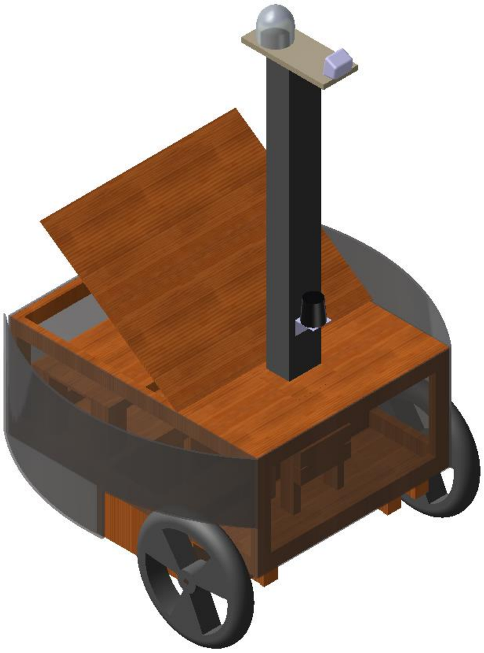
Embry-Riddle Aeronautical University

Z3RO (“Ozone”)



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1. Introduction

Ozone is the new successor in the trilogy of ZERO vehicles at Embry-Riddle Aeronautical University. Ozone continues the tradition of autonomous, intelligent, differentially-steered vehicles using a minimalistic sensor suite running with fully-integrated software. The sensor suite used for navigation consists of a differential GPS, a digital compass, a digital camera, and a planar LIDAR that is joined with a custom health monitoring software to keep the sensors running. The health monitor detects faults in connection and/or data and adjusts the output data accordingly to reduce the probability of failure. The aesthetic design follows the "zero-like" shape for a seamless zero-radius turning capability and general safety towards the environment. Ozone incorporates mechanical, electrical, and software system features that emphasize simplicity and safety. New features include a redesigned frame for lower weight and easier transportation, optimization of the software for faster decision making, and other improvements based on judges' feedback. The report outlines the development of these systems and the methods used for system integration.

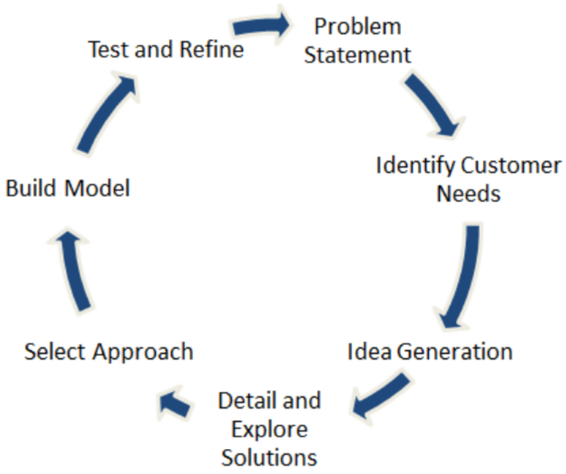


Figure 1: Design methodology.

2. Design Process and Team Organization

Table 1: Ozone's mechanical decision matrix.

Engr. Requirements	**Side Access Panel**	Top Trunk Access Panel	Exterior Wheels	**Interior Wheels**	**Circular PVC Pole**	Rectangular PVC Pipe	Low Hanging Payload	**Payload Inside Chassis**
Competition Size	5	5	5	4	5	3	5	5
Transportability	N/A	N/A	4	4	5	5	5	3
Weight	N/A	N/A	5	5	5	5	4	4
Water-Resistance	4	3	4	3	5	5	5	5
Accessibility	5	3	5	2	2	5	5	4
Aesthetics	4	3	5	3	3	5	5	3
Internal Organization	3	5	N/A	N/A	3	5	5	5
LIDAR Visibility	N/A	N/A	N/A	N/A	5	5	N/A	N/A
Camera Visibility	N/A	N/A	N/A	N/A	5	5	N/A	N/A
GPS Interference	N/A	N/A	N/A	N/A	5	5	N/A	N/A
Cost	N/A	N/A	N/A	N/A	4	3	4	5
Score	**21**	19	**28**	21	47	**51**	**38**	34

The overall design for Ozone was designed using a 7 step design methodology and with the intent to complete outdoor obstacle courses like the ones in the IGVC competition. Using sensor fusion on GPS, computer vision, and LIDAR obstacle detection, Ozone moves along a predetermined GPS course to react to visual cues like lines and flags, and physical objects like barrels and ramps, to safely reach the end of the course. Using the IGVC rules, new design constraints for Ozone's structure and software were defined, and then refined based on feedback from the faculty advisors and the judges from last year (Table 1).

2.1 Vehicle Cost

The cost of Ozone has been reduced by using the same reliable sensors used on previous Zero vehicles. The components labelled with a "(X)" in Table 2 below shows the new components that have been added to Ozone this year.

Table 2: Ozone's cost for all components.

