BENDER
Team KKQLO

The Citadel, the Military College of South Carolina
Submitted: May 14th, 2019

Faculty Advisor Statement

I, Robert J. Barsanti, Department Head of the Electrical and Computer Engineering at The Citadel, the Military College of South Carolina, certify that the design and development of the autonomous vehicle, Bender, by the individuals named on the design team is significant and equivalent to what might be awarded credit in a senior design course. Design changes from the previous entry are detailed in the enclosed report.

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INTRODUCTION

The KKQLO Senior Design Team built an autonomous vehicle, named Bender, designed to compete in the 27th annual Intelligent Ground Vehicle Competition (IGVC). Bender has been significantly upgraded from the 2018 entry and is designed to autonomously traverse the IGVC Auto-Nav course. This report will detail the design of Bender and focus on the improvements made during the past year.

ORGANIZATION

Team KKQLO consists of seven team members, five who accepted this challenge as their two-semester Senior Design project. Since only one of these five students could be available for travel to the competition, two other students joined the team in a non-credit capacity.

The Senior Design Team

Bill Quade, Jon Kelley, Stephan Kulick, Tsu-Hang Lee, and Nicholas Osmon chose the IGVC as their senior design capstone project. Bill Quade was able to travel to the 2018 competition with the previous year's team. Due to his knowledge of the competition and familiarity with the vehicle, Bill was chosen as the team leader and software developer. The team was then divided into electrical and mechanical teams in accordance with individual strengths. Due to professional and military obligations, Jon Kelley, Stephan Kulick, Tsu-Hang Lee, and Nicholas Osmon are unable to attend the IGVC competition. An estimated 950 individual-hours were spent in the research, design, implementation, documentation, and testing of Bender.

The Competition Team

To facilitate travel and provide continuity for the 2020 competition team, Rutledge Detyens and Nicole Flexner joined the team and along with their faculty advisor, Robert Barsanti will represent The Citadel at the 2019 Intelligent Ground Vehicle Competition.

DESIGN ASSUMPTIONS AND PROCESS

The base assumption for Bender's design was that the 2019 Auto-Nav course would be similar to the 2018 course. Under this assumption, the 2018 entry's performance was evaluated following the competition and great care was taken to document the vehicle's strengths and weaknesses. To overcome each of these weaknesses, the design process in Figure 1 was used.

Once these issues were identified, the team performed research to identify possible causes of failure and associated solutions. Each of these solutions were analyzed with consideration placed on the team's time, money, and abilities, and priority given to issues with the largest impact to the vehicle's overall success. Once a promising solution was selected, a team member was selected to propose a timeline of milestones and update the project's gantt chart. This allowed parallel development and accountability. Due to the accelerated timeline and completely new team, in process testing and simulation were heavily depended upon to ensure continued feasibility the solution and improvements were made as needed by identify the issues and continuing the design process.

The team chose to reuse the majority of the components from the previous year's entry including the base chassis and sensor suite. This allowed the team to spend more resources, both time and money, on addressing known issues.

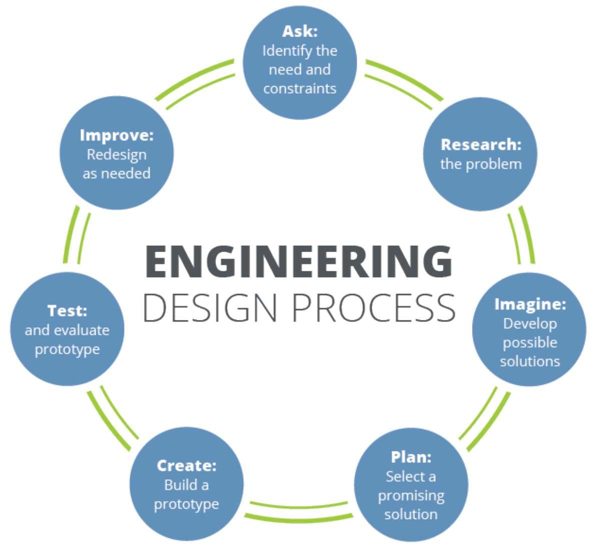

Figure 1. Engineering Design Process

Bender's top-level architecture was devised to use image processing and LiDAR to avoid boundaries and obstacles and GPS for waypoint acquisition. Development of data acquisition methods employing visible light, LiDAR or GPS was assigned to individual team members. The team leader assisted in all areas and had primary responsibility for ROS integration and for simulation activities. As will be detailed, Gazebo was chosen to simulate the vehicular response prior to final implementation.

