Autonomous Ground Vehicle Prototype via Steering-, Throttle-, and Brake-by Wire Modules

MQP-AW1-V2V1

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List of Acronyms

1/4-20	Shorthand for 1/4" Bolt with 20 Threads per Inch
3D	Three-Dimensional (as in 3D-Printer)
80/20	T-Slotted Aluminum Extrusion Framing Solution
ABS	Acrylonitrile Butadiene Styrene (Thermoplastic Polymer)
AGM	Absorbed Glass Mat (Battery Type)
ATX	Advanced Technology Extended Motherboard
AutoCAD	Auto Computer-Aided Design (Drafting and Technical Drawing Software)
CAD	Computer-aided design
CNAS	Collaboratively Navigating Autonomous Systems
CNC	Computer Numerical Control
DARPA	Defense Advanced Research Projects Agency
DRC	DARPA Robotics Challenge
DS1803-010	Maxim Electronics Digital Potentiometer
EBS	Electronic Braking System
ECU	Electronic control unit
EPC	Encoder Products Company
GPS	Global Positioning System
IC	Integrated Circuit
I2C or I^2C	Inter-integrated Circuit Connection
LIDAR	Light image detection and ranging
M3	Format for stating Metric Size 3 (as in Bolts or Hex Nuts)
MDF	Medium Density Fiberboard
MPH	Miles per Hour
MQP	Major Qualifying Project
NAPA	National Automotive Parts Association
PLA	Polylactic Acid (Plastic)
PWM	Pulse-Width Modulation
USB	Universal Serial Bus
WPI	Worcester Polytechnic Institute

Abstract

This MQP furthered previous developments working towards a vision-based autonomous ground vehicle. Through modular construction and engineering, all aspects of a self-driving vehicle were retrofitted onto our 1995 golf cart in conjunction with sensors, cameras, and computational power. This year the team improved upon the existing steering system, ruggedized the braking system, and automated the accelerator input. A graduate student partnered with our MQP team and provided software for the stereoscopic vision systems, image processing, and mobile path planning. In addition, our team upgraded the existing power systems to new deep cycle batteries that deliver consistent performance for longer testing periods. A utility rack was fitted to the back of the golf cart which holds additional batteries for the on board power systems in conjunction with the server in a sturdy chassis. Monitors were mounted, in an ergonomic fashion, to enhance the user experience. Each mechanical system was fitted with electrical sensors, for feedback, and is being read and controlled by microcontrollers connected to the server. All electronics are housed in a water-resistant environment for various terrain conditions. This platform is now prepared for future teams to develop software, mobile applications, and use the autonomous vehicle for various user applications.

Acknowledgements

We would first like to thank our motivated professor, Alexander Wyglinski, for his passion, charisma, and dedication to our team and the project. We would like to further our gratitude towards Worcester Polytechnic Institute including the Electrical and Computer Engineering Department, as well as the Robotics Engineering Department. We would like to thank all of the members of the Wireless Innovation Lab in Atwater Kent, who've welcomed our team with open arms. We couldn't have done this project without the assistance of Masters Student Guilherme Meira, of the Wireless Innovation Lab, with his contributions to stereoscopic vision and his thesis. We would like to thank the Atwater Kent Shop Managers William Appleyard and James P. O'Rourke for the guidance, education, and experience within creating our prototype. We would also like to thank the Worcester Country Club and Green Hill Golf Course for extending their technical experience with us throughout this project regarding golf cart servicing. We would also like to thank Air Incorporated for supplying our project with construction materials. We would also like to thank Paul Ventimiglia for his assistance in our Power Rationale. We would like to thank County Line Auto Body for teaching us proper technique for servicing, repairing and restoring the chassis of the golf cart and providing us the paint shop facilities. We would also like to thank BMW of Freehold, Mercedes Benz of Freehold, and Mercedes Corporate Engineers for generous time in teaching our team how the technologies worked, from a technical standpoint, on their flagship vehicles.

Without all of your contributions, this project would not have been possible.
We sincerely thank all of you.

-Robocart, 2015-2016

1 Introduction

1.1 Motivation

Many companies currently doing research and development have made promising statements about implementing autonomous vehicles within our everyday lives. Google's CEO, Larry Page, explained their personal motivation with transportation safety, job opportunities, more efficient use of time, and urban redesign. Scientific American even outlines some of the Intelligent Society of America's promises of a cleaner and more environmentally friendly future with the optimization of Self-Driving vehicles.

There are many positive outcomes from these autonomous vehicles and most, if not all, lineup with our personal motives for this project. The only difference between our team's motivation and technology giants such as Google, is that we wanted to make autonomous technologies more accessible to consumers by making an affordable prototype. Our team wants to design a cost-effective, efficient, prototype that mirrors the same benefits of autonomous vehicles in general: Quality of life improvements, positive environmental impacts, rethinking urban development, and increasing safety in transportation.

Autonomous vehicles have a promising future of making transportation time effortless and enabling the driver to partake in other activities. Consumers can enjoy the surroundings, travel effortlessly, be productive in transit and make more use of the time that people currently waste driving. With autonomous vehicles operating in the most efficient ranges of the vehicle's performance, positive environmental impacts will result from its use.

Our biggest motivation is the promised safety impacts. There are over 1.3 million deaths annually and 20-50 million injured or disabled from car crashes around the globe [07]. If our research could contribute towards the development and implementation of autonomous vehicles then our project is a success.

1.2 Current State of the Art and Issues

Many large companies around the globe are investing time, money, and resources into the development and implementation of autonomous vehicles. Some of the key players in the 2015-2016 academic calendar year include: Google, Tesla, BMW, Mercedes, Audi, and Lexus. Each of these companies have varied aspirations towards self-driving vehicles. Luxury auto manufacturers such as BMW, Mercedes, Audi, and Lexus, have implemented Level 2 Autonomy, as described in Chapter 2.2.3. Most of these are safety features, which protect the passengers from distracted driving or other motorists. Companies like Tesla and Comma.ai are implementing Level 3 Autonomy, which is handling most of highway driving with limited to no user interaction. Lastly, companies like Google and Comma.ai are trying to implement Level 4 Autonomy, or a driver-less car, which can operate on its own without a driver. All of these companies are contributing towards the development of this technology

There are also some problems with the current technology and policy regarding its implementation. Some of the technological limitations include bad performance in poor weather conditions, predictability, and connectivity over the internet [11]. These types of limitations inhibit the vehicle's ability to make instant decisions which endangers the passengers and pedestrians. This is why political figures become hesitant on allowing public testing until these technological limitations are sorted out. Companies need this public testing to ensure their software and artificial intelligence is up to par for legal qualifications. This coexisting battle has been going on the past few years, but states such as California, Nevada, Michigan, and Florida have already passed legislation allowing autonomous vehicles on public roads. Some other issues include liability and insurance problems of a driverless or software-based computer being involved in a motor-vehicle accident. With these types of expense, policy, liability, and driver-interaction problems, it will be a few years until these vehicles are a part of our everyday lives.

1.3 Report Organization

This report is structured into 8 chapters as seen in the Table of Contents. Our team's approach towards introducing this exciting topic starts with our Introduction and our Background / Tutorial Chapters. We then introduced our Proposed Design, in Chapter 3, for our prototype and explain each one of the elements our group has to overcome. Our team then explains how we tackled the three main components of autonomous vehicles, which we branded as the Trinity of Autonomous Vehicles, in Chapter 4, with the completion of the Throttle, Brake, and Steering assemblies. In Chapter 5 we discuss additional enhancements that our relevant to our specific prototype, and not autonomous vehicles in general. Our team discusses Body Restoration, Front Rack, Camera Mounts, Server Hardware and Software, as well as the overhaul in Power Systems on our prototype platform. In Chapter 6, we discuss our system integration and tying all of the sub-systems together. We reintroduce our proposed design and how we have come along. Chapter 7 discusses some of our experimental tests and various things for future development teams to take into consideration when working on this platform. Lastly, within Chapter 8, we discussed our conclusion and recommendations for future work to be done by other teams.

1.4 Project Contributions

This project's ultimate goal is to develop a high quality vision-based autonomous ground vehicle. This year, our team ensured that steering-, braking-, and throttle- by wire modules were installed and verified. By retrofitting our 1995 golf cart with sensors, cameras, and computational power, we prepared future teams for developing software platforms using our prototype.

The contributions to this project include:

- Implementing steering-, braking-, and throttle- by wire modules

- Verifying all mechanical systems with software tests

- Implementing additional enhancements: Power Systems, Server, Mounting Solutions

- Implementing a modular solution for future research and development

The outcomes of this project contributes to the research and commercialization of autonomous vehicles for future generations. Our research and development prepares an autonomous prototype platform as a solid foundation for future software development and implementation.

2 Five-Tier Structure of Autonomous Vehicles

2.1 Level 0 Autonomy

Starting out at Level 0, the lowest in the chain of autonomy, there are no technologies implemented to make the vehicle autonomous. The vehicle is completely driver-propelled and mechanically driven, where the human driver is in complete control of all functions of the vehicle. This was the most common level experienced by consumers until recently, where dynamic cruise control and other active safety features are becoming more popular.

2.2 Level 1 Autonomy

One elevated tier is Level 1, where one function of the vehicle is automated. As of March, 2015, there are multiple single-function implementations on vehicles today. A single function of autonomy may include, but not limited to the following: self-parking, anti-lane drift assist, dynamic cruise control, automatic braking, and impact embracing technologies. Car manufacturers such as Audi, Mercedes, BMW, and other luxury car manufacturers are experimenting with these high end technological features which use sensors and artificial intelligence to implement them into driving. Self-parking is available on many cars today, including many low-end economical cars due to its inexpensive implementation and the usefulness of the feature. The magnitude of self-parking varies from each set of technology but some vehicles have the capability of performing parallel parking in an adjacent spot where a driver releases control of the steering wheel, pressed a button, and the operation is executed and the car parks itself in between two vehicles. Other self-parking technologies are able to back into, and pull into spots, in a similar execution as mentioned above for the parallel parking sequence. Higher end self-parking technologies, typically seen in luxury prototype vehicles today, are able to drive themselves and park within a parking lot, or a multi-story garage and find a spot. The car can then be retrieved or

recalled from a smartphone app to pick up the driver from the drop off location. Some of these more advanced parking techniques may require the assistance of multiple functions being automated. Depending on the sensors and the technologies involved, they may be classified as Level 2 autonomy, which we will address later in the paper.

Anti-Lane Drift assist is another technology currently being implemented on luxury vehicles to this day, March, 2015, and they use sensors on both the left and right side of the vehicle close to the ground along the outer perimeter of the frame. These sensors detect the change in color and can recognize the outer boundary line of a roadway. While a driver is cruising on the highway, if a driver is sleepy, preoccupied, or under the influence, and starts to veer off into another lane, the anti-lane drift assist can detect the movement, and try to signal the driver to take control of the vehicle again. Some vehicles can only vibrate or make an auditory tone, whereas other vehicles can take control of the steering wheel and force the car to stay in the lane. All of these technologies require a driver to be actively engaged in driving, holding, and using, the steering wheel.

Dynamic Cruise Control is a technology associated with traditional cruise control. Cruise Control was becoming relatively standard on vehicles from 1985 – 1990 [08]. This technology allowed a driver to press a button to tell the car to maintain the speed it was moving at when the button was engaged. Modern cruise control technologies allow drivers to set, cancel, resume, increment, and decrement the set speed of cruise control. This allows drivers to have a much better experience while driving long distances to improve fuel efficiency and minimize muscle fatigue from constantly holding down a foot pedal while improving the quality and experience of driving. Dynamic Cruise Control, specifically accenting the dynamic portion, is able to modulate the speed based on assessing the distance in front of, or behind, other vehicles. If a vehicle begins to slow down, within reason, the car will slow down and speed up accordingly while maximizing fuel

efficiency and user experience. Automatic braking is a technology currently implemented on vehicles to stop a car in motion if imminent crashes are detected to protect the driver, as well as the car. Most notably, Mercedes, leads the forefront for this technology, advertising someone distracted behind the wheel, approaching a stopped vehicle, and with the car knowing its maximum stopping distance, and the driver is closing in on that distance, the car detects it will inevitably crash, and the on-board computer can take control of the vehicle and apply the brakes safely protecting the vehicle and its occupants. The last technology mentioned in this Level 1 function autonomy section is the impact embracing technologies. Vehicles have sensors all around the vehicle and can detect when another object is about to strike the vehicle. Mercedes, in particular, when experiencing a side, front, or rear collision, retracts the seats to a safer position, tightens the seatbelt, and prepares the airbags for firing to minimize any bodily injury, maximize the chance of survival from an impact, and move the passengers into the areas of strongest protection within the vehicle such as significant frame segments or supporting joints. All of these single-function autonomous features are implemented on all sorts of vehicles today and are appreciated, endorsed, and actively used in modern, May 2016, society.

2.3 Level 2 Autonomy

Moving onto the more advanced Level 2 distinction, vehicles have more than one function automated (from the few listed above), but insist that drivers still remain constantly attentive. One example is having Anti-Lane Drift Assist and Dynamic Cruise Control on a vehicle, or Automatic Braking when another vehicle is closing in on the minimum braking distance for the motor vehicle.

This allows the vehicle to remain within a lane, controlling steering, and dynamic cruise control regulating speed based on surrounding vehicles. Both of these technologies could be abused, or unintendedly purposed, to have the vehicle drive itself. Drivers who have these

technologies on their vehicles still must remain in a state of constant attention. Some of these autonomous technologies require the driver to keep his or her hands placed on the steering wheel at all times, while these technologies are engaged, forcing the driver to remain in control. These sensor sets, and artificial intelligence level is typically not powerful, or advanced enough to fully navigate and drive a vehicle on its own. These technologies in conjunction still don't abide by right-of-way rules, or anticipate any debris in the road or anything. This is why there is distinction that a driver must remain in constant attention and control of the vehicle.

2.4 Level 3 Autonomy

Level 3 is the fourth tier and typically defined as: "The driving functions are sufficiently automated that the driver can safely engage in other activities." [08] This is the tier Google is currently aiming for with their spinning LIDAR technology on top of Toyota Prius and Lexus vehicles.

Google is using a fast-spinning sensor which is able to see, interpret, and act upon the data collected around the vehicle. This is a much higher level of complexity compared to the previous tiers, because this sensor takes physics into consideration on moving objects, and is able to interpret data from 360 degrees around the car. The artificial intelligence on the Google Self-Driving Car is able to assess right-of-way, anticipation, react and respond to unexpected events such as pedestrians crossing illegally and interpret speed limit signs and street lights.

Level 3 Autonomy allows operators to partake in other activities while driving a vehicle due to the artificial intelligence and technology bundled with the car. The only implied condition is that the operator of the vehicle will be able to take over within a few moments notice.

In their current development, as of May 2016, companies such as Google are attempting to showcase the vehicle's ability to negotiate common scenarios and come up with solutions for

difficult conditions such as: snow, heavy rain, open parking lots, multi-level parking garages, construction zones, sun position and traffic lights. [03]

2.5 Level 4 Autonomy

Level 4, the final tier of autonomy, states that a car can drive itself entirely without a human driver. This has not widely implemented as of May 2016 except in closed professionally monitored scenarios off public roads. This is an area of interest to technology giants as they believe Self-Driving car technology will popularize within the next upcoming years as the physical technology improves, artificial intelligence, and processing power improve. There are few concept cars which use this modernized design and allow for very little input from the driver, but the technology is currently very experimental.

2.6 Chapter Summary

Autonomous vehicles are generally defined as "vehicles that are capable of sensing its environment and navigate without the active intervention of a human operator." [09] Sometimes associated as an autonomous car, driverless car, self-driving car, and robotic car, these technological advances applied to the everyday ordinary motor vehicle will revolutionize and change everyday life across the world. Automotive manufacturing giants such as Nissan, Toyota, Lexus, and Tesla are currently developing autonomous platforms for their current models on the retail floor. Other companies, such as Google, has been testing their autonomous rig on other manufacturer's vehicles and focusing primarily on the artificial intelligence to develop autonomous vehicles. All of these manufacturers have different methods for developing their driverless features. Each automotive giant has a different consumer audience in mind that they're developing for which creates a wide array of technologies currently on the market. Companies such as BMW and Lexus are focusing on partial driver-assistance features in their luxury class

vehicles, while Tesla is showcasing their autopilot feature to conduct a large percentage of highway driving with limited interaction. Companies like Google are looking to completely remove the human element from their prototype vehicles, some of which don't even have a steering wheel or accelerator pedal. Inevitably, these vehicles are making strides in the automotive industry and capturing the eyes of individuals and consumers alike.

With all of these companies in the private industry currently competing in inspiring consumers to purchase their vehicles, there has been a lot of development of various technologies. From entry level standard cruise control, to cheap standard safety equipment, to high end state-of-the-art LIDAR, nearly all spectrums of five-tier autonomy can be seen in modern society. As more development goes underway and processing and manufacturing costs go down, these companies hope to offer these technologies to everyday consumers. This Major Qualifying Project is going through the prototyping process that many vehicle manufacturers go through in equipping a vehicle in preparation for autonomous testing. Our team primarily focused on creating reliable and modular systems in preparation for future teams to do software testing on the prototype as seen in the following chapters.

3 Proposed Design

3.1 Concept Diagram

Robocart is an Autonomous Ground Vehicle that requires many subsystems to be working simultaneously to reach safe and reliable autonomy. Our group broke down the subsections as follows: Throttle, Brake-by-wire, Steer-by-wire, Chassis Reinforcement, Power Systems, Server, and Stereoscopic Vision.
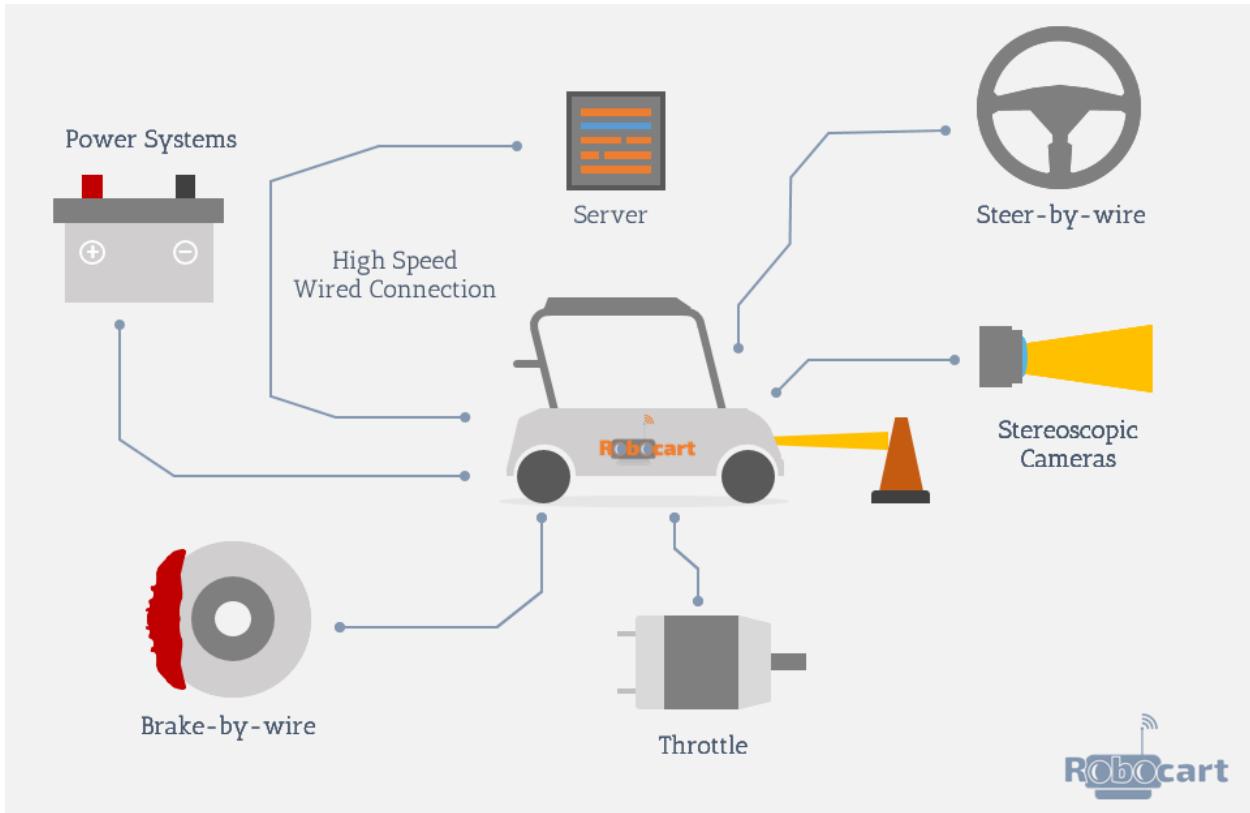
Figure 1: Overall System Architecture detailing relative subsystems.

3.2 Design Rationale

3.2.1 Throttle

The Throttle Control on the Autonomous Ground Vehicle had to have high resolution to have sensitive speed control with the ability to quickly accelerate and decelerate. There must also

be safety functionality implemented to ensure the throttle system is robust and reliable in software applications as well.

To reach these design specifications, our group collectively determined the simplest implementation would be to replicate the existing accelerator pedal, which is essentially a large potentiometer ranging from 0 ohms to 5500 ohms.

To replicate this electrical component, we implemented an Addressable Dual Digital Potentiometer from Maxim, specifically the DS1803-010. Individually, these integrated circuit chips sell for ~ $2.00 – $3.00 in bulk, and only slightly more for a one-off prototype. These cheap components allow us to keep the overall cost down and the modularity of a 16-Pin IC chip allows us to easily swap out the components in case of failure.

This integrated circuit operates, when communicating with a microcontroller over I2C protocol, by outputting resistances from 0 ohms to 10,000 ohms over 256 steps. This gives us precise and accurate control over the speed and we have fine control over acceleration and deceleration through software on the microcontroller as seen in the following chapters.

3.2.2 Brake-by-wire

The existing brake-by-wire system implemented by Prateek Sahay in the 2014 – 2015 academic year utilized a windshield wiper motor. This was a great idea as windshield wiper motors are powerful and often use worm gears to deliver high torque to the load. These motors could draw up to 50 amps at stall current, which is within the design specifications of our Sabertooth Dual 60 Amp Motor Driver.

The stall torque is 34 N-m, or 25 ft-lbs. Our group implemented a ¾" coupler to go from the windshield wiper motor to the industrial bearing bolted onto the I-Beam of the chassis. This ¾" coupler, acting perpendicularly to the motor, acts as a pulley, and using the equation

$\tau = F \times r$, we should have a force of approximately 66 pounds of force pulling back on the brake assembly. With a larger diameter coupler, we can maximize distance pulled on the vinyl-coated wire rope while minimizing the number of rotations allowing the brakes to be deployed more quickly than designs in previous years.

Considering the mechanical advantage of the brake lever arm from the physical brake pedal, this should be enough to apply the brakes comparably to a driver depressing the pedal. The vinyl-coated wire rope, in 3/32" diameter, will support working loads up to 184 pounds, which is within our force tolerance.

3.2.3 Steer-by-wire

The Steer-by-wire system implemented by Prateek Sahay in the 2014 – 2015 academic year is a powerful and conceptually sound design, but some further improvements had to be made for performance and implementation purposes. There was constant issues with aligning the Steering Column to the existing acrylic plates that were implemented in previous years. Upon further investigation, as seen in the following chapters, the acrylic plates were not centered and forcing the steering column out of alignment. Our first design choice was to remove these plates and come up with an alternate solution.

To correct the perpendicularity of the steering column to the existing steel plate, an extension had to be made to prevent the potentiometer from hitting the existing aluminum dashboard. Once the top of the plate was brought out, through small adjustments the plate was now perpendicular to the natural angle of the steering column. To replace the acrylic plates, and minimize friction, our team determined an additional ¾" industrial bearing should hold the steering column in alignment to the plates. Washers were used to fine-tune the distance between the plates to ensure the chain sits mechanically sound and parallel to all the sprockets.

