EMBRY-RIDDLE AERONAUTICAL UNIVERSITY – PRESCOTT, AZ

Design Report

May 15, 2018

Search and Rescue Ground Explorer

S.A.R.G.E.

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INTRODUCTION

Search and Rescue Ground Explorer, S.A.R.G.E., is an autonomous ground vehicle designed for two purposes. The first purpose is to assist in wilderness search and rescue missions and the second is to participate in the IGVC. S.A.R.G.E. was designed and built by a team of undergraduate students for their senior design course. The vehicle *was built from scratch* and was funded by the Undergraduate Research Institute (URI) and the College of Engineering at Embry-Riddle Aeronautical University – Prescott, AZ.

ORGANIZATION

The team is composed of eight students, primarily mechanical engineering majors, divided into three subsystems: a mechanical subsystem, an electrical subsystem, and a software subsystem. The

Table 1: S.A.R.G.E. Team Members

Team Members	Major	Area(s) of Concentration	Hours
Jacqueline Worley (PM)	Mechanical Engineering	Documents	456
Morgan Garone	Mechanical Engineering	Mechanical/Documents	482
Sara El Baissi	Mechanical Engineering	Electrical/Documents	419
Garrison Bybee	Software Engineering	Software	456
Grayson Lynch	Mechanical Engineering	Mechanical	514
Chad Abramson Jr.	Mechanical Engineering	Mechanical	410
Riley Griffin	Mechanical/Electrical Engineering	Electrical/Software	421
Mathew Todd	Computer Engineering	Electrical/Software	413

DESIGN PROCESS

As a senior design project, team S.A.R.G.E. worked on this project for two semesters. To stay organized, the team divided itself into three subsystems: mechanical, electrical, and software subsystem. During the first semester, the team focused on the preliminary design. Requirements and specifications were set to allow a smooth transition from the design process to the building process.

The team identified the two main goals concerning the vehicle: be able to participate in the IGVC and be able to assist in wilderness search and rescue missions. After identifying the objectives that must be addressed, the team brainstormed different design options and used a decision matrix to evaluate the most effective design solutions. During the building process, some adjustments have been made to the specifications to improve S.A.R.G.E.

INNOVATIVE CONCEPTS

S.A.R.G.E. is the first generation of Unmanned Ground Vehicles (UGV) at Embry-Riddle Aeronautical University – Prescott, AZ, that will compete in the IGVC. S.A.R.G.E. does not use a laptop as a processor. Instead, S.A.R.G.E. is equipped with a pocket-sized mini-computer: the Libre Computer Board ROC-RK3328-CC (Renegade).

COST OF S.A.R.G.E.

Table 2: Cost Table

Item	Unit Cost ($)	Qty	Cost + Shipping ($)
Brushless DC Motors	48.79	4	199.06
Speed Controllers	166.01	4	664.03
Aluminum	184.19		233.25
Ultrasonic Sensor	3.95	12	56.99
Renegade	55.00	1	55.00
TI Launchpad	9.99	1	12.00
Arduino MEGA	13.22	1	14.72
Steel	170.4		406.77
Wheels	52.66	4	227.28
Tires	47.56	4	198.56
Linear Actuator	139.99	1	172.30
Springs	45.00	4	180.00
Bike Shocks	75.00	4	300.00
100:1 Gear Boxes	150.00	4	600.00
Kinect V2	83.99	1	83.99
Step Down Power Module	9.58	1	13.50
Misc.	300.00	1	300.00
		TOTAL	**3,717.45**

MECHANICAL SUBSYSTEM

Overview

The vehicle's primary purpose is to aid in search and rescue missions in wilderness off-road terrain. The resulting design is a powerful 4-wheel drive vehicle much larger and heavier than most purpose built IGVC robots. While the vehicle has been constructed within the constraints of IGVC rules, the primary off-road purpose drove a physically massive design in order to provide a stable base on precarious terrain and carry a sizeable payload.

