiEN 5.0, see Figure 2 (TWI, 2024). Leading up to the preparation of the competition we were individually tasked with familiarizing ourselves with microcontrollers and various electronic sensors. As with all development, we ran into challenges periodically, making troubleshooting a significant phase throughout the construction of this robot. Discovering and alleviating the underlying issues of each sub-system led to new insights. This improved the robustness of the team and enhanced the design of ALiEN 5.0.

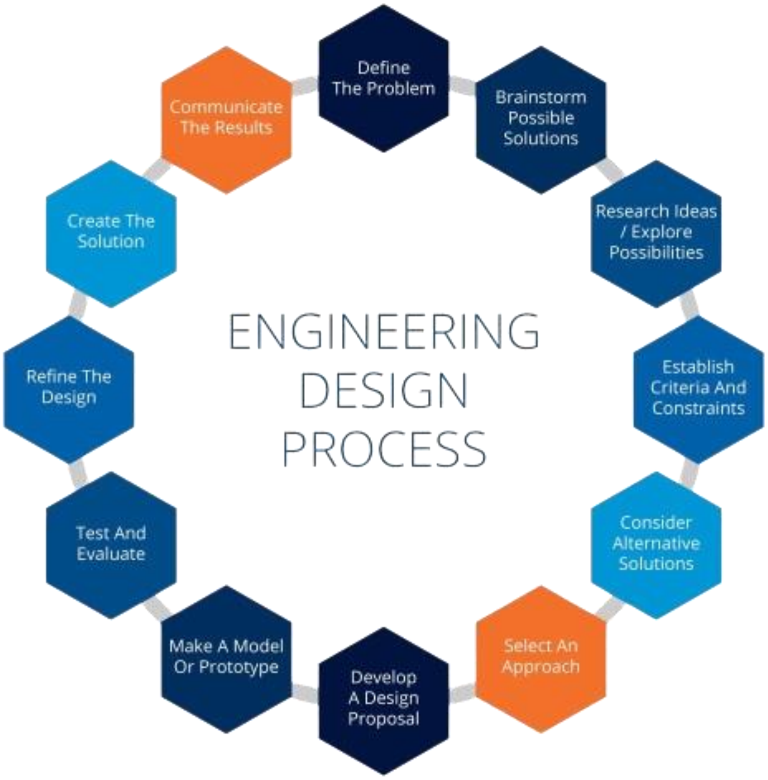

Figure 2. Engineering Design Process Graphic

During the active R&D period of this competition, our first objective was to define the criteria of this challenge as described by the official IGVC competition details and rules (IGVC, 2024). To be thorough, we distributed a quiz to test each team member's familiarity of the regulations. Then, we developed a plan of action for our remaining time of the semester and set expectations as a group. We took inventory of our equipment and brainstormed well-rounded ideas to solve this challenge. After choosing specific approaches that were guided by research, we set off to develop models, algorithms, and schematics and frequently documented each group's progress.

2. Effective Innovations in Vehicle Designs

2.1 Innovative Concepts from Other Vehicles Designed into ALiEN 5.0

Concurrent Engineering

For the ALiEN 5.0 build, our team concentrated on maximizing productivity and testing time. The modular design allowed us to capitalize on concurrent engineering to avoid bottlenecking. We organized ourselves into groups and integrated these standalone systems into the robot as each individual unit was developed. Because our team could research and program independently, individual groups could test their systems before integrating them to the robot. This mitigated the volume of issues at a given moment and allowed us to reach milestones at a faster pace. After teams integrated their system into the robot, they contributed to the other aspects of the build, such as electrical integration or assisting with manufacturing.

Distributed Intelligence with Centralized Control

The performance of autonomous systems is dependent on the quality of data retrieved from an environment and the application of that data in a systematic control algorithm. How this data is utilized is equally critical. ALiEN 5.0 was built using centralized control based on distributed intelligence.