Besides these mechanical adjustments, the motor calculations, torque specifications, current draw, and speed calculations were all correct from the previous implementations by Prateek Sahay.

3.2.4 Chassis Reinforcement

A lot of oxidation and rust were seen on the chassis and frame of the Golf Cart that should be addressed. Our team took wire brushes on power tools and removed the oxidation from the aluminum, and grinded down whatever exposed rust was on the non-aluminum metals. Oil-based paint was applied to the non-aluminum metals to prevent further rusting.

Some parts of the I-Beam Chassis running down the golf cart had to be cut to accommodate the brake systems as seen in the following chapters. These cut segments were reinforced with iron straight bars bolted to the aluminum assembly. This iron replacement should ensure the structure remains sturdy for future applications.

The body panels of the Golf Cart were also sanded to remove the existing paint, filled with compound to remove any dents or imperfections, sanded smooth, painted with primer, and painted with WPI Maroon as seen in the following chapters. These were cosmetic decisions, but enhanced the Robocart image we were trying to convey.

3.2.5 Stereoscopic Vision

A graduate student, Guilherme Meira, worked in conjunction with us towards reaching our goal of a true autonomous platform during the 2015 – 2016 academic year. Guilherme is a Masters Student who specialized in Raspberry Pi Stereoscopic Vision for his thesis. Based on his recommendations, our team designed a rack for the front of the golf cart that would allow the cameras to be spaced at variable distances to maximize the field of view. This gives us design and testing flexibility further along the process. The modular design of the 80/20 rack would also

accommodate additional monitors and hardware to be fitted to the golf cart for prototyping and testing throughout further development as well. A final prototype could have two brackets that independently install the cameras in one fixed optimal position. The design features of our prototype system will become apparent in the following chapters.

3.2.6 Server

In previous academic years other teams working on this Golf Cart attempted to make the vehicle autonomous via wireless communication to a remote server for image processing. Although this sounds exceptional in theory, real world latency, bandwidth, and connectivity jeopardize the safety and performance of the autonomous vehicle. To counter these issues, our team determined the Golf Cart would have the highest performance with the Server mounted on the back of the Golf Cart. After software is developed and resources are determined, a smaller and more cost-effective computer couple be implemented on future prototypes to maximize efficiency.

The steel cage on the Server was modified to a more condensed, but equally protective, state. This cage was then bolted onto a towing cargo utility rack for vehicles. Modular T-Slotted 80/20 Aluminum bars were bolted onto this cargo rack to accommodate rapid assembly and disassembly and ensure components can be added and removed, with ease, in the future.

3.2.7 Power Systems

After first inspecting the condition of the Golf Cart during the beginning of the 2015 – 2016 academic year, it was discovered that the existing batteries on the Golf Cart were from 2002 and our team suspected they may not sustain a charge or be usable for untethered operation. After load testing the fully charged batteries at a local Golf Course facility, the Golf Cart technicians recommended replacing the batteries. Luckily with our prototype and design flexibility, we were able to minimize cost and maximize power density for our application. We built a cost and

performance matrix in the table on the following page. Our group collectively determined the 29

HM batteries had the highest capacity, charge density, appropriate volume, and justified price for

our application.

Table 1: Battery Rationale

Battery / Group	Price $USD (Lower is Better)	"Reserve Capacity" Mins @ Current Mins @ 23 Amps (Higher is Better)	RC in 25 Amp Units Mins @ 25 Amps (Higher is Better)	Amp Hours (RC * 0.4167) Capacity (Ah) (Higher is Better)	$ / Amp Hour $ / Ah (Lower is Better)	Length In.	Width In.	Height (To Terminals) In. (Lower is Better)	Volume Ft^3 (Lower is Better)	Charge Density Ah / Ft^3 (Higher is Better)	Total Cost $USD (Lower is Better)
SL34MAGM	$119.88	120	110.4	46.00368	$2.61						$359.64
24 DCC	$79.62	150 Mins @ 23 Amps	138	57.5046	$1.38	10	6.5	9.5	0.35734972	160.9196728	$238.86
24 DC	$74.87	140 Mins @ 23 Amps	128.8	53.67096	$1.39	10	6.5	9.5	0.35734972	150.1916946	$224.61
24 MS	$59.88	90	82.8	34.50276	$1.74	10	6.5	9.5	0.35734972	96.55180365	$179.64
27 DC	$79.88	200 Mins @ 23 Amps	184	76.6728	$1.04	12	6.5	9.5	0.428819664	178.7996364	$239.64
29 HM	$84.67	225 Mins @ 23 Amps	207	86.2569	$0.98	12.75	6.5	9.5	0.455620893	189.3172621	$254.01
31 C	$99.87	190	174.8	72.83916	$1.37	13	6.5	9.5	0.464554636	156.7935273	$299.61
GC2 (Golf Cart) **	$84.52	105 Mins @ 75 Amps	315	215	$0.79	10.25	7	11	0.456742132	470.7251312	$507.12

Sam's Club now accepts American Express - Which Extends Product Warranty by 1 Additional Year & Purchase Protection for 90 Days

Sam's Club also acceps Business Checks for Tax Exemption for Educational Purposes with a WPI Letterhead

By Design Rationale, I would personally conclude the 29 HM is the best bang for your buck. I do have to check if the dimensions work for the Golf Cart (I believe they will)

** $ / Ah for Golf Cart Battery was Adjusted in Table to account for 6 Batteries (Double $ / Ah)

3.3 Project Logistics

Organization / Management, Coordination, Administration, and Execution

When Raymond and I began this ambitious project, we determined we should do an overall assessment of the Golf Cart and establish goals for the upcoming academic year. After disassembling the Golf Cart and getting a better understanding of previous work and current condition, we broke down our goals based on the following groups:

- Power Systems (Rob)

- Server and Server Rack (Rob and Ray)

- Throttle-by-Wire (Ray)

- Brake-by-Wire (Rob)

- Steer-by-Wire (Rob)

- Stereoscopic Vision (Ray and Guilherme)

- Software (Ray and Guilherme)

From a skills perspective, we broke down our talents into the three disciplines of Robotics Engineering:

- Electrical and Computer Engineering – Rob & Ray

- Computer Science / Software Engineering - Ray

- Mechanical Engineering - Rob

With these subdivisions of labor in the goals list above, each team member is able to focus their talents where most effective and most relevant. Considering our modular design, and our common Robotics Engineering background, each of our components will mesh well with the combined prototype.
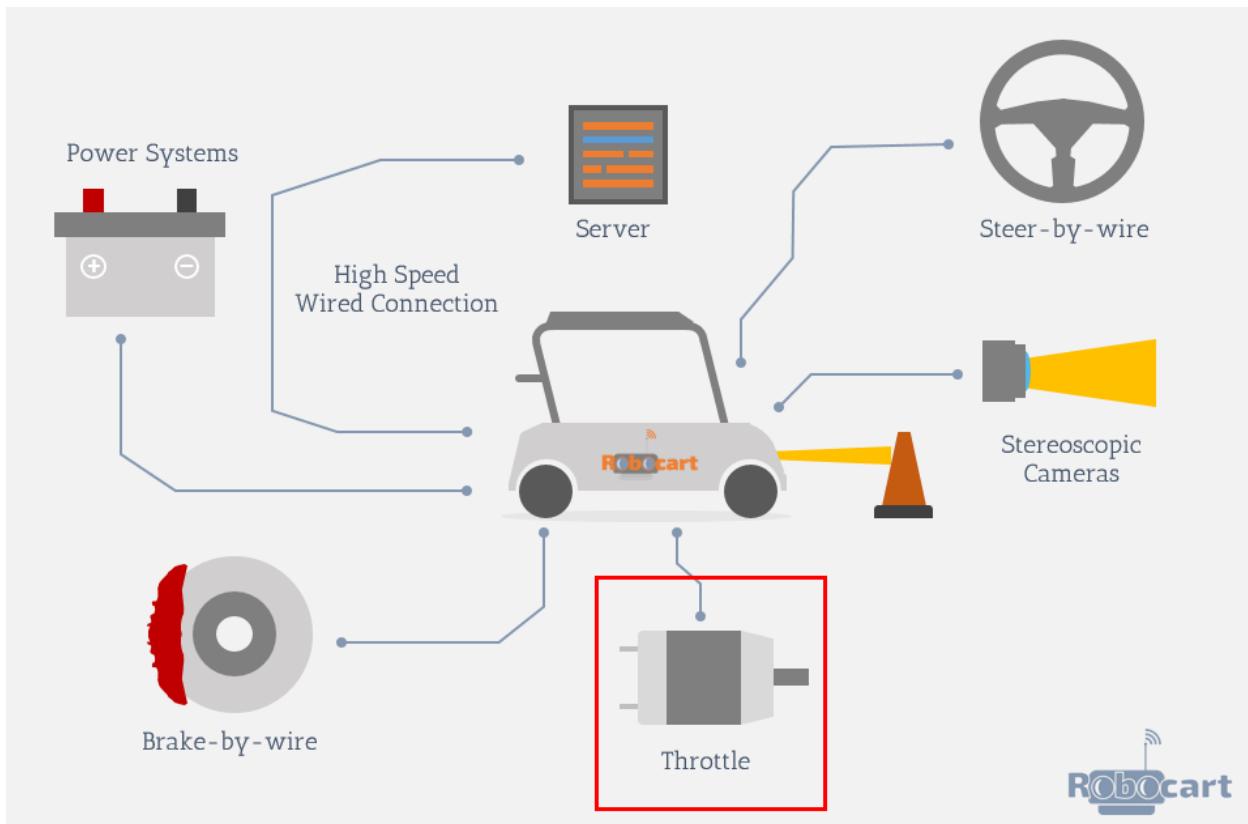
3.4 Chapter Summary

Our proposed design covers throttle control, braking control, steering control, chassis reinforcement, and additional reinforcements for mounting stereoscopic vison, server, and power systems. Each subsystem works independent of each other as its own system, however comes together to make the entire vehicle functional. By tackling the mechanical, electrical, and software components, as well as reinforcing the chassis and make improvements to the server and power systems, we were able to bring the golf cart together as an untethered vehicle capable of autonomous operation.

4 Trinity of Autonomous Vehicles (Throttle, Braking, and Steering)

4.1 Throttle

Throttle control is achieved with an Arduino microcontroller and a DS1803 digital potentiometer. Since the original golf cart is outfitted with a physical wiper potentiometer measuring from 5500 ohms at rest and 0 ohms full throttle, we can map the same values to the digital potentiometer. Through an inter-integrated circuit connection (I^2C), communication between the Arduino and DS1803 can be established. In this specific implementation, we used a preexisting "Wire" library supplied under a Creative Commons Attribution-ShareAlike 3.0 license. The following code snippet initiates the I^2C connection and begins communication with the Arduino via analog pins A4 and A5 on the Arduino for SCL and SDA pins respectively.

The original throttle system operated on a continuously variable potentiometer that changed its value from 5500 when the acceleration pedal is at rest, to 0 when the pedal is fully compressed. The simplistic nature of this mechanical system makes it easy to electronically replicate. There were two replacement control systems the team considered: a linear actuator to physically compress the acceleration pedal, or manipulate the existing electrical system. Ultimately the team chose the path of least resistance, making as few physical changes to the golf cart as necessary.

```
void setup() {
  Wire.begin();
  Serial.begin(9600);
}

void loop() {
  Wire.beginTransmission(0x28);
  Wire.write(B10101001);
  Wire.write(val);
  Wire.endTransmission();
```

Figure 2: Initialization of inter-integrated circuit communication

Since the DS1803 uses an 8-bit value (256 decimal values) to control 10,000 ohms of potentiation, we can obtain control of the resistance within 39 ohm accuracy with each increment or decrement of the control value. As the golf cart can achieve a maximum velocity of 20 miles per hour, control of this digital potentiometer would equate to being able to control the velocity of the golf cart within an accuracy of 0.1418 miles per hour as shown in the equation below:

$$\frac{20 \; mph}{5500 \; \Omega} \; x \; \frac{39 \; \Omega}{1 \; control \; tick} = 0.1418 \; mph \Big/ control \; tick$$

To integrate this system with that of the golf cart, the team attached a quad-pull-quad-throw switch that allows the manual switching between autonomous and manual driving modes design by the first year MQP team with the CNAS project.
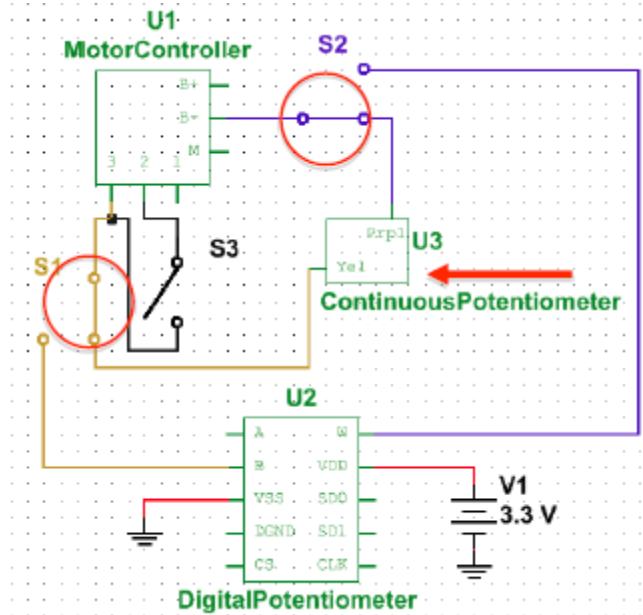
Figure 3: First Generation CNAS MQP concept put into practice
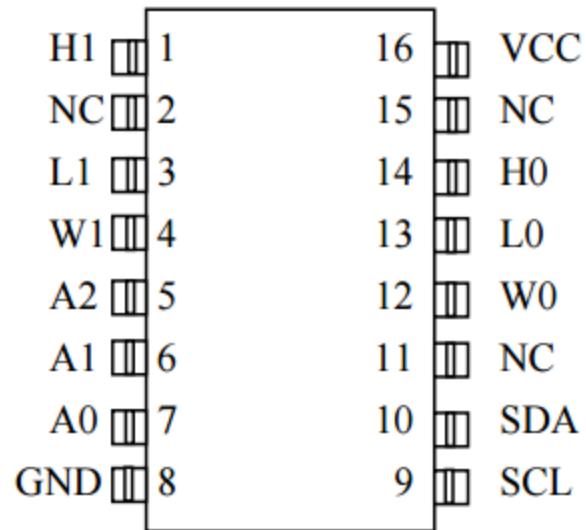
Figure 4: Pin Diagram from the Data Sheet of the DS1803-010 Digital Potentiometer
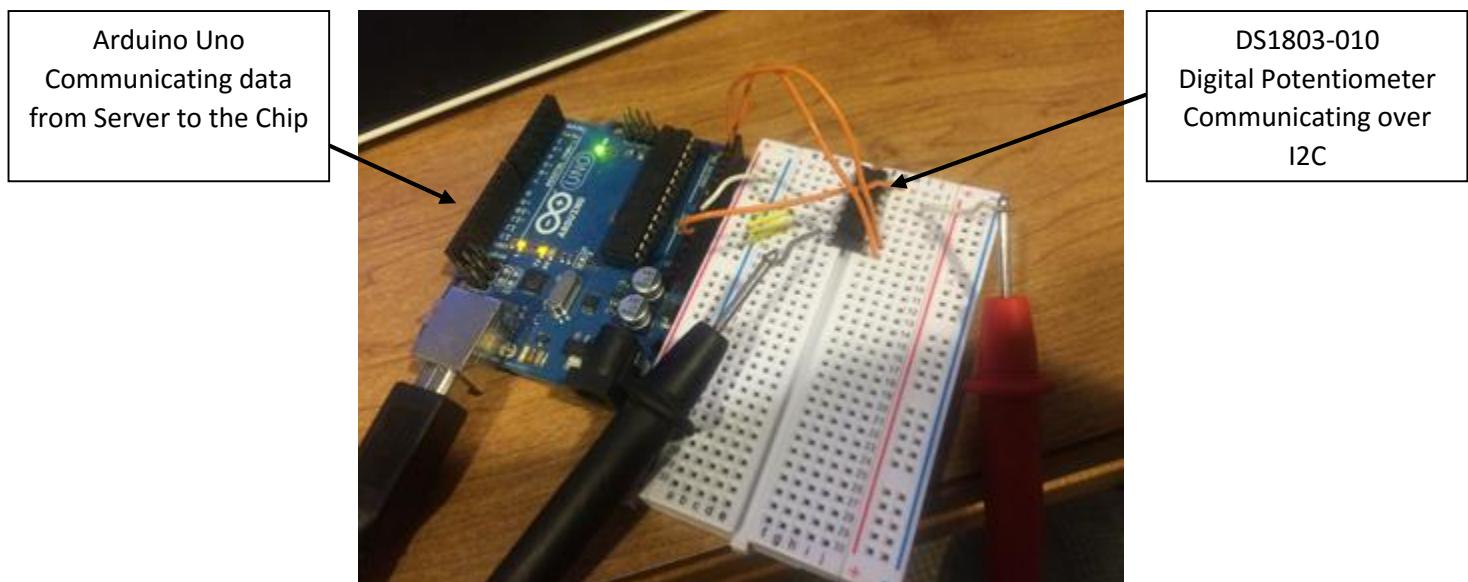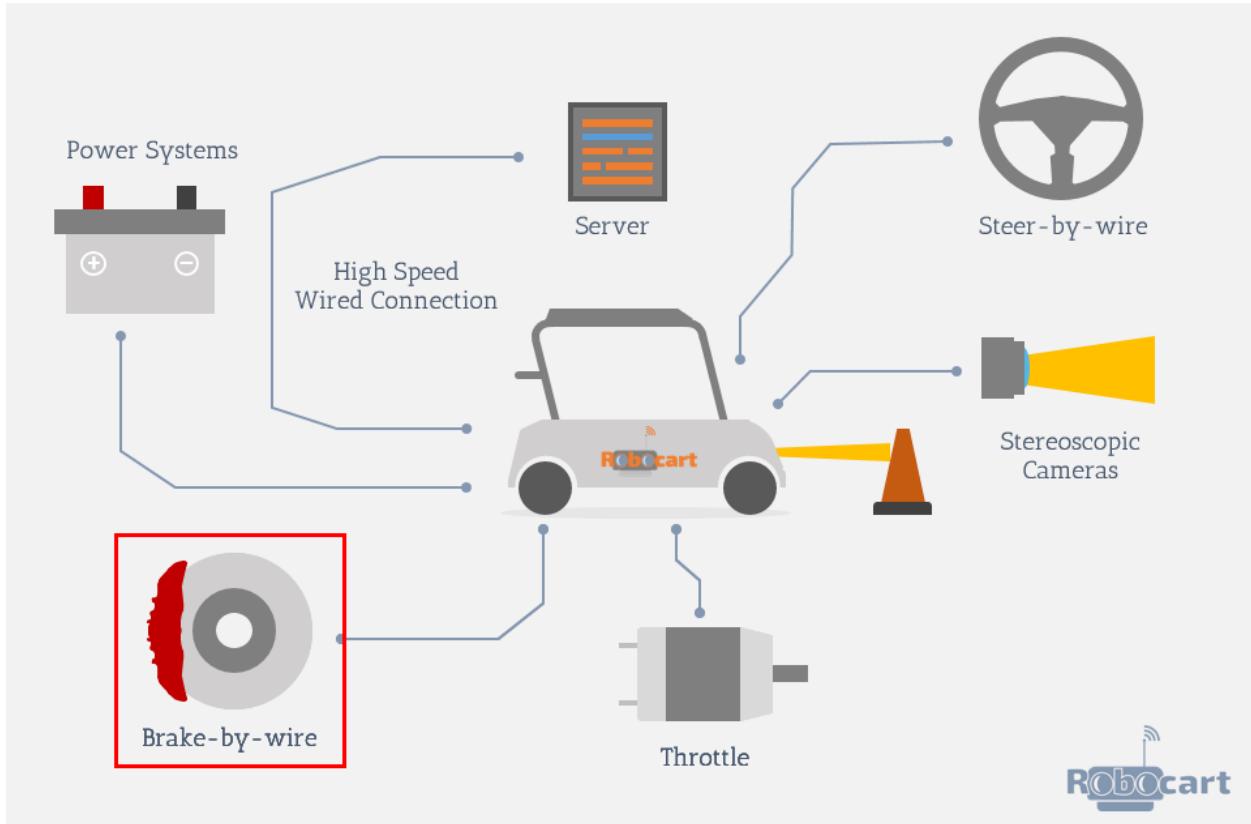
Figure 5: Sending Data from the Server to the Arduino (over USB) to the Digital Potentiometer over I2C Protocol

4.2 Braking

The next element our team wanted to address was braking. After the completion and testing of throttle, our team determined this would be the most appropriate time to implement and verify the braking system worked. Below is our proposed design flow chart showing the transition:

The second control system the team tackled was the braking assembly. Shown in Figure 7, the braking system uses a simple drum mechanism to slow the wheels. As explained below, in Figure 6, Drum Brakes work with a Brake Cylinder and a Piston. When the Piston is extended, the two Brake Shoes move outward towards the "Drum" which is on the wheel assembly. The stationary Brake Shoes expand outward onto the spinning drum, generating friction and slowing down the wheels. Overtime as the Brake Shoes wear down, the Adjuster Mechanism eases off and minimizes the gap for the Brake Shoes to come in contact with the Drum. Early on in the project,

took off the rear wheels and the hubs, which cover the drum brake assemblies to inspect their condition. This can be seen below in Figure 8.