Ozone's Components	Retail Cost	Team Cost
Sensors & Electrical		
Sager Laptop Computer (X)	$800.00	$800.00
GoPro Hero Camera	$400.00	$133.00
Sparton GEDC-6E Digital Compass	$1,350.00	$0.00
Hemisphere A325 GPS	$2,500.00	$2,500.00
Hokuyo UTM-30LX-EW	$6,500.00	$5,250.00
LiPo 6 Cell Battery Packs	$60.00	$60.00
Custom Power Board	$140.00	$140.00
Keyspan Serial to USB	$88.00	$88.00
Hauppauge Frame Grabber	$60.00	$60.00
HIGH Power Output LEDs	$75.00	$75.00
Electrical Subtotal:	$11,973.00	$9,106.00
Mechanical		
Quicksilver Motors (X)	$2,200.00	$1,550.00
Caster Wheel	$15.00	$15.00
Skyway Wheels	$120.00	$60.00
Wooden Frame (X)	$200.00	$200.00
Sensor Mast (X)	$50.00	$50.00
Sunbrella® Water-resistant Cover (X)	$50.00	$50.00
Mechanical Subtotal:	$2,635.00	$1,925.00
New Components Subtotal:	$3,300.00	$2,650.00
Total:	$14,608.00	$11,031.00

2.2 Team Composition

The Ozone team consists of the following 7 team members that have worked on Ozone over the past year (Table 3). This symbol "*" denotes each team member's main focus for the year.

Table 3: List of team members and their posted work hours

		Areas Of Concentration					
Team Member	Major	Mech.	Soft.	Elec.	Doc.	CAD	Hrs
Nicholas Middlebrooks (Team Lead)	Mech. Eng./Senior		X*	X			400
Marco Schoener (Soft. Lead)	Mech. Eng./ Senior	X	X*	X	X		600
Allen Perron (Mech. Lead)	Mech. Eng./Freshman	X*				X	350
Brandon Reichert (Elec. Lead)	Aero. Eng./Junior	X		X*			250
Yates Simpson	Mech. Eng./Senior		X*		X	X	450
Remy-Quinton Phillip	Civil Eng./Junior				X*	X	150
Parker Tyson	Aero. Eng./Freshman		X*				300

3. Innovations

3.1 Improvements

The following table (Table 4) lists the major improvements made to Ozone from the previous Zero vehicles. These improvements will be explained in the mechanical and software subsections later in this report.

Table 4: Overall improvements for Ozone.

Mechanical:	**Software:**
Compartmentalize Electronics	**More efficient algorithm**
Better Weatherproofing	**Parallelized processes**
Efficient Payload Placement	**Simplified Course Settings**
Improved Center of Gravity	**Local mapping**

3.2 Innovations

In addition to the above improvements, there are two main innovations that Ozone has over the previous generation Zero platforms. These innovations are the payload cage and the smaller frame that helps with transporting Ozone.

3.2.1 Payload Cage

The payload cage (Figure 2) is an enclosure to hold the payload low enough to help with an incline of 150% maximum. The cage also doubles as a secure mounting point for the laptop while still allowing for easy access.

3.2.2 Transportability

Ozone is designed for simpler, compact travel to and from deployment. The payload cage in the vehicle, which hangs for C.G. balance, slides into the vehicle to create flush bottom surface. The sensor mast is removable to simply transport alongside the vehicle. And the motor assembly is small enough to fit inside the vehicle.

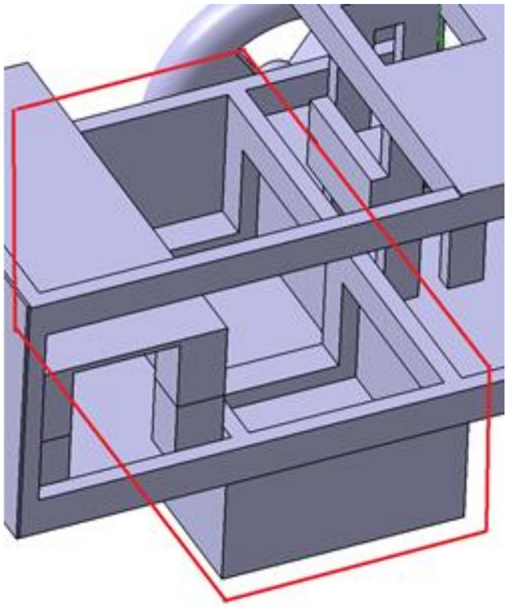


Figure 2: Payload cage outlined in red. The view is the top right of the vehicle.

3.2.3 Access panel

On previous Zero vehicles, all access to internal components were made through the sides, which required the human operators to crouch or sit on the ground to access the laptop. Ozone fixes this inconvenience by now having an access panel located on the rear of the top panel. This makes accessing batteries, the laptop, and all the wiring much easier to work on.

4. Mechanical

4.1 Vehicle Chassis

Ozone’s design keeps to the Zero philosophy, focusing on being safe, lightweight, and maneuverable. The chassis is constructed entirely of a pinewood rectangular structure with plywood and Lexan walls with safety bumpers in a “zero-like” shape. The chassis has 3 modular subassemblies: a removable drivetrain, a removable sensor mast, and a collapsible payload cage. The general access point of the vehicle is the trunk in the back of the vehicle where the electronics, payload, and onboard laptop can be accessed.

