Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
May 2, 2019
A Regional Conference of the Society for Industrial and Systems Engineering

Adaptation of Off-Road Software Navigation Package for On-Road Use with Autonomous Vehicles

Jeremy Angle[1], Clement Calderon[2], Jaylen Collier[1], Nicholas Gasparri[2], Wyatt Gengler[3], Zach Maxwell[2], Sam Norman[3], Mary Pollin[3], Joseph Cymerman[2], Sang Yim[3], Kathryn Pegues[1], and Carlee Bishop[4]

[1]Department of Systems Engineering
United States Military Academy, West Point, NY

[2]Department of Civil and Mechanical Engineering
United States Military Academy, West Point, NY

[3]Department of Electrical Engineering and Computer Science
United States Military Academy, West Point, NY

[4]MS Applied Technology
Decatur, GA

Corresponding author: kathryn.pegues@westpoint.edu

Author Note: Jeremy Angle and Jaylen Collier from the United States Military Academy's (USMA) Department of Systems Engineering, Nicholas Gasparri, Zach Maxwell, and Clement Calderon from the Department of Civil and Mechanical Engineering, and Sam Norman, Mary Pollin, and Wyatt Gengler from the Department of Electrical Engineering and Computer Science authored this paper. The research underpinning this paper was conducted under the supervision of Lieutenant Colonel Kathryn K. Pegues, Dr. Carlee Bishop, Major Joseph Cymerman, Dr. Peter Hanlon, Major Sang Yim, and Lieutenant Colonel Christopher Lowrance. In May 2019, the cadets will commission into the United States Army as Second Lieutenants in the Field Artillery, Cyber, Aviation, Engineer, and Ordnance branches.

Abstract: Advancements in autonomous navigation have the potential to increase soldier safety in hazardous environments while accomplishing mission requirements. The focus of this research was to advance the capabilities of the Robotic Technology Kernel (RTK). The team developed an autonomous system and then improved capabilities of the RTK software. The prototype system consisted of a Polaris GEM e2 vehicle with a LiDAR sensor, five cameras, and a GPS/IMU capable of obstacle detection and lane following. The team expanded RTK by modifying low- and high-level interface files to work with a different vehicle and sensor suite. Prior to this research, RTK could only provide autonomous navigation capabilities between GPS points while avoiding obstacles. This research was necessary to expand RTK capabilities to include street sign detection and lane following so autonomous vehicles can navigate roads safely and legally.

Keywords: Autonomous Navigation, Power Consumption, Signal Integration, Robotic Technology Kernel

1. Introduction

1.1 Background

Autonomous navigation has been a growing field of research and has the potential to greatly improve the safety and efficiency of roads (Goodall, 2016). 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 (Greenblatt, 2016). 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 which fosters innovation with the Robot Technology Kernel (RTK) software package. The RTK software repository was developed for use with autonomous vehicles in tactical environments, therefore it did not have the capability to autonomously drive on roads following accepted traffic conventions.

The secondary focus of the team is to compete in the Intelligence Ground Vehicle Competition (IGVC). 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 (Kosinski, 2018).

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.

1.2 Design Process

The research utilized the Agile Design Process (ADP) which led the team 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.

1.3 Design Overview

In addition to expanding the RTK abilities the team also adjusted the physical design of the prototype system to meet the dimensional requirements of IGVC. The prototype system consists of a Polaris GEM e2 (GEM) electric car powered by a Multiplexed Vehicle Electrical Center (MVEC) that is supplied by a six 12-volt battery system and a 5.0 kW-h AC induction motor. To gather data on the environment, the team equipped the vehicle with five Mako G-319C cameras, a Velodyne HDL-64E LiDAR for obstacle detection and an Xsens MTi-G-710 GPS for GPS and IMU data. This autonomous package was determined to be the most effective hardware setup for the vehicle after careful considerations of all the viable commercial alternatives and application of the engineering design process. The camera data runs through ethernet cables into a Netgear Power over Ethernet (PoE) Insight Managed Smart Cloud Switch that communicates with the AutonomouStuff Spectra computer. The LiDAR and GPS use serial communication to interface with the computer. The computer, switch, and battery are all housed underneath the seat of the GEM and are covered by a protective kick plate that doubles as a weather-proofing solution.

The software is broken up into Robot Operating System (ROS) nodes that provide individual capability. When combined, these ROS nodes form RTK and provide its existing capability (Lane, 2019). The nodes are broken up into ten main groups (Sensors, Perception, Localization, World Model, Navigation, Autonomy Mode Manager, Vehicle Management System, Motion Execution, PACMod, and IOP bridge). At the lowest level of environment perception, the Sensors node consists of drivers that run the various sensors and publish their data to ROS topics used by additional nodes. The lowest level of vehicle motion is PACMod which is a ROS node that forms the drive-by-wire system. This node translates desired vehicle inputs into commands that control the vehicle. It also provides feedback to the system on the vehicle's current physical state, including steering angle, throttle and brake positions, and transmission state. The combination of the other nodes processes the sensor data to form a set of desired behaviors for the vehicle that is then published to PACMod. The team modified existing RTK nodes to allow RTK's autonomous features to interface with the GEM.