Structure

The chassis is constructed from aluminum 25.4 mm square tubing with a 3.2 mm wall thickness. This material was chosen because it is strong, easy to fabricate, and a convenient shape for mounting components. The shape of the structure is designed to allow adequate mounting locations for the entire electronics suite, the large custom battery, and the competition-required cinder block.

Suspension

Due to the dual-purpose nature of the vehicle, the suspension is designed to function on wilderness terrain. The design concept is inspired by double triangulated 4-link solid axle suspension typically utilized by rock crawling Jeeps and trucks. The configuration of the suspension links allows the axle beams to withstand high lateral and axial loading while permitting articulation of the wheels over rough terrain. The suspension setup on the front axle beam can be seen in Figure 1 and Figure 2 below. The suspension on the rear axle is similar to the front with the only differences being the rear suspension links are 12.5mm longer than the front links.

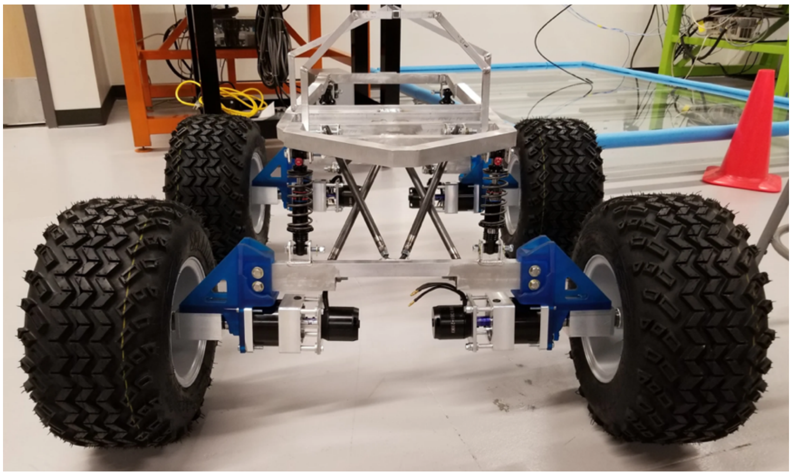

Figure 1: Suspension Front View

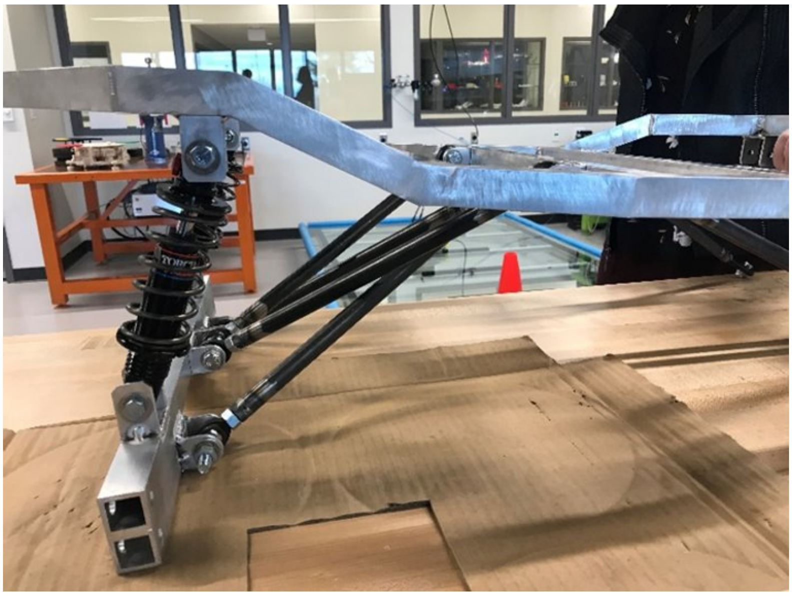

Figure 2: Suspension Side View

The shocks at each corner are common rear mountain bike shocks with adjustable rebound and spring preload and a 35 mm travel distance. The shocks came with 131.5 N/mm springs preinstalled which were determined to be too stiff for our application. We ran a MATLAB simulation of our vehicle travelling at the maximum allowable speed 5 mph over a small sinusoidal bump and were able to determine that a spring rate of 7.36 N/mm would be more appropriate given the vehicle's characteristics, namely weight and shock travel. Springs with the proper rate and dimensions were sourced and swapped onto the bicycle shocks. The suspension links and shocks connect the chassis to the front and rear axle beams which then articulate similarly to a standard automotive solid axle.

