Intelligent Ground Vehicle Competition - Self-Drive Challenge
2019 Design Report

Team Ghost Driver

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Introduction

Autonomous navigation has been a growing field of research and has the potential to greatly improve the safety and efficiency of roads [12]. There are many questions that still need to be answered regarding the ethics and legality of self-driving vehicles on standard roads. Effective self-driving vehicles can increase safety on the roads because of faster reaction times, communication with other vehicles and traffic lights, and the absence of human error which causes 93 percent of crashes [13]. To push the research forward in this area, the Ground Vehicle Systems Center (GVSC), under the U.S. Army Combat Capabilities Development Command (CCDC), started an autonomous vehicle competition for collegiate teams to drive Robot Technology Kernel (RTK) innovation. Because the RTK repository is a collection of navigation and control software designed for autonomous vehicles in tactical environments, there is an opportunity to develop RTK to autonomously drive on roads while following accepted traffic conventions.

Under the direction of the GVSC, the team will bring an improved version of RTK to the 27th Intelligent Ground Vehicle Competition (IGVC) at Oakland University. The IGVC Self-Drive Challenge tests the street capabilities of an autonomous vehicle with respect to both obstacle avoidance and speed. The competition test space consists of an obstacle course comprised of painted lines and generic roadway obstacles that must be navigated by the autonomous vehicle and is evaluated for both run time and ability to traverse the space while remaining on course [14].

The goal of this research effort was to adapt, expand, and evolve GVSC's RTK software repository to account for on-road driving. The team adapted a vehicle with a limited sensor package, altered the RTK software, and plan to test the vehicle across an obstacle course. The course will represent a real-world environment with intersections, obstacles, and road signs. This work increases the usability of RTK across the force structure by expanding the scope of use to include urban environments.

Organization

Team Ghost Driver is an interdisciplinary team consisting of eight seniors from three departments at the United States Military Academy. Wyatt Gengler and Mary Pollin majored in the Computer Science and Sam Norman majored in Electrical Engineering. Clement Calderon, Nicholas Gasparri, and Zachary Maxwell majored in Mechanical Engineering. Jeremy Angle and Jaylen Collier majored in Systems Engineering.

Design Process

The Agile process is an approach for developing products and services. This process consists of three main components; Product Backlog, all-at-once product development, and Sprints. Sprint Reviews were the periods of time that the team spent focusing on one major goal that it needed to complete. The research team had an initial meeting at the beginning of the project to discuss the scope of the entire project. There were six major goals that the team decided were necessary to be met in order to label the project as a success. Following the end of the first meeting, the six goals were arranged in order and each goal was assigned a sprint. The sprint review was a 4 week time block that the team was able to narrow its focus and optimize productivity on the project. The product backlog was updated at the beginning of every sprint review. The product backlog was used to break down the main goal of the sprint into subtasks that could be managed by the team. The team was able to access a central product backlog using Trello. Trello is an online platform that features a billboard software that allows users to make real time updates and keep track of completed tasks. All-at-once product development is a process that splits a group down into smaller teams. The smaller teams are assigned different subtasks to complete the main goal quickly and efficiently. This process limits the amount of wasted time of over allocating resources to one task at a time. The research team utilized the different skill sets of each member to optimize work time and increase productivity throughout the sprints.

The research team utilized the Agile Design Process (ADP) to define, plan, design, develop, and refine requirements. This allowed the team to remain within the scope of the initially defined problem and on schedule. The first step of the design process was to define the problem, followed by the creation of design functions. The design functions dictated the development of system requirements and restraints based on the IGVC guidelines. The competition format grades teams on the final product being affordable, reactive, user-friendly, safe, durable, and expandable. Using a Quality Functional Deployment Diagram (QFD) the different requirements were evaluated using specific and measurable characteristics of the alternatives. Each requirement was compared in relative importance to other requirements using a pairwise comparison chart. The QFD and pairwise comparison results were then combined to form the relative importance of each measurable characteristic. After generating a matrix of multiple potential design and hardware combinations, the relative value of each alternative was used to determine the most effective design alternative.

The team developed and considered 3 separate autonomous component packages during the design process. All of the packages achieve the same goal but at different costs in both time and money.

Alternative 1

The first package, Leveraged Maverick, was designed to be cost effective. Leveraged Maverick included IR sensors for obstacle detection/avoidance and lane detection/following. It utilized the Velodyne HDL-64E LiDAR for obstacle detection/avoidance. For computer processing, on-hand Linux and Windows computers were going to be used outfitted with Intel i7 processors and Nvidia GPUs. In terms of software, this alternative featured a planned expansion of RTK within the World Model. Adaptation would be needed to incorporate a different sensor suite than currently integrated into RTK. Modifications would not be made to the Maverick path planner. The team would make adjustments to the World Model that would result in the desired behavior from the existing path planner. The team expects that it would be able to achieve nearly correct behaviors with this strategy. However, because the path planner would not be adjusted, certain behaviors were expected to fail such as a left turn into the right lane. As with each alternative we would need to integrate RTK with PACMod, the software and hardware suite allowing for drive-by-wire control of the GEM e2. While this option was cost effective it failed to meet the team's design requirement of expandability. The lack of cameras integrated within the design prevents future implementation of object classification necessary for road sign detection.