Centralized control can be defined as a methodology of digesting and reacting to data where a primary controller or unit, typically a computer or microcontroller, coordinates all actions (Kovalenko et al., 2022). The controller receives data from various sensors, processes this information, then generates control signals. This architecture provides centralized decision-making and control and has been used for automated greenhouses (Banerjee & Singhal, 2010), variable power supplies (Hannonen et al., 2013), and robotic systems (Kabuka et al., 1988).

Distributed intelligence refers to a system of entities that conjoin to gather information and act upon it (Parker, 2007). In a distributed control architecture, an intricate control challenge gets segmented into smaller, localized issues with each one completing its own processing (Kovalenko et al., 2022, p. 8). ALiEN 5.0 effectively utilized this by giving each individual sensor its own microcontroller, embedded or otherwise, to handle pre-processing of information (i.e. Smart Sensors). This enabled each sub-system to make its own decision and communicate simply back to the central microcontroller. ALiEN 5.0 utilized centralized control with distributed intelligence, to accomplish course navigation. This unique approach has proven successful in prior competitions. Figure 3 illustrates how the ALiEN 5.0 system functions.

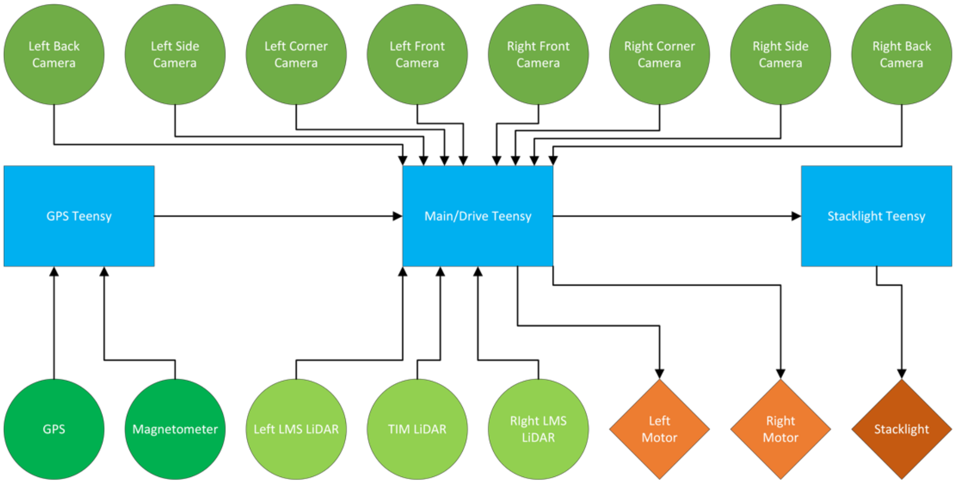

Figure 3. ALiEN 5.0 Systems Diagram

Baseplate

Another innovation was implementing a single base board upon which all electronics were mounted. In previous years, we separated the base panel into three sections, which caused difficulty when performing maintenance. Removing any single panel required mass unwiring of electrical systems, as well as the complete disassembly of the frame. With this new design, the panel could be easily replaced as the hole dimensions are uniform on all of the replacement boards.

Dimensional Changes

Another innovation from our previous design was our reduced footprint. Throughout our experiences with previous competitions, we noticed that our larger frames would run into the barrels and would cast shadows that interfered with our cameras because of the frame size. This year we eliminated both issues by creating our slimmest frame to date. The exterior dimensions are exactly to the minimum dimensions set by the IGVC rules, and we have reduced our frame height by approximately 75%. This means that our robot will cast less of a shadow and will be able to navigate the course with reduced risk of contacting the barrels.

2.2 Innovative Technology Applied to Vehicle

LiDAR

The ALiEN concept was first developed in 2019 for IGVC. Our team has refined the robot's design and is on the fifth iteration. ALiEN 5.0 utilizes sensor fusion of multiple technologies to achieve autonomous self-driving. The robot's design centers around the use of LiDAR technology for safety reasons, as it is far less prone to give false negative readings. In low light or low visibility scenarios, vision-only systems might not "see" people or obstacles, resulting in injury. To mitigate these issues of missed or false reads, multi-sensor systems were developed and deployed.