4.1.1 Drivetrain

The drivetrain consists of a pair of 24V Quicksilver motors, NEMA 23 15:1 planetary gearheads, and 12½” diameter Skyway wheels. The assembly consists of independent wheel-motor assemblies on a wooden plate that connects to the bottom of the chassis (Figure 3). The assembly also has rectangular, U-shaped braces with a through-bolt to hold the motor parallel to the vehicle and prevent bent or slanted tires.

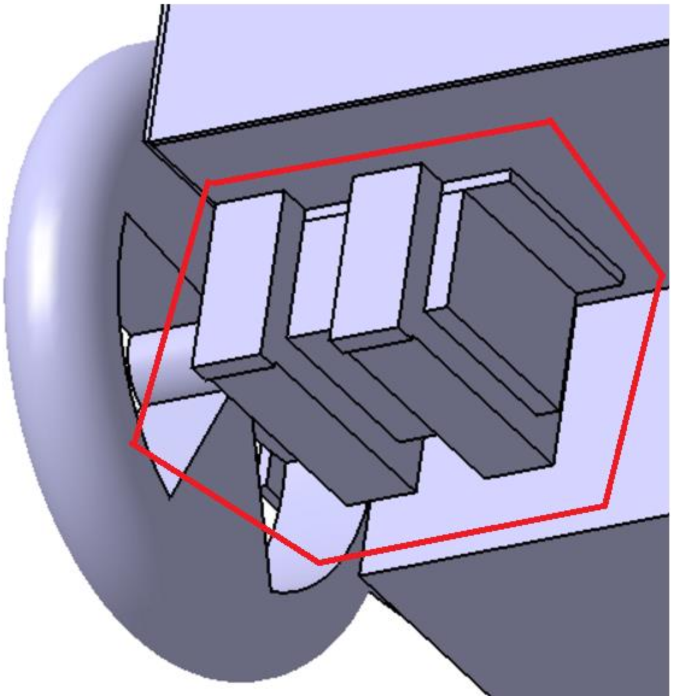


Figure 3: One half of the drive train for Ozone outlined in red.

4.1.2 Sensor Mast

The sensor mast is a 3.5”x2.5”x4’ rectangular PVC pipe that is mounted inside the chassis and holds most of the sensors. The material chosen is rigid and an easy off the shelf product that does not create any electrical or magnetic interference. Five components are attached: GPS, digital camera, planar LIDAR, safety light, and a stop button. The wires are fed through the mast and are fed through a hole at the bottom where the connectors meet.

4.1.3 Payload Cage

The payload cage holds a 20 lb. payload lower than the bottom base to ensure the center of gravity (C.G.) is lower than the axles. This is useful when traversing the ramp to keep the Ozone from tipping on the approach and departure inclines/declines of 15%, and can safely overcome a maximum incline of 150%. The secondary function of the cage is to hold the onboard laptop with the removable top cover of the cage. The cage is also designed for ease of travel, with the ability to be pushed into the vehicle so that the bottom of the cage is flush with the bottom of the vehicle. This smaller overall size makes packing it easier.

4.1.4 Weather-Resistant

Ozone is designed to withstand rain out on the course. Every part of the wooden chassis has been lacquered to make the wood water-resistant, and then the frame is covered with a Sunbrella® cover for extra resistant measures. The sensor mast has a flexible silicone sheet overlaid over the openings to prevent water from funneling into the chassis. The rear access panel has rubber strips along the inside edges to make a waterproof seal around the opening so that water doesn't get into the laptop compartment.

5. Electrical and Power Design

5.1 Power Distribution System

Ozone's internal battery powers most of the onboard electrical components (Figure 3) along with the drive motors. The power board takes in 24V unregulated from the 6-cell 24V Lithium-Polymer (LiPo) batteries to then split off into the following regulated voltages: 24V, 19V, 12V, 5V, and 3.3V. The sensors take the following voltages as shown in Table 5. The camera has its own battery pack and the compass runs off of USB power.