Alternative 2

The second package, Black Knight, was designed to be the most powerful of the 3 alternatives and the most similar to current RTK autonomous solutions. It included implementation of 5 stereo cameras, 2 Velodyne HDL-32E LiDARs, ultrasonic sensors and a custom built Linux computer. The stereo cameras provide depth to images useful in obstacle detection. The two Velodyne LiDARs are compatible with the current RTK solution with one LiDAR placed in the front of the vehicle and the other in the rear. The ultrasonic sensors are used for parking solutions. This alternative would have consisted of a completely new drive algorithm. The team would create a new behavior mode called 'Pilot' In which a separate algorithm based on machine learning would be controlling the vehicle. There would be no set behaviors. All vehicle behavior would be based on training. In this case full integration of base RTK would be needed and would also be running with an ability to override the system to avoid obstacles. Thus the LiDARs and cameras could be integrated directly, but the GPS/IMU would require some adaptation. This alternative would require massive development of a new system and would generally suit a future team with RTK already integrated. While this alternative would have simplified vehicle integration and adaptation to RTK it was determined to be too expensive in both time and money and therefore failed to meet the team's design requirement of a cost-effective product.

Alternative 3

The third and final package, Mule, is a combination of both Leveraged Maverick and Black Knight. It includes the sensors found in the current autonomous package. Software adaptation would be needed for all sensors. Once RTK is integrated with PACMod, the team would modify the path planner and world model. The team plans to modify the Maverick path planner for use. This would create differences in the costmap generation, and path planner behaviors to accommodate road logic such as turning into the correct lane and what to do when faced with different signs. It meets both design specifications by being cost-effective and expandable. However, it requires more adaptation to integrate the different sensors within RTK.

INNOVATIONS

To implement autonomous behavior, the team had to integrate the sensors and components with RTK. The software utilizes a costmap created by LiDAR data to make decisions regarding obstacle avoidance while simultaneously driving toward previously established waypoints. A costmap is an array of values representing the traversability of the space by the vehicle. At the node level, costmaps have a range of values between zero and one, with any value greater than 0.9 considered "lethal." The array values are multiplied by 255 so the final costmap ranges in value from 0 to 255. Thus, a region with a high cost will be avoided by the vehicle in favor of a route using a lower-cost area.

MECHANICAL DESIGN OVERVIEW

Drive-by-Wire Kit

The Platform Actuation & Control Module (PACMod) drive-by-wire system was installed by the component supplier, AutonomouStuff. It is the bridge between the vehicle commands given by RTK through the computer to the mechanical actuators moving the vehicle. PACMod exists as a node on the on-board computer within the Robotic Operating System (ROS) framework. At a high level, there are various topics within the PACMod node that act as publishers and subscribers to RTK. Some of these topics include steering, throttle, braking, gear selecting, and enabling among others. When a commanded input is given through an RTK topic, a specific PACMod topic subscribes to that RTK topic. Then, based on the value of the input, the PACMod topic will be passed through in the correct type to physically command the actuators to move to obtain the desired action on the GEM. After that, PACMod publishes another topic back to the RTK topic so that RTK can ensure that the correct desired action was taken. Within the PACMod topics, there are specific custom message types that include a variety of data types that get published and subscribed to RTK. In order to allow PACMod and RTK to communicate, conversion calculations are implemented in custom nodes to ensure that they are operating within the same range of values.

Suspension

The Polaris Gem e2 is equipped with MacPherson strut front suspension and trailing arm rear suspension. Both front and rear are fully sprung and damped to provide good ride quality. The MacPherson strut and trailing arm suspensions are both relatively simple but effective systems most notable for its low part count increasing durability and serviceability. The suspension system and tire sidewalls are the primary defense against shocks and vibrations translating through the vehicle to the sensitive electronics.

Weather Proofing

It was necessary to take weather-proofing measures to ensure the vehicle can operate in all weather conditions without damage to the hardware. The vehicle originally came without doors or a rear window. Since the computer, wires, and switch are housed within the body of the vehicle, doors were added to ensure that the equipment is not damaged by water when it rains and a rear window will be added before the competition. Additionally, weather-proof casings were added to the five cameras since they are mounted to the top the vehicle on the exterior.

ELECTRONIC AND POWER DESIGN OVERVIEW

Power Distribution System

Power distribution within the GEM system (figure 1) requires regulated application of power to the autonomous sensors and components. The autonomous package used to augment the GEM is designed to be powered with 120V American standard wall outlets. The GEM must power and interface with the autonomous sensors; therefore, modifications to the sensors' and components' power cables needed to be made to draw enough power from the GEM's onboard MVEC. The MVEC outputs 12 volts DC at 20 amps (10 amp fuses)[8]. The output from the MVEC is insufficient since many of the sensor components operate outside of this range. For example, the onboard Spectra computer requires 24 volts at 10 amps [6]. Therefore, a boost converter is used to sufficiently supply the computer with 24 volts of power at 10 amps.

