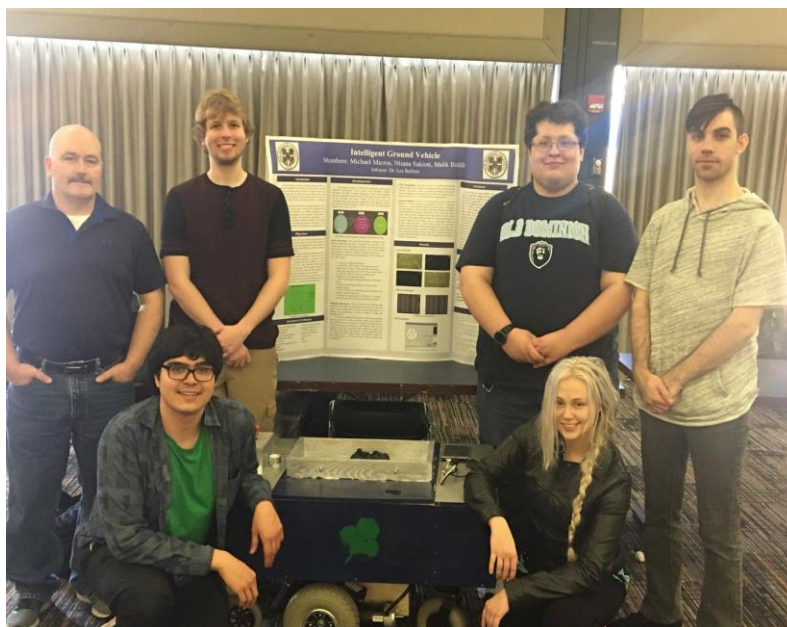


# Old Dominion University

## Intelligent Ground Operations Robot (I.G.O.R.)



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# 1.0 Conduct of Design Process, Team Identification and Team Organization

This section implicates the process undertaken to design the Intelligent Ground Vehicle (IGV). Additionally, the team identification and organizational methods will be discussed.

## 1.1 Introduction

The Intelligent Ground Operations Robot, or IGOR, is the subsequent incarnation of the Cilantro Autonomous Robotic Vehicle. IGOR consists of a variety of sensors to assist in navigation, including a CSP-IPMD4 Dome Camera, a RPLIDAR A2 Light Detection and Ranging (LIDAR) device, two CMUcam5 (PixyCam) cameras, and a BU-252 S4 Global Positioning System (GPS). These sensors, in correspondence with three Arduino Uno Microcontrollers and a desktop personal computer (PC), provide the necessitated intelligence of IGOR's surroundings to properly navigate a given obstacle course. The foci of the following implementation is that of IGOR's new aluminum case, the Robot Operating System (ROS) integration with the mentioned sensors, the combination of Open Source Computer Vision (OpenCV) and a Feed-Forward Convolutional Neural Network (FF-CNN) to allow for object detection and education, and a safety light indicator via the utilization of a Mokungit Light-Emitting Diode (LED) strip as per Section I.2, Vehicle Configuration, of The 26<sup>th</sup> Annual Intelligent Ground Vehicle Competition (IGVC) Rules [1]. IGOR's overhauled aluminum case allows for a more efficient, lighter, and overall more appealing outer structure. Integrating all of the sensor components with ROS allows for greater flexibility and provides the user with a more effective manner of exchanging required information between the sensors and the PC. Additionally, the ROS navigation stack allows the user to plot a destination and have the vehicle traverse obstacles discovered from the Dome Camera and LIDAR. The amalgamation of OpenCV and an FF-CNN provides the robotic vehicle with the ability to educate itself on a variety of objects and detect those objects through similarities in color and shape. Finally, as per the IGVC regulations, the LED strip is employed to display system behavior which is inclusive of error communication.

## 1.2 Team Organization

The senior design team that comprised the design and implementation team for IGOR is shown in Table 1. The team is constituted of two different groups each concentrating on different stages of implementation for IGOR yet contributing to each of the components specified. All members shown in Table 1 were either Electrical or Computer Engineering Majors or both.