The manufacturer of the Golf Cart, Club Car, fitted this Drum Brake design to the golf cart by implementing a brake wire system which is applied by pressing on the brake pedal, putting tension on the brake wire, extending the brake shoes which applies friction against the brake drum. This system is purely mechanical and has no means of autonomous operation. To prepare for autonomy, the team needed to install a coupler for an electrical system. To accomplish this, the team designed and created a custom brake coupler attached to a windshield wiper motor with braided steel wire and outfitted it to the chassis of the golf cart.
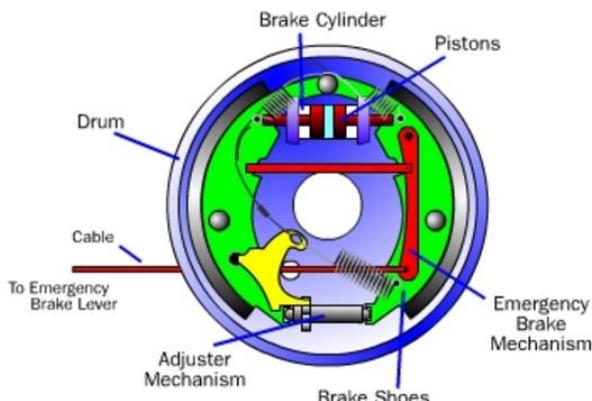
Figure 6: Drum Brake Diagram
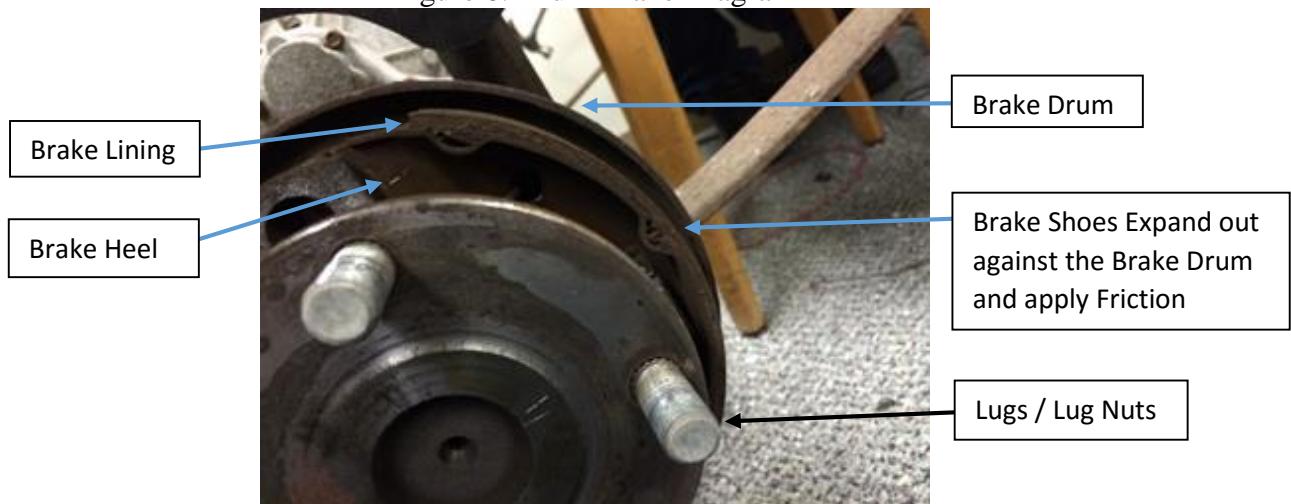
Figure 7: Labelled Diagram of Drum Brake Assembly
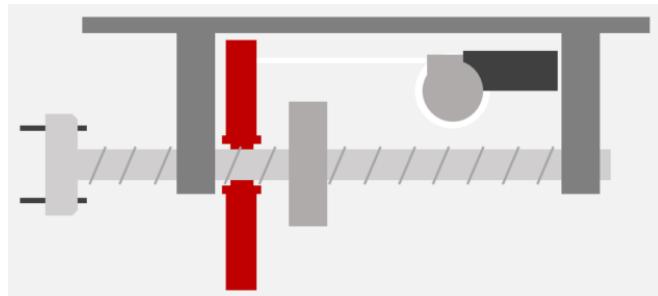
Figure 8: 2014-2015 MQP Brake-By-Wire Design

The task of creating a custom brake coupler was accomplished by using the lathe in the Atwater Kent Electrical and Computer Engineering shop. The team bored a hole out of a standard piece of ¾ inch aluminum stock, which was attached to a solid steel base housing a metal bearing for smooth rotation. The bored aluminum stock fit securely into the metal bearing assembly and allowed the mechanical system to be attached to the golf cart.

Lathe in Atwater Kent ECE Shop

Boring a Hole into the Aluminum Stock with a Drill Bit

¾" Aluminum Stock

Figure 9: Creating Custom Brake Coupler Sub-Assembly

Once the construction of the brake assembly was completed, the team needed to install the assembly onto the chassis of the golf cart. This proved to be far from trivial as parts of the aluminum I-beam had to be cut away to fit the industrial bearing. To do so, the team used a 4.5" diameter angle grinder to cut away at the chassis. The team wanted to limit the amount of metal grinded away from the chassis due to concerns of the tensile strength of the area. To avoid

compression and bending of the chassis after the I-beam were cut away, the team reinforced the

chassis with fitted steel plates. The process can be seen in Figures 10 and 11.

Location of the Windshield Wiper Motor

Location of Aluminum Coupler

Cutting Aluminum I-Beam on Chassis to make room for Industrial Bearing (Brake Assembly)

4.5" Angle Grinder Cutting Tool

Figure 10: Modifying the Chassis to Accommodate Bearing for Sub-Assembly

Tapping Threads into Aluminum Coupler for Set-Screw

Using a Vice to Ensure Coupler doesn't Move while Tapping Threads
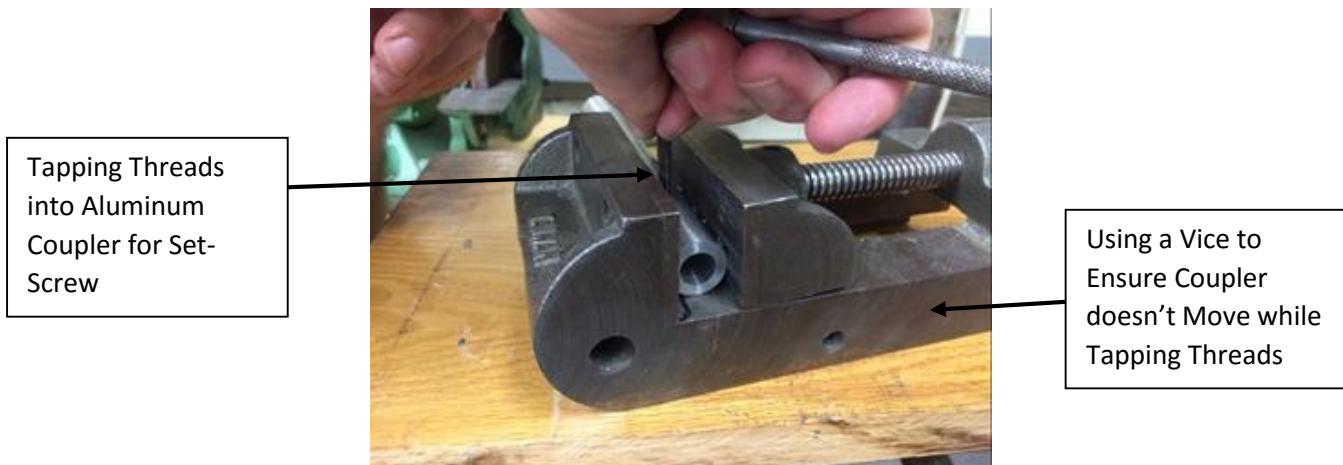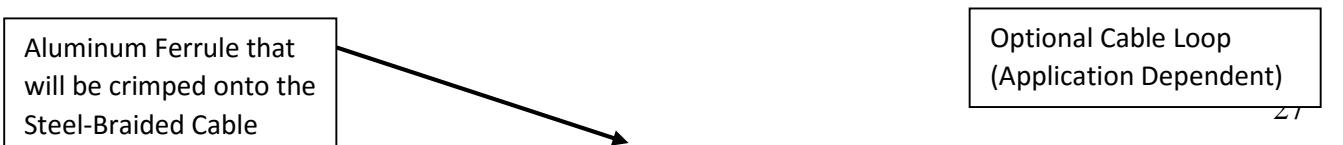
Figure 11: Tapping Threads into Aluminum Coupler for Brake Sub-Assembly

A hole was drilled out of the Aluminum Coupler, of 3/8" diameter, which was the thickness

of our vinyl-coated steel braided cable. To install the cable, the vinyl-tubing insulation is stripped

from the wire, an aluminum ferrule is attached to incoming and outgoing end of the brake lines

(through the loop of the coupler), and then a swaging tool finalizes the crimp. These elements can

be seen below in the following figures:

Aluminum Ferrule that will be crimped onto the Steel-Braided Cable

Optional Cable Loop (Application Dependent)
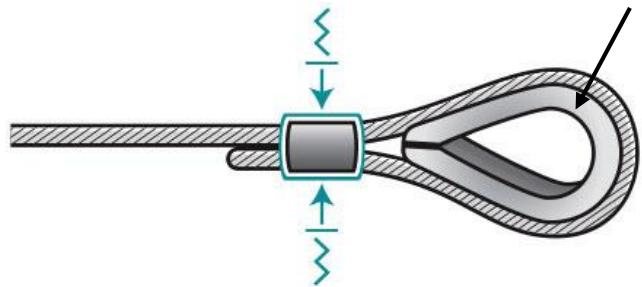
Figure 12: Diagram of the Steel Cable, Ferrule, and Optional Cable Loop

This would allow a snug and responsive fit when the motor spun the coupler. The larger diameter of the coupler, ¾", also maximizes linear travel, applying the brakes more quickly. Considering the safety aspect of our motivation chapter, this component was crucially important to the team. Above in Figure 12, you can see a set screw was originally tapped into the first iteration design of the brake system. Below, in Figure 13, you can see the Set Screw in place and the hole for the steel braided cable.

Aluminum Coupler with Set-Screw in place. Checking Perpendicularity

Hole Drilled out for Steel Braided Cable to pull on Existing Brake System.
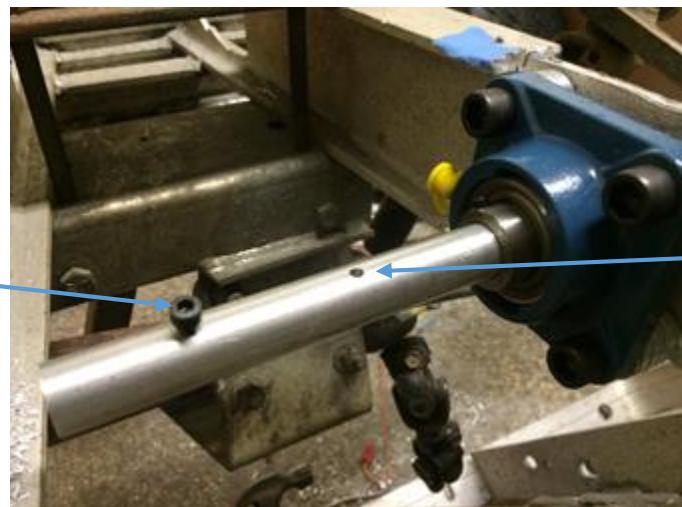
Figure 13: Checking Perpendicularity and Fit of the Aluminum Coupler

Holes drilled into Aluminum I-Beam Chassis for Windshield Wiper Motor

Multiple Washers were used for easy Calibration and a Perpendicular Fit.
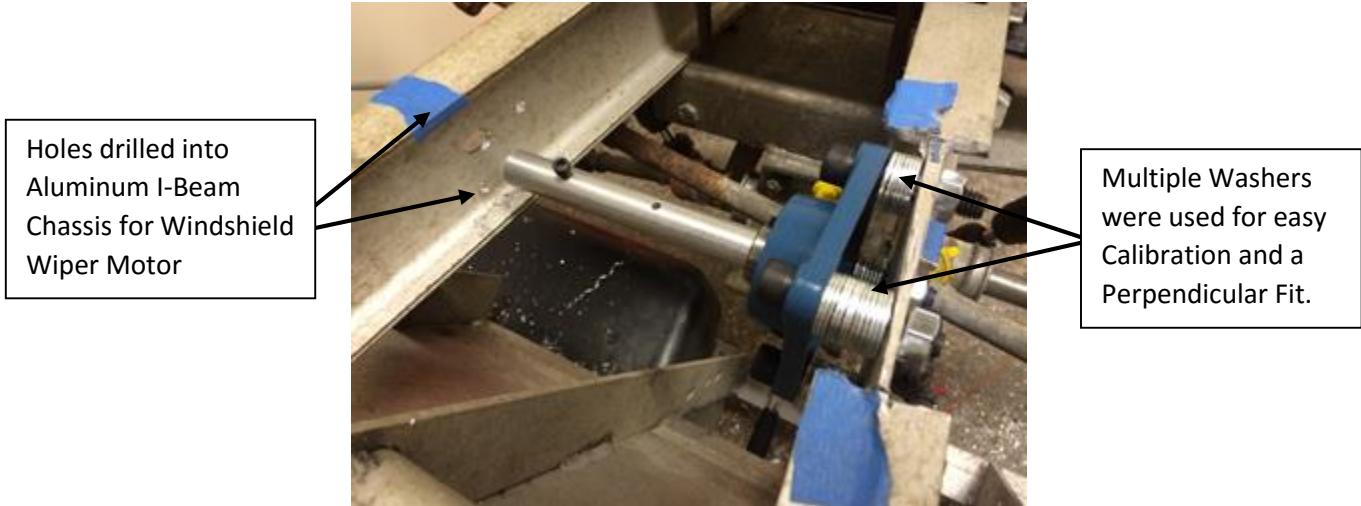
Figure 14: Washers were used to ensure Coupler was Perpendicular to the existing Brakes

Washers were used to compensate for the angle of the I-Beam chassis that runs through the frame of the Golf Cart. For best performance, the Motor-Coupler-Bearing system needed to be perpendicular to the Golf Cart frame and the existing Brake System to maximize torque and minimize response time. We were able to achieve this with a digital compass and slowly dialing in 0.0 degrees in respect with the existing brake system.

Figure 15: Alternate Perspective ensuring Coupler is Perpendicular to Brake Assembly

In our final design, we discovered that when the coupler shifted, even subtly, during testing, that the set screw would become dislodged from the flat portion on our Windshield Wiper Motor. To correctly fix this, we drilled a hole through the Aluminum coupler, and through the axle of the

Windshield Wiper Motor. We then fitted an M3 Bolt through the newly-drilled hole with an M3 Nylock Washer to ensure that the brake assembly wouldn't come apart, even after repeated use. Now there should be no slipping when the motor is actuated or when the manual brakes are depressed repeatedly.

Windshield Wiper Motor Installed

Set Screw Replaced with bolt for higher torque

Steel Braided Cable Tensioned and Installed on Brake Side.

Steel Braided Cable looped through and crimped

Chassis Reinforced using 1½" Iron Bar and bolts.
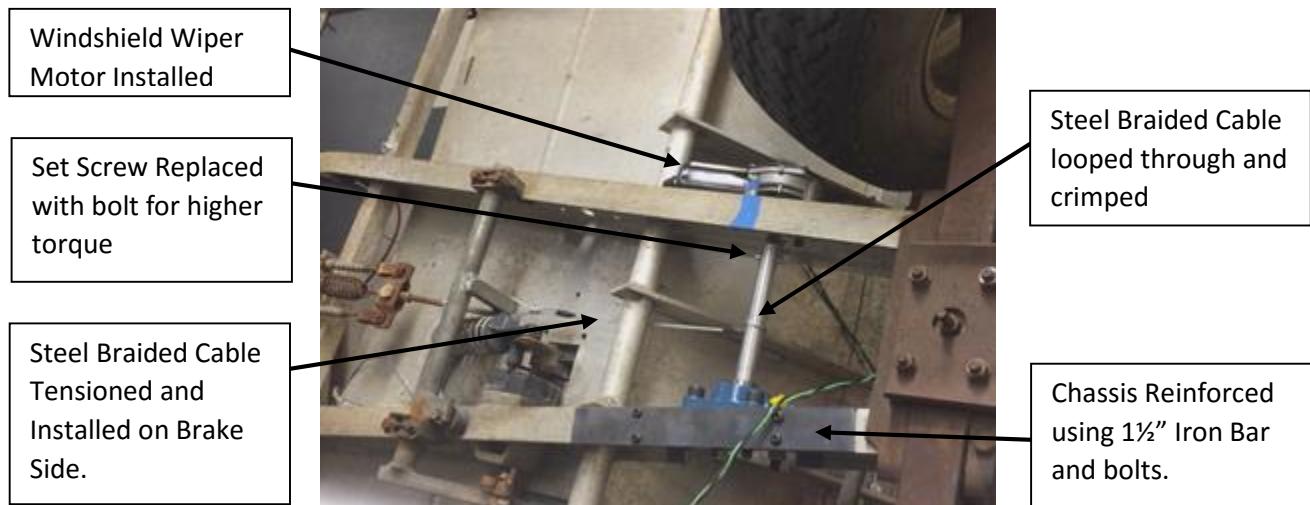
Figure 16: Final Configuration of Autonomous Brake Assembly

The final configuration of the autonomous brake assembly consists of the motor, steel braided cable, aluminum coupler and bearing assembly shown in Figure 16. Once the entire system was secured onto the chassis, testing was completed by supplying 12V to the motor until it spun enough to tension the braided cable and apply tension to the brake line and applied the brakes. Once this proved to work successfully, the configuration was attached to a Dimension Engineering Sabertooth 2x60 motor controller which supplied power to both the steering and braking motors. The motor controller operates via microcontroller pulses such as a PWM signal with a 2 millisecond period to control both speed and direction of the motors attach to the "motor 1" and "motor 2" lines corresponding to signals 1 and 2 respectively.

4.3 Steering

Like the other control systems of the golf cart, steering configuration was complete in 3 parts. First we assessed the current state of the assembly to locate areas of improvement, then the design and implementation of complete system, and finally verifying the new installation. As shown in Figure 17, the original steering configuration was out of alignment. This results in difficulty moving the chain and sprocket when applying control to the steering motor.
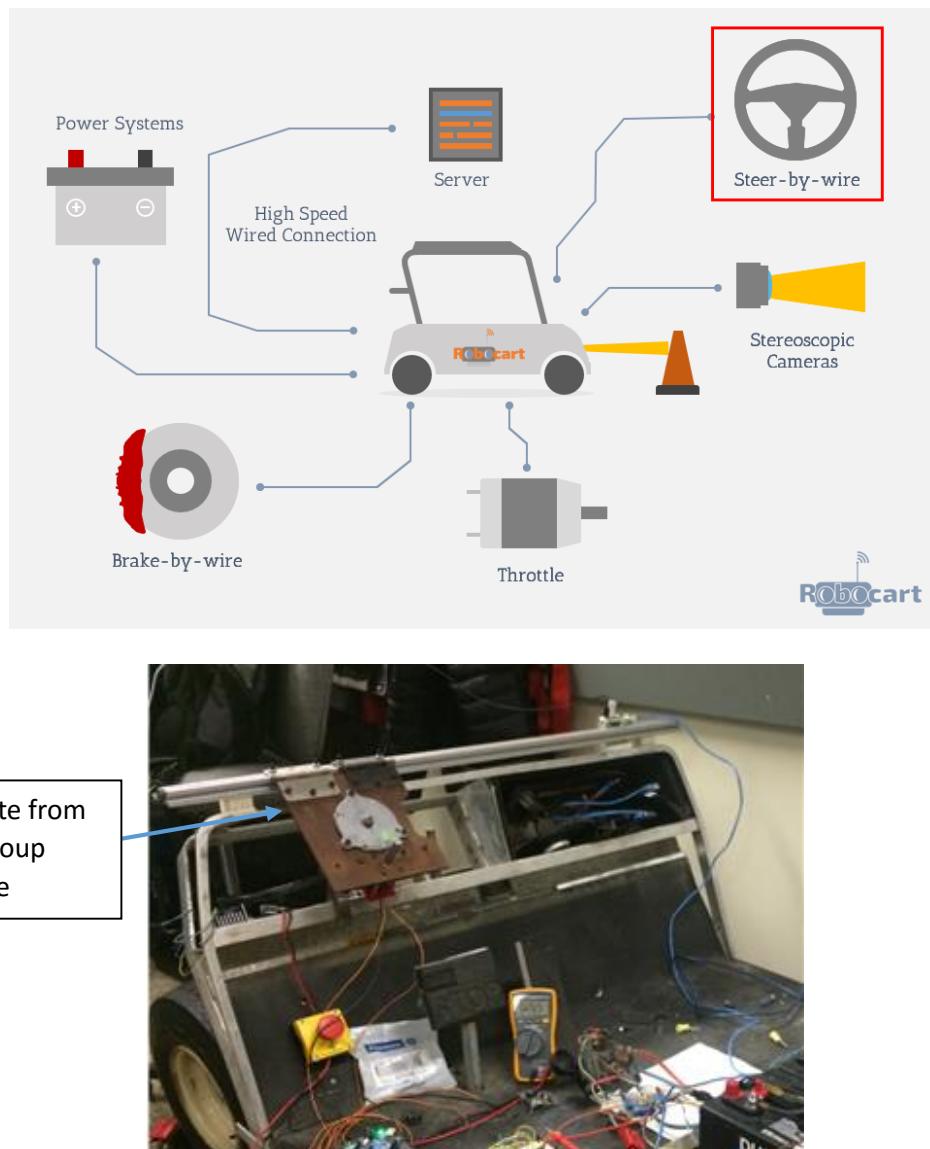
Figure 17: Condition of Steering Metal Plate from Previous Academic Year

Holes Laser-Cut from Previous Group Clearly out of Alignment

Figure 18: Holes improperly centered forcing the Steering Column out of Alignment

To address this issue, the team designed and cut an aluminum back plate to retrofit the previous design. This new design is sturdy enough to withstand the weight of the steering motor without bending, which would allow the steering column to rest perpendicular to the steering column.

Fresh Coat of Oil-Based Paint (to prevent future rusting) Applied to Old Plate
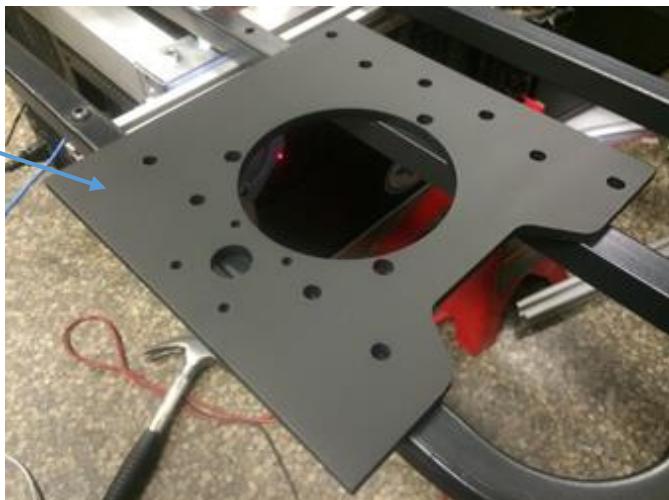
Figure 19: Metal Plate Grinded and Painted to prevent further rusting.

The cutting of our aluminum back plate design proved to be an obstacle as we did not have access to a 4" diameter hole saw, nor a computer numerical control (CNC) machine. To make the proper cut, the team drilled around the circumference of the desired hole and sanded away excess using a Dremel. The fit of the motor is shown in Figure 22.

AutoCAD Template for drilling holes along the perimeter of an inner circle
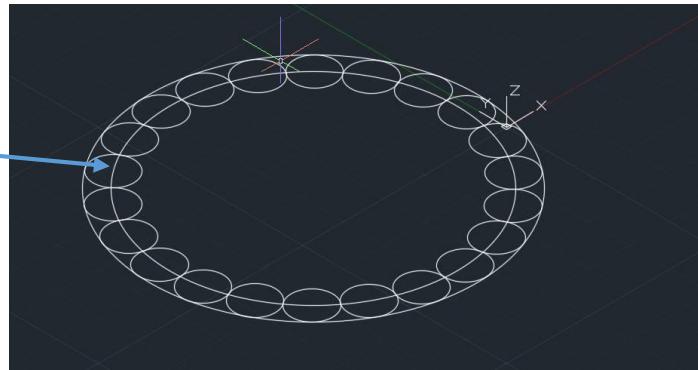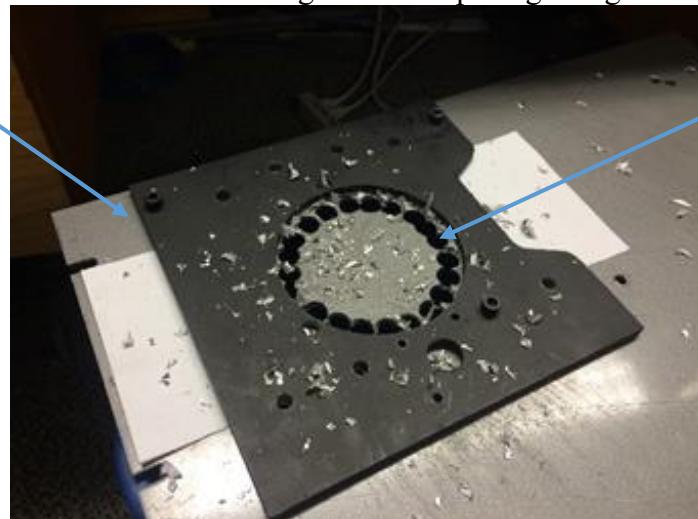
Figure 20: AutoCAD Model for Drilling ½" Hole Spacing along Inner Circle Perimeter

Cutting Supplemental Aluminum Plate to Support Steering Column Bearing

Creatively cutting out a 4" Diameter Hole in the aluminum without a Hole Saw

Figure 21: Cutting 4" Diameter Hole into Aluminum Back plate for Steering Column Bearing

Pancake Motor has Snug Fit on newly-cut Aluminum Plate
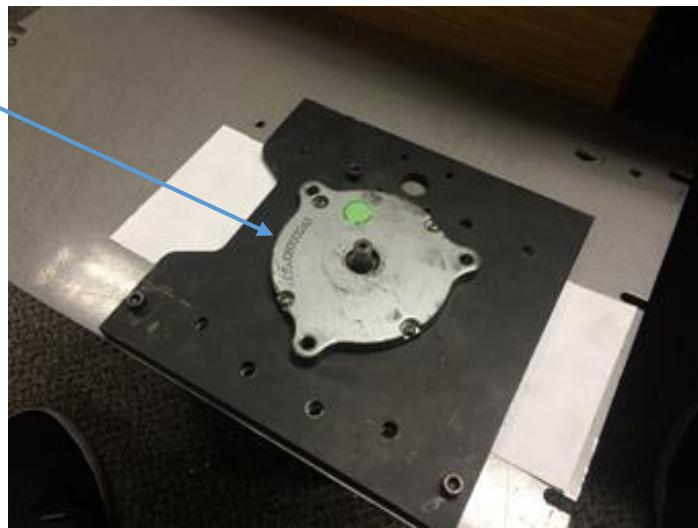
Figure 22: Testing if the Pancake Motor fits into the Newly-Cut Aluminum Plate

The next stage of the redesign was to mount the original housing for the steering control potentiometer on the new design. In doing so, the team realized that when the motor spun at high

enough speeds, the potentiometer would freely spin in its housing. This would be a problem when trying to obtain accurate information about the position of the steering wheel. The team addressed this issue with a 20-turn potentiometer bracket that secured the potentiometer in place while the motor is spinning. The design and implementation of the bracket is shown in Figures 23, 24 and 25.