INNOVATIVE CONCEPTS AND TECHNOLOGY

Team members spent a portion of their research time reading design reports of teams who had previously solved these specific problems. This allowed the team to quickly become familiar with solutions that work well for the IGVC application. A major point of failure of the 2018 entry was the lane recognition software. The 2019 vehicle's vision pipeline was modeled after the basic concepts of multiple teams who had success in previous years.

Other issues were vehicle specific in nature and required innovative thinking and problem solving. While many improvements were made, the following were correction to major points of failure:

Weatherproofing

In the previous year's design presentation, judges were concerned with Bender's exposed electrical components and weatherproofing plan of "a trash bag and duct tape." The safety and reliability of the vehicle was greatly considered in the development of a weatherproofing plan that could not only protect exposed electrical components from the elements, but also protect personnel from the exposed electrical system. IP65 was chosen as the goal for the system when attainable. Some off the shelf components were purchased and accompanied 3D printed containments to protect the equipment. A reduction in components was also required, so the team worked at improving the efficiency and use of space. The design differences can be seen in Figure 2.

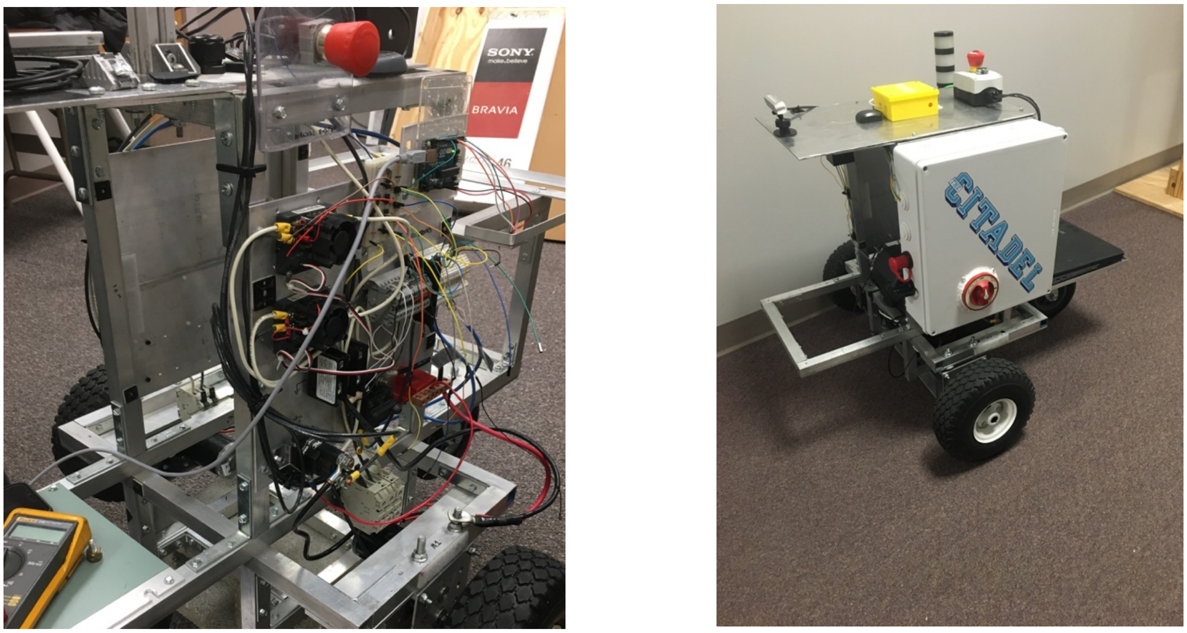

Figure 2. 2018 and 2019 Electrical System Weatherproofing

Control System

Microcontroller

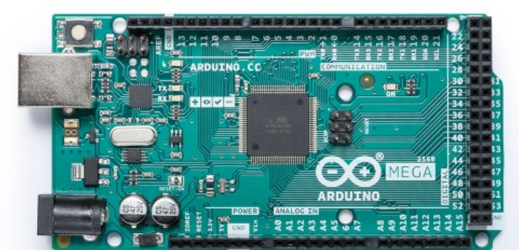

Figure 3. Arduino Mega 2560

The 2018 vehicle had five Arduino Uno microcontrollers, each processing a separate sensor input. This approach not only made weatherproofing more difficult but also presented an issue with the limited number of USB inputs to the vehicle's computer. To alleviate this issue, more robust microcontrollers were researched, and the programs were consolidated to take advantage of the new controller's capabilities. Bender now operates with two microcontrollers: an Arduino Mega for the drive and indication systems and a Teensy 3.5 for the sensor inputs. This dramatically reduces the number of components and allows for a simplified design.