Drivetrain

Each of the four wheels is independently driven by their own motor assemblies. A motor assembly consists of a brushless DC motor driving a 100:1 planetary gearbox selected to mechanically limit the vehicle below 5 mph at maximum motor speed. The gearbox drives a shaft through a bearing housing which then drives the off-road golf cart wheels. The entire motor assembly is held to the ends of the axle beams by a 3D printed plastic motor bracket made on a liquid resin stereolithography (SLA) printer. In order to verify that these printed motor brackets would hold the weight of the robot while under power, a series of finite element analyses were performed on ANSYS, and the design was refined until the brackets attained a safety factor of 2. A 3D printed blue motor bracket can be seen below in Figure 3 connected to a motor, gearbox, and an axle shaft.

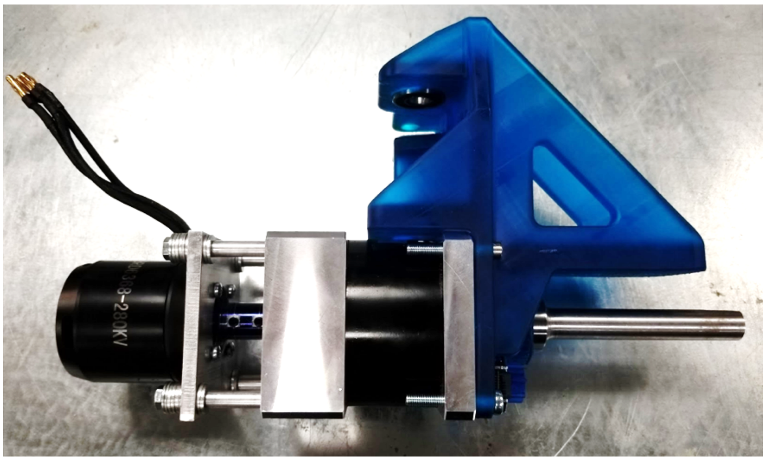

Figure 3: Drivetrain Assembly

The steering system is located on the rear axle and is controlled by a linear actuator. Because the vehicle is fairly large, a rear steering system was chosen for easier maneuverability around tight turns. To aid in precise steering, the motors are independently controlled by a 4-wheel software differential that directly correlates wheel speeds to the position of the steering actuator and the speed of the vehicle. Control of the software differential comes from a mathematically derived inverse differential kinematics model of the vehicle. The maximum steering angle on the rear axle can be seen below in Figure 4.