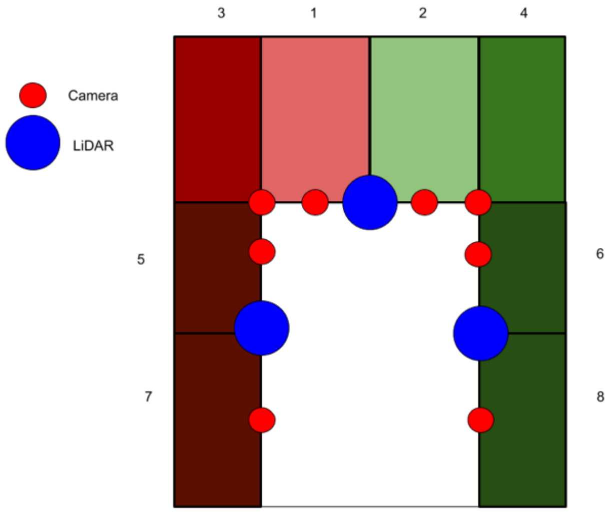

Figure 4. ALiEN 5.0 Zones of Interest

TIM-881P

The TiM881P LiDAR manages obstacle avoidance by analyzing the regions immediately ahead of ALiEN 5.0. It is positioned at the center of the front of the robot, giving the sensor a direct view of its zones. It conducts a scan of zones 1 and 2 to identify the presence of objects, providing ALiEN 5.0 with the necessary information to prioritize objects that require immediate attention.

LMS111-10100

The LMS111 LiDAR systems are deployed to identify six distinct zones on the sides of the robot, as depicted in Figure 4, and allow for efficient detection and analysis of potential hazards. The system is programmed with the SOPAS Engineering tool (SICK, USA). Figure 5 illustrates the LiDAR sensor (right) and user interface (left). Six fields were configured (Figure 4) with three fields covering each side of the robot. This was to prevent accidental collision of the robot with objects, such as barrels, during turns. The LiDAR sensors were programmed to send high signals when sensing an obstacle within their zones to the central Teensy 4.1 microcontroller. This feedback triggered a drive control algorithm to navigate ALiEN 5.0 away from the detected object(s) as needed.

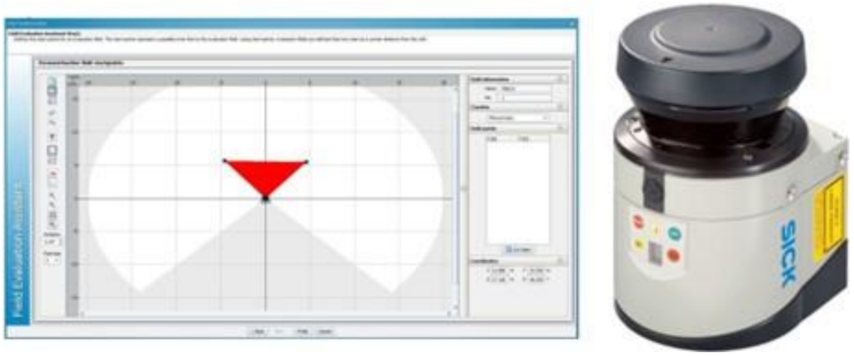

Figure 5. LiDAR User Interface (left) & Sensor (right)

3. Description of Mechanical Design

3.1 Overview

The mechanical design for ALiEN 5.0 improves upon the designs of all previous entries from Millersville University. Over the years, we made additional modifications and design changes resulting in a more robust system. This rendition is based on a different wheelchair chassis than the previous builds, which warranted a new frame to be built, and additional sensors, which require new mounting hardware to be developed. Key improvements include dimensional changes, increased sensor positioning and a new wire management system.