The Arduino Mega 2560 shown in Figure 3 was chosen to replace the Uno boards due to its increased interrupt pin and improved flash memory. The board features 54 digital I/O pins, 15 PWM pins, and 256 KB of memory operating at 16 MHz. This allowed the team to combine programs and replace the three boards that interfaced with the motor controllers, the wheel encoders, and the indicating safety light.

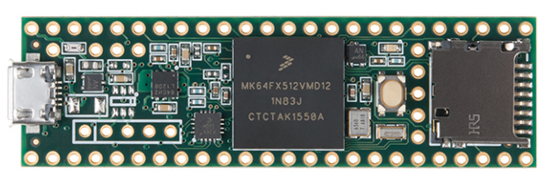

Figure 4. Teensy 3.5

A Teensy 3.5 shown in Figure 4 was picked to replace the interface boards of the GPS and IMU/Compass. This board features a 32-bit 120 MHz ARM processor powering 62 digital I/O pins and 3 I2C ports with a 5V operating voltage. This board was found to be great for handling the speed requirements of the attached sensors and produced a footprint reduction of 85%.

Camera

To implement the new vision pipeline, a new camera was purchased. The previous camera featured a fisheye lens. This allowed for a wider field of vision but required the image to be undistorted. The Intel RealSense D415 stereo-vision camera features two cameras and has a similar field of view without distorting the image. Removing this step reduces the computational requirements of the vision program. The camera also produces a depth image which can be used for obstacle detection similar to a LiDAR.

MECHANICAL DESIGN

Overview

Bender utilizes a lightweight aluminum frame design. Bender is a differential drive wheeled robot, with two mid-chassis drive and steerage wheels sporting rubber studded tires for traction on rolling grass terrain. A rear caster provides stability and a tight turning radius.

Frame and Structure

Bender's open aluminum frame and its appendages complies with all competition rules. Riveted angle-aluminum construction of a symmetrical chassis, shown in Figure 1, proved to be both lightweight and strong. To improve traction and turn radius, the upper frame was widened to house the battery and payload directly over the drive-wheels. A platform within the mid-section of the vehicle is designed to carry the payload. The mid-section of the chassis is taller and hosts not only the drive electronics and drive-train, but also the camera, LiDAR and GPS sensors.

Suspension

Dynamic loading is reduced by velocity limitations and weight containment. Pneumatic tires are sufficient suspension for the otherwise rigid design.

Weatherproofing

The IGVC is a rain-or-shine event, therefore it is vital that Bender's electrical components are protected from rain as well as splashes from wet terrain. To accomplish this, IP65 electrical boxes were installed to house all electrical components of the drive system. Custom housings were 3D printed for sensors and associated microcontrollers with cables passing through water-tight gland seals. The boxes are designed so all seams are designed to prevent entry and all sensors are suspended so in the event water manages to ingress, the sensor will be held above the liquid. The exception to this setup is the camera which requires an unobstructed view of the course but is water-resistant. To protect the camera, a 3D printed open-ended box was fabricated which provides sufficient protection during a rainy environment.

After adding the IP65 sealed boxes, overheating of the electrical components was a concern. To test this, a remote thermometer was placed inside the box during outdoor navigation testing which simulates the Auto-Nav competition. Even in direct sunlight, the difference of temperature between the inside of the box and ambient was negligible.

ELECTRONIC AND POWER DESIGN

Overview

Bender’s electrical system overhaul was centered around providing overcurrent protection via a fuse block and separating and marking different voltage systems to prevent damage to components due to over current or voltage. The utility of improvement is recognized in two occurrences during the previous year. The original design had black wires attached to the positive and negative terminals of the battery, resulting in reverse powering the H-bridge modules which broke them. Also, shortly before the 2018 competition, the 5-volt wheel encoders were inadvertently wired to the 12-volt supply, breaking the encoders. The system overhaul will protect against similar situations in the future.

Power distribution

Bender’s power source is a single 12V DC deep cycle marine/RV battery. This battery is connected to a terminal block and powers each load through individual ATC/ATO fuses selected with ratings above typical operating currents but well below damaging currents. These loads include the two motors, via motor drivers, and the indicator light. All sensors and microcontrollers are powered by the laptop computer’s USB ports.