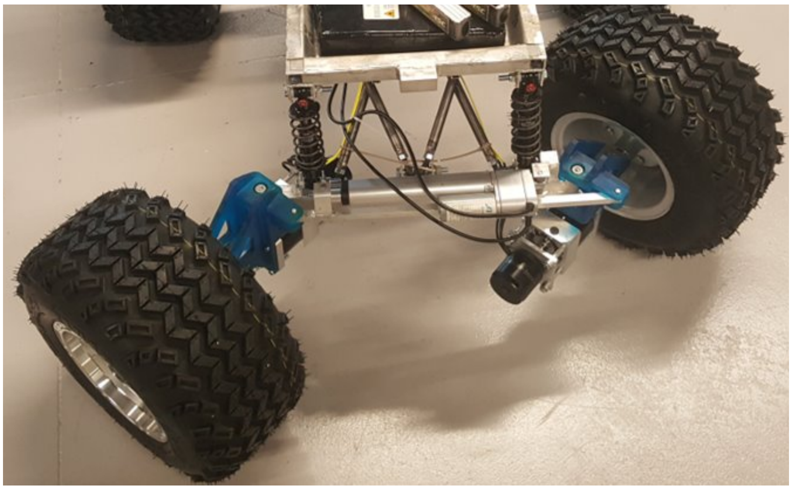

Figure 4: Fully Actuated Steering Assembly

Weatherproofing

The exterior shell is made of marine grade HDPE plastic sheets. The panels are sealed with epoxy and weather stripping foam, and all electronics are housed under this plastic shell. The complete plastic shell can be seen mounted on the robot in Figure 5 below. The white plastic panels on the side are access panels which open vertically as gullwing-style doors. Although the electric motors are exposed to the elements, the brushless DC motors are inherently waterproof and can operate submerged in water.

Figure 5: S.A.R.G.E with Body Panels

ELECTRICAL SUBSYSTEM

Overview

The electrical subsystem of S.A.R.G.E. features the latest technology to perform cutting edge search and rescue operations and navigation consisting of a Renegade mini-computer, an Arduino MEGA, a TI Launchpad, a linear actuator, four Racerstar 6368 motors, four FOCBOX electronic speed controllers (ESCs), a GPS, an inertia measurement unit (IMU), and ultrasonic sensors. The vehicle uses two different batteries to power all the components.

Power Distribution System

S.A.R.G.E. is equipped with two batteries. The main battery is an 8S7P battery and the secondary battery is a lithium-ion battery. The main battery has eight cells in series, providing 29.6 volts (V) nominal, and ranges from 25.6V minimum and 33.6 V maximum, and seven packs of eight cells in parallel, providing an increase in capacity and maximum current draw capabilities. With this 8S7P we have a capacity of 24.15 amp hours (Ah) at a coulomb rating of 10C. This battery can provide a maximum current of 241.5 amps, assuming no losses or terminal resistance. The total energy storage of the battery is 714.84 Kilojoules (kJ) at a nominal rating of 24.15 Ah and 29.6V. The lithium-ion battery, consisting of 56 cells, the 18650 cell, with a capacity of 3450 milliamp hours. Each cell provides a nominal 3.7V, and ranges from 3.2V minimum and 4.2V maximum.

The 8S7P battery provides power to the electrical speed controllers (ESC), which will then transmit power to the motors, and the linear actuator through a 12V voltage regulator. The lithium-ion battery provides power to all other electrical components, such as sensors, micro

One cable off the battery goes to power the motors, the other cable goes to the power regulators in order to power all the lower voltage electronics, such as the processors and sensors.

Regulators are populated together on a single circuit board with 30A, 15A, and 10A fuses contained in a fuse box for easy replacement if blown. Regulators step the battery voltage down to the desired 12VDC and 5VDC levels to operate the electronics suite. Relays switch on and off the optional auxiliary electronics as commanded by the main computer or user for power saving features.

The main battery can be charged simply by disconnecting it to the ESCs. The recharging cables are easily reachable. However, the main battery takes longer than normal batteries to charge.

Table 3: Electrical Components

Components	Operating Voltage	Source
ESC	28.8VDC	Main battery unregulated
GPS	5VDC	Aux Battery via 5VDC Regulator
Kinect v2	12VDC	Aux Battery via 12VDC Regulator
Ultrasonic sensors	5VDC	Aux Battery via 5VDC Regulator
Arduino MEGA	12VDC	Aux Battery via 12VDC Regulator
TI Launchpad	5VDC	Aux Battery via 5VDC Regulator
Renegade	5VDC	Aux Battery via 5VDC Regulator

Electronics Suite

The main computer running the electronics is the Libre Computer Board ROC-RK3328-CC (Renegade). It has the Tinkerboard form factor, meaning it is a pocket-sized single circuit board mini-computer visually identical to the Raspberry Pi 3 Model B. The Renegade features USB3.0, 4K-HDR, and DDR4 RAM support, all of which are not featured on the Raspberry Pi but required for processing the workload produced by the Microsoft Kinect v2. The Renegade communicates to the Microsoft Kinect v2, Arduino MEGA 2560 and TI Launchpad CC3200 through serial communication lines.[1]