The power supplied from the MVEC to the sensors and components comes from the GEM's six 12-volt battery system and therefore cannot supply 12-volts at a constant rate. This occurs because as the vehicle draws power over time the battery system's available power decreases. As the GEM's battery system drains through continued use the voltage being supplied through the MVEC will also become reduced over time. Supplying insufficient voltage to electrical systems causes the amperage supplied to increase which can fatally damage the components, this is known as a brown out. To eliminate the potential for a brown out, voltage regulators were employed. Voltage regulators ensure a constant voltage is supplied despite fluctuations in overall power output. After the voltage regulators were added to the vehicle the output of the regulators were tested at various intervals of power consumption. The team found the output of the voltage regulators to be constant even at changing levels of performance.

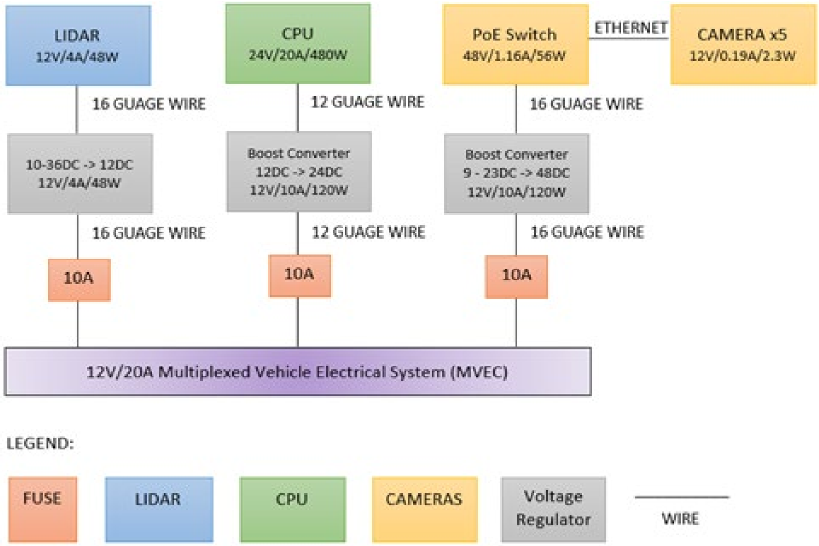
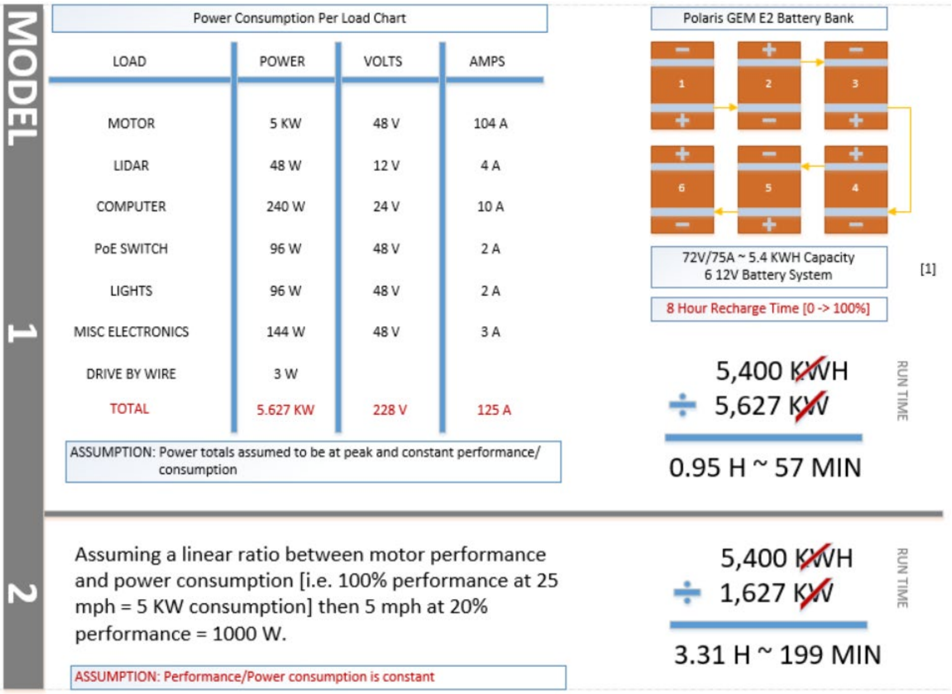