Motive Power

Two VIX FR801-001 motors, produced by CCL Industrial Motor Limited produce a nominal 64 Oz-In of torque at 27 A of current. These motors provide maximum power at 2655 rpm[1], and drive individual 12.76 to 1 gearboxes which reduce axle speed and enhance torque. This approach allowed moderately priced motors to deliver the torque, speed, energy consumption and ground clearance needed for this competition.

Electronics Suite

CPU. An ASUS Republic of Gamers (ROG) with Intel 3rd generation Core™ i7 processors and an NVIDIA GeForce ® GTX 670M Graphics Processing Unit (GPU) is Bender’s CPU. This computer’s performance and configuration is ideal for our vehicle. Four USB3.0 ports power and communicate with collateral components, eliminating the need for a 5VDC source. The ASUS ROG includes optimized thermal management, allowing it to remain at peak performance over a wide environmental range. A small power inverter has been added to constantly charge the laptop from the 12VDC battery, rendering laptop-only recharge unnecessary. Strategic partition of software across the of the laptop’s rotating hard disk and internal solid state drive dramatically impacts processing performance of selected systems.

Motor Controller. An Arduino Mega microcontroller receives an individual motor velocities from the laptop and produces a Pulse Width Modulation (PWM) signal to drive the vehicles two motors via Victor 884 motor controllers shown in Figure 5. The controllers recognize duty cycles between 1% and 60% as reverse rotation while duty cycles between 64% and 100% impart forward rotation. Any duty cycle between 60% and 64% translates to no movement, or neutral.

Figure 5. Victor 884 Motor Controller

Sensor Hardware

Bender's autonomy relies on an integrated set of sensors to allow for navigation. The vehicle must detect multiple obstacles and move accordingly to reach the destination. These sensors are a camera, a LiDAR, a GPS receiver, wheel encoders, and an IMU/compass, and are all powered via the computer's USB.

Vision. The Intel RealSense D415 camera shown in Figure 6 is a stereo imaging camera developed for robotics applications and features a wide field of view, 1280x720 resolution, and up to 60 frames per second over high speed USB 3.0. The camera uses RBG cameras and infrared to generate information about the color and depth of an image. This is translated to a ROS PointCloud2 message containing RGB-d (RGB with depth). This image is then processed to detect the lines.

Figure 6. Intel RealSense Camera

LiDAR. The 2-D planar sensor shown in Figure 7 is accurate to ±3% for distances beyond 1m and scans 240° to 5.6 meters. The sensor consumes a small amount of power and is lightweight, making it ideal for a mobile vehicle. Unfortunately, the Hokuyo URG-04LX-UG01 is designed for indoor use and can be saturated by outdoor lighting. Bender utilizes filtering and strategic shading to minimize the interfering solar noise[2] in order to allow use of this lower cost LiDAR component.

Figure 7. Hokuyo LiDAR

IMU/Compass. The SparkFun Nine Degree of Freedom (DoF) Inertial Measurement Unit (IMU) shown in Figure 8 uses a SAMD21 microprocessor in conjunction with a nine DoF sensor to provide 3-axis accelerometer, gyroscope, and magnometer information [5]. The accelerometer measures the vehicle's actual motion in the x, y, and z direction, while the magnometer provides a digital compass to read the vehicles heading without dependence on relative data. The IMU connects to the Teensy 3.5 via I2C.

Figure 8. SparkFun 9DoF IMU

GPS. The SparkFun GPS-RTK NEO-M8P-2 GPS unit shown in Figure 9 outputs NMEA strings via a Qwiic I2C connector to the Teensy microcontroller at a 4Hz rate. The horizontal accuracy is 2.5 meters and has a col Time to First Fix (TFF) of 29 seconds. The NMEA string is interpreted by ROS to generate a positional fix. This information is then used in the path planning algorithms.

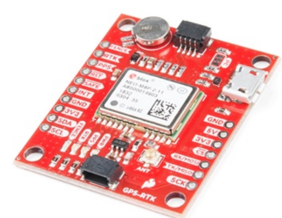

Figure 9. SparkFun GPS Receiver

Wheel Encoders. Each wheel is equipped with a US Digital E4T Miniature Optical Encoder with 100 count per rotation resolution shown in Figure 10. These 5V encoders provide an independent measure of the actual wheel rotation, which is read by the Arduino Mega microcontroller to provide feedback for the PID control calculations. This allows Bender to operate in a smooth, more controlled manner.