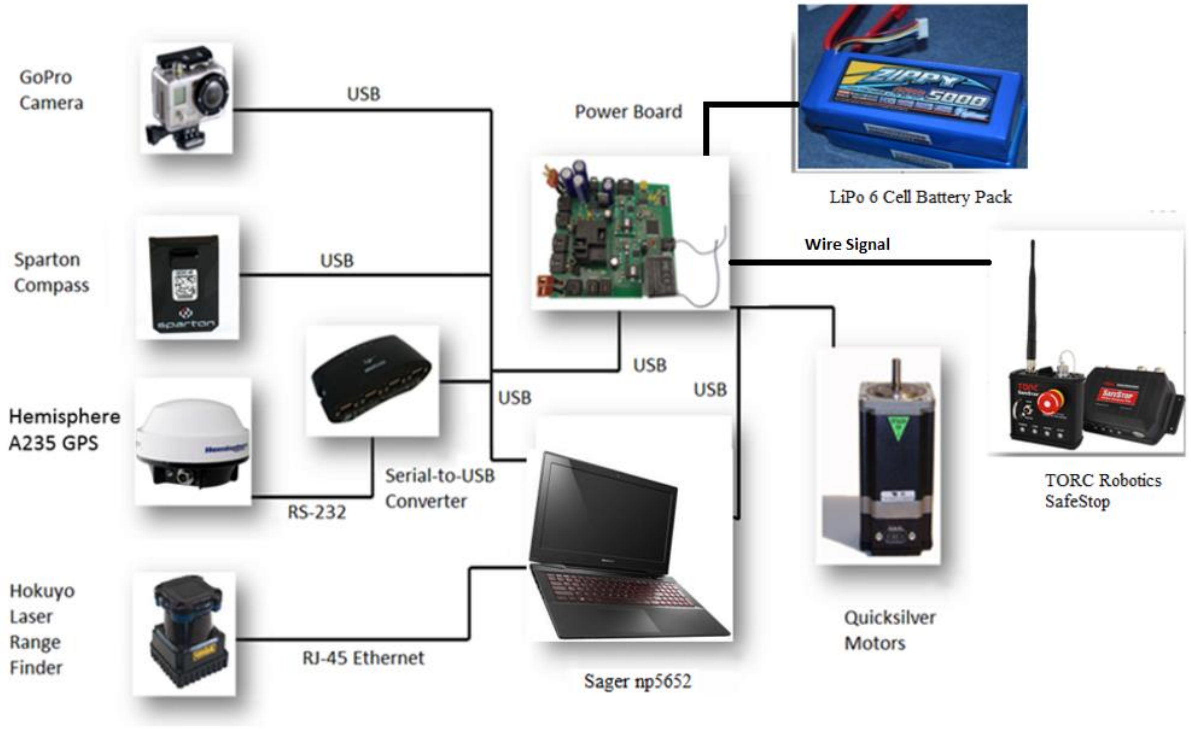


Figure 3: Ozone's electrical diagram with it communication lines.

Table 5: Ozone's power consumption for sensors and electronic components.

Sensor	Power Consumption	Voltage Range	Operating Voltage	Sources
Hemisphere A325 GPS	4.6 W	7 – 36 V	12 V	Power Board
Sparton GEDC-6E IMU	0.32 W	3.3 V	3.3 V	Laptop via USB
GoPro Hero camera	1.5 W	3 – 5 V	3.7 V	Battery Pack
Hokuyo UTM-30LX-EW	8 W	10.8 – 13.2 V	12 V	Power Board
Quicksilver Motors	150 W	12 – 48 V	24 V	Power Board
TORC Robotics SafeStop	8 W	10 – 40 V	12 V	Power Board
Sager Laptop	6 W	19V	19V	Battery Pack

The team took time to carefully design and test the custom board to handle each sensor and external components. The power board can run the overall system for 1 to 1.5 hours on a 5Ah 6-cell LiPo battery. The overall runtime of the vehicle is extended with a built-in hot swappable battery system that keeps the system running continuously. Each power connector for each components is protected by a fuse in the case of a power failure. The board is equipped with a remote control function from an RC transmitter/receiver and an Emergency Stop (E-Stop) control to handle all motor control and safety operations. The board is essential for all onboard operations of Ozone.

5.2 Safety

Ozone has two separate built-in safety systems: one implemented in hardware and one implemented in software. The hardware system is the primary safety mechanism for Ozone, utilizing the TORC SafeStop system to send a signal to kill the motors if any stop button (onboard or remote) is pressed or if the remote goes out of range (greater than ¼ mile). The software safety system is a "soft stop" through the remote controller without cutting the motor power. The indicator light signifies the state of the vehicle: blinking lights means Ozone is in autonomous mode and a solid light means Ozone has been mechanically stopped.

5.3 Motor Interface

Ozone uses an onboard Arduino-based microcontroller that is embedded inside the custom power board to relay commands to the motors. The onboard laptop communicates to the microcontroller using RS-232 serial communication using a UART interface on the power board. Ozone can also be driven in manual mode using the remote controller that controls the software safety system.

5.4 Sensor Suite

The central point of sensor and communication integration is Ozone's onboard laptop. The laptop is a semi-custom Sager laptop with an Intel i7 2.6 Ghz processor, 16GB of RAM, and a 500GB solid-state hard drive (SSD). The laptop runs a customized LabVIEW 2015 software package, for hardware communication and implementation of the autonomy algorithms. Ozone uses the following commercial off-the-shelf (cOTS) sensors: a Hokuyo UTM-30LV-EW, a Hemisphere A325 GPS, a Sparton GEDC-6E IMU, and a GoPro Hero camera.

5.4.1 GPS

The Hemisphere A325 is a combined differential GPS receiver and antenna that can access the GNSS and GLONASS signals, at a refresh rate between 10 and 20 Hz. The uncorrected accuracy ranges from 1 to 2 m, but uses L band corrections to bring the accuracy within 0.6m to 1m. Using built-in OMNIStar and a Kalman Filter in the software brings the overall accuracy down to 0.1m. The GPS communicates with the computer using RS-232 via a serial-to-USB converter.

5.4.2 Digital Compass

The Sparton GEDC-6E Inertial Measurement Unit (IMU) is a 9-axis system that has accelerometers, gyroscopes, and roll, pitch, and yaw. The accuracy in the heading is a 1° RMS accuracy at 0.1° resolution. The orientation data update at 20Hz and communicates over a RS-232 serial line.