Figure 1. Power distribution integration diagram

The primary objective in analyzing the GEM's power consumption was to determine maximum run time at peak performance and under competition demands. To determine the practical use and application of the GEM it was necessary to know what the operating conditions of the vehicle are; therefore, this section will analyze the power consumption of the vehicle. The GEM is equipped with a six 12-volt battery system. This system is used to power the vehicle, its electrical systems (lights, dashboard, etc.) as well as the autonomous package components (the LiDAR, five cameras, and an onboard computer) The GEM's overall battery capacity is 5,400 watt-hours [1]. The organic load of the vehicle, consisting of both the motor and standard electrical systems, utilizes 5,200 watts at maximum speed and electrical draw [1]. To determine the maximum runtime for the autonomous system, a power model based on battery capacity and overall load was developed to allow the team to determine the vehicle's practical application. The model assumes that the total load is constant at peak performance. This assumption is founded in the maximum voltage and amperage requirements being consumed by each component. The predictions above are based on maximum performance of the vehicle at a high rate of speed. The vehicle's top speed is 25-mph [1]. The vehicle's total runtime is found by dividing the total battery capacity by the peak load values. Therefore, the theoretical runtime of the GEM at peak performance is 61.8 minutes.

The GEM fully equipped with autonomous sensors has a combined load of 5,627 watts. The power requirements of the additional sensors and components increase by 7 percent to provide enough power for a runtime of 57.8 minutes. The GEM's top speed of 25-mph equates to 5,000 watts of power consumption; therefore, the 5-mph maximum speed limit set by the IGVC equates to 1,000 watts of power consumption [3][1]. This brings the GEM's total power load to 1,627 watts at competition demand. Applying this load total to the model results in a predicted run time of 199 minutes at competition demand. The GEM has a recharge time of eight hours to move from no charge to 100 percent charge. Given the predicted runtime at competition demands of approximately three hours (199 minutes) the recharge-to-use rate is 2.4 hours of re-charge time for every one hour of use. Knowing the recharge-to-use rate allows the team to effectively plan how the vehicle will be used and what its limitations of that utility are in terms of power.



Power Consumption Per Load Chart

LOAD	POWER	VOLTS	AMPS
MOTOR	5 KW	48 V	104 A
LIDAR	48 W	12 V	4 A
COMPUTER	240 W	24 V	10 A
PoE SWITCH	96 W	48 V	2 A
LIGHTS	96 W	48 V	2 A
MISC ELECTRONICS	144 W	48 V	3 A
DRIVE BY WIRE	3 W		
TOTAL	5.627 KW	228 V	125 A

ASSUMPTION: Power totals assumed to be at peak and constant performance/ consumption

Polaris GEM E2 Battery Bank

72V/75A ~ 5.4 KWH Capacity
6 12V Battery System

[1]

8 Hour Recharge Time [0 -> 100%]

$$\frac{5{,}400\ \cancel{K}WH}{5{,}627\ \cancel{K}W}$$

0.95 H ~ 57 MIN

Assuming a linear ratio between motor performance and power consumption [i.e. 100% performance at 25 mph = 5 KW consumption] then 5 mph at 20% performance = 1000 W.

ASSUMPTION: Performance/Power consumption is constant

$$\frac{5{,}400\ \cancel{K}WH}{1{,}627\ \cancel{K}W}$$

3.31 H ~ 199 MIN

Figure 2. Power consumption prediction model

Electronics Suite Description

RTK operates in conjunction with the PACMod drive-by-wire system. The electronic signals sent from RTK connect to PACMod through our autonomous package. The autonomous package consists of the following components: 1x Velodyne HDL-64E LiDAR (Light Detection and Ranging), 5x Mako G-319C cameras, 1x AStuff Spectra computer, 1x XSENS MTi-710 GPS/IMU, 1x PACMod drive-by-wire (DBW) system, 1x 8-port Power over Ethernet (PoE) switch, 1x Multiplexed Vehicle Electrical system (MVEC).

The Velodyne HDL-64E LiDAR was chosen because of its high data rate and accuracy. This LiDAR has 64 laser emitters and receivers to create a dense 3D point cloud with a 360 degree horizontal field of view [2]. The laser emitters are divided into 4 groups of 16 while the laser receivers are divided into 2 groups of 32 [2]. It is designed to have a 50 meter range for pavement and a 120 meter range for cars and foliage [2]. This is due to the differences in reflectivity of the materials, with pavement having a reflectivity of about 0.1 and cars having a reflectivity of about 0.8 [2]. This LiDAR has a 26.8 degree vertical field of view, ranging from +2 degrees to -24.8 degrees [2]. The user can select a field of view update between 5 and 15 Hz. This LiDAR outputs over 1.3 million points per second [2].

The 3D point cloud array can be visually displayed through programs such as rviz (ROS Visualization) which provides representations of the point cloud array which is made up of the intensities of object reflections within the environment. The array positions correspond to specific sectors around the circumference of the LiDAR. By filtering array values based on value, larger values being more “intense” objects, the GEM can determine whether it is faced with an obstacle or a clear path.

The Velodyne HDL-64E LiDAR was chosen due to its availability to the team as well as its ability to integrate directly with RTK as packages have already been created using the 32E version of the Velodyne LiDAR. The 64E model provides a denser 3D point-cloud output which allows for a more accurate representation of the environment.

