Embry-Riddle Aeronautical University

A-REX:
Autonomous Robotic Engineered Experience

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Statement of Integrity

I hereby certify that the design and development of this vehicle described in this report is significant and equivalent to what might be awarded credit in a senior design course. This report was prepared by the student team under the guidance of the faculty advisors.

Dr. Charles Reinholtz, Faculty Advisor

1.0 Overview

Embry-Riddle Aeronautical University (ERAU) purchased a Polaris GEM e2 Neighborhood Electric Vehicle, equipped with power steering and extended battery pack. The Vehicle modification developments yielded remote control (RC) and autonomous capabilities including drive-by-wire control of steering, brake, and throttle. During RC mode, the mounted Rocket M5 Radio allows for remote operator-unit control communication. Under autonomous control, the converted vehicle is capable of lane following, obstacle avoidance, and waypoint navigation. The perception in autonomous operation sensor suite includes a front-facing Velodyne Puck 16-Beam LiDAR, a Blackfly (formerly FLIR) PGE-2S32 Gigabit Ethernet camera, a rear-facing SICK LMS 151 LiDAR, and a VectorNav VN-300 Rugged GPS/INS system

Our team adapted the Robotic Technology Kernel (RTK) software, provided by U.S Army Ground Vehicle Systems Center (GVSC), resulting in autonomous capabilities. This report details the development of the systems and the methods used for system integration.

2.0 Conduct of the Design Process

2.1 Introduction

ERAU is sponsored to perform research under a U.S Army GVSC contract entitled, "RTC Logistics Automation." Many of the objectives of the IGVC Self-Drive Challenge overlap with the objectives of the contract, including converting the GEM e2 vehicle to drive-by-wire operation and equipping it with sensors for autonomy. The team elected to use the RTK software to control the vehicle, satisfying the software implementation and development requirements.

2.2 Team Organization

The development of this vehicle including design, manufacturing, and software implementation required a multidisciplinary engineering approach. Contributing to this approach were six undergraduate engineering students during the fall semester and five during the spring semester.

2.3 Design Process

Per each innovation, or change to the system, a seven-step engineering design process was used in order as shown in Fig. 1. In addition, four key factors were prominent in the planning portion of the design and development process including safety, performance, reliability, and modularity. It should be noted that a few key assumptions were made about sensor range, field of view, and update rates needed to traverse the competition course at the maximum allowable speed of 5 mph.

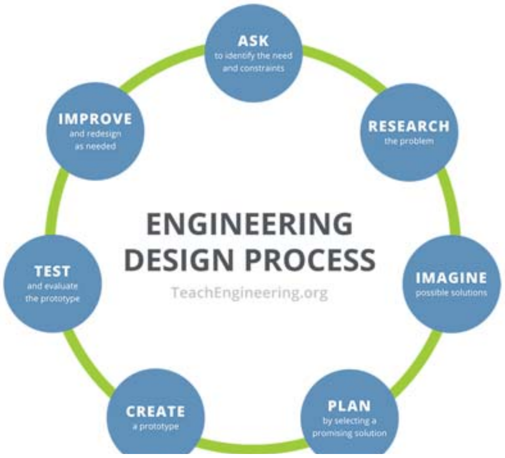


Figure 1: Seven-Step Design Process

3.0 Effective Innovations

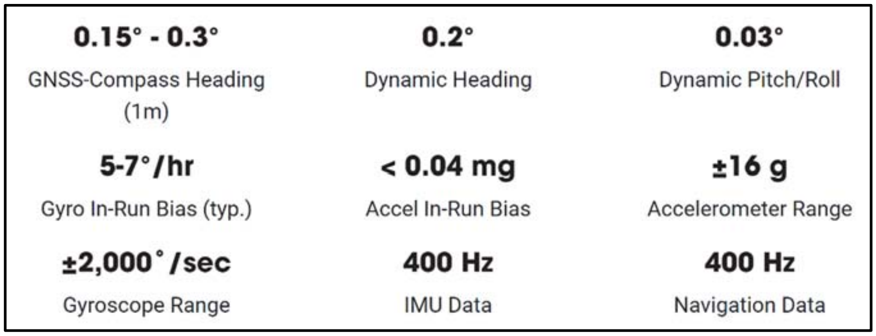
3.1 Overview

The innovations and progress made on the vehicle by the team during 2022 have enhanced the vehicle's safety and performance. Specifically, the adaptations to the visual capabilities and vision processing software as well as modifications increasing the robustness of the E-brake and tuning the controller for smoother power steering.

3.2 IMU/GPS

A major upgrade to the system during the 2021-2022 competition cycle was replacing the previously-used Hemisphere GPS systems with a VectorNav VN-300 system. The VN-300 is a miniature, high-performance Dual Antenna GNSS-Aided Inertial Navigation System that combines MEMS inertial sensors, two high-sensitivity GNSS receivers, and advanced Kalman filtering algorithms to provide optimal estimates of position, velocity, and orientation. The system uses two Tallysman GPS Antennas along with the IMU to give accurate static and dynamic heading measurements of +/- 0.2 degrees. The IMU collects data at 800 Hz while the GNSS has an update rate of 5hz. Sensor fusion occurs within the VN-300 itself to provide the most accurate data to the system. A key aspect of integrating the VectorNav system with RTK is the availability of user configurable messages in multiple formats, including ASCII, NMEA-0183 and VectorNav Binary messages. Key specifications for the VectorNav VN-300 system are listed in Table 1 below.