3D Printed Potentiometer Bracket with Notch to prevent spinning
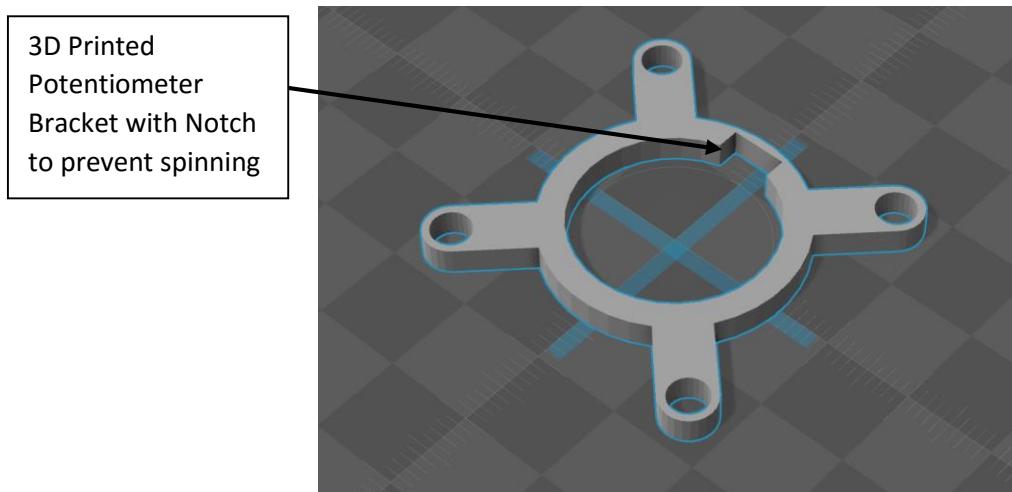
Figure 23: 3D Printed 20-Turn Potentiometer Bracket Designed in AutoCAD

20-Turn Potentiometer for Steering Position Measurements

Measuring all components precisely with Digital Caliber Measuring Tool

Figure 24: Taking Dimensions of Existing parts to Ensure Well-Fitting Bracket
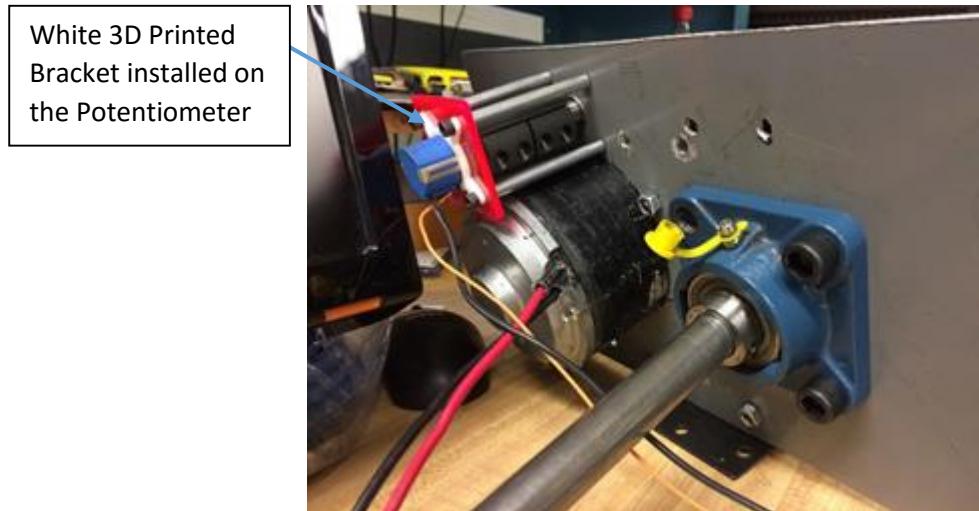
Figure 25**:** Reinstalling Steering Assembly to test Potentiometer Bracket and Fit

The final step in completing the steering assembly was to ensure the alignment of the sprocket-steering column system was perpendicular. This was completed with an Acetal Delrin plastic coupler machined on a lathe that ensured the steering column remained stable in the new design. Such a piece would secure the steering column in place as well as absorb any shock causing the steering column to quiver in place.
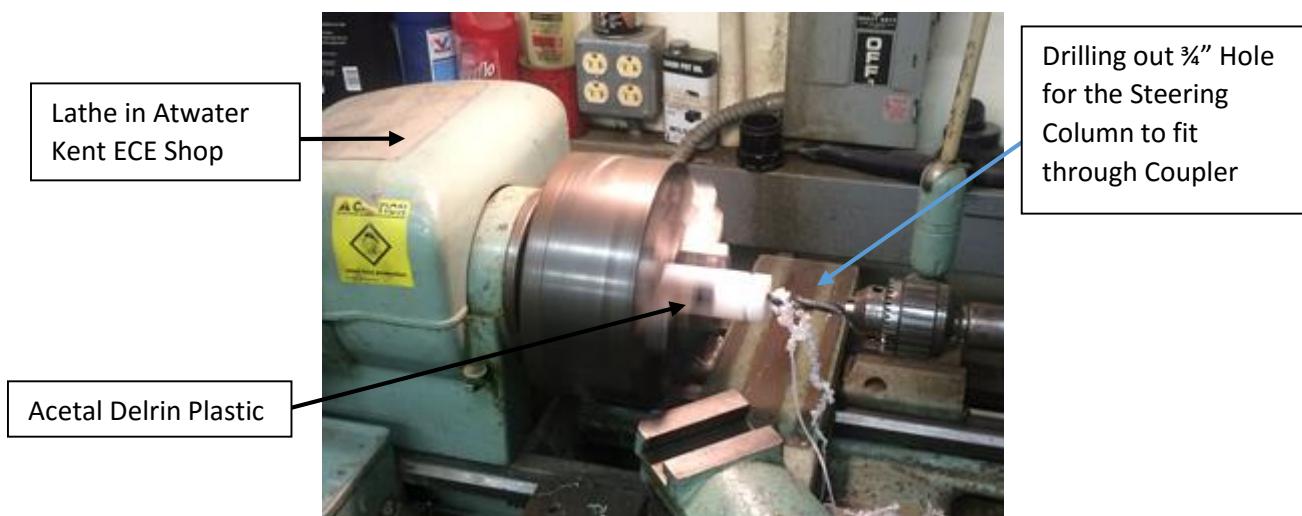
Figure 26: Machining Acetal Delrin Plastic Coupler for Steering Assembly

Once the alignment of the steering configuration was secured, the team tested the fit of the new design on the golf cart. Measurements were taking to ensure that each sprocket was flush so

that the chain would freely move the sprockets when the steering motor spins. Once this system was verified, the team applied several coats of oil-based paint to seal the metal from future rust and oxidation.

Figure 27: Testing the Newly-Cut Aluminum Back Plate before Final Assembly

All Hardware was Painted with Oil-Based Paint to protect from Rust.

All Hardware Components use Bolts and Washers

Potentiometer Bearing was tapped in

Right Angles were cut into the Old Iron Plate to accommodate Industrial Bearing
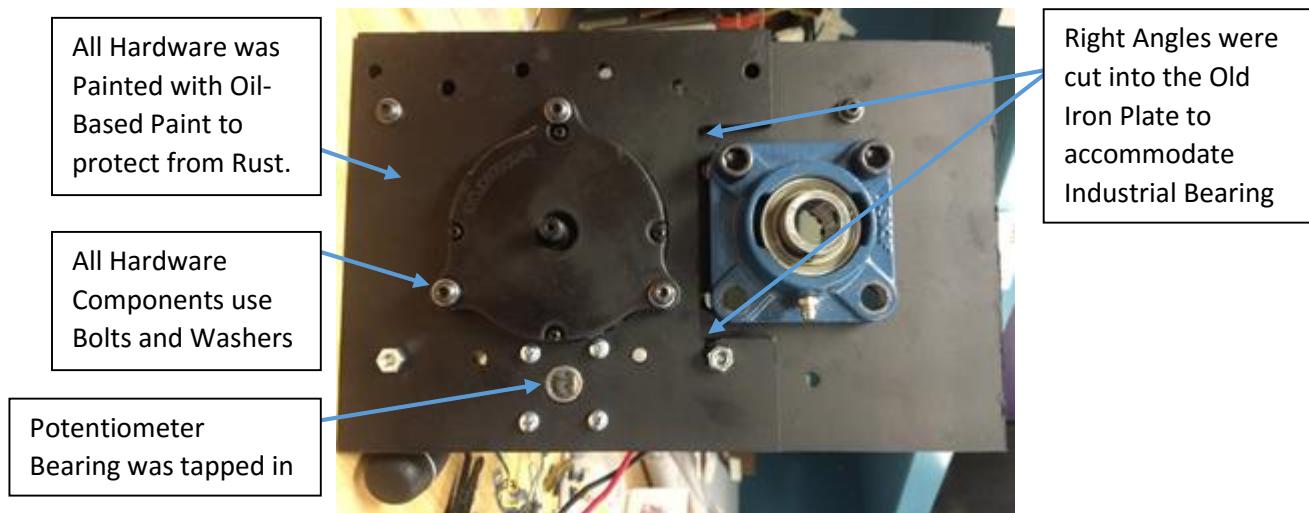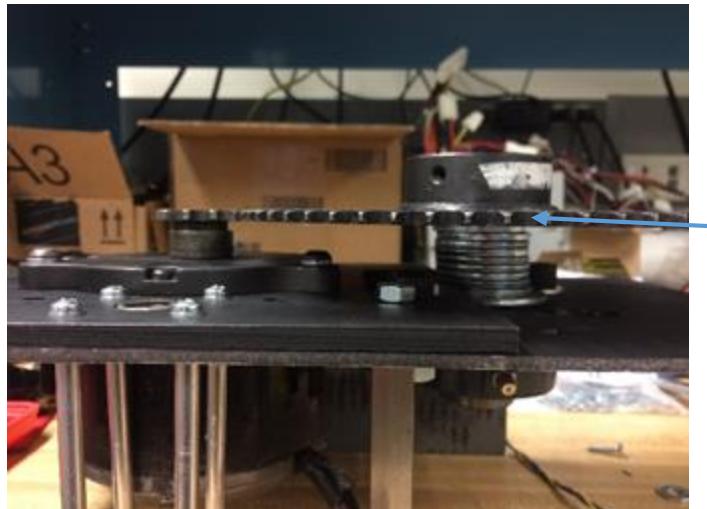
Figure 28: All Hardware Components were Painted, and Properly Installed

Verification of the final steering assembly was the final step in the redesign. Seen in Figure 29, the sprockets rested flush against each other, allowing a smooth rotation of the chain when the steering sprocket spins. Such a design was tested with the electrical control system put into place. Steering control is achieved by a pulse width module signal between an Arduino and a Dimension Engineering Sabertooth 2x60 motor controller. This motor controller supports six operating

modes, of which we used the Mode 2 which allows control via microcontroller pulses. The control signal uses a PWM signal with a 2ms period to control both speed and direction. With the Arduino Servo Library, we can effectively control the speed and direction of each motor attached to the Sabertooth motor controller.

Figure 29: Side Profile of Final Steering Assembly, Showing Alignment
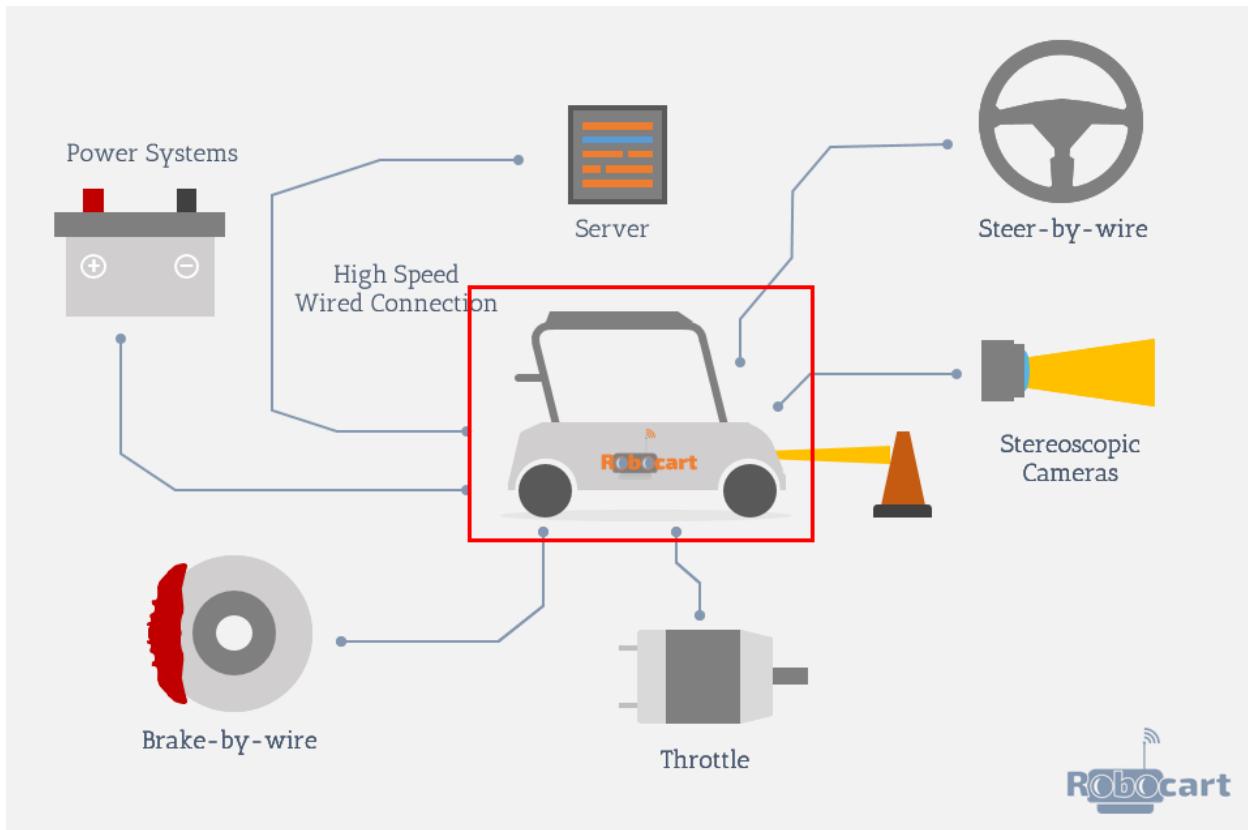
4.4 Chapter Summary

The implementation of the three main subsystems was the focus of this project. Each subsystem can operate completely separated from the rest of Robocart, which adheres to one of the project's overall goal of modularity. After each system was design and built, several tests were conducted on each proof of concept before implementing on the actual chassis. Once the subsystem was installed onto the golf cart, verification of functionality was once again conducted by using the server to communicate to each subsystem connected to an Arduino micro controller.

5 Additional Enhancements for the Autonomous Prototype

5.1 Body Restoration

When our team first started the project, we wanted to revitalize the Robocart name and image. The following chapter describes the restoration process the team undertook to give Robocart eye-catching appeal. Since the body of the golf cart should not be physically modified for it to still fit the chassis, we focused on proper automotive painting procedure and a clean finish.

We wanted to give the golf cart a new polished look to represent the modern technology that it is showcasing. At the beginning, our golf cart had hand-brushed lackluster red paint on it with dings and chips. After taking apart the golf cart to assess the condition of the chassis, the body panels were brought to County Line Auto Body in Jackson, New Jersey. The original paint job can be seen in the following Figures 30 and 31:

Body Panels painted in hand-brushed red paint
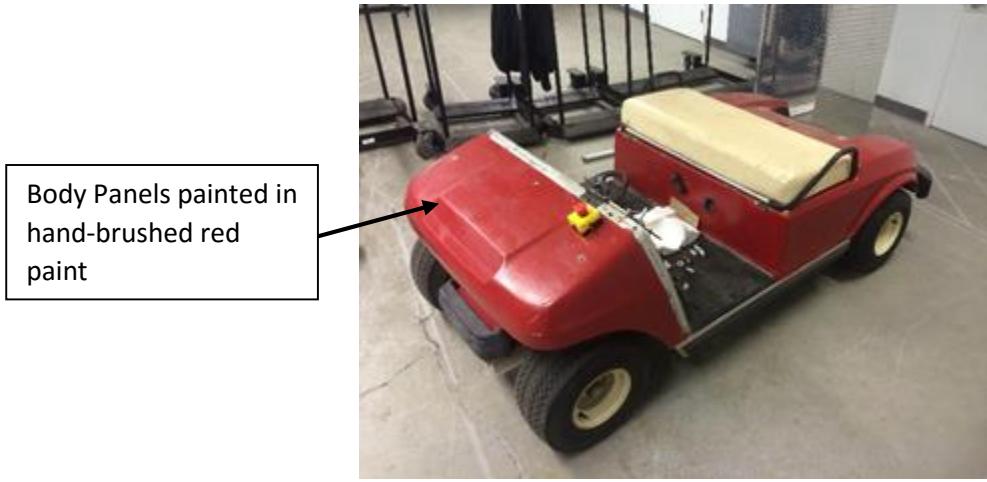
Figure 30: Original Condition of the Golf Cart Body Panels

Figure 31**:** Body Panels removed from Golf Cart and Transported to Auto Body Shop

Our team looked up the official WPI Marketing Team's colors that represent the University. The official WPI red can be seen in Figure 32 below, characterized by R172, G43, B55, or described by color "Pantone 187c."

Color that would be painted on the Golf Cart Body Panels
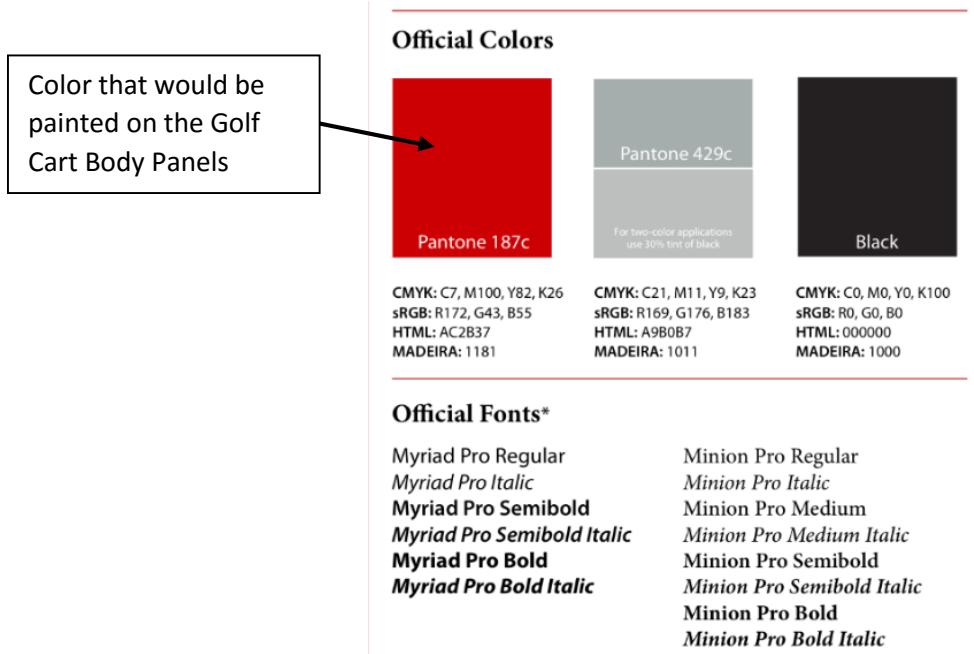
Figure 32: Official WPI Colors and Fonts

With access to an Auto Body DuPont paint shop, our team was able to mix the perfect blend of colors to match the university's trademark hue. All of the paint canisters can be seen below, in Figure 33, each with a significant color code identifier:

Figure 33: Various DuPont Stock Paints for Mixing and Matching to Color Cards

After sandblasting off the old paint job, filling in significant gouges, scratches, and imperfections, sanding the body smooth, we painted the body with a primer base coat. Then we

took the WPI blend of red with gloss and pearls added and painted the body. A clear coat was

added over the exterior to protect the finish. This is the new image of Robocart:

Thin Metal Wire was used to suspend the body panel during drying
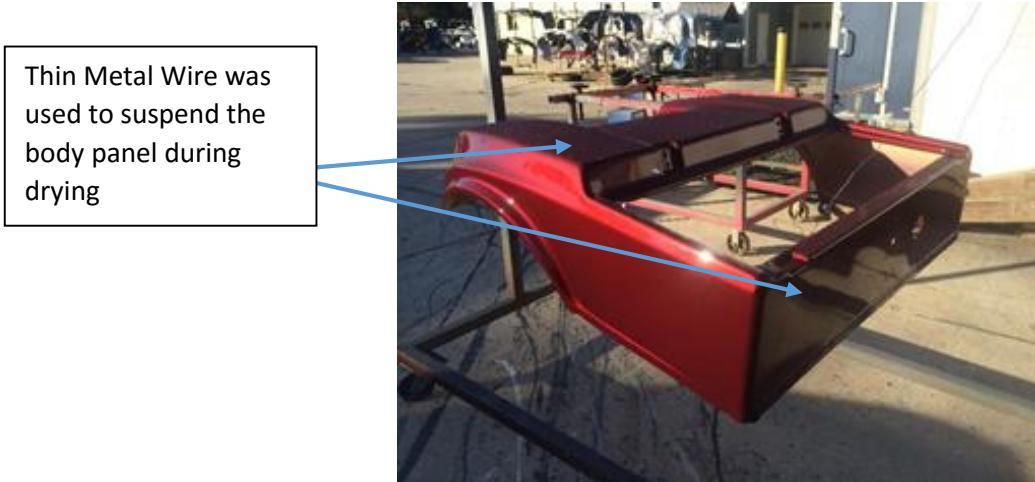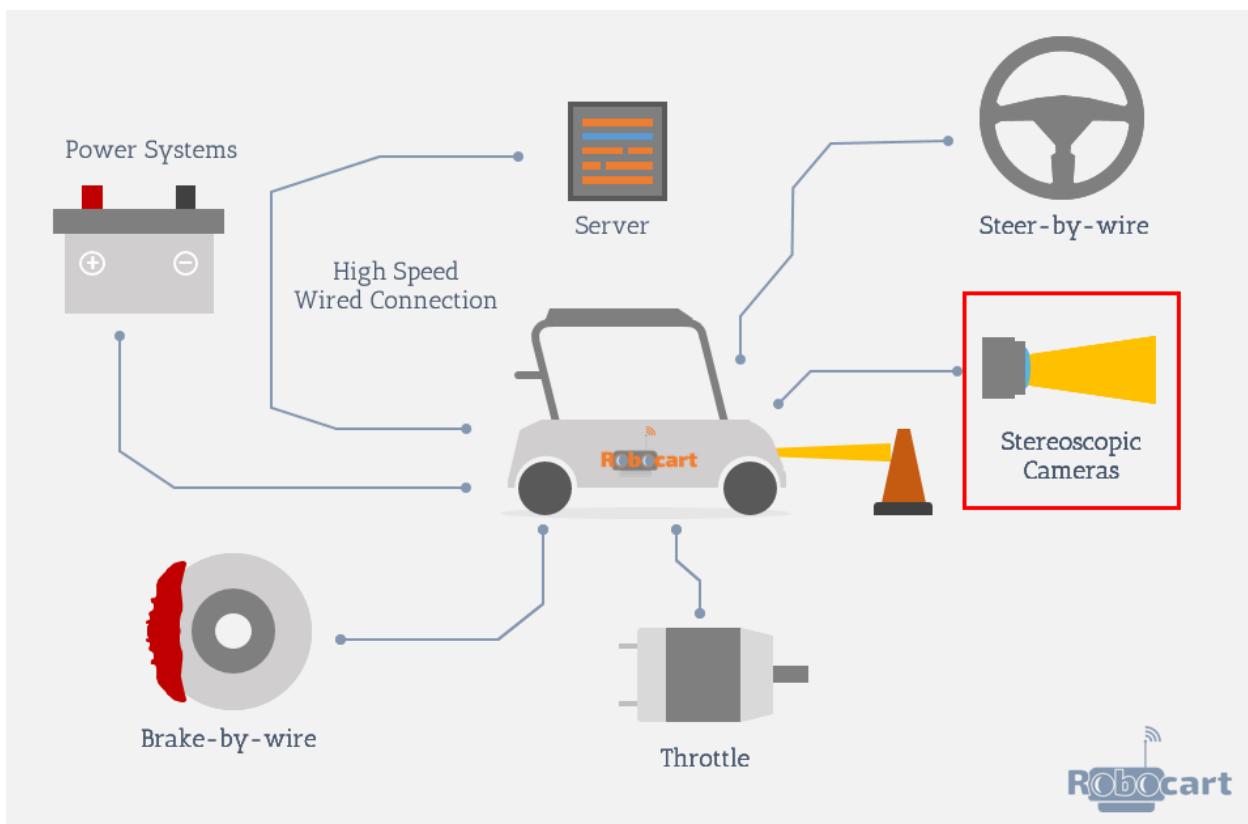
Figure 34: After Stripping Paint, Adding Compound to Damaged Areas, Sanding, Priming, and
Painting, the Rear Body Panel is complete.