Obstacle detection is based on two components. It relies largely on the output of a 3D point cloud generated by the LiDAR which works in conjunction with the five Mako G-319C cameras. The GEM must detect obstacles ranging in width from 18.1 inches 23.5 inches and ranging in height from 37 inches to 71.5 inches [3]. The GEM must detect and identify these objects as obstacles and stop within a variable distance of the obstacle (the exact distance will be provided at the IGVC).

5 Mako G-319C cameras were mounted to the GEM vehicle. Four of the cameras provide a 60 degree field of view and are mounted on each corner of the vehicle. The fifth camera has a 120 degree field of view and is mounted to the middle front of the vehicle to ensure complete overlap of viewing range and to better assist in lane and sign detection. The team designed a 3D representation of the GEM's field of view using the Solidworks CAD tool (figure 11). These cameras have a maximum frame rate of 37.5 frames per second. The cameras provide images with a resolution of 2064x1544 [4].

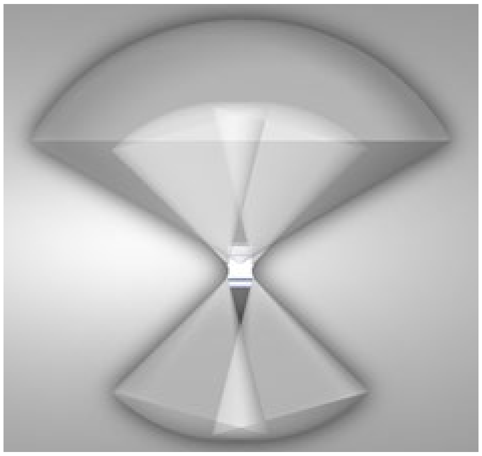


Figure 3. CAD representation of GEM field of view

The Mako G-319C cameras will assist in obstacle avoidance/detection in the same manner that it will perform lane-following and sign detection/interpretation. The Mako cameras can be individually addressed through IP address modification, this is a feature required for integration with RTK. The cameras will output raw video data routed through a switch and into the computer. The computer will analyze the video output of the cameras for certain shapes, colors, etc. that will identify obstacles and signs. Therefore, the cameras will be used for object classification. Without the implementation of machine learning the GEM will rely on pre-defined obstacles and signs that the computer will search for when processing the raw video output of the cameras. Once the cameras have identified an object it will be added to the GEM's cost map.

The Mako G-319C cameras were chosen due to the availability of a weatherproof housing accessory (figure 13). The cameras also met the required data output and connectivity specifications determined to be necessary for integration with RTK. The weatherproof housing ensures that the GEM is weatherproof and therefore can operate in all environments while protecting the cameras that are externally mounted to the GEM.

Accuracy of waypoint navigation depends on the accuracy of the GPS sensor that is being used to interface with RTK. The team is using the XSENS MTi-G-710 Series GPS/IMU. The electrical engineering and computer science department had the GPS and allocated it to the IGVC team, which made the solution cost effective. Due to the department's previous use of the GPS, pre-developed software existed for the use and integration of the GPS. The technical specification of the GPS pertinent to the IGVC is the horizontal position accuracy which is within 1-meter [5]. This capability will allow the GEM to navigate within 2-meters of GPS points during the competition [3]. The GPS connects to the computer and is powered through a single USB cable. While the GPS can be powered externally, powering it via the computer saves space within the vehicle because the computer will provide voltage regulation to the GPS. The GPS/IMU is mounted on top of the switch at the center of the vehicle within the cab. This serves as the weather-proofing solution; it also enables vehicle localization because RTK requires the IMU to be placed at the center point of the vehicle.

The autonomous components will interface directly with the AutonomouStuff Spectra computer. The computer is powered directly from the GEM's MVEC. The computer is custom designed for the team by AutonomouStuff. It contains an Intel Xeon processor and a Nvidia GPU [6]. The computer can demand up to 480 watts of power to operate at full capacity [6]. This presented a concern to the team as our MVEC can supply at most 240 watts of power to the computer. To mitigate the risk of a brown-out (supplying the computer with an under-rated amount of voltage) that could cause fatal damage to the computer we conducted benchmark testing to determine its capabilities operating at 240 watts.

The team used a Linux based benchmarking program from Phoronix Test Suite [7]. The team ran two separate benchmarking tests. The first was a video encoding test and the results demonstrated that at a marginal load the computer consumed no more than 72 watts of power. To push the computer the team ran a program simulating running through an entire video game in less than 10 seconds. This presented a large computational load on both the computer's processor and GPU. The results demonstrated that the computer only consumed 216 watts of power at high demand. Based on these results the team determined that supplying the computer with 240 watts would be sufficient for the processing loads of the computer when executing autonomous functions.

The computer meets the team's design specifications of expandability. As the project progresses and develops in complexity over the next several years the team predicts the implementation of machine and computer learning to be inevitable. The current leading solution in machine and computer learning is the Nvidia Drive PX processing unit. While working directly with AutonomouStuff the team found that it was their common practice to pair the AutonomouStuff Spectra directly with the Nvidia Drive PX to accomplish these autonomous behaviors.