5.4.3 Digital Camera

The GoPro Hero is an outdoor camera with a 5-megapixel sensor and 170° field-of-view (FOV). The image is streamed at 480p over a Hauppauge frame grabber at 20 Hz. The camera runs off of its own internal battery with a runtime of one hour of continuous streaming.

5.4.4 LIDAR

The Hokuyo UTM-30LX-EW laser range finder scans for up to obstacles up to 30m away within 270° FOV at ¼° resolution. The distance resolution is 1mm with an accuracy from 0.1-30m is ±50mm. The LIDAR uses a time-of-flight optical system to detect an obstacles' distance from the LIDAR. The LIDAR transfer the data using a TCP/IP protocol over Ethernet.

6. Software

6.1 Structure

The software was developed using National Instruments LabVIEW. As part of this software Ozone has an intuitive Graphical User Interface (GUI) to monitor, modify, and tune system functionality in real-time. The GUI helps verify real-time sensor statuses and path planning decisions for the current course. The flow of the code is organized for parallelized decisions that feed into a centralized trajectory planner. The highest priority for Ozone's trajectory planner can be seen below (Figure 4).

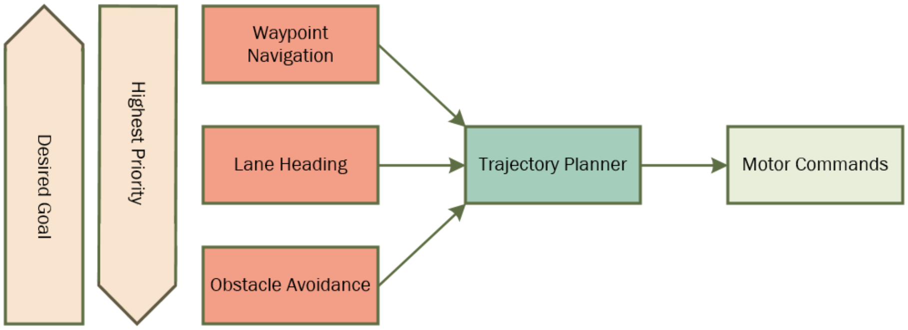


Figure 4: General software flow of algorithm priority to motor commands

6.1.1 Optimized Algorithms

Ozone is the first member of the Zero platform family that uses LabVIEW 2015, which brought many speed improvements to the code when upgrading from LabView 2013. Replacing old function calls with newer versions of the functions resulted in speed-ups of up to 100 milliseconds compared to the old code when making decisions in the trajectory planner, when tested on the same computer.

6.1.2 Parallel Processing

Since the Zero platform was introduced, the vehicles have been using a Dell Latitude laptop with an Intel 2nd generation i7 dual-core processor as the onboard processing computer for all decisions. This year, Ozone was upgraded to a new Sager laptop, with a top of the line Intel 6th generation i7 quad-core processor. This upgrade gives Ozone much more processing power than previous Zero vehicles, allowing for better use of LabVIEW's parallel processing ability. Now more decisions can be made at the same time, allowing for much quicker reaction times when running the same code compared to the old Dell laptop.

6.1.3 Simplified Course Settings

When the previous Zero vehicles were getting ready to complete one of the IGVC courses, there were many setting that the human operator had to change by hand to make sure the right number of waypoints were set, certain algorithms was enabled, among other miscellaneous settings. Now Ozone only has one setting that needs to be changed to switch from the qualifying course to the basic course to the advanced course, saving time for the human operator and making sure the settings are correct for every run.

6.2 Waypoint Navigation

The lowest priority for Ozone's trajectory planner is to follow the current waypoint location. This means that Ozone's final destination is the waypoint, but the lane heading and obstacle avoidance determine the actual path on how Ozone will reach the waypoint goal. The waypoint navigation algorithm calculates the angular difference, or error, and distance to the waypoint by using the GPS's position data and the IMU's heading data. The navigation data is sent to the trajectory planner as the goal point for all navigation data.

6.3 Lane Heading

Once the waypoint direction is determined, the next highest priority in software is lane detection. This stage identifies the real world location of the lanes. The following flow chart shown in Figure 5 illustrates the primary steps to achieve this.

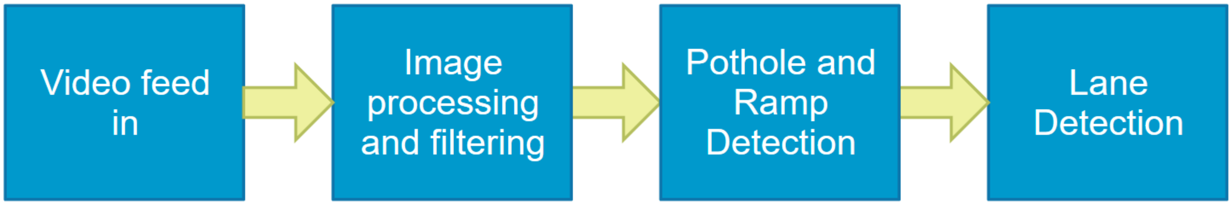


Figure 5: Lane detection flowchart.