Table 1: VectorNav VN-300 system Specifications



0.15° - 0.3°	**0.2°**	**0.03°**
GNSS-Compass Heading (1m)	Dynamic Heading	Dynamic Pitch/Roll
5-7°/hr	**< 0.04 mg**	**±16 g**
Gyro In-Run Bias (typ.)	Accel In-Run Bias	Accelerometer Range
±2,000°/sec	**400 Hz**	**400 Hz**
Gyroscope Range	IMU Data	Navigation Data

4.0 Description of Mechanical Design

4.1 Overview

The mechanical design approach for this project prioritized minimizing stock vehicle modifications. This approach aligned with the modularity and marketability goal by treating the autonomy kit as an accessory to a stock GEM e2 vehicle. The specifications of the A-REX GEM e2 are shown in Table 2.

Table 2: Polaris GEM e2 Vehicle Specifications

Vehicle Specification Table	
Engine & Drivetrain	
Battery Voltage	48V
Drive	Direct Front Wheel
Motor Size	6.7 HP (5.0 kW)
Motor Type	AC Induction
Top Speed	25 mph
Dimensions	
Cubic Feet of Cab	70 ft^3 (2 m^3)
Estimated Dry Weight	1,650 lb (748 kg)[1]
Ground Clearance	8 in (20 cm)
GVWR	2,000 lb (907 kg)
Overall Vehicle Size (L x W x H)	103 x 55.5 x 73 in (261.6 x 141 x 185.4 cm)
Payload Capacity	800 lb (363 kg)
Person Capacity	2
Rear Cargo Box Capacity	330 lb (150 kg)
Turning Radius	150 in (381 cm)
Wheelbase	69 in (175.3 cm)
Tires/Wheels	
Front Brakes	Disc
Rear Brakes	Hydraulic Drum
Tires	13 in. street-rated 155/80 R13
Suspension	
Front Suspension	MacPherson Strut - 5.6 in (14 cm)
Rear Suspension	Independent Trailing Arm - 6 in (15 cm)

Two major classes of physical modifications were made to the stock GEM e2 vehicle. First, the team added a suite of advanced sensors and electronics to facilitate autonomous operation. Second, the steering, throttle, service brake, and emergency (parking) brake were successfully converted to operate under drive-by-wire. In addition, the emergency stop system is activated via any of the five emergency stop buttons on and inside the vehicle, or via remote control. To assist selection and location of sensors, the team developed a Simulation Cuboid Model (SCM) in MATLAB. This confirmed the sensor field of view while determining the optimal sensor placement, which is detailed in the "Electronic Suite Description." A top-down view of the modeled environment is shown in Fig. 2. The SCM is a MATLAB tool that uses the camera and LiDAR position and technical specifications to obtain an expected range of view. The SCM ensures that there are no blind spots, given the chosen sensor placement.

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[1] Note that the maximum weight requirement, as specified in 1.2.2 Design Specifications in the 2019 IGVC Rules, was waived for teams using the GEM e2 vehicle, due to the additional weight of modifications for the Drive-by-Wire conversion and extended battery pack. This was approved by Mr. Gerald Lane of GLS&T via email on 09/18/18 stating that the Gross Vehicle Mass Weight (GVMW) of up to 2000 lbs. was allowable.

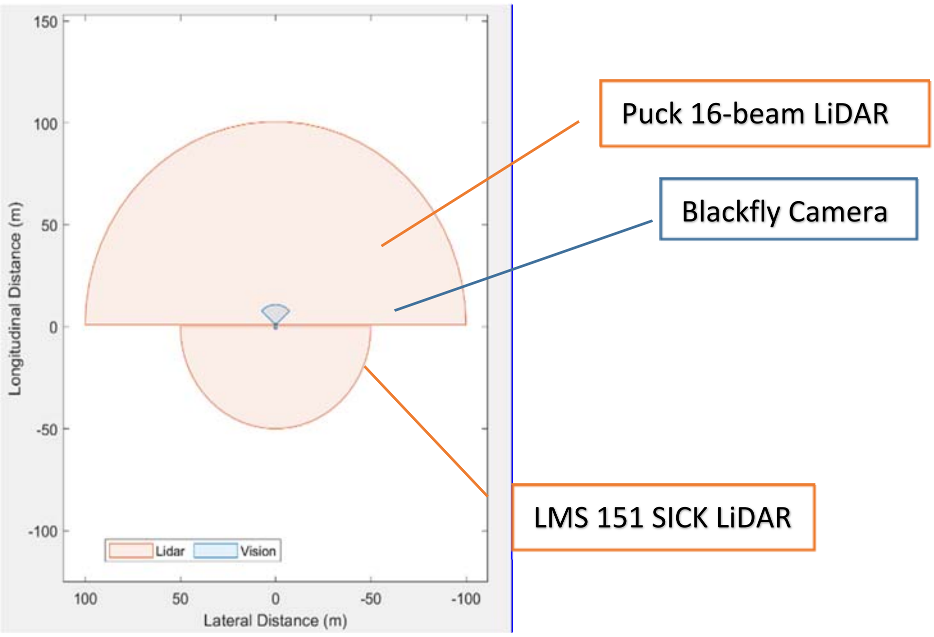

Figure 2: Depicts the MATLAB simulation cuboid model.