The cameras and the LiDAR will connect to the computer through a switch via an ethernet cable (figure 15). The GPS communicates with the computer via USB 2.0. The component connection types and data message types can be viewed on the hardware architecture glass box architecture diagram included in figure 16.

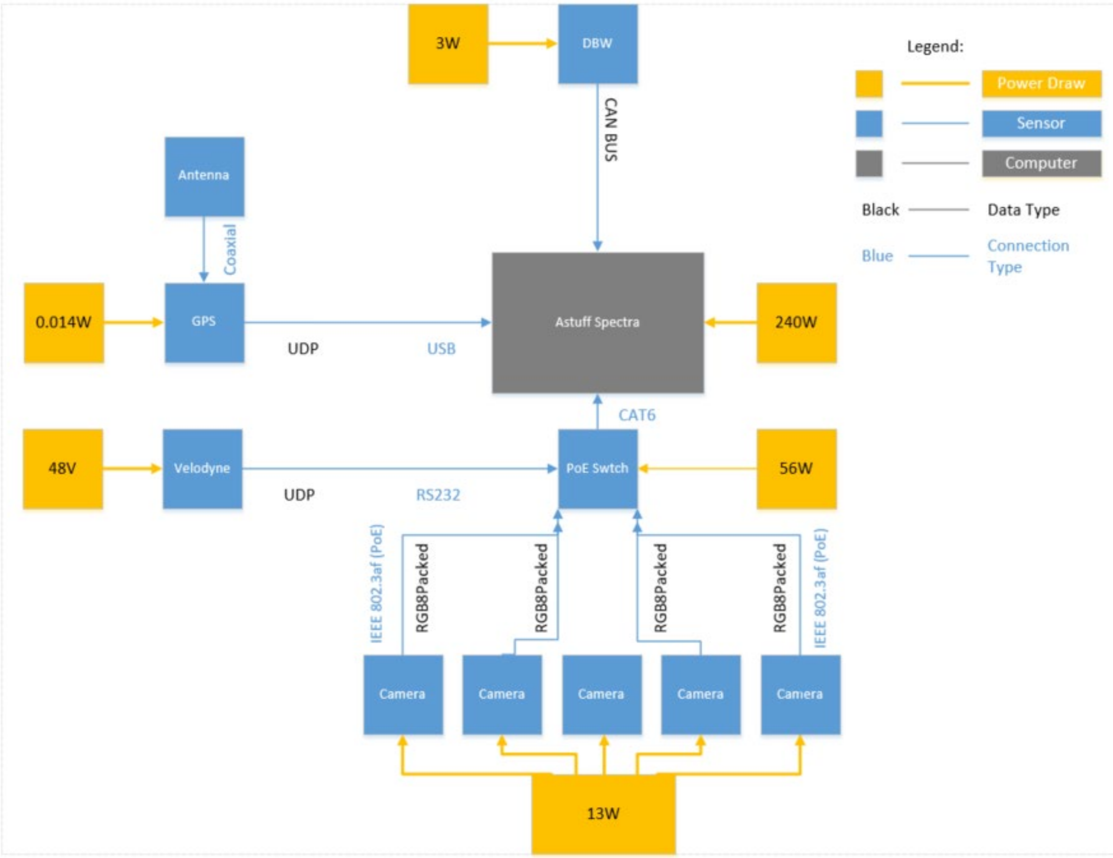


Figure 4. Hardware architecture glass box diagram

Safety Devices and Integration

The GEM has a physical emergency stop (E-stop) on the dashboard. To ensure safe operation of the vehicle, a safety-driver is always present when the vehicle is in use. If the vehicle is not performing as expected or is at risk of running over an obstacle, the safety driver will hit the E-stop, which cuts off the connection between the drive-by-wire system and the vehicle, and then press the brake pedal and/or engage the steering wheel to avoid an accident. Three external E-stops will be added to the vehicle before the competition in the case of the vehicle not behaving in the expected manner while a safety driver is not present.

SOFTWARE DESIGN OVERVIEW

Team Ghost Driver worked to adapt, expand, and evolve the RTK software repository by utilizing the already present waypoint navigation and obstacle detection capabilities as a starting point for autonomous navigation on roads. The team had to adapt RTK to work with a different sensor suite than had been used previously and to interface with an electric vehicle rather than a gas-powered vehicle.

Obstacle Detection and Avoidance

Obstacle detection is based on multiple data sources: the output of a 3D point cloud generated by the Velodyne HDL-64E and the conjunction of the five Mako G-319C cameras. Obstacles that are between 18.1 and 23.5 inches in width and between 37 and 71.5 inches in height must be detectable so that the vehicle can stop within a variable distance of the obstacle[3]. The LiDAR creates a dense 3D point cloud within a 100-meter diameter to identify the most unnavigable areas. RTK uses the 3D point cloud array, which is a collection of various intensities of objects within the environment, to interpret the environment. The array positions correspond to specific sectors around the circumference of the LiDAR. By filtering array values based on value, larger values being more "intense" objects, the GEM will be able to determine whether it is faced with an obstacle or a clear path.