3.2 Decision on Frame Structure, Housing & Structure Design

Our frame follows the same format as prior entries to the ALiEN family: using 80/20® (80/20 Inc., USA) 10-Series, T-slot aluminum extrusions. Two four-slot, 1 in by 1 in extrusions were used to mount the frame to the wheelchair chassis, while the main body of the vehicle is constructed out of 8-slot 3 in by 1 in extrusions. The slots in the extrusion are used to mount various components on the exterior and the baseplate. Twenty-four ¼-20 Button head socket cap screws and four 6-hole rectangular flat plates were used to hold the frame together. Eight gusseted inside corner brackets were used to vertically mount the two mounting rails and components. The 0.25 in smoked polycarbonate was used to encase the robot. The base also functions as a mount for internal electronics, and the top control panel also functions as a mount for mechanical emergency stop buttons. Knurled thumbscrews were used to make the top access panel easily removable.

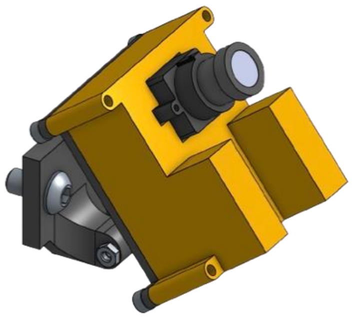

Figure 6. RT1062 Camera Casing

Since we upgraded our cameras from OpenMV H7 to OpenMV RT1062, a new version of our custom camera cases was developed (Figure 6). These cases operate on the same principle as our previous, but with increased rigidity, as well as modifications to the dimensions and mounting system. The hinge joint allows for 90º rotation and has been reinforced to sustain the impacts from the course.

Wire management was a major concern for this year’s design. Previous iterations of this design utilized wire loom that would slot into the internal 80/20 rails. Because we minimized the dimensions, and thus the number of internal rails, we decided to instead design and print wire clips and guides that would assist with organization of the system’s wiring. TPU grommets were designed to slot into the polycarbonate baseplate to allow for wires to run through it to access external sensors and systems. A benefit of this system over the previous is electrical maintenance. For example, to replace a wire on the previous builds, one would need to dismantle the wire loom to get to the wires inside. With the current system, to replace a single wire all that is needed is to simply remove one end of the wire clip and remove it from the channel.

When designing ALiEN 4.0, the LiDAR units had their own purpose-built casing which allowed them to be mounted on any of the front corners or on the GPS tower. With our new design, we mounted the two LMS-111-10100 LiDAR units on either side of the frame to allow them to have a full 180º view of either side. In addition, we mounted the TIM-881P on the front for frontal 180º vision. These mounts were designed with the 80/20 system in mind, so they can be moved horizontally along the frame.

3.3 Description of Drive-by-Wire Kit & Drive Train

Figure 7. The Pride Mobility Jazzy 660 ES

ALiEN 5.0 was built on the chassis of a donated electric wheelchair. This Jazzy 660 power wheelchair, made by Pride Mobility, features 14 in drive wheels, and 6 in caster wheels in the front and rear (Figure 7). The Jazzy 660 has 2.75 in of ground clearance, a factory turning radius of 20.5 in, and a carrying capacity of 320 lbs. after removing the chair. The motors receive pulse-width modulated (PWM) signals from the Teensy 4.1 microcontroller through a goBILDA motor controller. This control scheme allows for an improved zero-radius turn, with speeds of up to 5 m/h.

3.4 Suspension

The wheelchair chassis is driven by two gear motors and is equipped with Pride Mobility’s Active-Trac Suspension (ATX). The suspension system consists of coil-overs, which use linear compression springs to absorb the impact of oncoming obstacles. The system links the front caster wheels to the frame with the motors and drive wheels. When the front casters encounter an obstacle, they are moved upward, subsequently forcing the motors and drive wheels downward. This action assists the wheelchair in climbing over small obstacles. Additional extension springs assist in performing this action. The ATX works in unison with the rear suspension to respond to weight transfers. The frame was attached utilizing custom manufactured brackets which attach to the original seat bolt holes. These brackets then connect to a pair of running bars which mount to the frame.