Task/Object of Interest	Developer(s)	Assistant(s)
3-D Printing	Eric Patton	Adam Seay
Arduino Programming	Adam Seay, Joseph Blank	Justin Santos
Case Design	Adam Seay	Richard Kazmer
Documentation	Richard Kazmer	Jonathan Zeigler, Adam Seay
Electrical Wiring	Gordon Rarick	Richard Kazmer, Adam Seay
GPS	Gordon Rarick	Eric Patton
LED Strips	Joseph Blank	Adam Seay
LIDAR	Adam Seay, Gordon Rarick	Joseph Blank
PixyCams (Line Tracking)	Howard Edwards	Adam Seay
OpenCV, FF-CNN	Caroline Kuzio	Joseph Blank
ROS Integration	Adam Seay	Joseph Blank
ROS Navigation	Adam Seay	Joseph Blank

Table 1: Tasks Concentrated in Overall Design and their Affiliated Person(s).

## 1.3 Design Assumptions and Design Process

### 1.3.1 Design Assumptions

Each system was expected to perform sufficiently within inclement weather and, due to this design constraint, a sealed aluminum case in correspondence with rubber gromets were employed. Additionally, there was an assumption that the vehicle would need an adequate mechanical structure to carry 20 pounds (lbs.) of weight and, therefore, would require a redesigned case to provide for rigidity and strength.

### 1.3.2 Mechanical Design Process

As IGOR will be required to haul 20 lbs. during the competition, Mr. Seay and Mr. Kazmer decided that the first logical action to take would be to measure Cilantro's wooden case and apply a similar design to IGOR's case. As this case would be constructed of aluminum, which is rather expensive in large quantities, Mr. Seay, with the assistance of Mr. Kazmer, designed a case within Autodesk Inventor 2015. Finally, Mr. Kazmer was able to have the case built with the assistance and sponsorship of Protocase, a corporation located in Nova Scotia, Canada.

### 1.3.3 Electrical Design Process

IGOR contains a variety of electrical components to assist in navigation. Mr. Rarick, Mr. Kazmer, and Mr. Seay decided the best approach to wiring IGOR was to first draw up a basic schematic based on the required sensors, computer components, power switches, power relays, and power converters. The team then went to work utilizing the mounting structure employed by Mr. Seay's case design

to correctly attach all devices and, subsequently, wire each of the components up to two 35 milliamp-hour batteries connected in series.

#### 1.3.4 Software Design Process

The bulk of the required work for IGOR came with implementing the necessary sensor data collection, the OpenCV and FF-CNN, and ROS integration and navigation. The task the team decided to implement primarily was the functionality of each of the sensors. Each member was assigned a corresponding sensor they were supposed to research and determine how to operate. Subsequently, once each device was working programmatically, the sensor would then be integrated within IGOR's ROS core as a usable node to publish and subscribe to. The next major hurdle was that of creating an FF-CNN to train IGOR on necessitated objects. This task was done by first determining how to retrieve images from the Dome Camera through ROS. Once this process was determined, ROS integration was achieved via a node created for this specialized purpose in tandem with another that created an OpenCV object which then allowed the system to create a portable network graphics (PNG) file. This file then allowed Ms. Kuzio to write an FF-CNN program in Matlab that ROS can utilize as a node to train the system based on the image file fed-in and utilized as a ground truth. Finally, Mr. Seay determined that the ROS navigation stack was imperative for the proper traversal of the circuit and, therefore, researched the conceptual and applicative nature of the navigation stack. Mr. Seay then decided the best course of action was to implement a program that can utilize the navigation stack to drive IGOR in a simple manner and test it with cones that have purchase for just the occasion.

## 2.0 Effective Innovations in Vehicle Design

The information delegated to this section concentrates on the conceptual and applicative nature of innovative additions to IGOR.

### 2.1 Innovative Concept(s) Used in IGOR Adapted from other Vehicles

Deep Neural Networks (Deep Learning, DNN) are forms of machine learning algorithms that are constructed around the idea of learning data set representations rather than task-specific algorithms. Tesla Inc.'s Tesla Model S vehicle utilizes a form of DNN called a digital neural network which enables the vehicle to educate itself on items of interest such as road surfaces, sidewalks, and other vehicles [2]. IGOR employs a Faster Regional-Convolutional Neural Network (FR-CNN) which acts as a derivative of the FF-CNN. This FR-CNN has an average precision versus recall value of 66.06%.