T-slot aluminum framing system was added to the top of the vehicle mounting the VectorNav GPS and two safety lights, as shown in Fig. 3. The sensor bar attaches to the preexisting rails of the GEM e2, which allows for a clean finish while limiting any physical modifications needed. The sensor bar attachment also includes risers and a track guard. The risers prevent the sensor bar from physically touching the vehicle, and eliminating any friction and chafing leading to potential cosmetic damage. A rubber track was also added to prevent rain and litter collection in the 80-20 rails. The sensor bar attaches to the vehicle rails allowing it to be adjusted forward and aft on the vehicle.

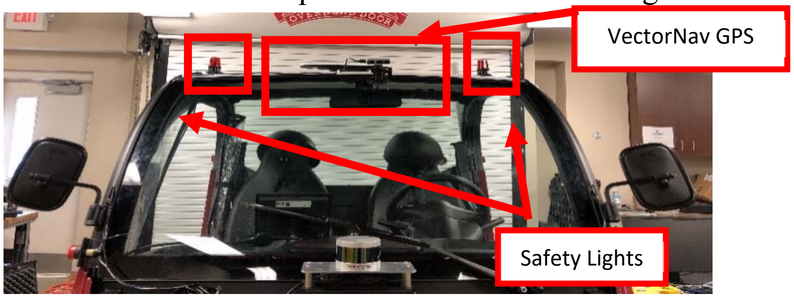

Figure 3: shows the sensor bar mount.

4.2 Emergency Braking System

A fail-safe emergency braking system was a modified from the stock parking brake. With the new design, an electromagnet holds the parking brake in the deactivated position. When the vehicle loses power, or when any of the e-stop buttons are pressed, the magnet is de-energized and parking brake is activated by a spring with stored potential energy. This system is fail-safe, in the sense that the brake is applied by default, and it is only disengaged when held in place by the magnet. When the vehicle is powered and in use, an active electromagnet keeps the parking brake disengaged. Once the vehicle loses power, the electromagnet will also lose power. This will result in a fail-safe braking system. When de-energized, the electromagnet loses contact with a plate connected to the parking brake. The spring will then force the parking brake to engage, thereby causing the car to come to a safe stop.

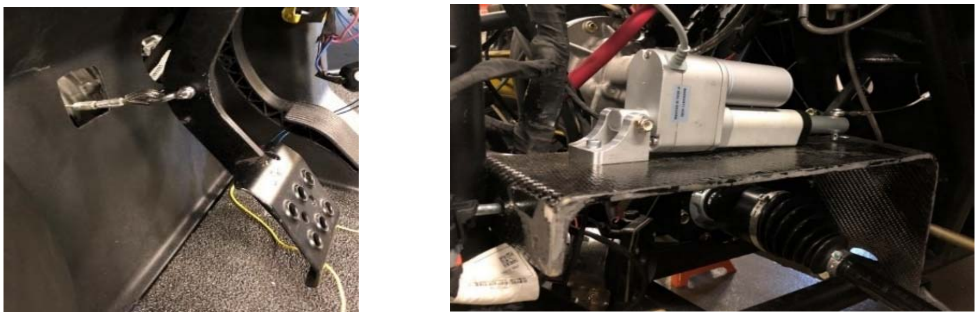

Figure 4: Re-designed Emergency Brake System

There are five E-Stop buttons located on the exterior of the vehicle. Figure 5 highlights two of them. Prioritizing the safety of riders, a fifth e-stop button is located between the driver and the passenger seats. If any of the buttons are pressed, power is cut to the contactor, the motor, and the electromagnet. The RC controller will also have an E-Stop switch that works the same as the buttons on the vehicle.

Figure 5: Emergency Stop Buttons Drive-By-Wire Conversion

To convert the vehicle to a drive-by-wire system, steering, throttle, service braking, gear shifting, and turn signal functions were first analyzed. Figure details the Drive-by-Wire functions and their relationships. The Polaris GEM e2 uses two potentiometers to send signals to the motor controller to change the speed of the vehicle. The potentiometer's output voltages from the throttle