Our frame is attached in reverse to the wheelchair chassis. The reason for this unusual modification is because we wanted to solve two problems we encountered with our 4.0 chassis. The first of which was our access to the payload and battery compartment. ALiEN 4.0’s battery storage was under the frame of the robot and was difficult to remove for charging. This solution allowed an open tray to be installed below the 5.0 frame to mount the 24 V battery and our payload. The second problem that this solved was with how we approached the ramp in the GPS Navigation section. As we saw with other robots, there were issues with balance when trying to get onto the ramp. Now we have the wheelchair chassis reversed, we are able to utilize the horizontal coil-over to allow ALiEN 5.0 to climb the ramp with ease.

3.5 Weather Proofing

With this iteration, we wanted to prioritize our weatherproofing solution, as we had encountered issues with water pooling in the frames of our previous designs. Our design utilizes rubber D-shape weatherproofing strips to seal the gap between the access and control panels, as well as an increased dimensional tolerance for the baseplate to reduce the likelihood of water entering the vehicle from below. To reduce any electrical hazards within the base, all components were mounted on 3D printed casings to reduce exposure to the baseplate. In addition, these casings also function as standoffs in the event that moisture gets into the frame.

4. Description of Electronic Power Design

4.1 Overview

ALiEN 5.0 is powered by a 24 V, 60 Ah sealed lithium iron phosphate battery. This battery allows the 24 V circuit to be powered, and by implementing converters, a 12 V and 5 V circuit. These different voltages allow all systems and electronic components to operate and function concurrently.

In the previous iteration of ALiEN (ALiEN 4.0, 2023) we had eliminated the 24/12 V DC/DC converter, as it had malfunctioned in the field with ALiEN 2.0 (2022). We believe that the failure was a result of back feed from the motors while transporting ALiEN 2.0, as the motors were on the 12 V circuit that year. We are confident that the 24/12 V DC/DC converter will not be a problem this year, as we have eliminated any possibility of back feed by disconnecting the motors during transport. The motors are also powered from the 24 V circuit this year, eliminating the problem of converters with the motors all together.

4.2 Power Distribution System

Each circuit is designed with specific components in mind. The 24 V circuit was designed to power the motors, LiDAR systems, and battery voltage indicator. The 12 V circuit is to power the remote/wireless emergency stop (e-stop). The 5 V circuit is primarily for our distributed controls: Teensy 4.1 and 3.2 microcontrollers, OpenMV RT1062 cameras, Global Positioning System, and magnetometer. These various circuits allow for each device to operate as intended, while simultaneously communicating with other devices. The control pinout diagram and the power distribution schematic for ALiEN 5.0 are illustrated in Figures 8 and 9 respectively.