## 2.2 Innovative Technology Applied to IGOR

IGOR utilizes ROS's navigation package which employs data taken from odometry, sensors, and a goal pose [3]. Functionally, this data is utilized by ROS to output safe velocity commands to the motors powering IGOR. As the LIDAR is not placed directly in the center of IGOR yet at a 6.5 centimeter (cm) offset from the front of the carriage, a transformation (tf) is used to alert ROS that the assumption the LIDAR is centered on the robotic vehicle is not applicable. Subsequently, tfs, odometry information, and sensor data is sent through ROS and, through the utilization of rviz, the end-user can send destination goals to the robotic vehicle and visualize the surrounding objects. Finally, with the culmination of this information, IGOR is able to traverse objects within its path.

## 3.0 Description of Mechanical Design

The information delegated within this section exemplifies the structural, frame, and weather-proofing attributes implemented into IGOR's mechanical design.

### 3.1 Overview

IGOR consists of two main structural components. The structure of IGOR is that of a Jazzy 1113 Wheelchair base and the casing is that of an aluminum box created by Protocase, Inc. Additionally, due to the E620 motors adopted from the jazzy 1113 Wheelchair base, IGOR is capable of reaching a top speed of 3.2 mph. This allows IGOR to traverse ramps adequately under normal weather conditions and with a high coefficient of friction, approximately greater than 0.4.

### 3.2 Frame Structure, Housing, and Structure Design

IGOR recycles a Jazzy 1113 Wheelchair Base for usage as the frame. In addition to this usage, the E620 motors previously utilized for the wheelchair were employed for IGOR as well. The frame structure consists of steel tubing interconnected through welding and mechanical ties, such as bolts and screws.

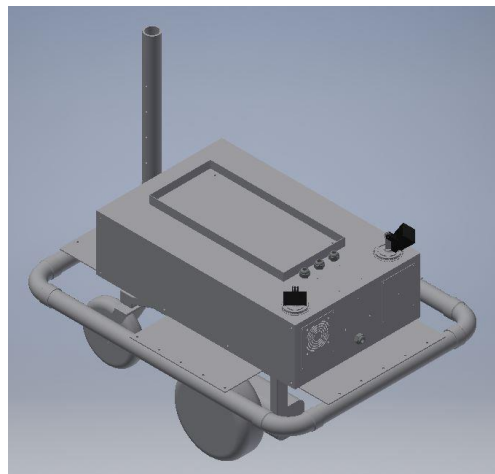


Figure 1: Autodesk Inventor Rendering of IGOR's Case.

The illustration within Figure 1 showcases IGOR's new case. The housing is currently constructed out of aluminum for the best weight-to-strength ratio. The frame structure of the wheelchair base has four cylindrical metal tubes in which this aluminum case can slide and lock into place. The case consists of two areas within the front of the case that is capable of mounting the pixycameras for line tracking purposes via OpenCV. The tubing traversing around the vehicle functions primarily as a bumper to IGOR to prevent the robotic vehicle from damaging itself upon collision. Additionally, the PVC piping that is mounted vertically is employed for the GPS unit to gather the best signal possible within the field. Ultimately, the structural design was a recycled wheelchair base (consisting of steel interconnected tubing) to reduce costs of development while, on the contrary, the casing of IGOR is an in-house designed aluminum case that was specially designed for the operation of this robotic vehicle.

### 3.3 Suspension

The suspension of IGOR is simply the suspension leftover from the recycled Jazzy 1113 ATS Wheelchair base. Currently, the springs and the frame structure are capable of providing IGOR with the necessary balance required to operate.

### 3.4 Weather Proofing

Protocase Inc. treated the aluminum case, which was design in house by Mr. Seay, with a special powder coat that wards of water. Additionally, electrical components on the outside of the vehicle, such as the pixycameras, have specially constructed 3D printed cases for protection. The GPS unit itself was constructed to be used in the outdoors as the system was created as waterproof. Rubber gromets were implemented to connect the external wiring of these sensors to the inside of IGOR's case to ensure that excess water would not damage the components within robotic vehicle. Finally, a rubber gasket was employed around the edge of the case to ensure proper weather proofing and protection of the electronics inside.