The Microsoft Kinect v2 features an infrared camera, a 1280x1024 resolution optical camera, and a LIDAR with 2048 levels of depth at 512x424 resolution. It outperforms its predecessor the Kinect v1, which has abundant online support in robotics. The Kinect was desired for its preconfigured hardware and software support. It also allows for newly released libraries from the large online Kinect development community to be ported so S.A.R.G.E. can be easily updated with the latest firmware and image processing techniques as outlined below in the software.

The Arduino operates the actuators for steering and traversing, along with collecting collision and compass sensor data. Collision detection comes from two Pololu HC-SR04 ultrasonic sensors on the face of the robot, and two more ultrasonic sensors directly below pointing downward. The ultrasonic sensors have a detection range of 2 cm to 400 cm. Compass data comes from the IMU included in the Kinect v2 and an additional IMU attached to the Arduino. The Arduino follows a desired bearing which is sent from the Launchpad as outlined below in the software.

The Launchpad functions as a serial communication bridge between the Renegade and the Arduino. It repeats most of the communication in both directions, but it is also able to filter out or interject any commands passed through Wi-Fi. The Launchpad is also responsible for collecting large amounts of data coming in from the GPS module, processing it into coordinates, and computing a desired bearing from its list of GPS waypoints. The bearing is then sent at a much lower rate to declutter the communication lines as much as possible. The Launchpad also processes communication to and from the user interface for the inoperability profile challenge as outlined below in the software.

Four ultrasonic proximity sensors are used for collision avoidance and cliff detection. Ultrasonic sensor data is collected directly from the Arduino interrupt pins to minimize loop execution time and response time for safety. An inertia measurement unit (IMU) provides compass data used for navigation. The IMU is calibrated for its location within the chassis. Roll, pitch, and yaw corrections are applied during image processing to account for the Kinect moving independently of the IMU.

Safety Devices

S.A.R.G.E. has two E-stops for emergencies: a mechanical E-stop and a wireless E-stop. The mechanical E-stop is implemented through hardware. It is a red push button placed in the back of the vehicle and is connected to the relay. When the mechanical E-stop is enabled, it cuts off the relay to the motors. The wireless E-stop, made from a modified wireless doorbell, is also connected to the relay. The relay will sense a voltage drop, then cut off power to the actuators as they are configured actively-high or known commonly as a dead-man's switch style configuration. To protect the linear actuator, power goes through a fuse bus. The vehicle has an 8S7P battery management system (BMS), monitoring the voltage of each cell of the main battery. It also features short circuit, over current, over voltage, and under voltage protection. Along with the BMS, there are several different fuses in place throughout the robot to ensure neither the battery nor electrical components will be damaged in case the BMS fails. The fuses are contained in central fuse box for easy testing or replacement of blown fuses.

SOFTWARE SUBSYSTEM

Overview

The software of the system is composed of firmware on the Arduino and the TI Launchpad and a software suite on the Renegade consisting of the Ubuntu 16.04 Firefly Linux Operating System, a Robotics Operating System (ROS) with supported libraries, a freenect2 library for the Kinect v2, and OpenCV3 for image processing. The firmware on the Arduino is responsible for proximity sensor data collection using interrupt driven code, as well as the motor pulse width modulation (PMW) control and GPS location input. The TI Launchpad's main purpose is to control the vehicle using WIFI and an XBEE communications module for Bluetooth.

Inverse Differential Kinematics

The inverse differential kinematic equations are applied in the Arduino firmware to the locomotion code to compute software differential speed ratios on each ESC. The software function applied to achieve differential steering has the current steering angle and speed as inputs, and then outputs the PWM values for each ESC needed to turn the wheels at the calculated ratios for the current steering angle applied. Each speed is adjusted through the inverse kinematics for independent wheel velocity. The range of the PWM for the ESCs ranges between 0 and 180. A value below 90 is reverse and over a value above 90 is forward. In order to not saturate the motors at full speed, the speed is limited to an input of 130 for forward or 50 for reverse during a turn. The speed is then mapped into a PWM for each motor, and then passed through the motor control algorithm to slowly increase or decrease each wheels' speed to prevent sudden velocity changes and minimize high amounts of stress in the motor brackets.