Software Strategy and Path Planning

RTK is currently designed for autonomous navigation in off-road environments. RTK utilizes waypoint navigation from GPS data integrated with LiDAR data. RTK uses a costmap to make decisions regarding obstacle avoidance while simultaneously driving toward the established waypoints. It currently takes in LiDAR data to create this costmap and avoid obstacles. To achieve lane-following behavior, it is necessary to have the cameras detect the lanes and add them to the costmap as obstacles. To do this, solid lanes will be treated as walls with a high cost on the costmap so that the vehicle does not cross them. Dashed lanes will have a lower cost on the costmap so that the vehicle can cross them to avoid obstacles such as pedestrians and other vehicles.

Map Generation

RTK uses the LiDAR data to create a costmap of the environment. A costmap is an array of values representing the traversability of the space by the vehicle. At the node level, costmaps have a range of values between zero and one, with any value greater than 0.9 considered "lethal." The array values are multiplied by 255 so the final costmap ranges in value from 0 to 255. Thus, a region with a high cost will be avoided by the vehicle in favor of a route using a lower-cost area. In order to integrate lane and sign-detection, the camera data must be used to create the costmap in addition to the LiDAR data. The cameras must be able to recognize lanes and signs in order to combine their data with that of the LiDAR while creating the costmap. This will allow the vehicle to treat solid lanes and stop signs as "lethal" obstacles as it traverses the environment.

Goal Selection and Path Generation

The team decided to use RTK's Maverick Path Planner. The Maverick path planner creates a costmap of the environment and then uses a rapidly-exploring random tree to determine feasible alternative routes for the system. The team chose the Maverick planner because of its ability to update the costmap as additional data is gathered. The planner facilitates rapid decision making and makes the system compatible with use in dynamic environments (Robotics Technology Kernel User Guide, 2018).

FAILURE POINT IDENTIFICATION AND RESOLUTION METHODS

Vehicle Failure Modes in Software and Resolutions

The primary way that software could fail stems from hardware failure or error. RTK needs the LiDAR and GPS to be operating in order to run in autonomy mode. If there is an error with either of these sensors, then RTK will fail. As features are added the team will need to create redundancy such that if one camera fails it does not cause system failure. This will be completed in the future with camera view overlap and ultrasonic sensors in support of the LiDAR.

Vehicle Failure Modes in Hardware and Resolutions

Prior to the installation of voltage regulators the hardware components were exposed to fluctuating voltage and amperage levels. This presented potential for brown-outs to occur within the individual components which could be fatal to the hardware itself. If any individual component was damaged the entire autonomous package could fail. Therefore, it was necessary to implement isolation techniques in the component installation design. Exposure to the elements is also a concern for the team and the GEM's hardware components. All of the components, except for the LiDAR and voltage regulators, are not designed to be weatherproof. Therefore, weatherproofing solutions needed to be installed with the autonomous components both external and internal to the GEM.

Software Failure Prevention Strategy

To create redundancies in the software the team has the Bitbucket code repository, which has the most up to date RTK code in the case that RTK needs to be reinstalled for any reason. Additionally, the team installed RTK on a total of three Linux computers, and installed WMI on two Windows computers and three Linux computers.

Hardware Failure Prevention Strategy

The two main concerns that came with hardware failure were components being affected by weather or damaged by fluctuating voltages. Additionally, the team needed to make sure that a singular component failure did not lead to a complete system failure. Weather-related damages were mitigated by implementing the weather-proofing solutions previously discussed to include the coverings on the cameras and installation of the doors. The electrical components were protected by voltage regulators that ensured a brown out did not lead to catastrophic failure. The team prevented a total system failure by making each sensor removable and had multiple sensors to cover any blind spots created by a downed sensor.

Vehicle Safety Design Concepts

The team implemented physical safety measures to ensure safe utilization of the vehicle during development and testing and to meet competition safety requirements. During the testing process, the team created a protocol to follow before using the vehicle. This safety protocol was printed and adhered to both sides of the vehicle for ease of use whenever a team member used the vehicle. Additionally, a safety driver was always present in the vehicle during testing so that we could physically stop the vehicle using the brake pedal if necessary. Seatbelts and helmets were worn during testing to prevent injury if the vehicle collided with an obstacle or tipped over.

The IGVC required the GEM to meet safety and operational requirements. The doors and side panels were required to meet this requirement. The team bought the components from Polaris in three separate kits to install them. The team faced initial setbacks. One of these setbacks was having the driver-side door shipped with a broken window system. The team attempted to fix the door on our own; however, it was determined that it would more cost and time efficient to send the door back to Polaris to have a replacement sent in return. This was possible due to identifying the problem early on to ensure the return process would be complete before the IGVC begins on June 7th, 2019.