Figure 10. US Digital Encoders

Safety Devices

Bender is equipped with manual and wireless emergency stop (E-stop) systems. A manual E-stop switch is in series between the battery's positive terminal and the motor/motor controllers, and immediately interrupts all motive power when engaged. Though Bender can be stopped using the wireless Xbox 360 controller to send a neutral PWM signal, a 12V 10A Relay with RF Remote Control is integrated to disrupt power as the software-independent remote shutdown required by IGVC rules.

To alert those in the vicinity of the vehicle, a Banner TL50 indicator light is attached. The light's status is controlled by the Arduino Mega microcontroller and a bespoke control circuit. The microcontroller and circuit are designed so that when the vehicle is powered and under manual control, the green light is on and solid. When the vehicle is placed in autonomous mode, the green light begins to flash. In the event of an emergency stop, the light will shine red to show the stop demand was acknowledged.

SOFTWARE AND MAPPING

Overview

The Robot Operating System (ROS) is used to connect all sensors through an open source library database with hardware drivers and algorithms.

Robot Operating System (ROS). ROS totally controls the vehicle. This middleware from the Open Source Robotics Foundation, first developed at Stanford University in 2007, contains many useful tools and libraries to simplify the robotics development process. Being open source, ROS encourages collaboration between users through various forums and wiki pages. ROS provides tools developed by expert laboratories to address the complex tasks such as mapping environments and navigating autonomously.

Bender relies heavily on the partitioned nature of ROS. The vehicle operates on a series of nodes communicating with each other through a publishing and subscribing protocol. This is contrary to most other development environments where all code is interconnected regardless of intent. For a node to communicate with another within ROS the user must initiate a publisher command in the publishing node and a subscriber command in the subscribing node. This generates a ROS topic holding the published information. These topics are like C++ structures in their architecture since they contain both header information and pertinent data. The ROS graphical interface allows the user to know exactly what topics are within what nodes. The node architecture also allows the reuse of variable names without conflict.

The node architecture also allows C++ and Python code to be used together. Since each node is independent of another, one node can be written in C++ while the other is written in Python. This was useful as it allowed team members to choose the language they were most familiar with and allowed for parallel development and implementation. The passing of topics through publishing and subscribing is handled through ROS specific protocols and therefore is not affected by a specific node's language.

Lane Following

The lane detection was a point of failure in the 2018 entry. After much research of both design reports and university and industry research of automotive lane detection and following strategies, a totally new approach was taken. This strategy is to turn the lane lines into a wall which the path planning and mapping software treat like any other obstacle. To do this, a video feed from the RealSense camera is taken and passed through a series of filters designed to standardize the image and reduce computation requirements, which is a major concern of machine vision. The final image results in the lines and potholes white and all other portions black. A Gaussian filter then determines which pixels are part of lines and potholes. An Inverse Perspective Matrix (IPM) is used to transform the camera image to an overhead view. This black and white overhead image is then converted to a point cloud by computing the distance and angle from the camera and is sent as a ROS PointCloud2 message to the mapping and planning software. The design approach shown in Figure 11 was designed for speed and reduced computation requirements.