2. 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. RTK’s 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 (RTK Bitbucket, 2018).

3. Electronic and Power Design

3.1 Power Consumption System Design

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 Velodyne LiDAR, five cameras, and an onboard computer) The GEM’s overall battery capacity is 5,400 watt-hours (Polaris, 2011-2012). 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. 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. 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% 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 (Polaris, 2011-2012). 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% 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.

3.2 Power Distribution System Design

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 (Eaton, 2017). The MVEC outputs 12 volts DC at 20 amps (10 amp fuses). 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 (AutonomouStuff, 2018). 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.

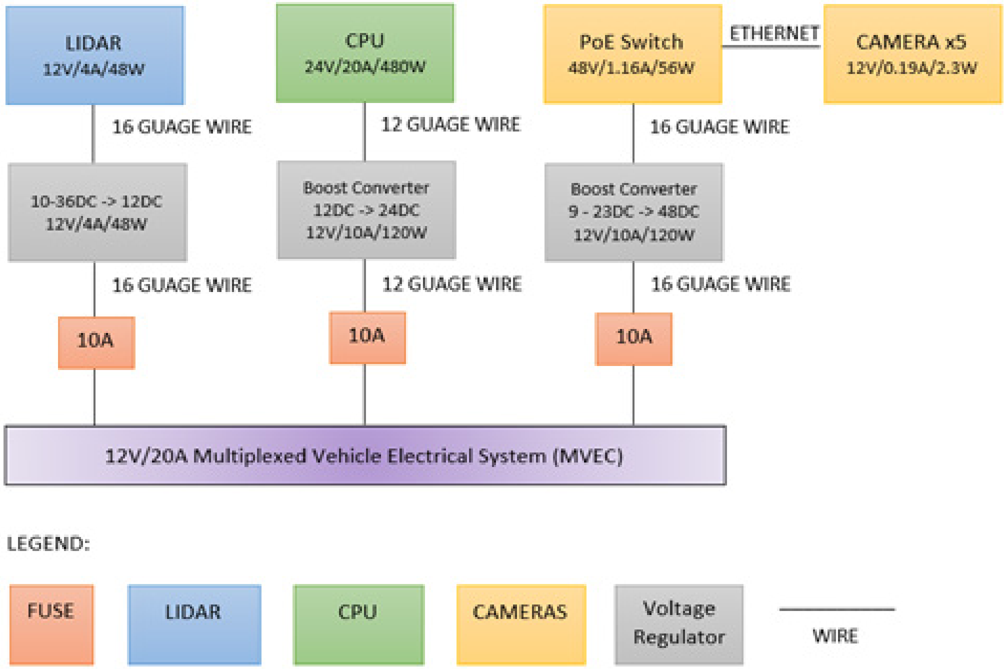


Figure 1. Power distribution integration diagram

4. Software

4.1 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 (IGVC, 2018). The LiDAR creates a dense point cloud within a 100-meter diameter to identify the most unnavigable areas. The GEM 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.

4.2 Software Strategy and Map Generation

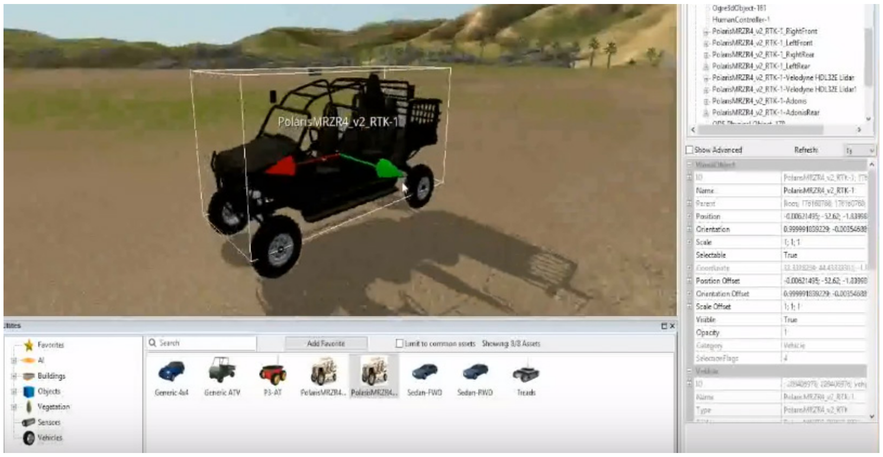
RTK is currently designed for autonomous navigation in off-road environments. RTK utilizes waypoint navigation from GPS data integrated with LiDAR data. RTK uses a costmap to make decisions regarding obstacle avoidance while simultaneously driving toward the established waypoints. It currently takes 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.