SIMULATIONS EMPLOYED

The team used the Autonomous Navigation Virtual Environment Laboratory (ANVEL) to simulate the placement of the sensors on the vehicle before the GEM arrived. Since the GEM did not arrive until

December, it was necessary to begin planning the placement of the sensors and integrating RTK in ANVEL prior to its arrival.

Simulations in Virtual Environment

The ANVEL simulation (Figure 5), once linked with RTK, provided a Military RZR (MRZR) vehicle model but did not include a model for the GEM e2. The team was able to utilize the MRZR for simulation purposes to test RTK since it closely resembled the GEM e2 vehicle. The exact dimensions and specifications of the vehicle did not influence the success of the simulation since the focus was on integration of RTK rather than vehicle dynamics. Based on this assumption, it was not necessary to create a new GEM e2 model compatible with ANVEL. Since the vehicle did not arrive until December 2018, it was necessary to use ANVEL to model the sensor placement and test using RTK to drive the vehicle and use waypoint navigation. After the vehicle arrived, ANVEL was still utilized to integrate RTK while the sensors were being mounted and the power supply was being integrated.

Name	PolarisMRZR4_v2_RTK-1
Position	-0.00621495; -52.62; -1.83998
Orientation	0.999991839229; -0.00354688
Scale	1; 1; 1
Selectable	True
Position Offset	-0.00621495; -52.62; -1.83998
Orientation Offset	0.999991839229; -0.00354688
Scale Offset	1; 1; 1
Visible	True
Opacity	1
Category	Vehicle
SelectionFlags	4

Figure 5. Screenshot of ANVEL simulation with MRZR vehicle

Theoretical Concepts in Simulations

The ANVEL simulation allowed the team to begin using the path planners within RTK. The basic path planner in RTK is called the A* (A-star) planner which utilizes the classic A* search algorithm. This algorithm uses a predefined map of the area and combines the cost of moving from the starting point to a given location with the cost heuristic of moving from the given location to the final destination [18]. The Maverick path planner, which was used by Team Ghost Driver uses the Rapidly-exploring Random Tree Star (RRT*) path planning algorithm. This algorithm is an improvement over the basic RRT algorithm which uses a random number generator to generate a point on the map which is then connected to the nearest node. In doing so, the point is checked to ensure it is not on an obstacle and the connection to the nearest node does not intersect an obstacle either. RRT* optimizes the RRT algorithm by calculating the cost of each vertex and then replacing more expensive vertices with cheaper ones. Additionally, RRT* rewires the tree by checking if each neighbor can decrease its cost by connecting with a new vertex rather than its previous parent. This allows the RRT* algorithm to create smoother and shorter paths. However, it is very computationally heavy and is not as efficient as RRT [19]. The ANVEL simulation software allowed Team Ghost Driver to use the RTK path planners in a simulated environment and see how the vehicle behaves differently before the GEM arrived.

PERFORMANCE TESTING TO DATE

The process of performance testing consisted of first launching the launch file to "activate" RTK and PACMod. Then the team was able to list all topics in either PACMod or RTK and ultimately echo those topics so that the team could see which specific topics were being affected by certain actions. For instance, when the team wanted to test steering, it would manually publish a steering value in RTK to obtain a desired steering wheel angle. The team could confirm this desired angle by echoing the RTK topic /vehicle_interface/steering_input. Then the team would echo the PACMod topic(s) it planned to be subscribing to this RTK topic. In this case, the PACMod topic would be /pacmod/as_rx/steer_cmd. The team were able to see that when publishing a certain value for the steering input in RTK, the PACMod topic would be echoing a different value. As a result, a custom node had to be created that converted the RTK steering input value to the PACMod steer cmd value so that they were operating on the same scale of values. In determining how to do the conversions between RTK and PACMod, the team was able to see the different message types that each each RTK or PACMod topic was using. Within these message types was a group of data types that made up the specific message type. In the steering example, the RTK message for steering input was called a Float32Stamped which included a float32 data type, and the PACMod message type for steering cmd was called PositionWithSpeed with data type float64. As a result, these message types had to be converted so that they operated on the same scale; a command in a float32 would have a proportional change in a float64. It is important to note that these message types are not native to the specific topic; they could be used in other topics as well. This process was continued for each topic such as throttle, braking, and gear selecting, among others. As it stands, the team has basic integration of RTK and PACMod so that the vehicle will navigate to a plotted GPS waypoint. In other words, RTK and PACMod are communicating (publishing and subscribing) with each other to allow for basic GPS waypoint navigation.

INITIAL PERFORMANCE ASSESSMENTS

Team Ghost Driver has fully interfaced RTK with the GEM. As a result, the vehicle can successfully complete waypoint navigation autonomously. The LiDAR has been integrated and can detect obstacles. However, it cannot currently avoid obstacles because it needs to be properly oriented. The vehicle does not currently have the cameras integrated so it does not have lane-following or road sign detection capabilities. The team plans to integrate the cameras for lane detection before the competition in June.

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