Map generation and goal selection

Map generation at the moment is implemented by plotting post processed data and waypoints to Google Earth. However, current development of the next mapping software has map generation processed live on the Renegade as the robot traverses or rotates using 2D Gmapping techniques through use of the ROS environment libraries.

The primary method of localization and navigation is through GPS waypointing and Gmapping. Given a desired GPS waypoint from a list of preconfigured waypoints, the robot adjusts its current bearing to match a desired bearing. The use of Gmapping reveals from painted lines if the robot is stuck in a dead-end location and if it should therefore look for an exit.

Software strategy and path planning

Given that the robot needs to start in the opposite direction as the waypoint, it will need to prioritize avoiding lines rather than heading directly to the desired waypoint. To accomplish this, the robot starts the course run off by doing a 360 degree turn to perform an initial scan of its environment. A Houghline transformation is applied to map out painted boundary lines. Results are mapped using the Gmapping technique configured in ROS. If navigating a maze of white lines, A* or similar path planning algorithms available with ROS will be applied but aren't desired if not performing a competition course run. The path planning algorithm has then obtained a starting direction and the integration of object avoidance sensing in ROS will assist.

Obstacle detection and avoidance

Image processing is done by the Renegade on the data stream being received from the Kinect v2. An open-source library, libfreenect2[2] is used for capturing raw data from the infrared camera, optical camera, and LIDAR on the Kinect v2. The data is transformed with OpenCV3 for line detection, and additional gaming libraries are used for human detection. When an object is identified, it is classified into what type of object it is. If the object lies in the path of the robot a sub-waypoint gets assigned, otherwise it gets mapped to be used in future navigation if necessary.

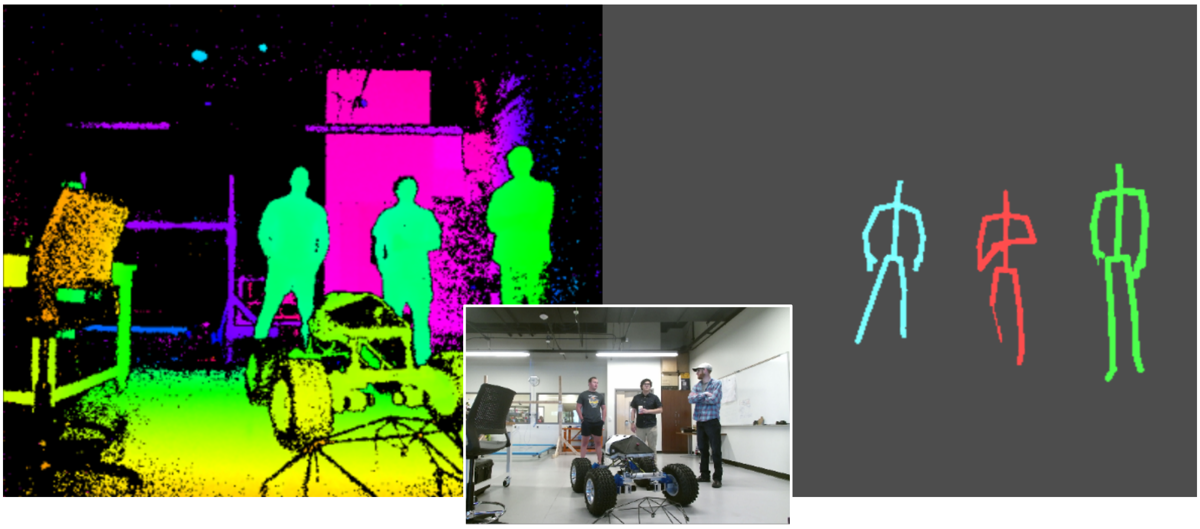

Figure 6: Microsoft Kinect v2 SDK included gaming library showing multiple humans are detected and assigned different colors while anything that is not humanoid gets cut out of the frame