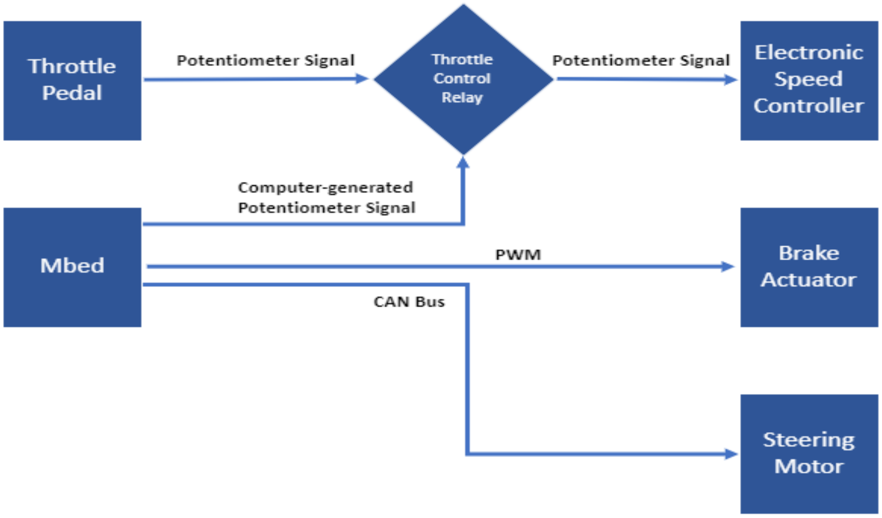

Figure 6: Depicts the drive-by-wire structural outline

pedal were first read using an Arduino microcontroller. After the voltage data was collected, a linear function relating the voltage output from the throttle pedal to the vehicle's speed was developed. This relationship was then used to create digital signals that related to a desired speed from a Mbed microcontroller. The digital signals sent from the Mbed are pulse-width-modulated (PWM) signals. The speed controller on the GEM e2 expects an analog signal, therefore a low pass filter was implemented into the circuitry to control the vehicle's speed. The low pass filter consisted of a capacitor and a resistor, in which high frequencies are filtered out by the capacitor only allowing lower frequencies to pass through the circuit. This smoothed out the PWM signal to be read by the speed controller as a continuous analog signal. The low pass filter had a cut-off frequency of 10 Hz. To switch from manual and autonomous modes, the throttle pedal and the Mbed were connected to a relay that normally allows the raw throttle pedal signals to pass through. To limit the speed of the GEM e2 to 5 mph the software will not allow the Mbed to send PWM signals that relate to a speed higher than 5 mph. The GEM e2 uses an Allied Motion autonomous ready POW-R STEER Actuator. This actuator is controlled using CAN signals. CAN signals are 64-bit messages in which the first part of the message is the message identifier. Identifiers for a command message and a feedback message were found in the manual for the power steering actuator. Once the identifiers were found the next step was to send a message to the power steering actuator to make it actuate. To send a message to the power steering unit the first byte of the CAN message indicated the mode for the power steering actuator as explained in the Manual. Mode 5 was used to allow the user to send a desired wheel position and wheel speed to the power steering actuator. The desired steering wheel position is sent as a 32-bit signed integer that is then split into 4 separate bytes in the CAN message. The same process was done for the steering wheel speed with a 16-bit integer split into 2 bytes. For the feedback, the same process for sending a message was used in reverse where 4 bytes representing the steering wheel position were converted into a 32-bit integer and then converted into position in revolutions. The power steering actuator was limited to 2.5 revolutions to the left or right.

The vehicle indicators and gear shifter operate on similar systems, with 3-state pass-through relays governing the mode of each system. For the blinker, the three modes are left blinker, right blinker, or neither. For the gear shifter, the modes are forward, neutral, and reverse. Using simple MBED-controlled relays, the vehicle can easily toggle any of these modes, and set the desired driving gear or activate the required turn signal.

4.3 Weatherproofing

A waterproof IP65 (Rated Dust-tight and protected against water projected from a nozzle) L-com NEMA (National Electrical Manufacturers Association) enclosure was used to house the computer, many of the power converters, and other sensitive components. This enclosure makes the electronic subsystem modular and easily transportable. The electronic connections are routed through a connection panel that is also IP65 rated to allow sensor communication with the internal laptop while allowing for the system to remain waterproof.

4.4 E-brake

The E-brake implemented in previous years failed to meet competition requirements and therefore was redesigned, the new E-brake system now meets requirements and is more robust and reliable. Additionally, it minimizes unwanted motion in the system and brings the vehicle from the competition speed of 5 mph to a complete stop within 10 ft when tested under expected competition conditions. The same system, which operates as the parking brake, can hold the vehicle on a paved surface with a 12.5% grade.

5.0 Description of Electronic and Power Design

5.1 Overview

The team designed the power system to provide the ability to run all onboard components from the existing vehicle's 48-volt power system. The first step in the design process was to create a wiring diagram to develop an understanding of how to place the wiring throughout the vehicle. Based on the equipment stored, we used the wiring diagram to determine the component box requirements. Next, we outlined the initial component boxes and designed a mockup. Once completed and verified, the component cases were ordered and received. Then, the mockup design materialized by modifying the ordered component cases. Wires were installed in the vehicle and connected to the installed component cases. This marked the completion of the setup of the electrical system.