Figure 35 and 36: Alternate View of Rear Body Panel (left) Front Body Panel (right)

5.2 Front Rack and Raspberry Pi / Camera Mounts

As mentioned in our proposed design, our team determined we needed some sort of modular rack in the front of the golf cart to accommodate the Raspberry Pi Computers, Camera Modules, power lines, Ethernet cables, monitors, and other prototyping equipment. Part of our design rationale was to have this assembly be modular, so we could easily remove it, service it, disassemble, and reassemble it at any given time. When prototyping anything, you need accurate dimensions, which can be seen below when taken with a digital level from an iPhone accelerometer.

Measuring the Angle / Incline of the Dashboard

Describing Chassis Features that need to be accommodated for in CAD

Estimating 3D Printed Block Dimensions to make Front Rack Parallel to Floor Pans
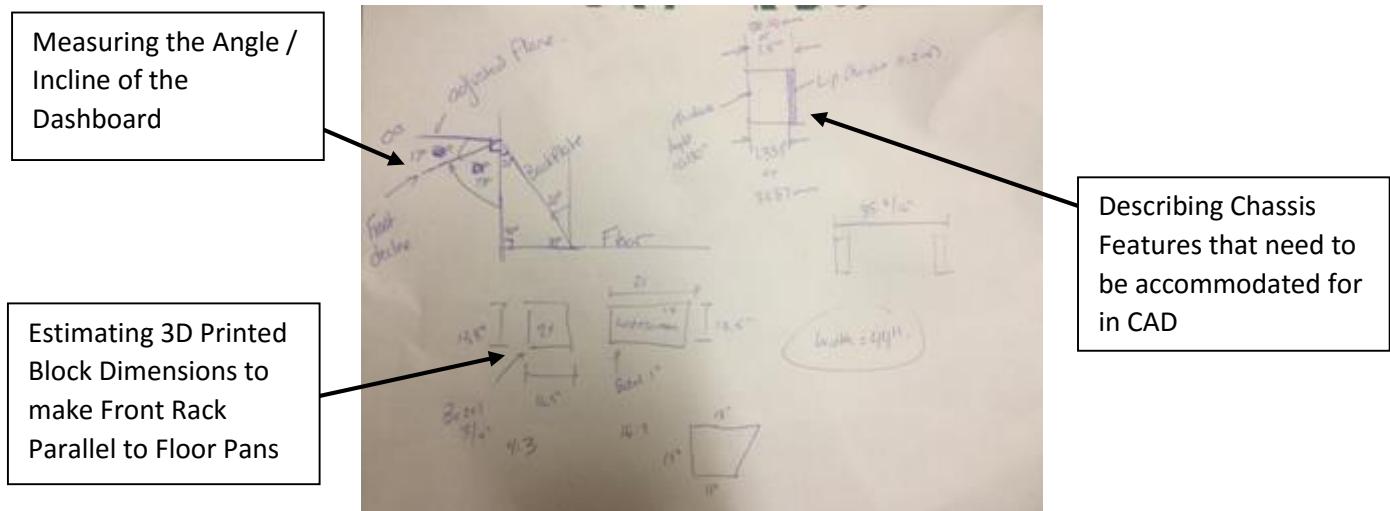
Figure 37: Dimensioning and Measuring Angles of the Golf Cart Chassis for Prototyping

Our team 3-D Printed a polylactic acid block which we secured to the aluminum dashboard of the Golf Cart chassis with bolts and hex nuts. Using "Hex Nut Traps" which are the rectangular holes on the side of the prototyped part, a 1/4-20 hex nut will sit perfectly flush along its shorter edges, preventing rotation. A hole is exposed on the underside of the plastic part. A complementary hole is drilled through the Golf Cart Aluminum Dashboard, and a bolt is secured through the plastic to the metal hex nut. This ensures a strong, tight fit without using many materials. This design retains simplicity, minimizes number of parts, and ensures strength while maintaining the overall modularity we had in mind. Multiple pictures of this design can be seen in the following figures:

80/20 T-Slot Extruded Aluminum bolted to 3D Printed Assembly

3D Printed Block orients the Aluminum to be Parallel to the Floor
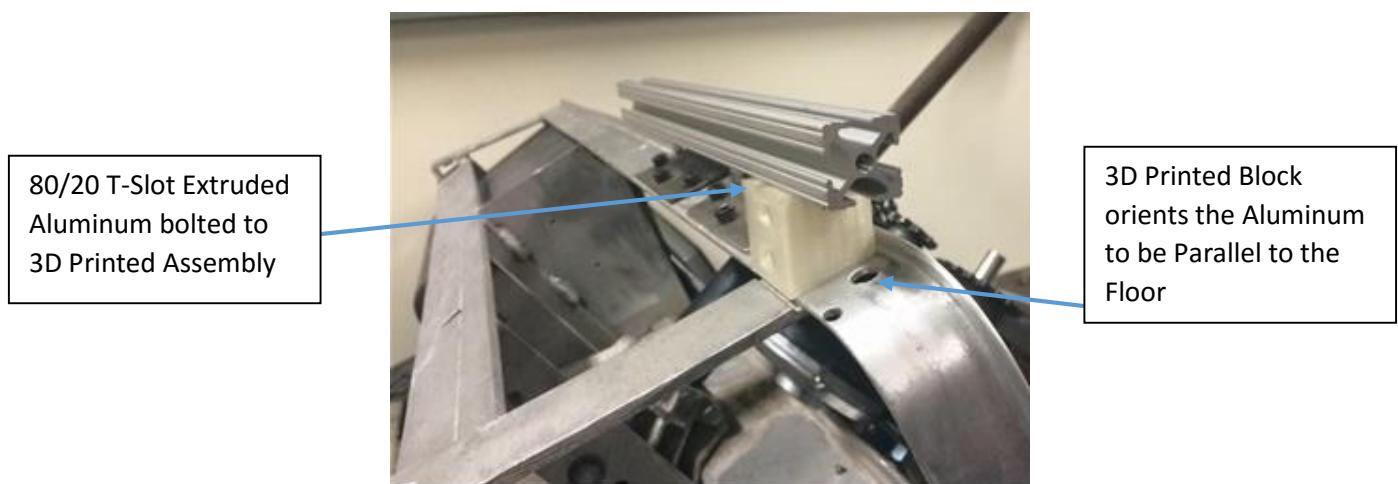
Figure 38: Testing fit of 3D Printed Bracket and the strength of the 80/20 Mounted on the block

Figure 39**:** Side Perspective of Front Rack to ensure Perpendicularity to Floor Pans

To mount the Raspberry Pi Computers to the 80/20 T-Slotted Aluminum Extrusion, our team designed and 3D-Printed a bracket out of polylactic acid that would match the mounting holes of the Raspberry Pi and center 1/4-20 bolts to be mounted onto the 80/20 framing solution. Triangles were cut out of the design as it was not a structural load-bearing component to save on plastic, and cost, without compromising the integrity of the design. The narrower rectangle, in Figure 40, is intended to be below the Ethernet and USB ports to match the footprint of the Raspberry Pi.

Raspberry Pi is mounted by M3 Bolts on these 4 corner holes

Triangles were cut out to maintain strong and ridged design while minimizing cost

1/4-20 Bolts are used on the sides to attach to the 80/20 Front Rack
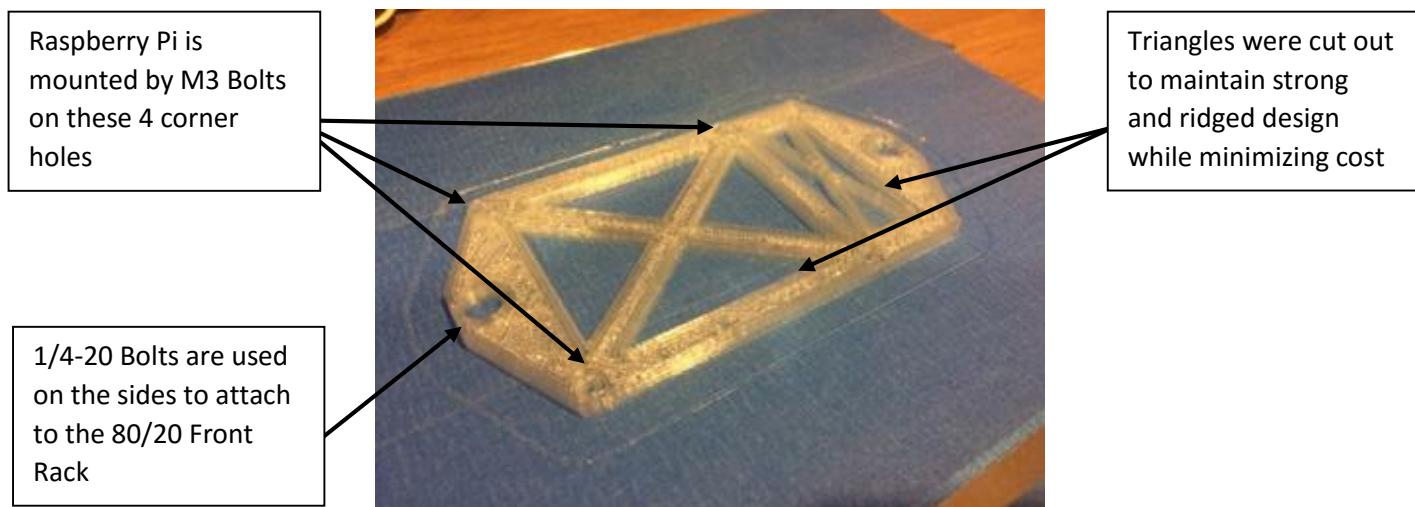
Figure 40**:** 3D-Printed Raspberry Pi to 80/20 Bracket we designed.
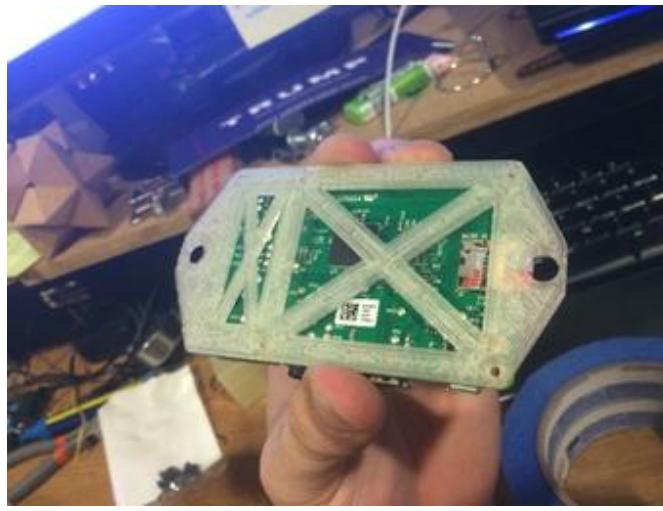
Figure 41: Checking Raspberry Pi Hole Alignment on the 3D Printed Bracket

T-Nuts were used to slide along the 80/20 for fine adjustments but once tightened, remain locked in the channel of the aluminum
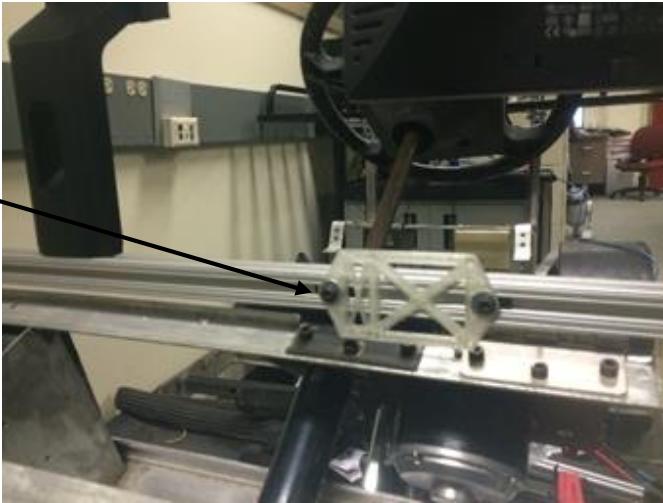
Figure 42: Checking compressional strength of 3D Printed Bracket and Ease of Adjustability

M3 Bolt Risers for the Raspberry Pi Camera Plate

Raspberry Pi Camera Mounting Holes
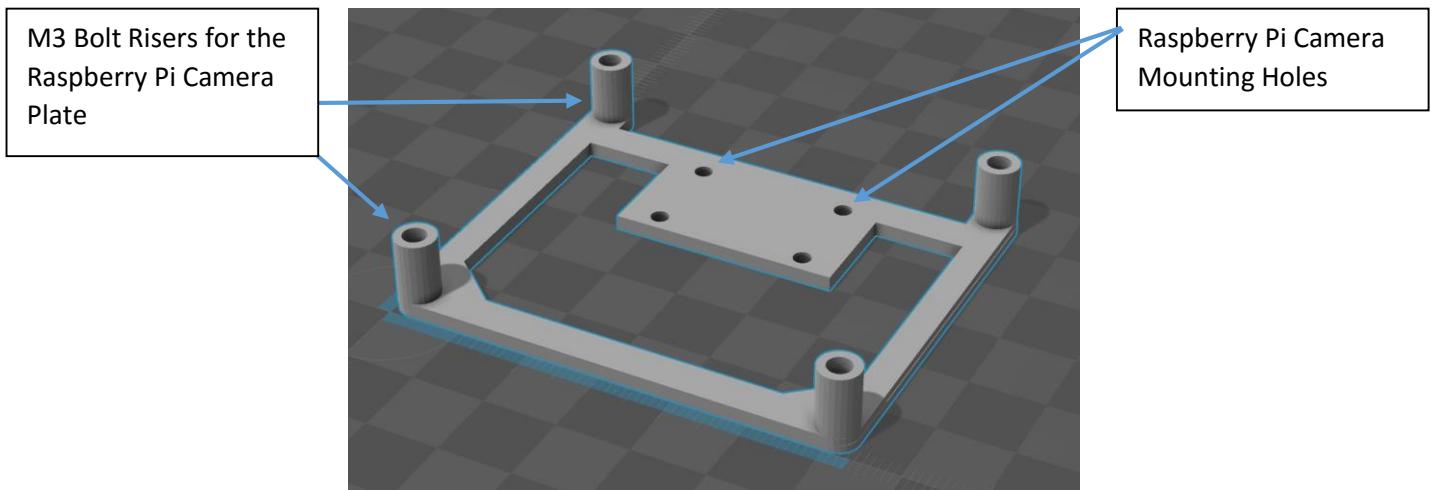
Figure 43: Rendering of Raspberry Pi Camera Bracket our team designed.

M3 Bolts securing the Camera Bracket to the Raspberry Pi

White 3D Printed Camera to Raspberry Pi Bracket

Figure 44: Raspberry Pi Camera Bolted to Bracket and Aligns with Raspberry Pi Hole Mounts

1/4-20 Bolts Secure the Raspberry Pi – Camera system to the Modular 80/20

GPIO Pins are still exposed for additional components to be connected to Raspberry Pi
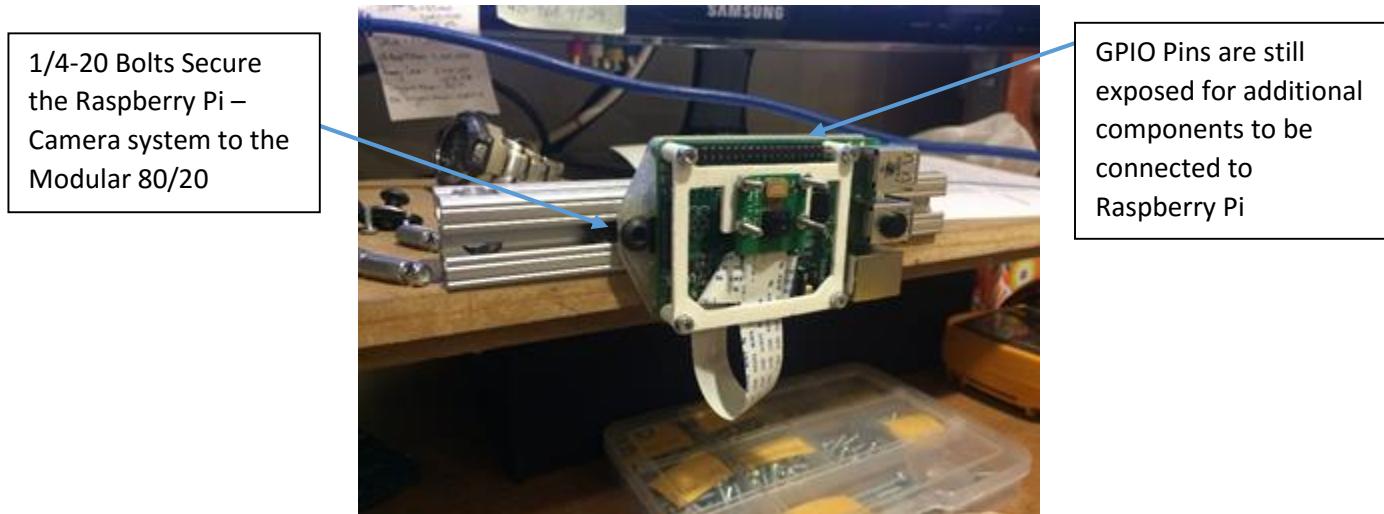
Figure 45: Checking Fit of Raspberry Pi – 80/20 – Camera Bracket System

Modular 80/20 allows for additional components, such as monitors, to be mounted to the Front Rack

The Raspberry Pi with Cameras can translate along the front of the rail to optimize Field of View during testing.

Figure 46: Screens attached to the modular 80/20 rack for testing and displaying functionality
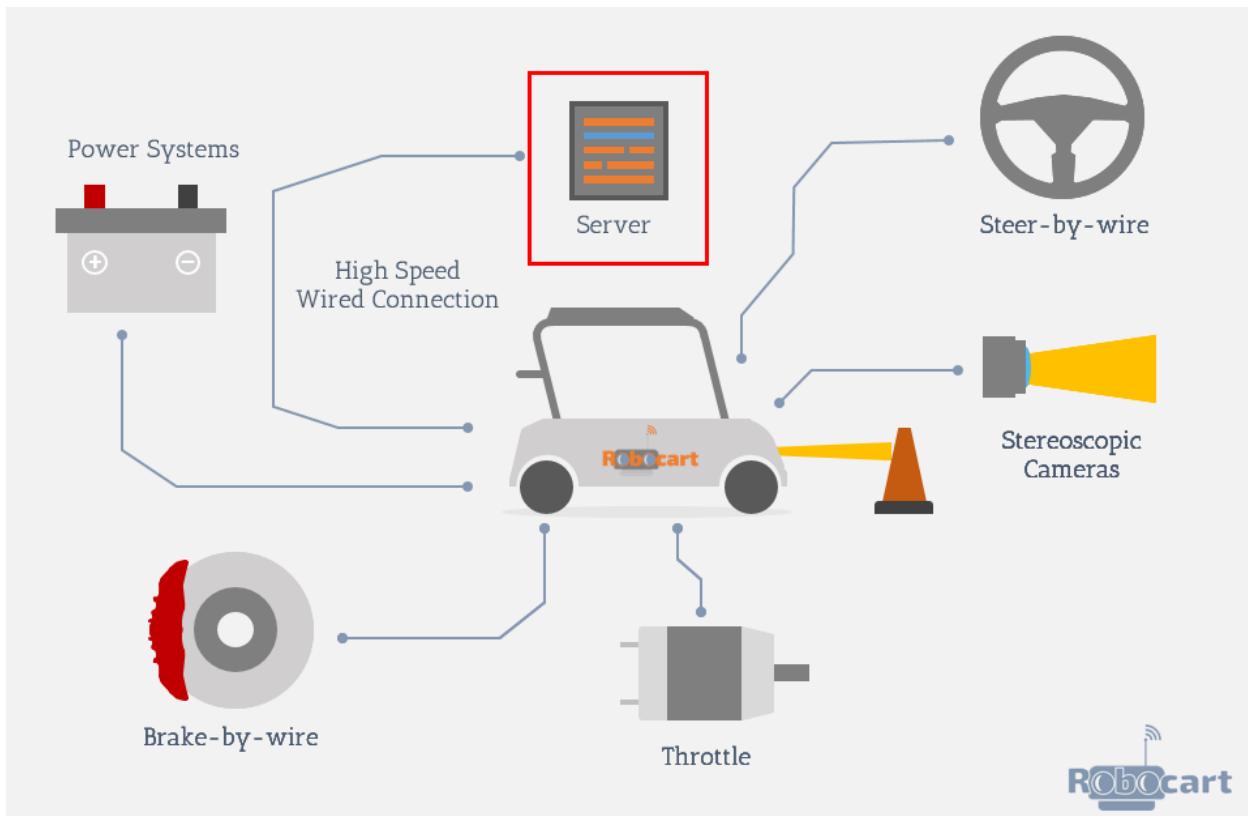
Raw Camera Data, Server Information, Terminal Console, and other Valuable Information can be seen on the Prototype Displays

Figure 47: Alternate Perspective of First Iteration Prototype of Autonomous Ground Vehicle

5.3 Server (Software) and Server Rack (Hardware)

In previous years, other MQP teams attempted to wirelessly transmit raw data to a remote server for image processing and computation. Although this worked as a proof of concept, problems with latency, occlusion, and packet loss were providing erroneous data to the Golf Cart. To rectify this, our team determined it would be optimal to move the Server onto the cart and tether all of the image capturing devices (Raspberry Pi) to the Server over Ethernet cables through a local unmanaged network switch. This would provide low-latency, high bandwidth, high resolution and optimal performance for navigating off of processed images. A previous MQP team built a metal cage around the server to protect it when deployed in the field for testing.