6.3.1 Image Processing and Filtering

At the initial stage, image processing is applied to the input image so that relevant information can be extracted from it. The first step in this stage is to resample the image to a 720 x 480-pixel resolution to reduce processing time. Next, various color planes in the resampled image are manipulated to distinguish the white lanes from the grass, and a Gaussian blurring filter is then applied to reduce noise in the image data. Box covers are then applied to the image to mask out the robot's body from the image, since it is also irrelevant information. Finally, the image is adjusted for barrel distortion and a final cropping is applied to the image to remove remaining irrelevant background data. Figure 6 illustrates major steps in image processing.

Figure 6: Image processing images where the lines are filtered out and the image is overlaid with read lines to show the actual detected lines. The yellow dot determines the heading in relation to the vehicle.

6.3.2 Pothole and Ramp Detection

The next stage in lane detection is to identify the potholes and the ramp in the image. In both cases, the algorithm checks the image for a particular shape of a set area: a circle or a rectangle. If the circle criteria is met, the algorithm will identify this as a pothole; whereas, if a rectangle criteria is met, the algorithm will identify this as a ramp. When the ramp is detected, its entire visual appearance shines as bright as the surrounding lines due to its high spectral reflection. The ramp problem is combatted by generating a blank strip down the center and uses the edges of the ramp as a pseudo-line, especially since the actual lines are within a few inches of its edge. The pothole information is then passed to the Obstacle Avoidance algorithm to ensure the pothole is treated as an obstacle.

6.3.3 Lane Detection

This final stage identifies the position of the lane from the previously processed image. A brightest pixel algorithm and a Hough transform are used to identify where the lane is located in the image. The brightest pixel algorithm isolates the white pixels by scanning both horizontal and vertical lines for the pixel(s) of highest value. Hough transform uses a voting system to determine the slope and distance to the dominant line traced by the pixels of each half-image. It is possible that no line is detected in the image if no candidate receives a minimum number of "votes" in order to be considered a line. If lines do exist, they are categorized as horizontal or vertical, and compared with each other as parallel or intersecting.

6.3.4 Flag Detection

For the advanced course in the competition, blue and red flags are randomly assorted in a row arrangement. The flag detection algorithm is set up to be switched on when the robot reaches this section of the advanced course, and it uses three simple steps to navigate effectively as seen in Figure 7. First, it retains the same box covers as the lane detection algorithm to block out parts of the image that are near the horizon or vehicle. Then it performs a mixed-plane threshold based on hue (color), RGB ratios, and HSL values to determine pixels that qualify as either blue or red. Finally, a particle filter is used to eliminate blobs that are too small or too large to possibly be flags. In addition, the field of view for detecting the flags has been reduced to lower the probability of detecting objects off the field. The flag heading to stay between the red and blue flags, with red on the right, is sent to the trajectory planner to set a goal for finishing the course.

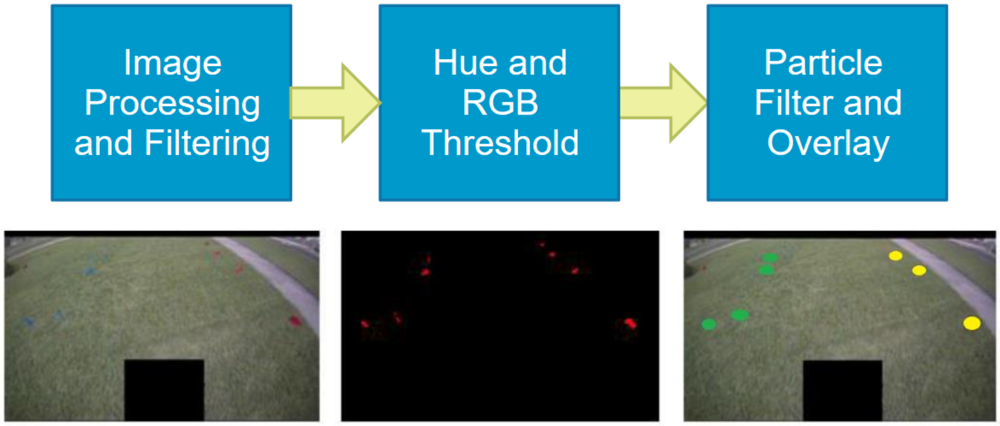


Figure 7: Flag detection process where the red and blue flags are detected and overlaid with green circles for blue and yellow circle for red.

6.4 Obstacle Avoidance

The obstacle avoidance has the highest priority for the direction of motion control. The obstacle avoidance takes precedence in motion control in order to avoid all obstacles. The algorithm scans over the entire FOV of the LIDAR scanner and camera-based obstacles, such as potholes, and detects all potential gaps that the vehicle can travel. The vehicle uses gap detection to determine the difference between obstacles and gap that meet the vehicle's width tolerance of about 1.2 m. All of the gaps are labelled as left-handed and right-handed openings that are used to calculate all available center angles. The array of angles are sent to the trajectory planner to provide multiple potential paths that can be narrowed down to an efficient direction.