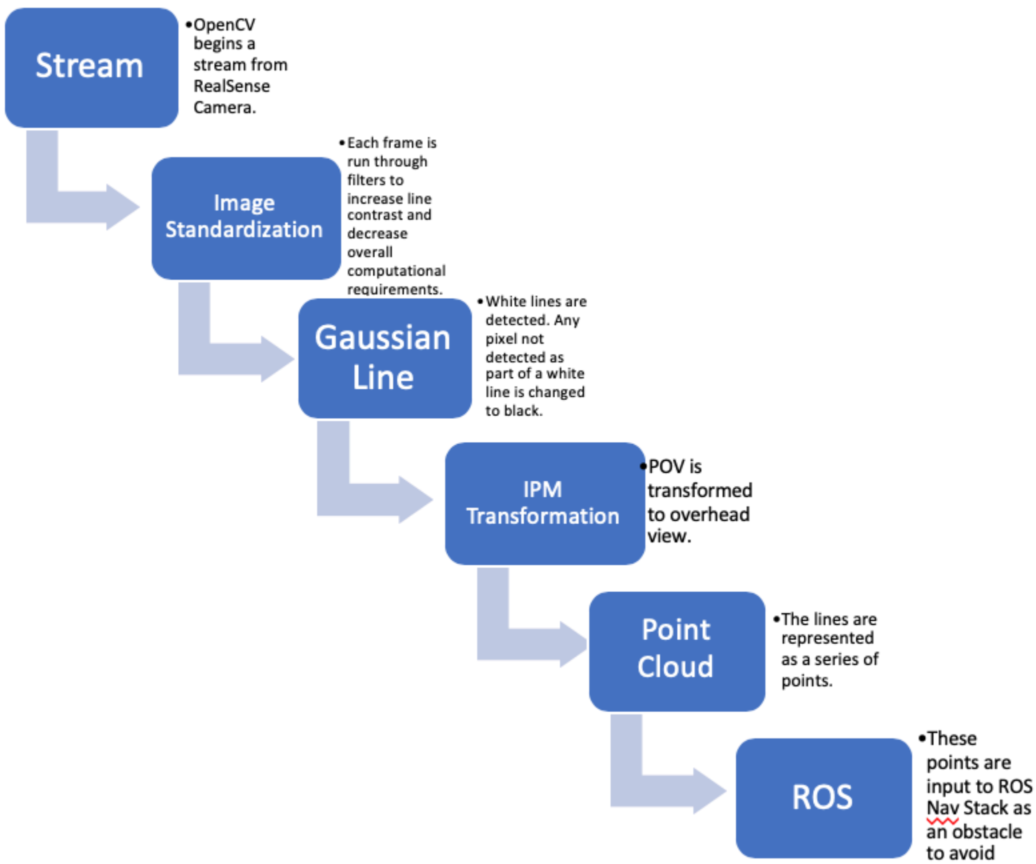

Figure 11. Vision Pipeline

Obstacle Avoidance

Bender detects obstacles using a Hokuyo 2-D planar LiDAR, optimized for semi-predictable objects such as traffic cones of varying color, but also capable of detecting bushes, trees and man-made obstacles. The LiDAR detects objects within a 180º field of view. The angle and distance of the object are then filtered to remove noise and erroneous readings and then a local costmap is created to distinguish obstacles and free space for the path planning program.

Software Strategy and Path Planning

Bender utilizes a program based on the ROS Navigation Stack's "move_base" program. The customization of the program deals with the specific parameters and gives the vehicle the ability to build the map while it traverses the area, vice relying upon a known map of the area. This is an improved and more robust system than the prior path planning program and has shown well in testing.

Map Generation

The Simultaneous Localization and Mapping (SLAM) approach was implemented on the 2019 vehicle. This approach works well with the path planning program which is designed for this operation. Two maps are produced: A global map which starts as 100x100 meters, and a local map which is fixed at 6x6 meters. The global and local maps are layered so the vehicle is simultaneously aware of its location on each. The local map stays centered on the vehicle and includes all obstacles and lines currently seen by the sensors. The global map is in a fixed location dependent on the vehicle's initial location and has the ability to expand as needed. This map contains the goal as well as all of the obstacles and lines previously seen by the sensors. By layering the two maps, the path planner is able to find the most direct path to the goal location and track all obstacles and lines.

GOAL SELECTION AND PATH GENERATION

Each goal position is fed to the path panning program by a state machine program that waits until a goal is achieved before sending the next goal. This is in contrast to previous goal selection programs which sent all goals to the planner simultaneously. This had the ability to cause problems if one of the goals was off of the initial global map as the initial map.

Upon receiving a new goal, the path planner places the goal on the global map and a global path is produced. This global path may pass through unknown areas or unknown obstacles. The path planner then looks at the local map and produces a path that will allow the vehicle to move out of the current local map while attempting to stay close to the global path and avoiding obstacles and lines. As the vehicle moves a short distance, the local map is moved to re-center around the vehicle and the process repeats.

FAILURE MODES, POINTS AND RESOLUTIONS

The points of concern for failure exist mostly in the software, specifically the localization. A covariance matrix is utilized within the Extended Kalman Filter (EKF) which is designed to correct for slight variations and noise inherent in low-cost electronic sensors. This matrix employs values of "trust" for each sensor's reading. It has been noted by external sources that the fluctuation of the GPS receiver will most likely differ in different locations on the globe and with differing weather conditions. This means that the EKF will likely have to be recalibrated upon arrival at the Oakland University campus. Failure to set these values properly will result in a vehicle that is incapable of determining precise GPS locations and may not be able to arrive at the ramp entrance.