Upon starting project, Server was enclosed in this steel frame and was meant to be stored off the Golf Cart.
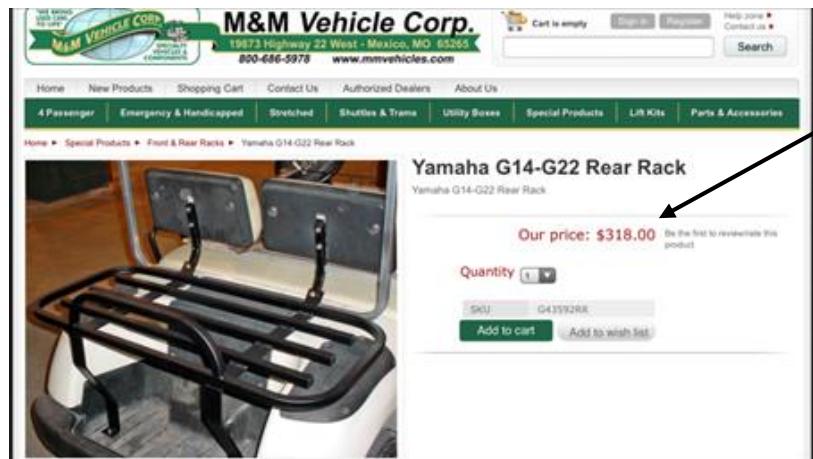
Figure 48: Original Angle-Iron Enclosure to protect the Server

To move the server onto the Golf Cart, our team looked at other commercially viable solutions for cargo and equipment. We found utility trays (See Figure 49) and cargo racks (see Figure 50) but these were usually priced outside of our budget and provided us with limited attachment options. Our team opted for a custom modular design using a cost-effective commonly available tow-hitch utility rack and 80/20 T-Slotted Aluminum Extrusion.
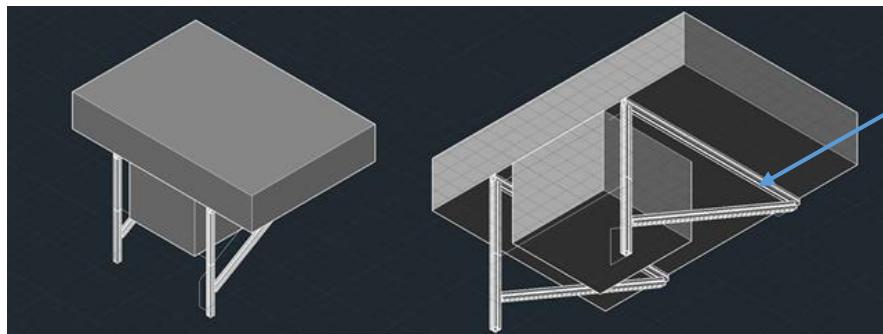
Figure 49: Cargo Box / Tray Solution from JustGolfCarts.com

Comparable Designs were available but with less modularity and for much more money.

Figure 50: Commercial Equivalents of our Modular Cargo Utility Rack

Our initial solution can be seen below, in Figure 51, modeled in AutoCAD, a commercial

software application for 3D computer aided design and drafting:

Original Design was a Right Triangle to support the back of the Cargo Rack

Figure 51: AutoCAD Rendering of First Iteration Design of Cargo Utility Rack

Below, in Figure 52, you can see the assembled Tow-Hitch Utility Rack, purchased from

Harbor Freight, which will hold all of our additional batteries, server, and equipment, while

maintaining a modular design using the 80/20 T-Slotted Aluminum Extrusion seen in Figure 53:

This is a $40 Cargo Tow Rack from Harbor Freight which will adequately cover our purposes for this prototype.

Cargo Rack has similar metal square tubular construction as seen in previously stated commercial products.

Figure 52: Square Tubular Based Construction on Towing Cargo Rack

Figure 53: Taking Inventory of Various Lengths of 80/20 Modular Framing Solution

Air Incorporated generously donated scrap pieces of 80/20 to use for our Project. Our team took inventory of the lengths, features, and imperfections on the aluminum extrusion before allocating them towards our project. These allocations and inventory sheets can be seen below in Table 2:

Table 2: 80/20 T-Slotted Aluminum Scrap Inventory Sheet

	Fractional (US Standard) - 1010	Low Profile Drilled Holes	Threaded?	Deep / Wide Holes
2	31"	3	Both Ends	
3	18"	0	1 End	
4	36"	0	No	Both Ends
5	31"	2	Both ends	
6	17-3/8"	2	No	
7	32"	3	No	1 Small / 1 Large
8	19"	0	No	
9	16"	0	No	
10	31"	2	Both Ends	
11	12-9/16"	0	No	
12	11"	4	No	
13	65"	0	1 End	
14	11"	4	No	
15	2-3/8"	1	No	
16				
17	Metric - 25mm x 25mm			
18	36-3/4"	0	Both	
19	25-3/4"	2	No	
20				
21	302.3125"	Our Design		
22	*0.23	2x 31" Vertical		
23	69.531875	2x 19.25" Horizontal		
24		2x xx" Diagonal		
25				
26		Rear 20" Support Bar		
27		Front 20" Support Bar		

After speaking with the mechanical engineers there and drawing out our design on Isometric Drafting Paper, we had a pretty good understanding of what type of design considerations we should keep in mind. Our drafts can be seen below in Figure 54:

Original Location of 90-Degree Aluminum Brackets for Structural Integrity
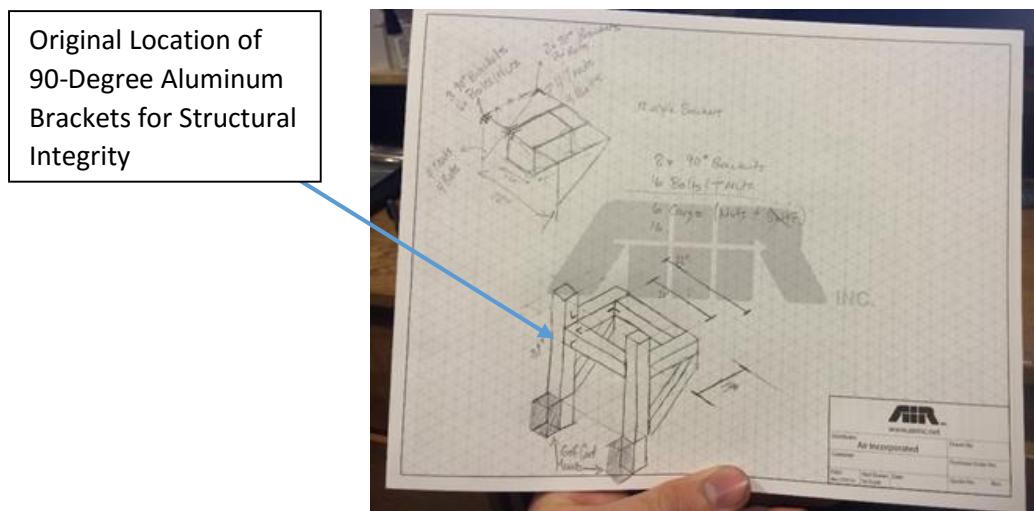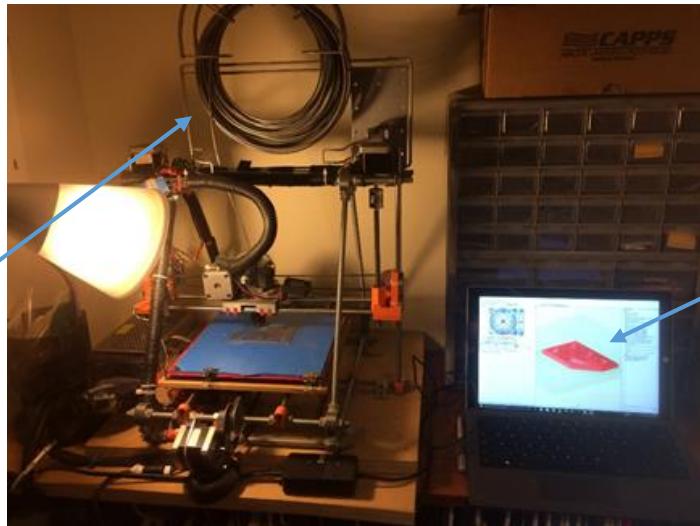
Figure 54: Design was drawn out on Isometric Drafting Paper.

Our team considered commercially manufactured 80/20 90° Pivot Brackets, as seen below in Figure 55. They are very strong and excellent in specific applications, but were overblown for our application. Our team determined it was more cost effective and convenient to 3D-Print Pivot Brackets as the polymer Polylactic Acid (PLA) was beyond strong enough for our application.

Aluminum Pivot Brackets were available but expensive. For our purposes, PLA is strong enough

Figure 55: Commercially available 80/20 pivot brackets

Brackets were printed out of Polylactic Acid (PLA) at 185 Degrees Celsius, 35% Infill, 3 Vertical and Horizontal Shells

80/20 Pivot Brackets seen here on Pronterface, the 3D-Printer Interface Program

Figure 56: 3D Printing our own 80/20 Pivot Brackets

After printing out four brackets, our team bolted them onto random sized pieces of 80/20 from the inventory sheet above. Our test can be seen below in Figure 57. We were just interested in the structural integrity and strength of our newly-printed parts. From a cost saving perspective, our team printed out 8 brackets for approximately $6.40 whereas the commercial equivalents would have been in excess of $70 before shipping and handling. This was an 11-fold cost effective design decision.

Three Aluminum Angle Brackets were used here to ensure structural integrity

Two Pivot Brackets were added with a Diagonal Member to support the load acting on the end of the 80/20 Bar
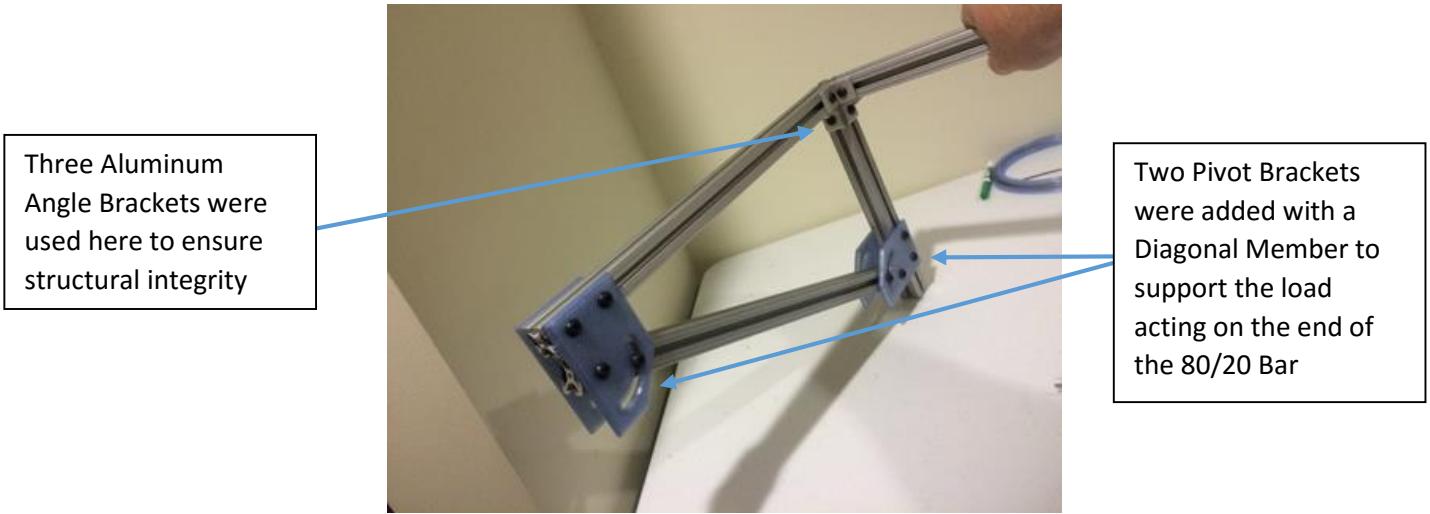
Figure 57**:** Testing the strength and fit of our 3D-Printed 80/20 Pivot Brackets

To reassure our peers of the strength of Polylactic Acid (PLA), Makerbot Industries, a New York City-based company founded to engineer and produce 3D-Printers, conducted a study on the impact, tensile, compressive, and flexural strengths of 3D-Printed plastics. Their results can be seen below in Figure 58.

Impact (Un-notched IZOD)
ASTM D256

PLA		ABS	
STD	1.8	5.7	STD
MAX	4.1	6.2	MAX

Impact Strength in ft-lb/in

Tensile Strength
ASTM D638 Type IV

PLA		ABS	
STD	6783	4936	STD
MAX	9531	5532	MAX

Peak Stress in PSI

Compressive Strength
ASTM D695

PLA		ABS	
STD	2600	1100	STD
MAX	13600	7100	MAX

Peak Stress in PSI

Flexural Strength
ASTM D790

PLA		ABS	
STD	8970	5344	STD
MAX	13731	8646	MAX

Peak Stress in PSI

Figure 58: Makerbot's PLA and ABS Strength Data for 3D-Printed Plastics

With these numbers in mind and our application considered, we carefully designed our Pivot Brackets with flexural and compressive strength in mind to ensure structural integrity. The annotations and labels in Figure 59 explain our design choices for our brackets:

Rectilinear Layers on the Surface for Flexural Strength

Concentric Layers on the Mounting Holes for Compressive Strength on Bolts
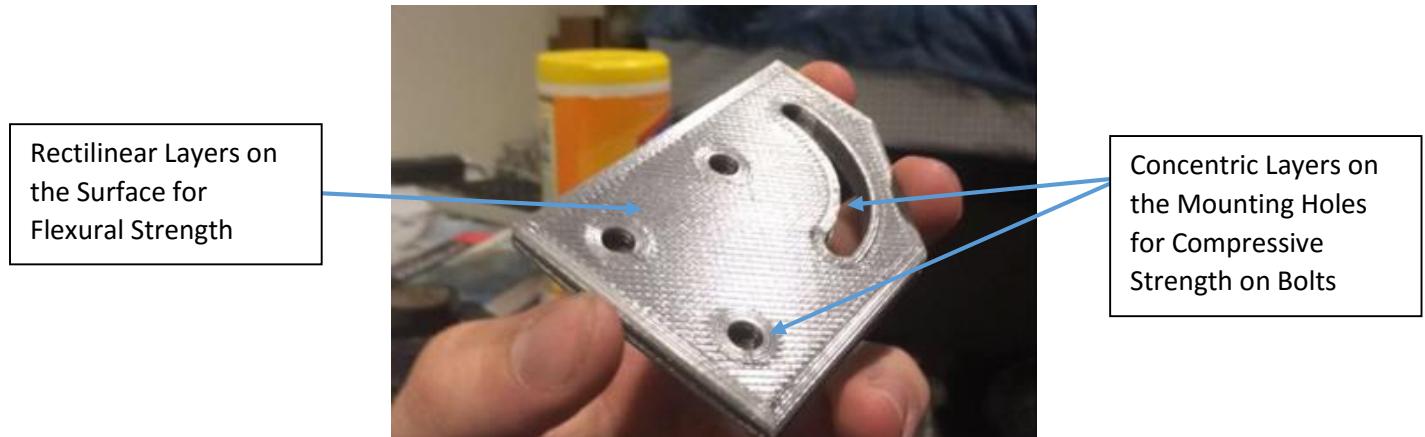
Figure 59: Showing the Finish and Construction of our 3D-Printed 80/20 Pivot Brackets

5.3.1 Attaching the Cargo Utility Rack Posts to the Prototype:

Using the geometry of the existing holes on the Golf Cart, such as the ones for the old backrests or the canopy top, our team was able to frame out the parallel and perpendicular lines on the rear golf cart panel. These markings allowed us to cut lines perpendicular to each other and prevent paint chipping. Both of these elements are required to get a snug, professional, and polished look for the final prototype:

Pilot holes drilled into the corners before linear cuts are made

Many layers of painters tape was used to prevent Paint Chipping
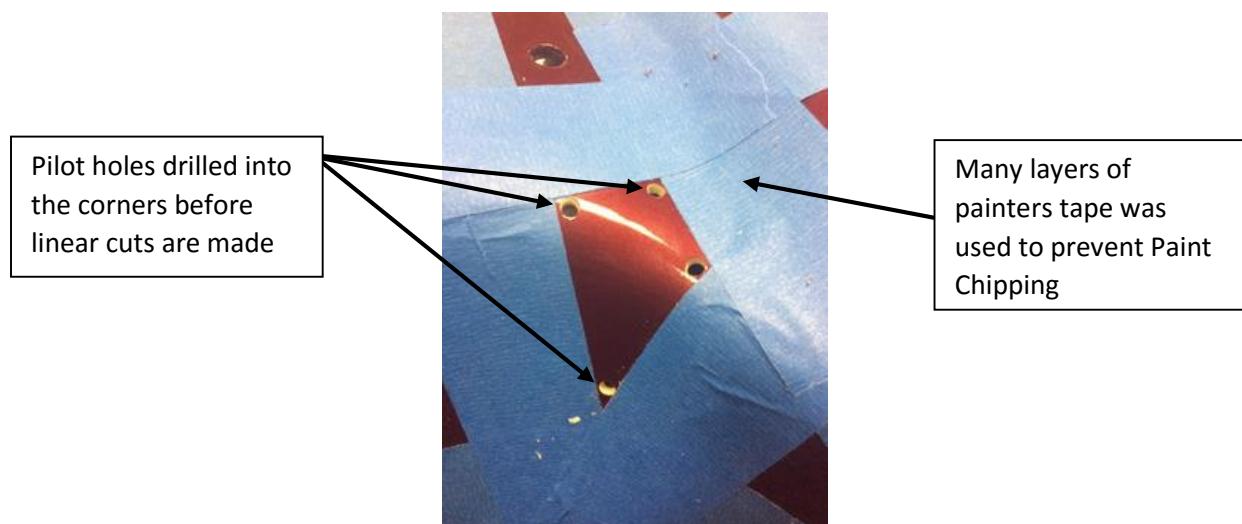
Figure 60: Preparing the Rear Body Panel for Modification by Drilling Pilot Holes in the Corners

After pilot holes were drilled in the corners, a sharp cutting blade was used on a Dremel, at medium speeds, to cut through the panel. When looking down, the holes should resemble a 1.25" x 1.25" square. Due to the stylish and sloping nature of the back of the Golf Cart to accommodate golf club bags, precise measuring tools had to be used to ensure proper cuts were made. Our painters tape framing and notes can be seen below in Figure 61:

Using Geometry of the Existing Holes, Parallel and Perpendicular Painters Tape was laid on the Body Panels

Using a Dremel and cutting attachment, straight lines were cut through the body panel before sanding
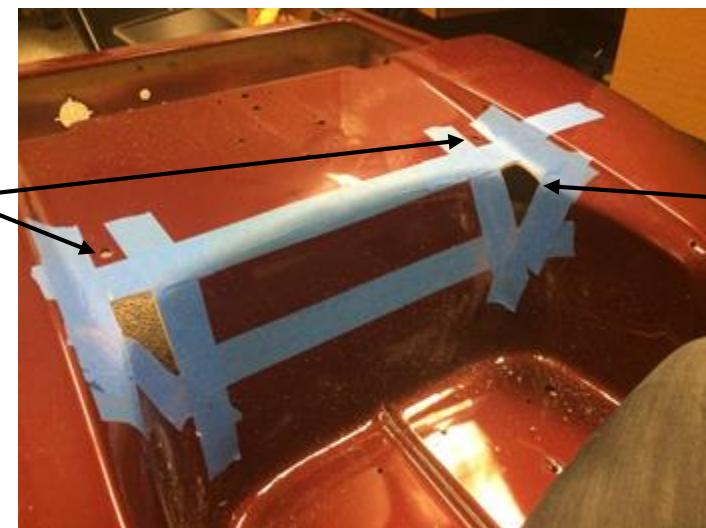
Figure 61: Framing and Layering Painters Tape on the Body Panel to Prepare for Cutting

Additional layers of Painter's Tape was added along the perimeter of the cuts to ensure that the paint didn't chip up while cleaning up the cuts. Once the initial cuts were made, the cutting blade was swapped out for a sanding drum on the Dremel. At slow to medium speeds, any remaining excess from the cuts were sanded down to leave a polished clean cut in the body panels. This process can be seen below in Figure 62:

Additional layers of Painters Tape was applied to ensure no further paint chipping

Sanding Attachment was used on Cordless Dremel to smooth out rough edges for precise and snug fit
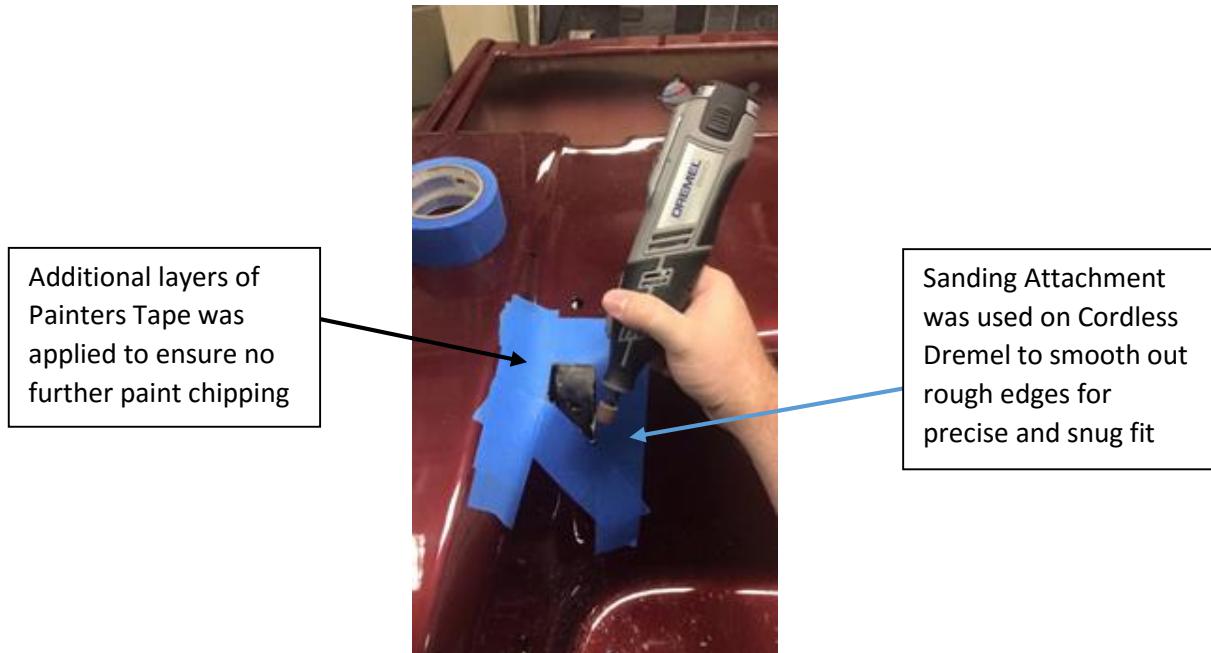
Figure 62: Adding Additional Layers of Painters Tape and Sanding down any rough cuts