## 4.0 Description of Electronic and Design Power Design

This section explains the overall power distribution and electronic components within IGOR. Each of the sensors and computer components power consumption will be discussed.

### 4.1 Overview

IGOR consists of numerous sensors, such as the RPLIDAR A2, CSP-IPDM4 Dome Camera, Bu-252 S4 GPS and two PixyCameras, which assist in determining the position, orientation, and direction in which the vehicle needs to travel. In conjunction with power relays, voltage converters, Arduino Uno microcontrollers for decision making, a PC to function as the intermediary between devices, a Wireless E-Stop for emergencies, two batteries for power, and, finally, a Sabertooth Dual 25-Amp Direct-Current (DC) Motor Driver to deliver the proper signals to the E620 motors, IGOR is able to sufficiently travel along the designated course with no additional instruction/input from the user surveying the event. Additionally, this section details the quantitative characteristics of the power distribution throughout IGOR.

## 4.2 Power Distribution System

IGOR is provided power through two 12-volt, 35 ampere-hour (Ah) UB12350 Batteries connected in series. This provides a total electric potential of 24-volts at 35 A-hours. The product of these two quantities leads to 0.84 watt-hours (Wh), or equivalently, 840 milliwatt-hours (mWh). The maximum runtime of IGOR is approximated at 4.5 to 5 hours. Due to this revelation, the battery is capable for running 5-hours at 5.95 A (29.75 Ah) for a C value (recharge and discharge rate) of 0.2.

## 4.3 Electronics Suite

The electrical components of this system are inclusive of a BU-252 GPS Unit, a RPLIDAR A2 device, a CSP-IPDM4 Dome Camera, and a Gigabyte 78LMT-USB3 Motherboard w/AM3+ Socket. This Gigabyte Motherboard has an AMD FX 8320E 8-Core Processor in addition to Corsair Vengeance 8GB(2X4GB) Random Access Memory (RAM). The PC is also outfitted with an ANATEL PCI Wi-Fi Card and three Arduino Uno microcontrollers. For controlling the E620 motors connected to the Jazzy 1113 ATS wheelchair base, a Sabertooth Dual 25-Amp DC Motor Driver is employed. Finally, an external USB Hub, Adafruit LCD HDMI Panel, Advantech SmartWorx Ethernet Switch, Onboard Power Hub, and Wireless E-Stop are employed to assist in the transferring and the displaying of data as well as controlling the flow of electrons to the device. All devices are powered through a common +24-volt power bus and a ground bus to act as a reference voltage. Continually, the PC has an Opus DCX6 DC-DC Converter connected to the common +24-volt bus for a 12-volt input in correspondence to a 30 A current for a total power consumption of 360-watts.