5.2 Power Distribution System

The battery and charging system remain the same as on the manufacturer-supplied vehicle. The manufacturer distance AGM battery option that doubles base vehicle rage from 30 to 60 miles was selected to allow for longer run times with added equipment. The battery pack for this option includes 8 batteries at 6v each for a 48v system. The power for all added components was converted from 48v to 24v and 19v. The component box system is controlled by a switch in the cabin of the vehicle controlling a relay. Buck Converters were used to convert 48v battery power to these other required voltage levels. This eliminated the need to add a second power source to the vehicle. The power for the drive-by-wire system was kept separate from the power for the sensing system. Designing it this way was important because it allows the sensing system to continue sensing the surroundings even if the power is removed from the drive-by-wire system. Power could be removed either by turning it off or by hitting one of the emergency-stop buttons

5.3 Electronics Suite Description

The Gigabyte Brix S computer utilizes an Intel Kabylake i5-7200U processor to process data and performs navigation calculations. The Sparton IMU houses a 3-axis gyroscope, magnetometer, and accelerometer. The Velodyne Puck 16- Beam LiDAR is a multi-plane LiDAR used to detect objects in front of the vehicle. The Intel Real Sense Camera is a depth perception camera, being utilized for sign detection, and could be used in the future as a redundant detection device for the Velodyne LiDAR. The SICK LiDAR is a single-plane LiDAR used for detecting objects behind the vehicle while in reverse. The POE Switcher is used for the computer to manage the data coming more easily from the added components. The Rocket M5 Radio is used for communication to and from the base station. The new VectorNav VN 300 provides precise location and heading information both statically and dynamically. The ability of this system to provide precise heading information while the vehicle is stationary was a major upgrade compared to the Hemisphere GPS and separate Spartan IMU used in previous competitions.

5.4 Power Steering motor PID Tuning

The ERAU self-drive team focused significant effort on determining the optimal steering control settings for smooth, precisely controlled steering performance. This was an important improvement, since the previous motor response to Controller Area Network (CAN) steering commands was erratic. This was achieved through tuning the GLOBE POW-R STEER® Electric Power Assisted Steering (EPAS) steering motor supplied by Allied Motion, over the CAN bus. The tuning now ensures steady turning for the vehicle during autonomous operation. Table 3 summarizes the method used for PID gain tuning based on the instructions provided by Allied Motion.

Table 3: Power Steering PID Tuning Process

Gain (Tuning Order)	Process	Effect	Starting Value	Approx. Range
P (1)	Increase to desired responsiveness, decrease if wheel motion becomes "Jerky".	Increased responsiveness of steering commands.	10	50-150
I (3)	Increase until control becomes more volatile with new commands.	Stabilize control when giving new command.	0.1	0.1-2.5
D (2)	Start low, increase until unsteady shaking stops improving.	Balance wheel while holding steering angle.	0.01	0.01-0.5
C (4)	Increase until final desired state is achieved.	Lower total error/oscillations.	0.01	0.01-0.05
SL (N/A)	Do not change.	Anything but 0 will be unstable.	0	0

6.0 Description of Software Strategy and Mapping Techniques

6.1 Overview

The team is using the Robotic Operating System (ROS) on a Linux computer to run the Robotic Technology Kernel (RTK) to give the GEM e2 self-driving capabilities. RTK is a software system provided by the United States Army CCDC Ground Vehicle Systems Center (GVSC) and is used by the University for research and development under the restrictions of a Non-Disclosure Agreement. An Mbed microcontroller is used to interface with necessary vehicle systems. Nodes were built in C++ code that picks up encoded serial data from the Mbed and publishes the data as the ROS topics necessary for the RTK nodes to run. A hex file was built to launch some of the sensor drivers and to pass correct parameters to their corresponding launch files. The ROS launch files initialize the nodes and nodelets that interpret sensor data and Mbed commands. These nodes communicate back to the Mbed through serial with the proper driving commands for actuation. For vision and lane detection, a MATLAB script was used to process vision and serialize the data to be published as a ROS topic similar to the LIDAR's point cloud. A remote Windows machine is used to send GPS waypoints and paths through the Warfighter Machine Interface (WMI), which packages the data in a way the RTK understands and can use for navigation. An overview of the RTK modules that are used by the vehicle is shown below, in Fig. 7.