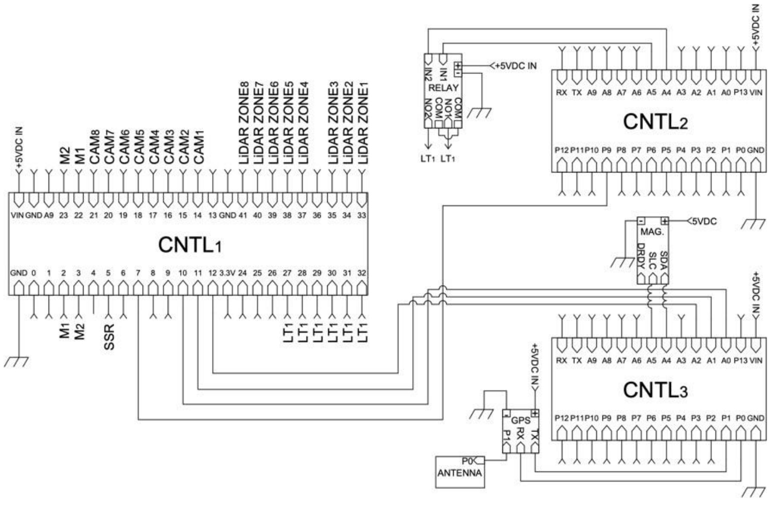

Figure 8. Control Pinout Diagram

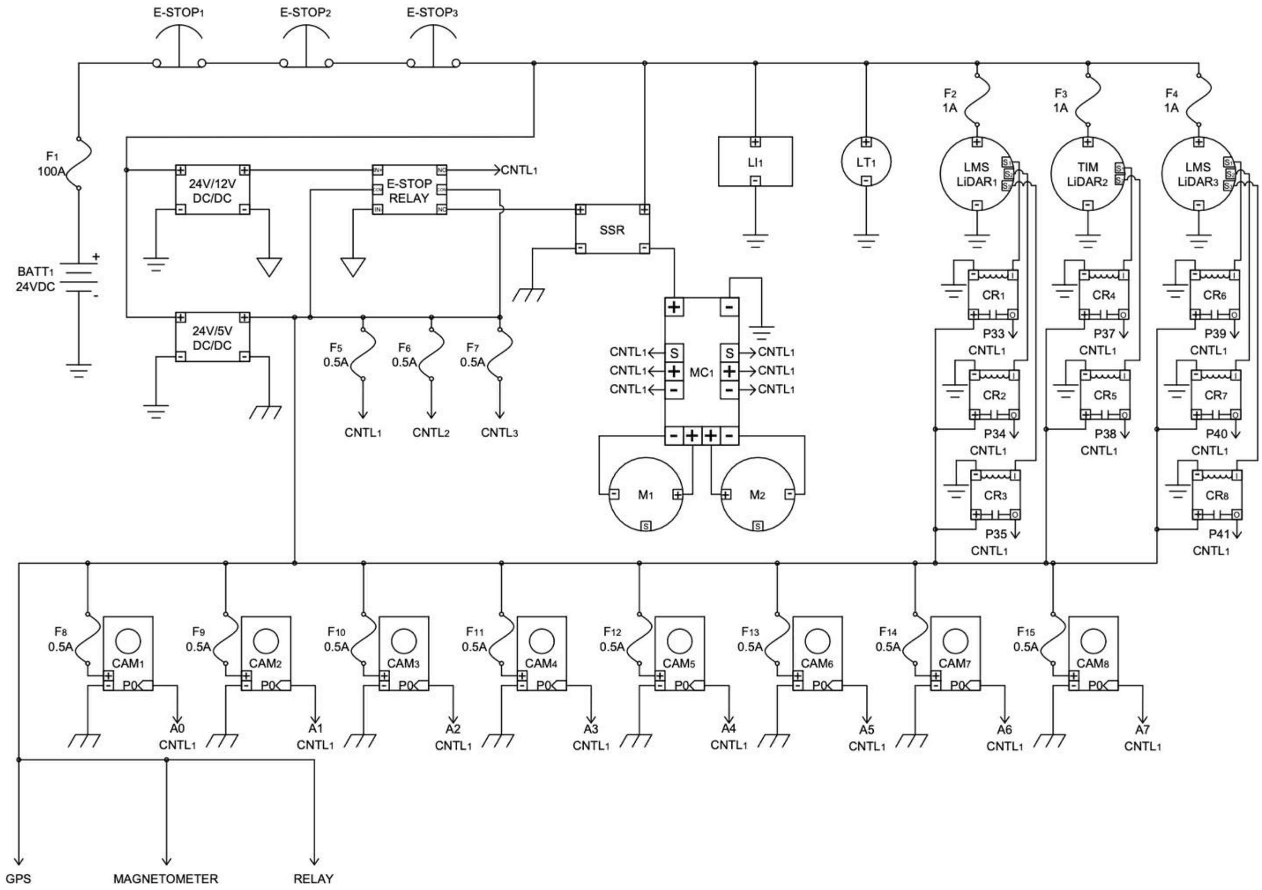

Figure 9. Power Distribution Circuit Schematics

4.3 Electronics Suite Description

Table 3 is a compiled list of all sensors or controllers used in the distributed controls of ALiEN 5.0.