Another point of concern found in testing is differing light conditions and their effect on lane line and pothole detection. Shadows of the vehicle and obstacles can fool the vision pipeline into seeing a break in the line of a disappearing pothole. This was partially accounted for by increasing the amount of delay time a visual obstacle is considered after it has disappeared from the camera's view. The vision filter was also redesigned to allow for a parameter input for the values of intensity to consider "white," allowing a quick edit once Bender is ready and on the competition field.

Testing

The vast majority of testing has been via Gazebo simulation, as explained in the following section of this report. During the final weeks, outdoor testing became a priority and small course to simulate the Auto-Nav course was used to test the ability of Bender to qualify. During this testing, the need for a filter for the LiDAR signal was discovered. As the specific model of LiDAR purchased by the 2016 Citadel IGVC team is an indoor LiDAR, it would often times see "ghost" obstacles in brightly light outdoor areas. A range filter was used to replace the erroneous readings with a distance that was further than the range of the mapping filter, therefore they were ignored.

Safety Design Concepts

Safety designs were added to this year's vehicle in the form of weatherproofing and over current/voltage protection. By placing electrical components inside weatherproof boxes, the components were no longer exposed to personnel who previously had access to 12V DC bus bars and ground bus bars. The over current/voltage protection was added to developed to protect the equipment, but a failure of the equipment could cause unintended operation of the robot resulting in harm to personnel.

Additionally, the payload is secured with a lashing strap in the center of the vehicle whereas it was previously held to the front with a bungee cord. This is intended to prevent a loss of payload which could not only damage the vehicle but could result in harm to personnel.

SIMULATION

Gazebo

Gazebo, an Open Source Robotics Foundation simulation product with ROS interface was utilized to simulate Bender's design and interactions with the virtual competition courses. Gazebo, first developed in 2002 at The University of Southern California for simulating robots in outdoor environments, employs the Open Dynamics Engine, a high-performance library for simulating rigid body dynamics. It interfaces with ROS in the same manner as physical hardware. The use of Gazebo allowed rapid implementation of navigation algorithms without the need for physical hardware. This radically compressed development time and ultimately, made competition in the 2019 IGVC possible.

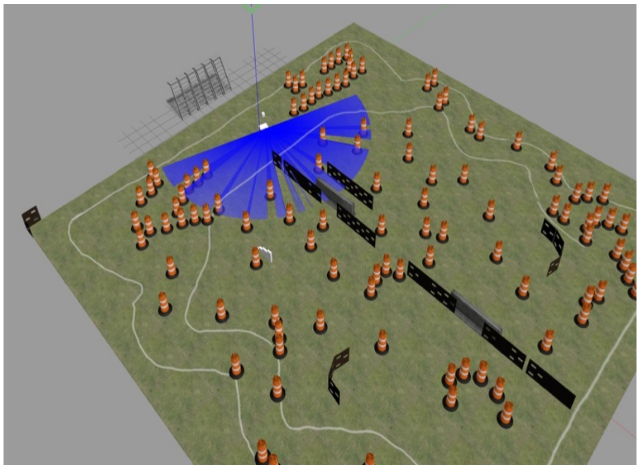

Figure 12. Gazebo Model of Bender on Outdoor Course

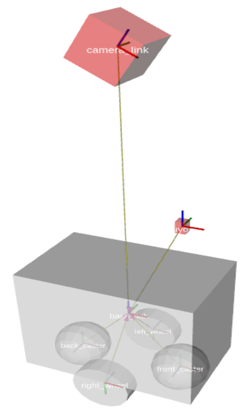

Figure 13. Simulated Model of Bender

Figure 12 shows Bender in the simulated environment. Figure 13 is of Bender within the simulation. The robot model is implemented in the Unified Robot Description Format (UDRF). The barrel cones and white lines are similar to those expected in actual competition. This is extremely useful as construction of a scale practice course is not possible at The Citadel. "Gazebo Bender" can navigate any course from any computer, allowing algorithms to be rapidly tuned. This testing method was developed by the 2018 and was utilized for testing by the 2019 team as well.

Theoretical Concepts in Simulation

Most importantly, the simulation translates to real hardware. Except for timing parameter, the algorithms used in ROS are unaware that a simulation is occurring. LiDAR is simulated to exactly match the Hokuyo model. The camera models the RealSense camera in resolution, focal length, mounting point, and orientation. This allows direct interchange of ROS code between simulation and physical hardware.