6.5 Map Generation

Ozone collects and stores a local map of its surrounding during a run to ensure no backtracking in the course. The map consists of previous global pose and relative obstacles and visual obstacles to feed into the algorithms and trajectory planner.

Ozone takes in local vehicle position data and data from the camera and LIDAR to generate a map where stationary objects are placed in relation to Ozone's frame of reference. This map knows where Zero has been and where the obstacles were placed so it has a memory of what was detected. This map helps Ozone prevent itself from going back to where it has already traveled, and to make sure it is still heading forward to the waypoint goal. This map is saved into the logging data for review after runs to review how Ozone detected the different obstacles during the run to help tweak the settings for the next run. Ozone makes a new map each run so that the current settings aren't trying to compare to old data recorded with different settings.

6.6 Path Planning

6.6.1 Trajectory Planner

The trajectory planner is responsible for generating an appropriate heading to the motor controllers to follow based on all the information fed to it from the active algorithms. It is made up of two parts: the desired heading and the desired goal. The heading is selected based on available algorithm data from the software subsystem hierarchy seen below in Figure 4. The desired path goal uses a reverse priority order: waypoint navigation, lane heading, then obstacle avoidance. The goal heading is where Ozone wants to end up, and uses the desired heading to figure out how to navigate to the goal heading.

The waypoint navigation subsystem is the first step in finding the goal heading by initially finding the most direct route to the desired goal. Next the desired heading is updated with the input from the lane heading subsystem. This takes into account the lanes up to five feet in front of Ozone to keep Ozone inside the course. Finally, the obstacle avoidance subsystem is used to prevent Ozone from hitting any obstacles. The combination of these algorithms will choose to find the heading to meet the priority heading criteria while attempting to converge to the goal heading.

7. Failure Modes

7.1 Mechanical

In the redesign for Ozone, easy access to the motors and their components was a key point of the design to help prevent mechanical failure. Ozone is using a new set of motors and gear boxes this year, so the chances that they will wear out are miniscule. The new gearboxes and motors have a brand new mounting bracket and wheel screws to prevent issues with the motors or wheels falling off of the chassis. All the components of the motors are easily accessible for quick removal should an error arise that requires the replacement of any part.

7.2 Electrical

The wiring subsystem is all handled by industry standard connectors. The batteries are connected to the power board using XT60 connectors, and the sensors are powered from the power board using Molex connectors. These allow for quick removal when trying to diagnose connection issues. Should a connector need replacement, it is quick and easy to crimp a new Molex pin on and fit into a new connector.

7.3 Software

7.3.1 Health Monitoring

The software is only as durable as the communication with the sensors. Some sensors have a tendency to lose connection when connectors are jolted and/or general communication crashes. The software is constantly monitoring the sensor connections for any errors that may arise from communication protocol issues or disconnections and attempts to reset sensor connection. During the reset, the algorithms send a dummy set of data, as if the course is free, and then uses the existing feedback data to aid in temporary travel. The dummy data sends a trigger to show that the map should take over until new sensor updates occur or if the approximated location has no new data.

7.3.2 Vision Processing

With vision-based algorithms, the toughest part of maintaining great results is to have a usable threshold to find the white lines. The physical and solar interference affect the actual image quality. The most pertinent change is the change in sunlight: the direct sunlight versus a cloudy day can change mid-run and affect the amount of luminance on the ground. The software combats the chance in sunlight issue by preparing to find a very sunny set of lines on the ground. With the dead grass and flowers in the lanes, these objects could be considered as potholes or the ramp (based on size of patches) to help filter them appropriately (based on vision algorithms) and continue navigating accordingly.

7.4 Testing

Ozone was tested in an outside environment that was similar to the IGVC competition layout. The white lines painted on the grass with orange traffic barrels placed throughout made for a great place to test Ozone in a pseudo- competition environment.

Before the outdoor test could be conducted, each subsystem had to pass a quality assurance check to make sure the systems were still working. Each of the sensors, being reused from last year, were checked in the lab to ensure the cables still had a good connection for both power and data. The electrical system was also tested in the lab, where a problem was found in the embedded Arduino microcontroller and UART connection, so both had to be replaced.

Before physically making the new frame, it was first created as a CATIA model, where the stresses and strains on the frame could be measured and adjusted before making the first prototype. This ensured that the frame wouldn’t fall apart after being assembled and loaded. Once assembled, the frame was checked to make sure that it could withstand the weight of all the components and the C.G. would prevent tipping during drive operations over the course and the ramp.