5. Implemented Solutions

Most of the issues encountered during the design effort centered around software integration of the sub-systems used for obstacle detection. These issues were addressed and solved so that the GEM is now capable of using drive-by-wire. RTK currently communicates with ROS topics using custom RTK ROS messages to interface with the drive-by-wire ROS node. This node directly communicates with a drive-by-wire system installed in all vehicles intended for use with RTK. The GEM uses a PACMod drive-by-wire system mapping Controller Area Network (CAN) commands that directly control the vehicle using ROS topics with custom PACMod ROS message types. Thus, to use RTK's existing vehicle control code the team needed to map all the input code from RTK's drive-by-wire node to the matching topic in PACMod. Additionally, the message types were in different forms and the expected values were on a different scale. Each of these had to be translated to represent the proper information in both RTK and PACMod. RTK also expects certain topics to be published back to it representing the current state of the vehicle such as steering angle and brake and throttle position. These topics also needed to be translated from the corresponding PACMod ROS node and message type back to RTK. Once these adaptations were complete, RTK's drive-by-wire node was able to communicate with the PACMod drive-by-wire system. At this point, the vehicle has full functionality with RTK. In addressing these obstacles, the team gained a deeper understanding of the original RTK software and how the files interacted to allow for waypoint following with obstacle detection.

6. Simulations Employed

The ANVEL simulation, once linked with RTK, provided a Military RZR (MRZR) vehicle model (Figure 2) 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 2. Screenshot of ANVEL simulation with MRZR vehicle

7. Progress to Date

The GEM has the power source and the sensor suite consisting of five cameras, Velodyne 64E LiDAR, and GPS integrated. RTK was installed on the Spectra computer. The system has a working drive-by-wire system in place that can accelerate and stop the vehicle and turn the wheels left and right. RTK uses an existing drive-by-wire system that is typically installed into each new vehicle. The GEM uses PACMod software and hardware provided by AutonomouStuff to drive the vehicle through ROS topics for steering, acceleration, transmission, and other status reports. The team created three linking nodes to allow RTK to communicate with PACMod instead of the existing RTK drive-by-wire system. The team also created a new launch file to launch the specific packages needed for the LIDAR setup, vehicle dimensions, and custom nodes. Once debugging of these components is complete, RTK's base abilities of obstacle avoidance and waypoint navigation will be implemented on the GEM.

8. Acknowledgements

The research is sponsored by the U.S. Army Combat Capabilities Development Command Ground Vehicle System Center, who provided a significant portion of the funding for the project as well as guidance towards software design and integration. The team would like to thank Mr. Guervey Mosquera and the Engineering Support Group (Department of Electrical Engineering and Computer Science) as well as Mr. Roderick Wilson and the Lab Technicians (Department of Civil and Mechanical Engineering) for their help with software integration and hardware acquisition. The team would also like to thank Jack Hartner and Will Smith for their continued help with RTK as well as Caleb Imig and Rinda Gunjala from AutonomouStuff for their help with providing documentation used in designing the power distribution system.

9. References

AutonomouStuff (2018). AStuff Spectra Datasheet. https://autonomoustuff.com/wp-content/uploads/2019/01/Spectra_Datasheet_New_v2.pdf.

Intelligent Ground Vehicle Competition (2018). Official Competition Rules, Details, and Format. http://www.igvc.org/2019rules.pdf.

GEM e2 Service Manual. (2011-2012). Personal Communication, March 7, 2019.

Goodall N. (2016). Can You Program Ethics into a Self-Driving Car? *IEEE Spectrum,* 53, 28-31, 57-58. Retrieved from https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7473149.

Greenblatt N. (2016). Self-Driving Cars and the Law. *IEEE Spectrum,* 53, 46-51. Retrieved from https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7419800

Kosinski, A., Tarakhovsk, J., Iyengar, K., Lane, J., Cheok, K. C., & Theisen, B. (2018). Developing Autonomous Street-Legal Vehicles: Analysis Of 2017 Intelligent Ground Vehicle Competition (Igvc) Self-Drive/Auto-Nav Competition Vehicle Design And Implementation. *2018 NDIA Ground Vehicle Systems Engineering and Technology Symposium*.

Lane, G. (2018). Great Lakes Systems & Technology LLC & US Army TARDEC Robotic Technology Kernel (RTK) Logistics Automation Autonomous Driving Research Opportunity for USA Universities and Colleges competing in the 2019 IGVC Self Drive Challenge. Retrieved from http://www.gl-systems-technology.net/uploads/3/4/5/7/34572805/gls_t_rtk-igvc_overview_3_june_2018.pdf.

Lane, G. (2019). RTK. *Great Lakes Systems and Technology, LLC*. http://www.gl-systems-technology.net/rtk.html.31M-300-0-SALES. (17, May 11). Retrieved from https://www.eaton.com/Eaton/ProductsServices/Electrical/ProductsandServices/Transportationsolutions/PowerDistribution/VehicleElectricalCenters/MultiplexedVehicleElectricalCenter-mVEC/index.htm

Robotics Technology Kernel User Guide. (2018). Retrieved from RTK source code.