After dimensioning all of the edges and testing the fit with the 1¼" square tubing, the painters tape was removed. The square tubing was secured once again to the chassis using the ½" bolts and hex nuts and the body was lowered over the posts and snug against the chassis. Due to careful measurement and planning, the resulting product came out very clean as seen below in Figure 63:

The 1-1/4" Square Tubing fits snug and flush with the new cuts in the Body.
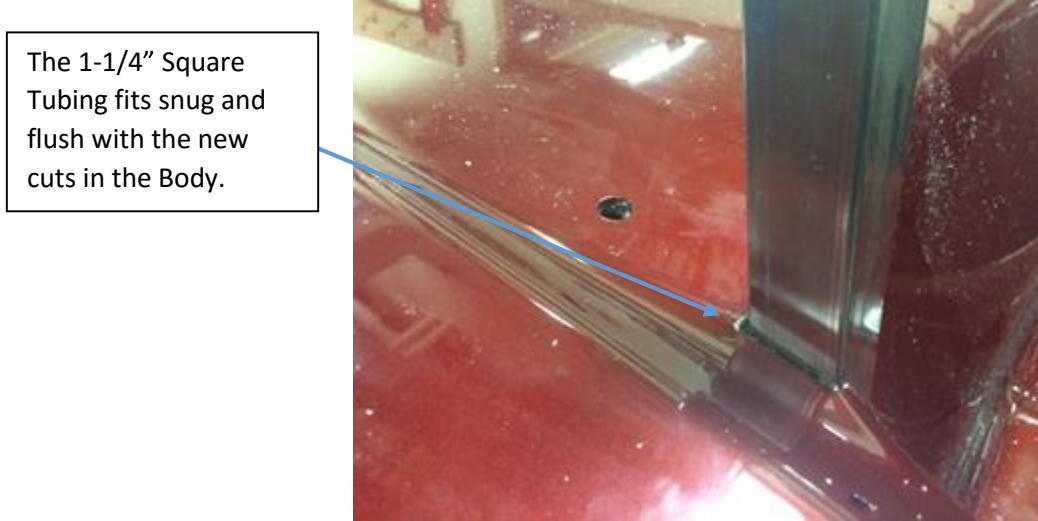
Figure 63: Square Tubing fitting flush with the new cuts in the rear Body Panel
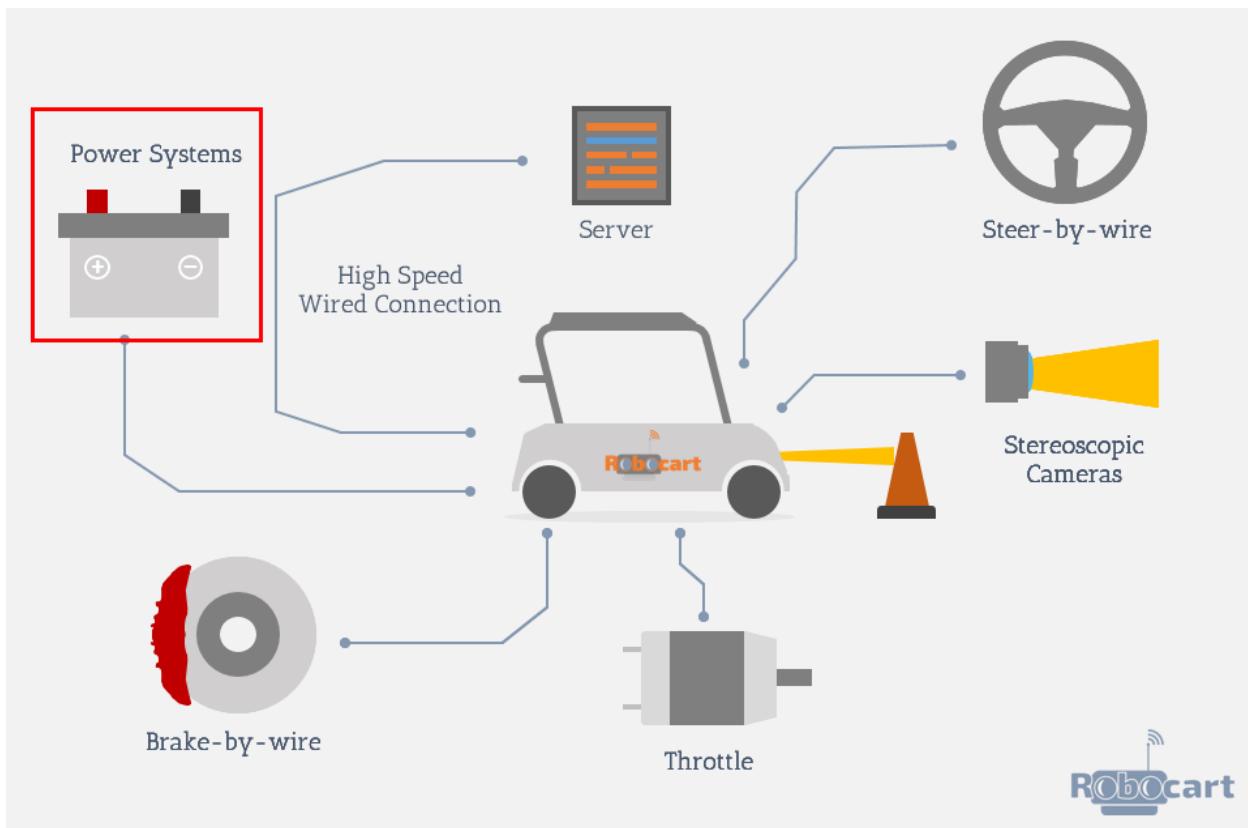
Our Cargo / Utility Rack, which is bolted onto the 1" x 1" imperial 80/20 T-Slotted Aluminum Extrusion, was lowered into the 1.25" x 1.25" square tubing. Weight was slowly added onto the utility rack to ensure that, under load, it would hold up to our performance specifications. The final Square Tubing, 80/20, Cargo / Utility Rack system can be seen in the following figure:

Figure 64: Rear Perspective of the Cargo Rack and Square Tubing mounted through Body Panel

5.4 Power Systems

The power systems behind Robocart was one of the first areas of improvements our team identified since the vehicle cannot operate without a source of power. As previous project had not focused on power systems, this year's project brought improvements to the batteries to light. This section will focus on the considerations when replacing batteries, physically modifications for housing, as well as preliminary testing to ensure electrical sustainability.

Our team visually inspected the batteries when we received the Golf Cart in September 2015 and they seemed corroded and in poor condition. To test our theory, the team brought the batteries to local Worcester Country Club and had them load tested by the Golf Cart technicians there. They informed us the batteries were from 2002, maintained in somewhat poor condition, and deemed they should be replaced. Some bulging on the side walls of the battery can be seen,

which is usually a sign of a weathered battery and should be replaced, when possible. The original

condition of the batteries can be seen below in Figure 65 and Figure 66:

Batteries were 8V NAPA Specialty Golf Cart Batteries from 2002

Figure 65: Condition of the Golf Cart Batteries starting the project in September 2015

Lots of corrosion can be seen around the terminals

The batteries were also bulging on the sides

Figure 66: Batteries exhibiting bulging on the sides and corrosion at the terminals.

Battery Details:
Configuration: 6x 2002 8-Volt NAPA Deep Cycle Batteries
Condition: Charged, Load Tested, Needed to be replaced
Proposed Solution: Replace with Marine Grade Deep Cycle Batteries for Cost Effectiveness
Batteries Considered: -AGM (Absorbed Glass Mat) -Wet Cell (Flooded) -Gel Cell

Our team went out to local battery department stores and looked at the different form factors, prices and capacities. Afterwards we determined price per amp hour, volume, charge density, and total cost of the entire bank. Our results can be seen below in Table 3:

Table 3: Battery Design Rationale

Battery / Group	Price	"Reserve Capacity"	RC in 25 Amp Units	Amp Hours (RC * 0.4167)	$ / Amp Hour	Length	Width	Height (To Terminals)	Volume	Charge Density	Total Cost
	$USD	Mins @ Current	Mins @ 25 Amps	Capacity (Ah)	$ / Ah	In.	In.	In.	Ft^3	Ah / Ft^3	$USD
	(Lower is Better)	(Higher is Better)	(Higher is Better)	(Higher is Better)	(Lower is Better)				(Lower is Better)	(Higher is Better)	(Lower is Better)
SL34MAGM	$119.88	120	110.4	46.00368	$2.61						$359.64
24 DCC	$79.62	150 Mins @ 23 Amps	138	57.5046	$1.38	10	6.5	9.5	0.35734972	160.9196728	$238.86
24 DC	$74.87	140 Mins @ 23 Amps	128.8	53.67096	$1.39	10	6.5	9.5	0.35734972	150.1916946	$224.61
24 MS	$59.88	90	82.8	34.50276	$1.74	10	6.5	9.5	0.35734972	96.55180365	$179.64
27 DC	$79.88	200 Mins @ 23 Amps	184	76.6728	$1.04	12	6.5	9.5	0.428819664	178.7996364	$239.64
29 HM	$84.67	225 Mins @ 23 Amps	207	86.2569	$0.98	12.75	6.5	9.5	0.455620893	189.3172621	$254.01
31 C	$99.87	190	174.8	72.83916	$1.37	13	6.5	9.5	0.464554636	156.7935273	$299.61
GC2 (Golf Cart) **	$84.52	105 Mins @ 75 Amps	315	215	$0.79	10.25	7	11	0.456742132	470.7251312	$507.12

Sam's Club now accepts American Express - Which Extends Product Warranty by 1 Additional Year & Purchase Protection for 90 Days

Sam's Club also acceps Business Checks for Tax Exemption for Educational Purposes with a WPI Letterhead

By Design Rationale, I would personally conclude the 29 HM is the best bang for your buck. I do have to check if the dimensions work for the Golf Cart (I believe they will)

** $ / Ah for Golf Cart Battery was Adjusted in Table to account for 6 Batteries (Double $ / Ah)

Existing Battery Trays were showing rusting and covered with some battery acid.

Figure 67: Battery Trays showing signs of rust from weathering and battery acid exposure.

Our team determined it would be most structurally sound if we installed a panel that was braced on both sides, at all points, for the best case scenario results. Our team opted for ¼" Medium Density Fiberboard (MDF) due to its high manufacturer standards for straightness of the panels. We then drilled four holes through each board, and through the aluminum. We secured the boards to the chassis with bolts, washers, and hex nuts. We placed two batteries cautiously on the center

battery tray, and to our expectation, the panels supported the batteries without any sign of wear, warping, or deviation. We deemed this upgrade a success.

Wood Floor Pans were Cut, Painted, and bolted to sturdy parts of the existing chassis to support the weight of the new batteries and protect the electronics
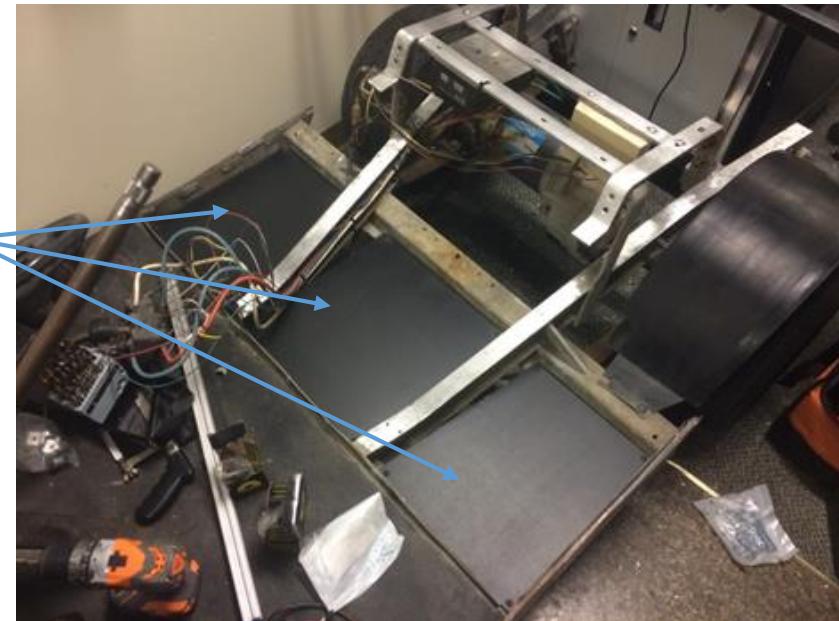
Figure 68: New Battery Pans bolted to the Golf Cart Aluminum Chassis
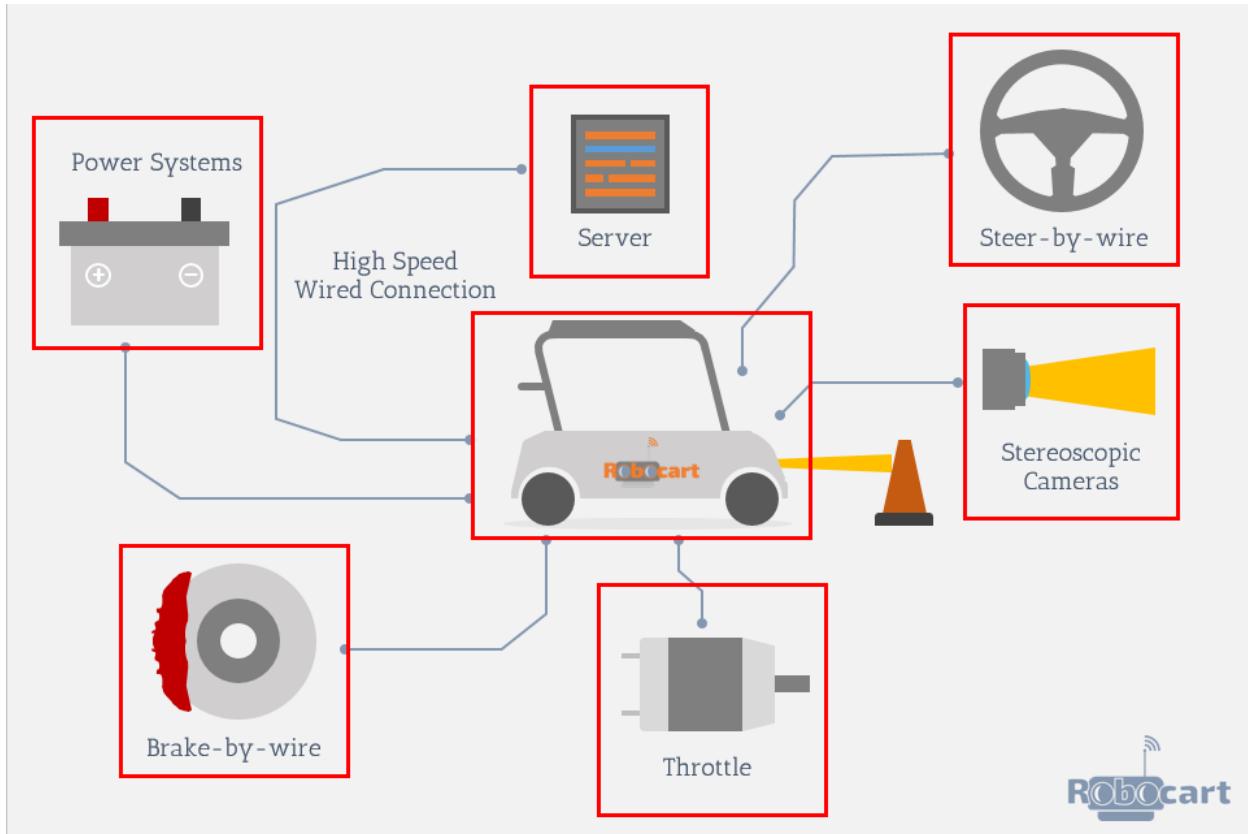
5.5 Chapter Summary

A secondary goal of this year's project was to improve the physical appearance of Robocart, as well as reinforce the existing chassis with mechanical improvements. Once body restoration had been complete, the team worked on designing mechanical components to house the Server and raspberry pi cameras for future project work. Finally to finish chassis renewal, the team analyzed and replaced the existing power systems with a new battery configuration.

6 System Integration

6.1 Assembly Diagram

The final objective of this project was to integrate all control systems of Robocart together into one centralized hub. Doing so would simplify assembly and disassembly should future modifications be made.

6.2 System Integration and Electrical Harness

To reiterate the team's goals at the start of the project, we wanted to obtain control of the three main subsystems of the golf cart: steering, braking, and throttle control systems. To do so, the team established communication between the high-level information processing of the server with the low-level hardware control of each subsystem. After each subsystem was successfully integrated and verified, the team consolidated all wires and electrical systems to one central bundle of cables to organize and distinguish each electrical system. A 24-pin ATX computer power supply

connector was used to group all connection to the electrical control systems of the golf cart to one central hub. Doing so allows easy continuity checks during system calibration and diagnostics, as well as modulation when the golf cart needs to be transported between operation and storage. The pin configuration of the connector is shown in Table 4.

Table 4: 24-Pin Connector – Female / Electronics Box End

	Color Wire	Description	Connection Notes
0	Color Wire	Description	Connection Notes
1	Brake +	3 Feet, 12V, 18 Gauge, Rated for 60 Amps	To Sabertooth
2	Brake +	3 Feet, 12V, 18 Gauge, Rated for 60 Amps	To Sabertooth
3	Brake -	3 Feet, 12V, 18 Gauge, Rated for 60 Amps	To Sabertooth
4	Brake -	3 Feet, 12V, 18 Gauge, Rated for 60 Amps	To Sabertooth
5	Pancake +	3 Feet, 12V, 18 Gauge, Rated for 60 Amps	To Sabertooth
6	Pancake +	3 Feet, 12V, 18 Gauge, Rated for 60 Amps	To Sabertooth
7	Pancake -	3 Feet, 12V, 18 Gauge, Rated for 60 Amps	To Sabertooth
8	Pancake -	3 Feet, 12V, 18 Gauge, Rated for 60 Amps	To Sabertooth
9	X	<NO WIRE>	<NO WIRE>
10	Pot	Steering Pot Wiper	Pot Wiper - Read by Arduino
11	Pot	Steering Pot Low	Pot Low - Connected to Ground
11	Pot	Steering Pot High	Pot High - Connected to High (5V?)
13	X	<NO WIRE>	<NO WIRE>
14	Blue	Ignition Blue (Parallel with Actual Ignition)	Connected to Relay - Controlled by Arduino
15	Green	Ignition Green (Parallel with Actual Ignition)	Connected to Relay - Controlled by Arduino
16	Purple	Accelerator Wiper?	1x SPST Switch between Manual / Toggle / Autonomous Modes on Wiper
17	Yellow	Accelerator High Voltage?	Pedal and Digi Pot High Voltages Tied Together
18	Black	Accelerator Ground	Pedal and Digi Pot Grounds Tied Together
19	S1	Pancake Motor Signal (for Sabertooth)	Arduino Signal controlling Sabertooth
20	S2	Brake Motor Signal (for Sabertooth)	Arduino Signal controlling Sabertooth
21	12V+	From Rack Battery	To Sabertooth
22	12V+	From Rack Battery	To Sabertooth
23	GND	From Rack Battery	To Sabertooth
24	GND	From Rack Battery	To Sabertooth

6.3 Prototype-Specific Enhancements

In addition to the three main subsystems for propulsion, braking, and steering, our team mentioned additional enhancements that were made for our particular autonomous prototype. We first restored the body, rebranding the name Robocart with a new, and appealing look. Our team then created a front rack on the Golf Cart by 3D-Printing a bracket to make a parallel-to-floor beam of 80/20 extruded aluminum. We mounted peripherals such as Raspberry Pi Computers, Cameras, Brackets, Monitors, and channeled wires through the aluminum for a polished look. We

then tackled the Server integration with both hardware and software. From a physical, hardware, perspective, our team cut the cage that housed the server into a small form factor and then bolted it onto a cargo towing utility rack. We framed the rest of the utility rack with modular 80/20 and installed square tubing on the chassis of the golf cart to accommodate our custom rack. We then added additional power supplies to the cargo rack to increase the mobile longevity of the power systems on board the golf cart. For software, the server was reimaged with Ubuntu 14.04. All embedded microcontrollers, Arduinos, were hooked up to the server through USB. All the Raspberry Pi Computers communicated with the server over an Ethernet Switch, mounted to the Golf Cart. Guilherme Meira handled image processing with the Raspberry Pi Cameras and mapped control commands to the Arduino Serial Monitor which drove our mechanical subsystems. Lastly our team tackled the power systems. We replaced the older poor-conditioned deep cycle batteries for a brand new set of marine-grade deep cycle batteries. With flexibility in form factor, we were able to use a cost matrix to get the best performance per dollar and keep the costs down. After some verification testing and proof of concept testing, we pushed our design to the extremes and ensured it would hold up to the test conditions for next year's software applications. With these three essential systems followed by the four enhancement systems, we were able to accomplish all seven goals addressed in our proposed approach top-level diagram above.

6.4 Chapter Summary

The integration of the system focused on bring all electrical components added to Robocart to one centralized hub. Using the server as a command center, we were able to communicate to each subsystem of the golf cart and remotely control each of the subsystems. Once control was verified, all wires and electrical components were consolidated for each access and removal should the golf cart need to be relocated.

7 Experimental Tests

7.1 Introduction

Throughout the course of this project, the team compiled a list of experimental tests and procedures to which had both positive and negative outcomes. In this chapter, we will focus on these procedures and their outcomes. Let this chapter be a stepping stone for which future project teams can use as a guide for potential risks and failures.

7.2 Steering Over-rotation

Due to the design of the current rack and pinion system of the steering assembly, it is possible to spin the steering wheel and attempt to turn the wheel beyond its physical limitations. Doing so would cause the rack and pinion to separate, making it impossible to turn the wheel unless the system was reassembled. Such a case could also cause the rack and pinion or subparts to bend or shatter. Neither scenarios would have a quick fix, therefore it is in the project's best benefit to refrain from overdriving the steering without using feedback from the steering potentiometer.

7.3 Steering Overdrive

Another potential threat to the stability of the steering system is the overdrive of the steering motor. Supplying the motor with a voltage beyond 6V would destabilize the chain and sprocket, causing the chain to separate from the sprockets. To resolve this issue, reattached the chain around the sprockets in the order from smallest to largest. When parts of the chain is around the largest sprocket (the steering column sprocket), slowly spin the sprocket until the entire chain rests fully around all sprockets. It may help if the set screws for each sprocket is loosened such that each spins freely. Another method that the team found was effective in reattaching the chain was to take all three sprockets off of the steering assembly, wrap the chain around the largest

sprocket, then fit the smaller two within the chain. Afterwards, reassemble the three sprockets back onto the steering column assembly and tighten the set screws.

7.4 Throttle Signal Short

An important aspect of the operation of the autonomous golf cart lies in throttle control. As stated in the chapters covering the original operation of the golf cart, the onboard computer handles every electrical operation of the entire vehicle. However, the system is still simplistic in nature as this vehicle was manufactured in the year 1995. That being said, the signal the computer reads as throttle control is an analog signal representing the voltage of the continuously variable potentiometer that changes when the acceleration pedal is compressed. Should there be a short in any part of this system, the computer will read the signal as a 0V signal, which is when the acceleration pedal fully compressed. For the current state of the system, this is dangerous when implementing autonomous operations.