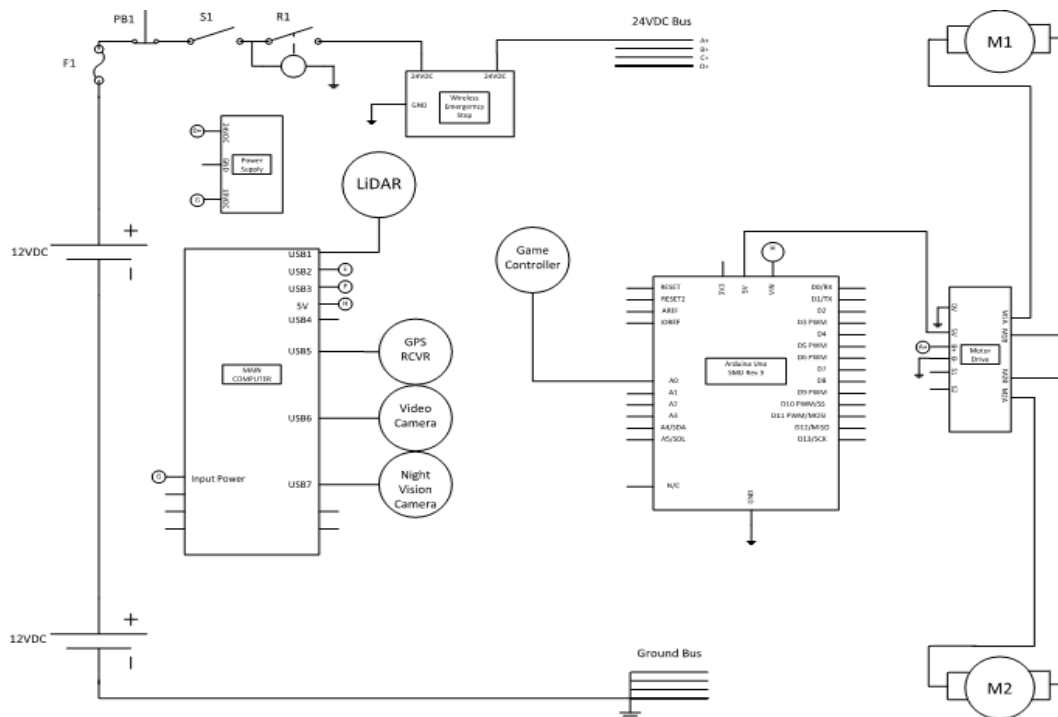


Figure 2: Electrical Components of IGOR.

## 4.4 Safety Devices

IGOR contains three different electrical devices to assist in maintaining the safety of the surroundings. Primarily, IGOR utilizes a Wireless E-Stop which can be triggered via a button that is wirelessly connected to the device. Whenever an issue occurs, or something of possible environmental harm happens, this device, when triggered, will cause the power relay to change state, thus creating an open circuit. Similarly, a large red pushbutton is located on the back of IGOR that provides the same purpose, however, this necessitates physical connection with a user. Finally, an LED strip is utilized to communicate errors and the underlying state of IGOR during operation.

## 5.0 Software Strategy and Mapping Techniques

This section concentrates on outlining the programmatic, integration, and mapping techniques that were necessary for autonomous nature of IGOR.

### 5.1 Overview

IGOR consists of three Arduino Uno microcontrollers with each having an applied purpose. The primary Arduino Uno within the system sends instructions to the Sabertooth motor controller via the usage of an Arduino sketch. In similar fashion, the remaining two Arduinos handle the data processing of the Inertial Measurement Unit (IMU) and the vehicle state and error communication of the LED strips. Data between the remaining sensors, either connected to the Arduinos as supplementary devices or to the PC, is exchanged through the integratory system of publishers and subscribers, ROS. In addition, ROS, through a series of laser scans and image processing matters, is able to map the requisite area surrounding the vehicle.

### 5.2 Obstacle Detection and Avoidance

The mapping of the surrounding areas is done primarily from the LIDAR system. IGOR will also utilize a dome security camera that functions as a publisher to an Open Source Computer Vision Library Node (OpenCV) written in C++. This node will convert the ROS object into an appropriate PNG file and, subsequently, output that file into the Ubuntu filesystem. Summarily, this will allow the convolutional neural network to educate itself of the object by taking the PNG file as input and then, through proper decision making and coordination with the E620 motors, the system shall be able to avoid the obstacle. Objects are typically detected at an approximate distance of 10 feet. Potholes typically are the primary topic of concern for IGOR and, through the utilization of the dome camera, the system is able to traverse around the pothole through the usage of motor commands sent from an Arduino. This process is executed after the system determines a circular shape on the ground with a continuous region of color.



### 5.3 Software Strategy and Path Planning

Essentially, the approach taken to constructing the required software for IGOR was iterative. A large amount of manpower was implemented to determine certain necessary characteristics of the system, such as the correct ratio between motor speed and linear velocity values, the LIDAR mapping, ROS integration and navigation, and, finally, object recognition and avoidance. There is no set path the robotic vehicle will take; it is entirely dependent of, first, whether there is an object impeding its path and, second, if there are white lines preventing it from turning a certain direction. Once it looks at these two quandaries, the appropriate motor commands will be send to the E620 motors to traverse around the objects while staying inside the boundaries of the course (the white lines).

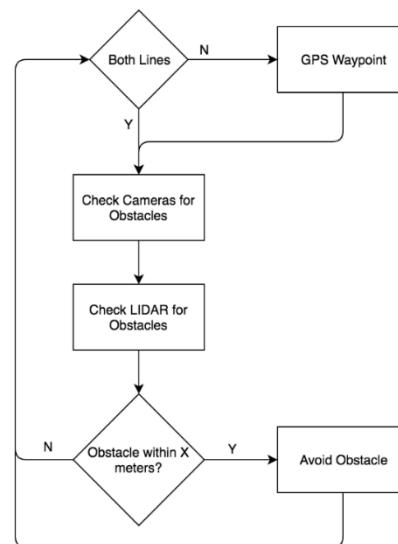


Figure 3: IGOR Control Decision Process.