PERFORMANCE TESTING TO DATE

Barring simulation, at the time of this report, Bender has limited testing in fully autonomous mode. Individual portions of the system have been tested for robustness and key deficiencies have been noted and are being handled with the same engineering design process shown in Figure 1. During initial research of sensors and parts, the safety and accuracy requirements were considered heavily. All parts were predicted to pass. The following table shows the testing a calculation determined to be vital to completing the on the real IGVC Auto-Nav course:

Test	Method	Requirement	Results
Max Speed	GPS program with max velocity command	<5 MPH	2.7 MPH
Wireless E-Stop Distance	Test and measure	> 100 feet	>250 feet
Incline	Aluminum boat ramp	15% (8.53º)	>20% (11.31º)
Battery Power	Current test calculation	> 6 Minutes	2-3 Hours
Reaction Time	Obstacle placement	N/A	Immediate
Obstacle Detection	Test and measure	N/A	5 meters
GPS Accuracy	Test and measure	N/A	~1 meter (2.5 meters per datasheet)

VEHICLE COST

As detailed earlier, some key components from prior IGVC vehicles were reused on Bender to defray costs. The following Bill of Materials documents the complete material costs.

Description	Qty	Part Number	Supplier	Unit Price	Extended Price
Robot Chassis	1	001	Citadel	$250.00	$250.00
LIDAR	1	URG-04LX-UG01	Hokuyo	$1,040.00	$1,040.00
Camera	1	RealSense D415	Intel	$149.00	$149.00
GPS	1	GPS-RTK NEO-M8P-2	SparkFun	$195.95	$195.95
GPS Antenna	1	Venus816	SkyTraq	$12.95	$12.95
Battery	1	HP24DC	Duracell	$86.99	$86.99
Arduino Microcontroller	1	Mega	Arduino	$22.00	$22.00
Teensy 3.5 Microcontroler	1	TENSY35	PJRC	$24.25	$24.25
Laptop	1	ROG GL5 Series	ASUS	$1,500.00	$1,500.00
Laptop Power Supply	1	A32NI405	EBK	$299.00	$299.00
RGB Light Sensor	1	ISL29125	SparkFun	$8.00	$8.00
Inertial Measurement Unit	1	9DoF Razor IMU	SparkFun	$35.95	$35.95
Encoder	2	E4T-250-100-D-S-D	US Digital	$24.81	$49.62
Molex Connectors	2	CA-MIC6-SH-NC-1	US Digital	$35.50	$71.00
Wireless Controller	1	Xbox 360-JR9-00011	Microsoft	$45.61	$45.61
Controller Receiver	1	Xbox 360-882224248495	Microsoft	$5.99	$5.99
Motor	4	FR801-001	CIM Robotics	$27.99	$111.96
Motor Controller	2	Victor 884	Vex Pro	69.99	$139.98
Wheels	2	490-325-0012	Lowes	$39.98	$79.96
Wheels (Caster)	2	GACK04KDSX	Lowes	$49.98	$99.96
				TOTAL	**$4228.17**

INITIAL PERFORMANCE ASSESSMENT

Bender's initial performance has been promising but not fully satisfactory on the simulated course. Fine tuning of the software parameters will continue through the beginning of the IGVC and forward. The team is optimistic that with continued testing and the use of the engineering design process, Bender will overcome these hurdles.

REFERENCES

[1] VEX Robotics. (2019). CIM Motor. [online] Available at: https://www.vexrobotics.com/217-2000.html [Accessed 9 Apr. 2019].

[2] Hokuyo-aut.jp. (2019). Scanning Rangefinder Distance Data Output/URG-04LX-UG01 Product Details | HOKUYO AUTOMATIC CO., LTD.. [online] Available at: https://www.hokuyo-aut.jp/search/single.php?serial=166 [Accessed 10 Apr. 2019].

[3] En.wikipedia.org. (2019). Lidar. [online] Available at: https://en.wikipedia.org/wiki/Lidar [Accessed 11 Apr. 2019].

[4] US Digital®. (2019). E4T Miniature Optical Kit Encoder. [online] Available at:

https://www.usdigital.com/products/e4t [Accessed 7 Apr. 2019].

[5] M0, S. (2019). SparkFun 9DoF Razor IMU M0 - SEN-14001 - SparkFun Electronics. [online] Sparkfun.com. Available at: https://www.sparkfun.com/products/14001 [Accessed 8 Apr. 2019].