Table 3. List of Devices, Voltage, and Descriptors

Device	Operating Voltage	Description of Component
LiDAR (3x)	24 V	Object detection. Sends high signal to main Teensy.
Motors (2x)	24 V	Rotate the wheels, driving the robot forward.
Stack Light	24 V	Signals condition of robot: powered on, in autonomous mode.
Remote Estop	12 V	Emergency stops robot remotely.
Open MV RT1062 Cameras (8x)	5 V	Smart sensors in eight locations. All cameras are used for pothole and line detection.
Teensy 4.1 Microcontroller (1x)	5 V	Teensy 4.1 used for main drive code, basis of all function for robot.
Teensy 3.2 Microcontroller (2x)	5 V	One Teensy 3.2 is used for GPS/waypoint navigation. One Teensy 3.2 is used for Stack light processing.

4.4 Safety Devices with Integration into System

Safety was a priority with this iteration of ALiEN. Three mechanical emergency stops were designed to be accessible from behind and on either side of the robot. In addition, there is also a remote emergency stop capable of quickly stopping the vehicle when triggered. To mitigate replacing microcontrollers, sensors, and imaging devices, appropriately rated fuses were designed in line to each critical component. To further increase safety, an innovation we developed was acrylic covers on the fuse boards. These acrylic covers are transparent, allowing for easy visual diagnostics of fuses, while still protecting the operator from live voltages.

5. Description of Software Strategy & Mapping Techniques

5.1 Overview

Our software strategy was deployed on a Teensy 4.1 ARM-based microcontroller (Figure 9, CNTL1). The CNTRL1 is the central hub for controlling our drive motors, and it runs an obstacle avoidance and waypoint navigation algorithm. CNTRL1 receives all inputs as parallel binary inputs and makes decisions based on the current state. In addition, CNTRL1 receives heading directions from the GPS module in the form of parallel binary inputs.

5.2 Obstacle/Line Detection & Avoidance

Physical obstacle avoidance is achieved via three SICK LiDAR sensors. Within the LiDAR system's programming environment, multiple zones were set up on each sensor. If an object is sensed within two meters of the front or side of the robot, it is detected in one of these eight zones (see Figure 4). The triggered zone will send a "high" signal to CNTRL1.

Path-planning decisions are made using eight zones (see Figure 4) and to react to obstacles within ALiEN 5.0's path (see Appendix A). The algorithm chooses between three possible degrees of turning: soft turn, sharp turn, and pivot in place turn. If there is no viable path for the robot, it will stop to reassess its environment. If no obstacles obstruct the robot, it will commence GPS navigation toward the next waypoint, which has two possible degrees of turning in each direction.

5.3 Additional Creative Concepts

One creative concept that was implemented was to smooth jerky motor movements. The Controls team created a function to smooth the acceleration of the motors as speed changes occur. This function remedied the issue of abrupt starting and stopping, as well as preventing the jerkiness of extreme speed changes such as full speed forward to reverse. It is called once every main loop cycle. This function was achieved through simulating a Pulse-Width-Modulation (PWM) signal by stepping the speeds up or down with a set delay per increment. The ramping function is skipped if a new decision from the robot does not require an equal speed to the previous decision.

Another creative concept we implemented allows for convenience in changing speed values. The Controls team created a global speed modifier variable which proportionally changes the speed of all turns and straights. This function reduces the need to tweak speeds in multiple places, while increasing the adaptability of ALiEN 5.0 in different environments.

6. Description of Failure Modes, Failure Points & Resolutions

Several critical issues and failure modes were revealed through testing and the construction process. In the event of a failure during testing, the team would work through the problem in several ways. If the issue was particularly difficult, individuals would record it, research the issue, develop a workaround, and continue implementation or find an alternative solution.

6.1 Vehicle Failure Points & Resolutions

Table 4 below outlines some significant software, electrical, and mechanical failure points, and resolutions.