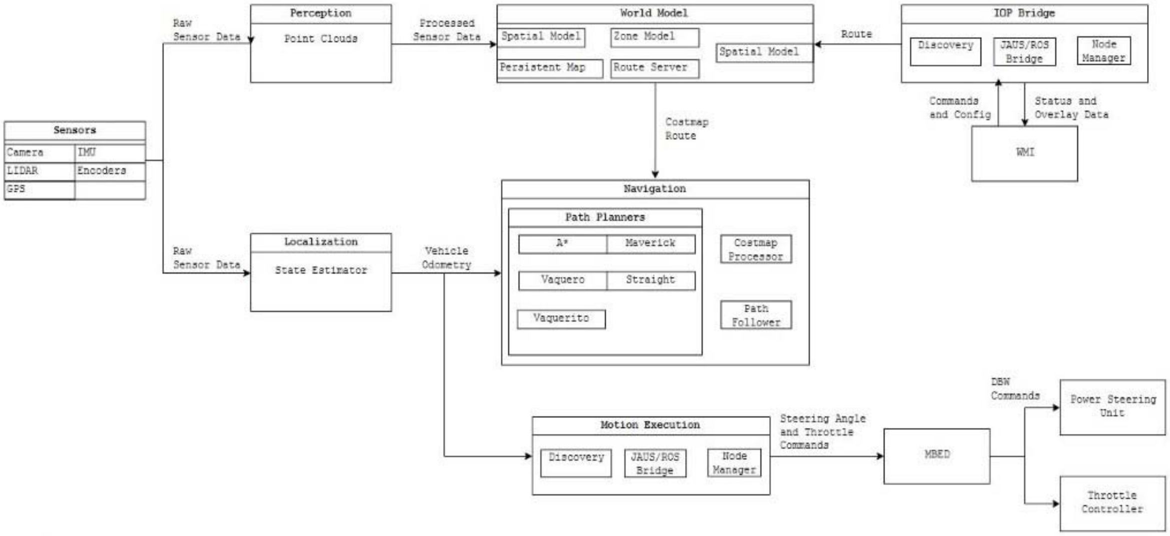

Figure 7: RTK Module Overview

The A-REX team made a ROS package that mimics necessary topics from the RTK motion control system. This package contains the state of the transmission which is used for determining the direction for the near field positioning, the robotic state of the vehicle whether it be stopped, manual, or autonomous, and the behavior state which determines which path planner that is going to be used, and transfers and published the encoders. Along with this package, a vision package is publishing positions of the lanes using array markers. These will act as road boundaries or add immediate waypoints that are centered between the lanes. The workflow for this package is depicted in Fig 8.

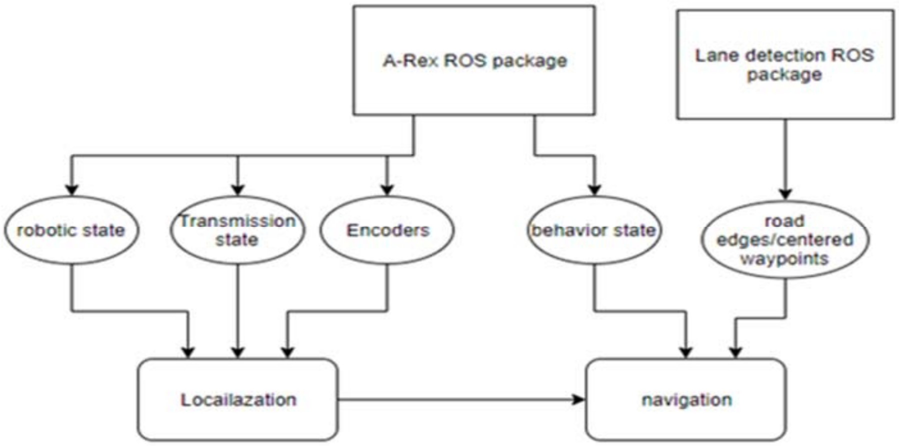

Figure 8: Layout of ROS Packages and Communication

6.2 Obstacle Detection and Avoidance

The vehicle uses a Velodyne VLP-16 LiDAR (Puck) as its main obstacle detecting sensor. When active, this 16 beam LiDAR returns a point-cloud of distances to objects at a rate of 20Hz. The effective field of vision of the LiDAR is 30 degrees vertically (+15 and –15 degrees) and 210 degrees horizontally. To integrate the sensor into the system, the ROS driver for the Puck is used. The device communicates to the main computer via ethernet connection. RTK natively supports this sensor so little modification was needed to be made in order to integrate it into the system.

The Point cloud produced by the Velodyne Puck is fed into the Perception module of RTK where it is processed and fed forward into the World Model module. Once in World Model, cost maps are generated; these cost maps are used to identify areas the vehicle should avoid with higher costs corresponding to elevated avoidance priority. In addition to generating cost maps, the World Model module generates a near-field frame based on sensor data and vehicle starting position, which, along with GPS, is then used to build the global frame or far-field frame. From the world model, the cost maps are sent to the Navigation module. Ultimately, the Navigation module uses one of five available search algorithms (A*, Maverick, Vaquero, Vaquerito, or Straight) to identify a path that avoids any detected obstacles while heading to the current GPS waypoint. From navigation, corresponding speed and curvatures are outputted to follow a path. These topics are sent to motion execution.

Motion execution takes the speed and curvature output from navigation. This module sends the speed as measured from the encoders through a PID controller, which then outputs a throttle command. The module also sends the curvature through the steering calibration that also includes a PID to the feedback position of the steering wheel, which outputs a steering command. Both the throttle and steering command are sent to the Mbed where these topics are executed. Figure 9 depicts the flowchart used detailing the obstacle-avoidance process.

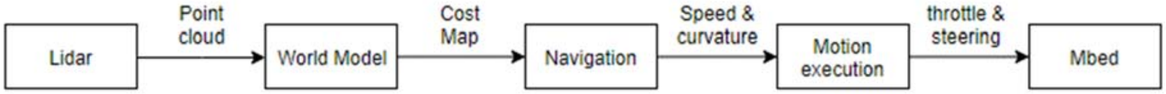

Figure 9: Shows the flow chart depicting the obstacle avoidance decision-making.