### 5.4 Map Generation

The generation of the subject area will be completed primarily from the LIDAR. The LIDAR will generate the necessitated physical objects within a 358 degree arc as to alert the vehicle of possible dangers and to prevent the robotic vehicle from wrecking.

### 5.5 Goal Selection and Path Generation

The goal will be provided through a small script given upon arriving at the beginning of the competition. The system is capable of reading the numerical coordinates of the script and, therefore, acting upon them by driving to the required destination. During the competition, path generation will be done by first preventing the device from taking the true shortest path due to the requisite direction of the obstacle course and the lines outlining the track. A pseudo-barrier will be implemented within the code that will tell the system that the only manner in which to travel upon initialization is forward. Subsequently, the system will utilize the GPS waypoints provided by the competition and traverse the obstacles through the utilization of an object

avoidance formula produced by educating itself about the objects on the course. GPS navigation is typically in the realm of 0.6 meters accuracy during clear conditions outdoors.



Figure 4: Illustration from a Test Course Used for IGOR.

## 5.6 Additional Creative Concepts

The system is constantly looking and learning new shapes, colors, and regions of interest thanks to the introduction of the FF-CNN. This allows the system to constantly be ready, if given a proper size of samples, to functionally detect and avoid new obstacles that may cause havoc if the system is unaware of such obstacles.

## 6.0 Failure Modes, Failure Points, and Resolutions

This section details possible failures in the design of the system and the attempt(s) at producing a correction.

### 6.1 Vehicle Failure Modes and Resolutions

The two primary failure modes of IGOR are that of the numerical value of the motor speeds to be written to the E620 motors to grow out of bounds, causing the robotic vehicle to spin widely out of control, and the possible inability to act to a new object if too few samples were taken. The first can be solved by emergency stopping the vehicle and restarting the Arduino Uno that control the device and the latter can be fixed by improving the FF-CNN to add a greater degree of average accuracy and speed.

### 6.2 Vehicle Failure Points

The primary vehicle failure point on IGOR is that of the area that holds the weight during the obstacle course. The wheelchair base itself is capable of holding a 300 pound human,

however, the casing, which is constructed of aluminum, is thin and can easily morph if greater than a few dozen pounds is placed upon it. A possible solution would be to have a case that is thicker and made of a metal that is less prone to bending, such as steel.

### 6.3 All Failure Prevention Strategies

IGOR currently has a limited selection of failure strategies employed. Currently, the robotic vehicle has two ways to determine linear velocity to assist in navigation. The first method is that of determining the velocity from the IMU and, if the Arduino or IMU fails, the system will fall back onto utilizing the GPS unit for linear velocity. Upon the chance that the dome camera system fails, the LIDAR unit is capable of detecting objects that lie directly in front of the vehicle, however, only simple motor commands can be sent with this backup method.

### 6.4 Testing

IGOR had a variety of tests ran for each of the applicable portions of its design. These tests were inclusive for the subject areas of mechanical and electrical components. Additionally, the robotic vehicle had certain environments in which the robotic vehicle was placed in order to better experiment with its capabilities. These environments are inclusive of simulations, in-lab applications, and real-world tests. Firstly, with regards to the mechanical components, a simulation was run on Autodesk Inventor 2015 to determine the possible damaging and morphing of the case due to weight. Accordingly, the case is capable of holding approximately 50 lbs. before there is deformation. Electrically, the system is able to maintain all sensors and computerized devices for about 5 hours of run time. Additionally, the emergency stops responded immediately after each subsequent attempt as what was required from specifications. Simulations were executed with rviz within ROS to determine the effect of placing a coordinate and determining how IGOR would attempt to traverse itself there. The robotic vehicle was taught images within the lab, in addition to outdoors, to determine if, constrained to a region of interest for the learning algorithm, that the light levels have no appreciable effect on the object that is of interest to the machine learning algorithm.