Table 4. Overall Failure Points and Resolutions

Area of R&D	Recorded Issue	Resolution
Software	The LMS LiDAR system boot time is approximately 30 seconds, and the GPS connection time is approximately 5 seconds.	Separate circuits to allow for initialization of sensors.
Software	The line detection machine vision cameras pick up noise from environmental lighting conditions and the ground.	Applied a gaussian filter and a lens shroud.
Software	The ramping function overrode the path decision-making ability of the robot.	Added an interrupt in the ramp function to analyze certain ZCN changes and break out of ramping if necessary.
Software	Encountering zone conditions that cause the robot to become stuck.	Read as INVALID STATE and stop to allow robot to rechart course.
Software	OpenMV RT1062 Cameras stuck in boot loop.	Bypassed the DFU loop and flashed the cameras with updated firmware.
Software	The GPS and compass would often give inaccurate readings.	Routine recalibration of the compass and calculating waypoint offsets when necessary.
Electrical	Loose wires on camera sensors.	Soldering where possible or using multiple pin connections.
Electrical	Automotive wire connectors do not always contact.	Switched to Anderson connectors.
Electrical	Wire loomed wire lines did not fit in the extruded sections of 80/20.	Wire clips were designed to fit directly into the slots of 80/20 extrusions, holding wires in place.
Electrical	The light on the Teensy 3.2 remained on for eight minutes after all power was disconnected.	Made multiple adjustments and then the light went out with time.
Electrical	Troubleshooting the “rat’s nest” circuitry configuration.	Color coded the wire to make a visual tracing of the circuit effortless.
Electrical/Controls	Camera signal was connected to the wrong signal pins on the Teensy.	Placed pins correctly and updated schematics.
Controls	Custom remote E-stop could not reliably transmit the stop signal.	Reverted to a reliable remote E-stop.
Controls	The physical mount of the way point module (GPS and Compass) would provide weak signal or incorrect data.	Mounted the module high relative to the robot.

7. Simulations Employed

The distributed control model demands a heavier emphasis on performance testing as opposed to simulations as the robot processes environmental information in real-time. To retrieve feedback from the complete system, the CNTRL1’s SD Card read/write capabilities were used to create a dump file with data from the latest processes. Physically connecting to the microcontroller and process devices provides real-time data via serial monitor or visualization. The software packages for each process controller provide a means of testing the sensors on a smaller scale before integration onto the final product. In particular, the SOPAS Engineering Tool provides a real-time visualization of the LiDAR zones, while the Open-MV IDE provides a live video output from our Open-MV RT1062 cameras.

8. Performance Testing to Date

We continue to follow our philosophy of concurrent engineering in the integration of our sensors. In other words, our teams build and test systems on a smaller scale using their respective sensors. Once satisfied, the system is integrated into the main project and tested. Table 5 outlines the dates in which these qualifications were achieved.

Table 5. Onboard Integration Performance Testing Dates

Date	Line Avoidance	Object Avoidance	Pothole Avoidance	GPS Navigation	Compass Navigation	Remote E-Stop
April 12	-	X	-	-	-	-
April 26	-	X	-	X	X	-
May 3	-	X	-	X	X	X
May 10	X	X	X	X	X	X

At the time of submission, ALiEN 5.0 successfully demonstrated basic obstacle avoidance in its preliminary stages. GPS waypoint navigation and lane line avoidance have been implemented on the platform. Our primary focus will be to improve our lane line avoidance ability, to tune the speeds of the robot in the decision matrix to minimize lap times, and to test with the payload.

9. Conclusion

The Millersville University Mobile Robotics Team has confidence that ALiEN 5.0 will place highly among the competition entries. Our use of the SICK LiDAR systems, as well as the Open-MV RT-1062 camera systems, has allowed the team to develop an innovative and efficient autonomous navigation system for our latest IGVC robot, ALiEN 5.0.

Our biggest lesson from this build is understanding the strength of effective teamwork. As individuals, we made vigorous efforts in our contributions. However, without one another, this project would not have been feasible. The varied perspectives of each member added a robust characteristic to this robot. The varying perspectives from team members working on the project allowed us to create the most robust system to date. While we still have minor things to integrate, we are comfortable with our progress thus far, and we are looking forward to participating in the competition and networking with other institutions at the event.

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11. Appendix

Appendix A: CNTRL1 Drive Code Flow Chart