6.3 Software Strategy

The software strategy to integrate the RTK modules given by GVSC into the vehicle's system was to divide and conquer. Independent subgroups worked on getting specific modules operational later integrate everything together. One group worked on the localization sensors that and created ROS drivers to publish data in a format that the RTK Summit State Estimator node would be able to use. The second group was working on the vision and perception nodes (Camera, LiDAR). The VLP-16 LiDAR is natively compatible with RTK, so their job was to install the correct driver and change the source code to work with the 16 laser Velodyne rather than the 32 laser one. Vision in RTK is not used for the same purpose that the competition requires (Lane detection, obstacle detection/classification), so the team only focused on getting ROS to publish camera data. These teams were also in charge of making hex and launch files that would ensure the sensors were connected and sending data, as well as creating any other C++ code necessary for pre-processing of sensor data. Another group working on Mbed code that would be used for the control module and drive-by-wire.

6.4 Path Planning, Goal Selection, and Path Generation

Path planning in the RTK depends on the WMI waypoints given and on the RTK's obstacle avoidance, world model, and localization nodes. The waypoints need to be set in the WMI when the vehicle is in autonomous mode and has a "ready" health status (not E-STOP or any other error state). The vehicle uses localization node to transform the coordinates into the near-field and builds and navigates a modified Euclidian path towards the goal. The LiDAR data used by the world model node creates a cost map with obstacles and no-go zones that are used by the built-in A* algorithm in the RTK path-planning node to create the modified Euclidian path as the vehicle moves and the map gets updated. Vision will detect lanes and create intermediate waypoints between them for the RTK's path planning and navigation unless no lanes are detected or there is an obstacle in the way. No lanes will depend solely on RTK path planning, and detection of an obstacle during lane following will cause a change of lane or full stop. Figure 10 depicts a flowchart illustrating the logic flow from user input GPS waypoints to output throttle and steering commands.

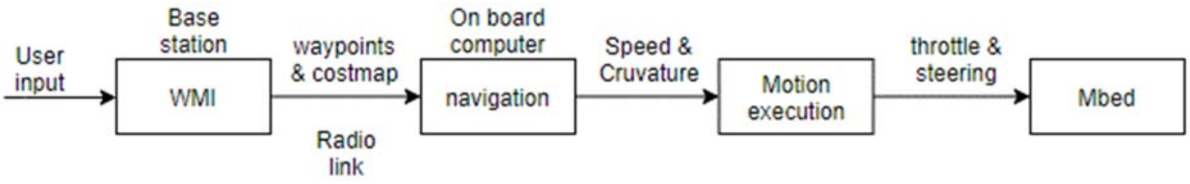

Figure 10: Shows the flow chart depicting the path-planning and autonomous decision-making process.

6.5 Map Generation

The World Model portion of RTK is responsible for generating maps that are used for vehicle navigation. Specifically, as sensor data is acquired and processed by the Perception module, cost maps are generated that correspond to the environment directly around the vehicle. Furthermore, these cost maps are used to create a vehicle near frame: the near frame is a map that includes obstacles and their distances to the vehicle with respect to the vehicle's origin. Once a near field map has been generated, it is placed into the global frame by attaching GPS data. These maps are then used by the navigation module to generate a path for the vehicle to travel that avoids obstacles and reaches designated waypoints.

7.0 Failure Points Identification and Resolution Methods To Be Used If This Failure Occurs

Although the vehicle was designed for maximum safety, failures are always possible. To combat this possibility, several different failure modes have been identified and resolutions have been implemented to minimize the negative results of any failure.

7.1 Vehicle Failure Modes and Resolutions

The software is only as reliable as sensor data, so communication with the sensors is a critical function. The RTK Health Monitoring System is constantly monitoring the sensor communications for any errors that may arise from communication protocol issues or disconnections. It does this by monitoring the "heartbeat" frequencies of the sensor signals. If the frequency of the data packets from these sensors or systems changes, the RTK will recognize that an error may be occurring and will enter the appropriate mode to counteract the error. Entering any failure state will result in the emergency stop system being engaged, and an error message will be displayed on the dash-mounted monitor. The failure state is also reported to the base-station computer through the WMI, so remote operators will know that the vehicle has encountered a fatal error.

7.2 Vehicle Failure Points and Resolutions

Mechanically, the vehicle is a stock GEM e2 platform enhanced with actuators, sensors, and computer control. We expect the base mechanical vehicle systems to generally maintain the reliability of the original system. In designing the subsystems added to the base vehicle, the team focused on simplicity and modularity. As a result, components are easily removable and replaceable. An onboard toolbox that contains necessary tools to swap out many components and subsystems is carried on-board the vehicle for quick repairs.

It was important that the driver always has priority in controlling the vehicle. Along with the software controlling the linear actuator to stop the vehicle, the driver can always use the standard brake pedal to bring the vehicle to a stop. If power to the vehicle is lost, the electromagnet is disengaged and the parking brake will be applied, bringing the car to a gradual stop.

7.3 All Failure Prevention Strategy

If failure occurs, emergency precautions have been implemented into the software and hardware of the vehicle. Our vehicle is equipped with five emergency-stop buttons. Four are located on the outer sides of the vehicle and one in the center console inside the vehicle. The outer E-Stop buttons were arranged so that someone on the outside of the vehicle would be able to access it without placing themselves in the path of the vehicle. The inner E-Stop button is easily accessible to both the driver and passenger, located between their seats.