Additional creative concepts

The Kinect v2 requires a 64-bit processor, a dedicated USB 3.0 bus, and 2GB of DDR4 or faster RAM. Given that the Raspberry Pi 3 Model B only has the specifications to support the Kinect v1, the choice of main computer was upgraded from the Raspberry Pi to the Renegade. The operating system support was released for the Renegade on March 20th, 2018. The Renegade mini-computer has the 64-bit processor, a dedicated USB3.0 bus, and 2GB of DDR4 required to support the Kinect v2. Since there is a lack of online engineering community support for the Renegade due to its infancy, this has made the integration non-trivial but also very customized to the rest of the system. There have been no prior examples or guides found during research of the Renegade running a Kinect v2. The setup procedures have so far consisted of a mix between examples of an Ubuntu 16.04 desktop computer and NVIDIA Jetson TX2 module with a large expansion board running the Kinect v2.

For power saving features, firmware implemented on the Arduino and Launchpad are thorough enough to where if needed, SARGE could turn off the Renegade and Kinect v2 to save power in between unobstructed waypoints. Firmware has access to basic collision avoidance and compass following features. Since the communication is done through the Launchpad, toggling these power saving features are available to the user and desirable if traversing long distances.

FAILURE MODES

The 3D printed plastic motor brackets have the lowest safety factor of 2 and are the first expected failure of the vehicle on the mechanical subsystem. For this reason, the team will be bringing additional motor brackets to the competition. In the event of a mechanical failure, the entire robot can be easily mechanically serviced with a standard set of wrenches and sockets and screwdrivers. A central fuse box is implemented for easy access to checking and replacing blown fuses.

SIMULATION

A 2D simulation was done on MATLAB to show the differential inverse kinematic of the vehicle. S.A.R.G.E. is rear steered and four wheel drive. The screenshot of the simulation, shown in Figure 7, helped identify the speed that should be given to each wheel during turns.