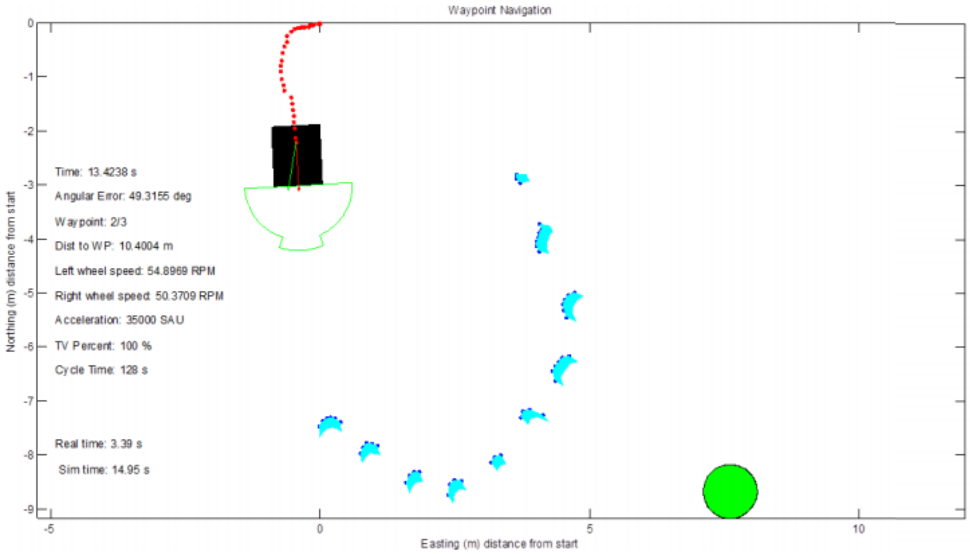
The subsystem tests were performed before each time Ozone was tested outside to ensure no problems had arisen between tests. This allowed for problem-free tests of the software. As each software algorithm was tested, from waypoint to obstacle avoidance, a remote E-Stop, operated by a secondary team member, was always at the ready to prevent unexpected drive patterns for a safer test environment.

7.5 Safety Concepts

Ozone has Lexan bumpers on the side of the chassis so that if any obstacles are bumped, the side will deform instead of the object being moved. This is also good for interacting with human operators so the side will deform before hurting them. In the front and back, where the main access areas are located, the edges of the frame have been lined with foam. While not as shock absorbent or “deformative” as the Lexan, it is still a barrier between obstacles and the hard frame edges.

8. Simulations

The team has also developed a data logging system which gathers all sensor and algorithm information into a text file that can be later imported into MATLAB and replayed. The data logging system helps immensely with the testing and refining process by identifying problems that cannot be immediately noticed by vehicle performance inspection during a test. The output of the program is shown in Fig. 8. The black rectangle represents the robot, while the blue represents obstacles, and the green circle is the target waypoint. The green semi-circle extending from the vehicle is the obstacle avoidance range, which will cause a reaction from the robot. The red dots show the vehicle's GPS trail. On the left hand side are numerical values that can be customized to whatever the user wishes to see, including elapsed time, wheel speeds, and latency.



Time: 13.4238 s
Angular Error: 49.3155 deg
Waypoint: 2/3
Dist to WP: 10.4004 m
Left wheel speed: 54.8969 RPM
Right wheel speed: 50.3709 RPM
Acceleration: 35000 SAU
TV Percent: 100 %
Cycle Time: 128 s

Real time: 3.39 s
Sim time: 14.95 s

Figure 8: The screenshot depicts the robot (black) driving towards the waypoint (green), but detects obstacles (blue) in its path.

9. Performance

Ozone is designed to meet the requirements of the IGVC competition. The operational performance of the general vehicle is that the operational speed we can maintain is 2.5mph (5mph max) for 1.5 hours of runtime. The vehicle can climb and descend the 15% incline ramp without any issue of tipping or bouncing off. For Ozone's perception, all obstacles can be detected from 0.1 to 30m at 1mm steps and all visual objects are detected up to 5m away at a refresh rate of 20Hz. When dealing with complex obstacles, Ozone handles them with pothole detection and map generation: pothole detection finds the potholes on the ground and passes them as obstacles to the obstacle avoidance; and the complex obstacles, such as switchbacks and dead-ends, the map generator keeps track of the local data to reference where the vehicle was to or if it remains in a section for too long to help move Ozone along and prevent backtracking. When approaching a waypoint, the vehicle hits the waypoint between 0.1 to 0.75m until moving on. When it comes to dealing with failure points, all sections are tested before they go out: the mechanical systems are checked and replaced if getting worn out or broken; the electrical system is checked for wiring issues; and the software is tested piece by piece and when performing outdoors, a safety member is ready to stop the vehicle in the event of unexpected reactions. To date, Ozone is able to perform waypoint navigation, lane heading, obstacle avoidance, vision detection and mapping, all wrapped into the trajectory planner. The hierarchy of decisions still have some issue with filtering some outlier heading(s) data from obstacle avoidance. For the most part, Ozone will be tuned to accept better results to traverse the course with greater ease.

10. References

[1] IGVC Rules committee, “IGVC Rules 2016,” http://www.igvc.org/2016IGVCRules.pdf (accessed on March 15, 2016).

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[3] Schoener, M., Middlebrooks, N., and others, “Embry-Riddle Aeronautical University – Zero,” http://www.igvc.org/design/2015/7.pdf. Annual Report. Embry-Riddle Aeronautical University, 2015. Web.

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May 15, 2016

Intelligent Ground Vehicle Competition
AUVSI Foundation

Dear IGVC Judges,

I certify that the engineering design of Ozone, as described in the accompanying report, has been significant and is equivalent to that required of a senior design project.

Sincerely,

Eric Joe Coyle
Associate Professor of Mechanical Engineering
Embry-Riddle Aeronautical University

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