7.4 Testing Vehicle Safety Design Concepts

The vehicle was tested in an outside environment similar to the IGVC competition course. 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, was checked in the lab to ensure the cables still had a good connection for both power and data.

Testing started with jacking up the vehicle to test the throttle, steering, and braking control for the drive-by-wire system. Before outdoor testing occurred, the vehicle was thoroughly checked over to ensure all safety features were working. This included the emergency stop buttons, seat belts were used, helmets were worn securely, and the testing site was cleared.

The fail-safe emergency brake system implemented in the original GEM conversion was unreliable and would not always allow an operator to set it. Furthermore, when in the brake off mode (set for fail-safe actuation) a microswitch that was designed to indicate the brake was off and the vehicle was ready for operation would sometimes not be depressed. This motivated the redesign of the e-brake system discussed previously. After implementing the redesigned parking brake, all wiring related to the emergency braking system was tested. Once all wiring was confirmed to be fully functional all e-stops were tested to verify they would disengage the electromagnet causing the parking brake to engage and cutting power from the vehicle motors. After all stationary testable safety features were checked, the vehicle was driven to an isolated area with similar terrain to that expected at competition where the limits of the system were tested. On marked pavement, the vehicle was driven up to competition speed and the e-brake engaged upon crossing predetermined pavement markers. All e-stop buttons were used in the tests and results were consistently within predetermined acceptable margins. The parking brake limits were further tested on measured pavement ramps to determine the maximum slope at which the parking brake could hold the vehicle with two passengers. In a similarly isolated area, after bringing the vehicle to a complete stop on a ramp with a measured slope, the parking brake would be engaged followed by a slow release of the brake pedal to see if the vehicle could maintain parking on the slope with parking brake alone. The angle tested on was gradually increased until failure and then tested several times on similar slopes to that of initial failure.

8.0 Performance Testing to Date

Integration unit tests were performed at each stage of development. The simplest tests involved just the individual sensors. These tests ranged from verifying that a sensor was sending appropriate data, to testing the camera system outdoors. More complex testing was done on the Drive-By-Wire system and autonomous systems.

The first system that was developed and tested was the Drive-By-Wire system. Safety checks occurred at critical points on the vehicle, including the following sub-systems; throttle, steering and braking. Upon lifting the vehicle, remote control throttle testing commenced. We tested the throttleat various levels to confirm that throttle control was precise and reliable, especially at the low (below 5 mph) speeds required in competition. Reverse and Neutral "gear" changing were also tested initially with the vehicle on jack stands. Initial testing of steering control was also performed using the remote control with the car lifted. Once the steering system was determined to be reliably controlled, steering and throttle were tested at the same time. This process was repeated for the braking system. Afterward, we conducted road tests in a controlled environment. These tests included driving the vehicle exclusively by RC with the driver prepared to hit the emergency stop and the service brake at any time.

Figure 31: Obstacle Avoidance Testing

The autonomy tests were by far the most rigorous tests done on this vehicle as the autonomous systems create the greatest safety concerns should any errors occur. All autonomy tests took place in a controlled environment, with only testing personnel in the vicinity. During autonomous testing, two people were always in the vehicle wearing helmets and seatbelts. In addition, the remote control was also with them, and the driver was prepared to hit the service brake to override the autonomous system while the passenger operated the emergency stop system. Autonomy tests were conducted progressively, starting with simple paths with no obstacles and gradually getting more complex. The first tests involved testing only GPS waypoint following. The vehicle was given a single waypoint to head towards, and it was then started in various positions and orientations relative to the waypoint. Once these tests were wholly successful, obstacle avoidance was added. In this case, the vehicle was given a single GPS waypoint to head towards, but this time an orange traffic barrel was placed in its path. Similar to the waypoint following tests, the vehicle was started in various positions and orientations. Other tests were conducted as well, such as guiding the vehicle to navigate between two obstacles on its way to the goal and having to weave between obstacles and hit multiple waypoints along the way. Figure 18 shows an example setup of obstacle avoidance testing, where the vehicle is being encouraged to drive between two orange traffic barrels. The last autonomous system to be tested was the lane-following system. In order to test this, similar tests to the ones described above were conducted. First, the vehicle was given one waypoint and made to reach it by following a set of lanes. Then, the tests grew more complex, including the addition of obstacles, as well as multiple waypoints to hit along the path. In these tests, the vehicle was also started in various orientations, and the lanes were set up in such a way that there was no straight shot to each waypoint.

9.0 Initial Performance Assessment

At the time of this report, RTK-based GPS waypoint following, and obstacle detection and avoidance are functioning, but they are not reliable. Additionally, all hardware and communication systems are functional. A vision module has been developed that can perform lane detection, but this capability has not been fully integrated into the vehicle as part of the RTK. A user can insert waypoints using the Warfighter Machine Interface (WMI) provided by GVSC and the vehicle is able to autonomously plan a path and follow it, avoiding any obstacles that it encounters. As discussed in section 9 above, this capability has been successfully tested. Both the main navigation computer and the drive-by-wire microcontroller can communicate with all appropriate sensors, actuators, and onboard electrical components. The mechanical design is complete, and all sensors have been mounted and are functioning as intended.