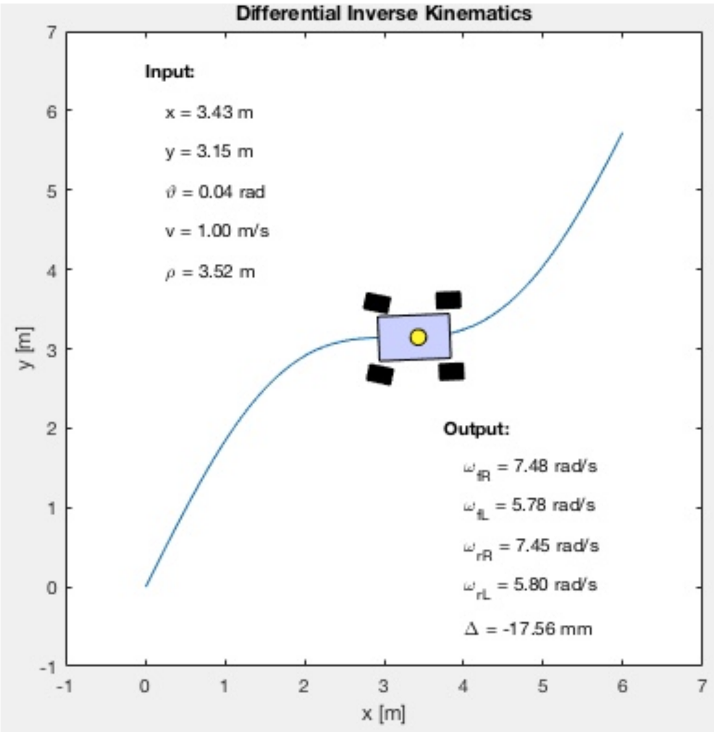

Figure 7: MATLAB Simulation of the Differential Inverse Kinematic

PERFORMANCE TESTING

Initial testing verified accurate firmware performance when it comes to GPS waypointing, the serial communications bridge, software differential steering, and the vehicle is proven to be mechanically reliable under standard driving conditions. GPS coordinates are correctly parsed at an average of 3 Hz outdoors. Encoders and ultrasonic proximity sensors were tested on interrupt driven pins and collect data at about 10 Hz. Testing of the previously chosen LIDAR and mini-computer resulted in electrical failure during two of two attempts, but it was evident that the raw LIDAR data received, and manipulation attempts to this data weren't adequate for either the competition or search and rescue. Attempts spent on manipulating the LIDAR data temporarily deferred image processing of both optical and infrared imaging. However, this opened the door for entertaining the desired new hardware upgrade which combines support of infrared, optical and LIDAR.

Additional desktop performance tests of the substituted mini-computer and Kinect show an image capture and processing of about 2 frames per second (FPS) when rendering to a 4KHD monitor. This includes advanced image processing techniques such as registering the LIDAR data with the optical feed to filter data out of range. This should be adequate for the current speed, however, is a sought-after improvement.

Figure 8: Live stream capture from Renegade rendering infrared, optical, and depth registration

INITIAL PERFORMANCE ASSESSMENTS

Initial assessments show a need for improved wire management, higher data collection rates, and higher quality data processing per amount of time. After upgrading the hardware, more information is being processed per amount of time by sacrificing time resolution, but the quality of information outweighs the negative impact. Overall data collection rates are also higher as the previous system rates ignored the use of optical and infrared collection and processing. The performance of the upgraded system has room for optimization as unofficial community support claim to achieve 3 FPS when using similar hardware configurations. Firmware will need to be upgraded from initial assessments as communication format changes but otherwise shows no signs of needing major upgrade.

CONCLUSION

S.A.R.G.E. was built following two primary goals: compete in the IGVC 2018 competition and build a search and rescue vehicle. The vehicle is quite larger than most IGVC robot, but with its rear steering, S.A.R.G.E. can make tight turns for its size. S.A.R.G.E.'s aggressive design was chosen to allow it to go through rough terrain. Slight modifications and tunings are still being made to S.A.R.G.E to prepare for the competition in June.

REFERENCES

[1] Libre Computer CC Boards Comparison. (n.d.). Retrieved May 3, 2018, from https://docs.google.com/spreadsheets/d/1GuB_AInWH0PTC0kyX1ulTQqlnBVnZSCKzQ-KqV7CX4s/edit#gid=0

[2] Libfreenect2.0.2. (n.d.). Retrieved May 2, 2018, from https://openkinect.github.io/libfreenect2/

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May 14th, 2018

To whom it may concern:

To fulfill the requirements of the eight-credit robotics capstone sequence offered by the Department of Mechanical Engineering at Embry-Riddle Aeronautical University – Prescott Campus, which comprises two senior level design courses, i.e., ME 407 – Preliminary Design of Robotic Systems and ME 420 – Detail Design of Robotic Systems, a multidisciplinary team made by 6 Mechanical Engineering students, 1 Software Engineering student, and 1 Computer Engineering students opted to design and fabricate a mobile platform to be used for Research And Rescue (RAS) tasks and also to be tested during the 2018 IGVC. The members of the capstone team are: Chad Abramson (ME), Garrison Bybee (SE), Sara El Baissi (ME), Morgan Garone (ME), Riley Griffin (ME/EE), Grayson Lynch (ME), Mathew Todd (ME), and Jacqueline Worley (ME). The project, which has been named Search and Rescue Ground Explorer (S.A.R.G.E.), was started during the Fall 2017 and terminated during the team Critical Design Review Presentation on April 27th, 2018.

Please do not hesitate to contact me if you have any additional questions.

Sincerely,

Iacopo Gentilini

Iacopo Gentilini