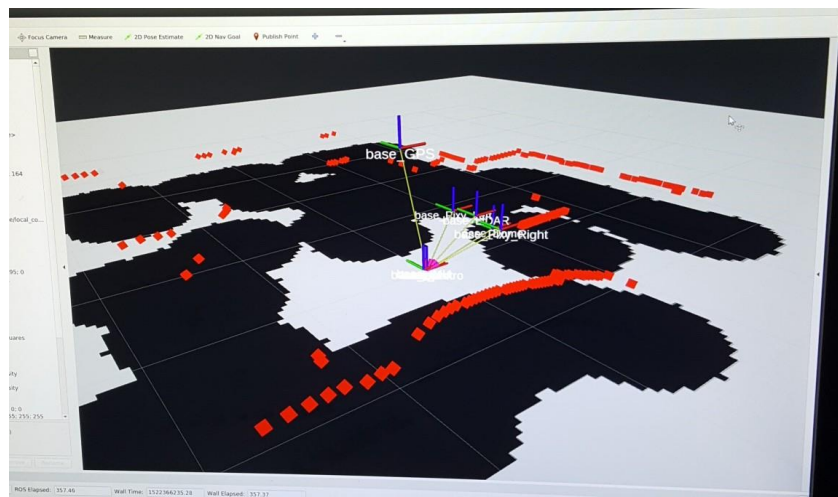


Figure 4: LIDAR Output in rviz.

## 6.5 Vehicle Safety Design Concepts

IGOR employs two distinctive safety implementations with an additional safety implementation being a derivative of the former. Firstly, the LED strips were employed to adhere to the guidelines of the competition as to alert people around the robotic vehicle the current status of IGOR and whether an error has occurred. A physical E-Stop via a pushbutton on the back of IGOR is used to allow those close to the vehicle to prevent the E620 motors from receiving power and, therefore, cease operations. A derivation from the physical E-Stop world is that of a wireless E-Stop that, in addition to tripping the power relay as before to cease power transport, allows the user to do so at a distance as to prevent possible injury to the person(s) involved or damage to the vehicle.

## 7. Simulations Employed

This section discussed, in brief, simulations employed to test and evaluate IGOR in addition to an often-discussed topic of the simulation of an entire virtual course for testing.

### 7.1 Simulations in a Virtual Environment

The primary simulation employed for IGOR is that of a combination of rviz to monitor how the system scans the objects around itself and how the robotic vehicle acts when a location is plotted within the ROS navigation stack.

### 7.1 Theoretical Concepts in Simulations

An oft discussed topic within the team is that of an entirely simulated test course for the robotic vehicle. This will allow IGOR to test newly implemented functionality without the need to actually turn the vehicle on, take it outside, construct a course, and then run the course to get qualitative and quantitative results. Concepts used within rviz include analytical trigonometry for the determination of angles and Euclidian geometry to understand the basis behind how the coordinate plane is laid out within rviz.

## 8. Performance Testing to Date

### 8.1 Component Testing, System and Subsystem Testing, etc.

IGOR has been tested extensively within the field. Currently, IGOR has ran a theoretical course setup within Old Dominion University's Kaufman Mall to test the effect of sunlight and weather on the dome camera, LIDAR, and GPS unit. In addition, particular emphasize was placed upon testing the software, especially the ROS integration and navigation stack. The ROS integration of the sensors and the publisher and subscriber routine between each other has lead for a precise and efficient manner in which to handle data. The ROS navigation stack is still currently in development and testing as to enhance the system for the upcoming competition and, in addition, to iron-out issues with decision making patterns causing odd turning behavior with the vehicle.

## 9. Initial Performance Assessments

The autonomous systems are in continual development and, therefore, require more experimentation and effort to increase accuracy. The performance of the electrical systems are satisfactory, and no issues have arisen regarding them in their current state as shown in Figure 2. The mechanical systems are nearing completion; all the remaining work on such is on hold until the new case is delivered.

## References

- [1] “The 26th Annual Intelligent Ground Vehicle Competition (IGVC) & Self-Drive (formerly Spec 2),” 26-Oct-2017. [Online]. Available: <http://www.igvc.org/2018rules.pdf>. [Accessed: 01-May-2018].
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