7.5 Steering Potentiometer

Part of this team's accomplishments included creating a bracket to mount and secure the steering potentiometer onto the back-plate of the steering assembly. By doing so, the potentiometer would no longer be allowed to freely rotate should enough torque be applied from the steering motor. This year's design allows accurate readings from the potentiometer. However, there is no mechanical stop to which stops the spinning of the motor when the potentiometer have reached either a maximum or minimum. When the potentiometer is spun beyond its limits, this would cause erroneous readings from the potentiometer as well as affect future readings.

7.6 Speed Control

There are currently no means of monitoring the velocity of the vehicle when in operation. The current method of speed control is by mapping the digital potentiometer values to estimated

velocities as the vehicle is driving on a flat surface. However, these values would change with the slightest change in inclination. Future considerations may include outfitting a motor encoder to the electrical motor powering the golf cart or the back wheel shaft to record the rotations per minute. Because such a system still relies on relative positons and velocities, slippage would still need to be account for. Combining internal relative data with global positioning satellite data may be a possible solution for future teams to explore further.

7.7 Braking Motor

Much like any motor, when the motor stalls, it will pull as much current as it can from its power supply until either the supply or the motor overheats or burns out. The windshield wiper motor attached to the braking assembly only needs several rotations in either the clockwise or counterclockwise direction to apply tension to the brake line and engage the brakes. Any attempt to drive the motor once the brakes are fully engaged will cause the motor to stall. Stalling the motor for extended periods of time may potentially damage both the motor and the power supply it is connected to.

7.8 Chapter Summary

The implementation of the three main subsystems this project had focused on did not prove to be trivial. As the team designed and implemented each subsystem, new problems arose and were addressed. Main issues around the control of the subsystems involved being aware of the physical limitations of the existing golf cart as the team had to work around these limitations by making note in software.

8 Conclusion & Future Work

At the conclusion of this year's project work, the team has outfitted a 1995 Club Car golf cart with the mechanical and electrical systems in preparation for autonomous operation. The team improved upon previous project teams' designs, as well as providing new designs covering flaws not addressed in previous projects. Although the team tackled all three control systems of the vehicle: steering, throttle, and brake control, the project is by no means complete. The following sections outline potential areas of improvement for future teams to build upon, as well as problems mentioned from the Experimental Tests chapters that may be addressed to improve the quality of testing and operation.

8.1 Mobile Path Planning and Collision avoidance

Mobile path planning is currently a separate project worked as a Master's thesis under the advisory of Dr. Alexander Wyglinski. Areas of improvement include but not limited to serial communication between low-level control systems and high-level navigation commands, and further integration between throttle, brakes, and steering control.

Work involving low-level collision avoidance mechanism may also be further explored as currently there is no mechanism is directly communicate with the control systems of the golf cart in the event of oncoming collision. Potential systems may include ultrasonic sensors that directly communicates to the Arduino microcontrollers attached to the motor controllers such that in the event of oncoming collision, information would not needed to be relayed to the server for processing then for driving data to be relayed back for control systems to be applied.

8.2 Integration with Maps for Navigation

One area that was explored but not focused on was the integration with GPS data and maps. The team successfully installed a Globalsat BU-353 GPS receiver module for the Ubuntu platform of the server. Data was then retrieved from the GPS module through the use of `gpsmon` command as plain text. Future projects can be focused around processing and analyzing the collected data to be able to accurately predict the trajectory of the car based on current position, speed, and acceleration data available internal to the vehicle. Further work may be done to integrate with map data by using longitude and latitude information to update the location of the golf cart in real-time.

8.3 Application Integration

Another possible lead for the expansion of this Major Qualifying Project may be towards the development of applications supporting the operation of the autonomous vehicle. Such application may be on smartphone, desktop, or web platforms. Such apps could use information available on the user's platform such as a phone's GPS location data, and combine that with the location of the golf cart to plan routes for automatic pick-up and drop-off of passengers. Other applications may focus on diagnostics information of the autonomous vehicle such to monitor the position, velocity, acceleration, battery life, and other pertinent information.

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Reference URLs:

http://www.thingiverse.com/thing:873036/#comments
80/20 Adjustable Angle Bracket on Thingiverse

http://www.mmvehicles.com/Yamaha-G14-G22-Rear-Rack.html
Rear Rack we're closely replicating

https://eu.makerbot.com/fileadmin/Inhalte/Support/Datenblatt/MakerBot_R__PLA_and_ABS_Strength_Data.pdf
3D Printed Strength Test

http://www.ebay.com/itm/Waterproof-DC-DC-Converter-Regulator-36V-Step-down-to-12V-120W-10A-Golf-Cart-NEW-/351252726738?hash=item51c84b43d2
36V -> 12V 10A = 120W
$13.78

http://www.ebay.com/itm/Waterproof-DC-DC-Converter-Voltage-Regulator-36V-Step-down-to-12V-120W-10A-/291323889848?hash=item43d441c8b8
36V -> 12V 10A = 120W
$15.98

http://www.ebay.com/itm/Waterproof-DC-DC-Converter-Voltage-Regulator-36V-Step-down-to-12V-120W-10A-/321166218041?hash=item4ac6ff9339
36V -> 12V 10A = 120W
$17.56

http://www.ebay.com/itm/Waterproof-DC-DC-Car-Voltage-Converter-36V-Step-down-to-12V-10A-Power-Supply-/141757728866?hash=item21016b4862
36V -> 12V 10A = 120W
$13.99

http://www.ebay.com/itm/DC-DC-Step-Down-Converter-Voltage-Regulator-36V-TO-12V-30A-360W-Waterproof-/252085811752?hash=item3ab17c3a28
36V -> 12V 30A = 360W
$39.90

http://www.ebay.com/sch/i.html?_from=R40&_trksid=p2050601.m570.l1313.TR0.TRC0.H0.XDC+36V+Step+Down+12V+.TRS0&_nkw=DC+36V+Step+Down+12V+&_sacat=0
The Classification of this part is a "Voltage Reducer"
Step Down (36V -> 12V)
Buck Converter
Voltage Converter / Voltage Regulator

http://www.omega.com/pptst/DRF-VDC_VAC.html

Voltage Conditioner – to smooth the 60Hz 120V Sine Wave coming from the Power Inverter

Appendix A

EPC's Magnetic Absolute Encoder

Source: encoder.com

Reply   Reply All   Forward   Chat

MA63S quote

Sarah Walter [sarahw@encoder.com]

To: Sahay, Prateek

Friday, January 30, 2015 1:18 PM

Flag for follow up. Start by Saturday, February 28, 2015. Due by Saturday, February 28, 2015.
You forwarded this message on 2/3/2015 7:14 PM.

Prateek,

Thank you for your phone call today. Below is a link to the datasheet along with pricing.

EPC part# **MA63S-??**
http://www.encoder.com/literature/datasheet-ma63s.pdf

MSRP: $780.00 ea   Student Discount of 30%: $532 ea

WARRANTY: 3-years from date of EPC shipment.

Let me know if you have any questions about the configuration or anything else.

Regards,

Sarah Walter
Technical Sales Manager
Encoder Products Company | www.encoder.com
464276 Highway 95 South | Sagle, Idaho 83860
T: 800.366.5412 Ext. 4785 | F: 208.263.0541 | E: sarahw@encoder.com

DISCLAIMER: Encoder Products Company (EPC) has made our best effort in providing this cross reference. Due to the many variations of encoder specifications between manufactures, it is ultimately the responsibility of the customer and/or EPC Distributor to verify that our suggested cross reference will work in the intended application. Each encoder is custom built and EPC will not be responsible if our suggested cross fails to perform due to the configuration of the customer's application. Once built and shipped, EPC products are not returnable.

Appendix B

EPC's Magnetic Absolute Encoder Specification Sheets

Source: encoder.com

MODEL MA63S – MULTITURN ABSOLUTE ENCODER

FEATURES

Standard Size 25 Package (2.5" x 2.5")
Durable Magnetic Technology – No Gears or Batteries
Servo and Flange Mounting
Multiturn Absolute Encoder (14 Bit/39 Bit)
SSI and CANopen Communications
IP67 Sealing Available
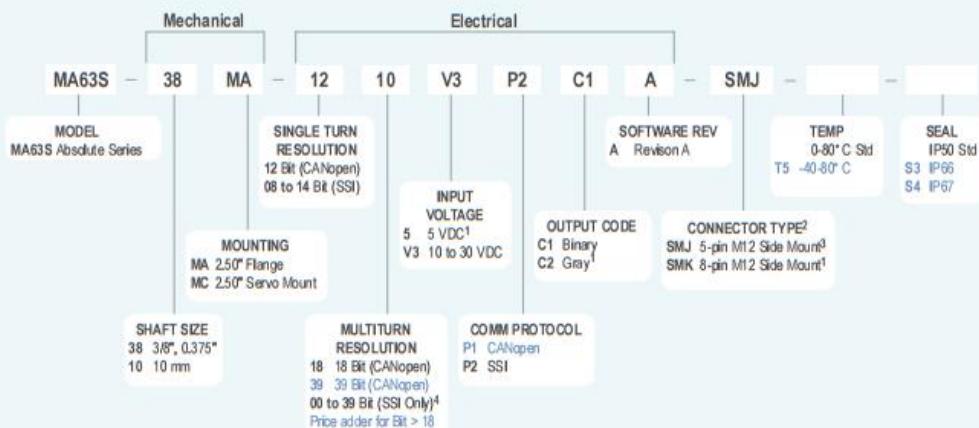
The Model MA63S Multiturn Absolute Accu-Coder™ is ideal for a wide variety of industrial applications that require an encoder with the capability of absolute positioning output, even in power-off scenarios. Its fully digital output and innovative use of battery-free multiturn technology make the Model MA63S exceptionally reliable. The MA63's robust and durable magnetic technology and available IP67 seal readily handle the harshest industrial environments, including those with elevated electrical noise. Available with several shaft sizes and mounting styles, the Model MA63S is easily designed into OEM and aftermarket applications.

COMMON APPLICATIONS

Robotics, Telescopes, Antennas, Medical Scanners, Wind Turbines, Elevators, Lifts, Motors, Automatic Guided Vehicles, Rotary and X/Y Positioning Tables

MODEL MA63S ORDERING GUIDE

Blue type indicates price adder options. Not all configuration combinations may be available. Contact Customer Service for details.

Mechanical			Electrical								
MA63S	38	MA	12	10	V3	P2	C1	A	SMJ		

MODEL
MA63S Absolute Series

SINGLE TURN RESOLUTION
12 Bit (CANopen)
08 to 14 Bit (SSI)

SOFTWARE REV
A   Revison A

TEMP
0-80° C Std
T5   –40-80° C

SEAL
IP50 Std
S3   IP66
S4   IP67

MOUNTING
MA   2.50" Flange
MC   2.50" Servo Mount

INPUT VOLTAGE
5   5 VDC[1]
V3   10 to 30 VDC

OUTPUT CODE
C1   Binary
C2   Gray[1]

CONNECTOR TYPE[2]
SMJ   5-pin M12 Side Mount[3]
SMK   8-pin M12 Side Mount[1]

SHAFT SIZE
38   3/8", 0.375"
10   10 mm

MULTITURN RESOLUTION
18   18 Bit (CANopen)
39   39 Bit (CANopen)
00 to 39 Bit (SSI Only)[4]
Price adder for Bit > 18

COMM PROTOCOL
P1   CANopen
P2   SSI

NOTES:
1   Available with SSI only.
2   For mating connectors, cables, and cordsets see Encoder Accessories on page 102 or visit www.encoder.com. For Pin Configuration Diagrams, see page 107 or visit www.encoder.com.
3   Available with CANopen only.
4   For single-turn resolution, enter '00' (SSI only).

MODEL MA63S SPECIFICATIONS

Electrical

Input Voltage	10 to 30 VDC max SSI or CANopen
	5 VDC SSI Only
Input Current	50 mA max with no external load
Power Consumption	0.5 W max
Resolution (Single)	12 bit (CANopen)
	8 to 14 bit (SSI)
Resolution (Multi)	Up to 39 bit multiturn
	(CANopen or SSI)
Accuracy	+/- 0.35°
Repeatability	+/- 0.2°

CANopen Interface

Protocol	CANopen:
	Communication profile CiA 301
	Device profile for encoder CiA 406
	V3.2 class C2
Node Number	0 to 127 (default 127)
Baud Rate	10 Kbaud to 1 Mbaud with automatic bit rate detection

Note: The standard settings, as well as any customization in the software, can be changed via LSS (CiA 305) and the SDO protocol (e.g., PDOs, scaling, heartbeat, node-ID, baud rate, etc.)

Programmable CANopen Transmission Modes

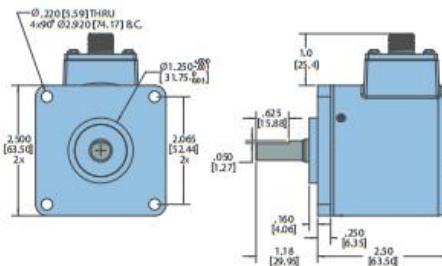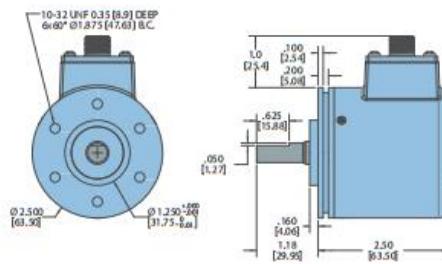|	
Synchronous	When a synchronization telegram (SYNC) is received from another bus node, PDOs are transmitted independently
Asynchronous	A PDO message is triggered by an internal event (e.g., change of measured value, internal timer, etc.)

SSI Interface

Clock Input	Via opto coupler
Clock Frequency	100KHz to 500KHz
Data Output	RS485 / RS422 compatible
Output Code	Gray or binary
SSI Output	Angular position value
Parity Bit	Optional (even/odd)
Error Bit	Optional
Turn On Time	< 1.5 sec
Pos. Counting Dir.	Connect DIR to GND for CW
	Connect DIR to VDC for CCW
	(when viewed from shaft end)
Set to Zero	Apply VDC for 2 sec
Protection	Galvanic Isolation

Mechanical

Max Shaft Speed	8,000 RPM
Shaft Material	303 Stainless Steel
Radial Shaft Load	80 lb maximum
Axial Shaft Load	80 lb maximum
Starting Torque	1.0 oz-in typical with no seal
	3.0 oz-in typical with IP66 shaft seal
	7.0 oz-in typical with IP67 shaft seal
Housing	Black non-corrosive finish
Weight	20 oz typical

Environmental

Storage Temp	-25° to 100° C
Humidity	95% RH non-condensing
Vibration	5 g @ 10 to 2000 Hz
Shock	100 g @ 6 ms duration
Sealing	IP50 standard; IP66 or IP67 optional

MODEL MA63S 2.5" FLANGE MOUNT (MA)

MODEL MA63S 2.5" SERVO MOUNT (MC)

All dimensions are in inches with a tolerance of ±0.005" or ±0.01" unless otherwise specified. Metric dimensions are given in brackets [metric].

WIRING TABLES

SSI ENCODERS

Function	Pin
Ground (GND)	1
+VDC	2
SSI CLK+	3
SSI CLK-	4
SSI DATA+	5
SSI DATA-	6
PRESET	7
DIR	8
Shield	Housing

CANOPEN ENCODERS

Function	Pin
+VDC	2
Ground (GND)	3
CAN $_{High}$	4
CAN $_{Low}$	5
CAN $_{GND}$ / Shield	1

Appendix C

Steering Motor Specifications Sheet

Source: alibaba.com

Welcome to   Product Description   Company Information   Our Services   Packaging & Shipping

Verified Supplier | Zhejiang Xiangyang G...   Add Company to My Favorites   Onsite Check

7YR

Zhejiang Xiangyang Gear Electromechanical Co., Ltd.

Home   **Product Categories**   **Company Profile**   **Contacts**

Home > Product Categories > DC MOTOR > XYD-13 24V-48V electric bike kit Brush DC Motor

XYD-13 24V-48V electric bike kit Brush DC Motor

FOB Price:	US $ 1 - 100 / Set | Get Latest Price
Min.Order Quantity:	100 Piece/Pieces
Supply Ability:	10000 Piece/Pieces per Week per item
Port:	Ningbo, SHANGHAI
Payment Terms:	L/C,T/T,Western Union,MoneyGram

Contact Supplier   **I'm Away**

Start Order   Add to Inquiry Cart   Add to My Favorites

This supplier supports Trade Assurance.
Follow the Trade Assurance process and get:
- On-time shipment and pre-shipment product quality safeguards
- Refund up to the covered amount agreed with your supplier
- Supplier's Trade Assurance Limit: US $27,000

Learn More ›

See larger image

Verified Supplier - Zhejiang Xiangyang Gear Electromechanical Co., Ltd.

China (Mainland) | Manufacturer | Contact Details

Experience: Established 2000
15 years OEM

Performance:
78.4% Response Rate

Search products here

Product Showcase

Product Categories

ELECTRIC SCOOTER

DC MOTOR

DC MOTOR FOR TRICYCLE

CONTROLLER

MOTORCYCLE SPROKET

Motorcycle/Automotive Gear

PLANETARY REDUCER

GEARBOX

Ungrouped

Product Detail

Report Suspicious Activity

Quick Details

Place of Origin: Zhejiang, China (Mainland), Zhejiang, China	Brand Name: XYD, XY	Model Number: XYD-13, XYD-13
	Usage: Boat, Car, Electric Bicycle, Fan, Home Appliance	Certification: CCC, CE, ROHS, ROHS
		Type: Micro Motor, DC Motor
Construction: Permanent Magnet	Commutation: Brush	Protect Feature: Explosion-proof
Speed(RPM): 2600-3000	Output Power: 350-800W	Voltage(V): 24v-48v
Efficiency: IE 3	Part: Motor	Motor: Brush
Voltage: 24V-48V		

Packaging & Delivery

Packaging Details:	Carton with Foam
Delivery Detail:	30 days after payment

Specifications

Brush DC Motor XYD-13
Electric Bicycle/Scooters Motor
24/48VCD,600/750W
20A,2600RPM
CE certificate,RoHs.

Appendix D

Brake Motor Specifications Sheet

Source: usfirst.org

2003 SPEC SHEETS

DELPHI INTERIOR AND LIGHTING

BOSCH VAN DOOR MOTOR SPECS

No Load Speed:	75 RPM
Stall Torque Clockwise:	34 Nm
Stall Torque Counter-Clockwise:	30 Nm
Stall Current:	44 Amps
All specs at 12 Vdc.	

Bosch Motors are used in the 1999 Toyota Sienna and the 1999 Ford Windstar. If you wish to purchase an additional Bosch motor, you must buy the entire "Power Sliding Door unit". The Bosch motor is the right hand side motor. Great care must be taken when removing the motor from the front door unit. The retaining clips must be removed from the output shaft or damage will occur to the shaft

FISHER-PRICE MOTOR INFORMATION

The following are approximate performance data for the Fisher-Price motor/gearbox sets supplied in the kits.

Motor no-load speed	15,000 RPM
Motor stall current	57 A
Motor stall torque	0.380 N-m (mili-NEWTON meters)
Gearbox ratio	124:1
No-load speed w/gearbox	100 RPM (estimated)
Stall torque w/gearbox	34.7 N-m (estimated)

GLOBE MOTOR

GLOBE MOTOR AND DRIVE ASSEMBLY SPECS
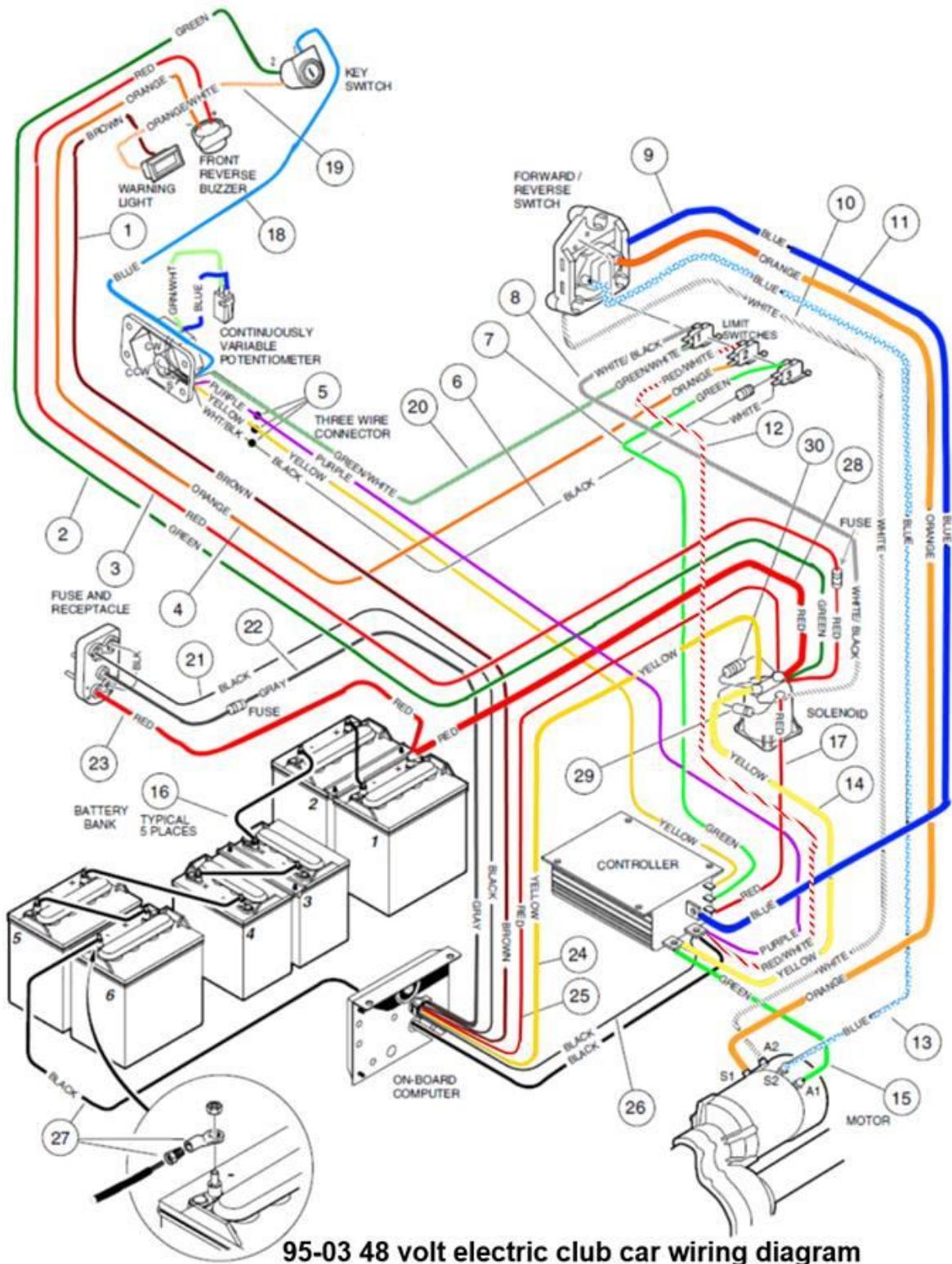
	Motor with Drive Assembly	Motor Only
No Load Speed:	87 RPM ± 1	97 RPM
Stall Torque:	150 In-lb	30 oz-in
Stall Current:	18.5 Amps	18.5 Amps
No Load Current:	0.820 Amps	0.820 Amps
	All specs at 10 Vdc.	

Warning: The Globe Motor cannot support side loads.

Appendix E

1995 – 2003 48 Volt Electric Club Car Wiring Diagram

Source: clubcar.com

95-03 48 volt electric club car wiring diagram

Appendix F

Power Inverter Specifications

Source: Centech.com

Source: http://www.manualslib.com/products/Cen-Tech-66817-3544955.html

Specifications

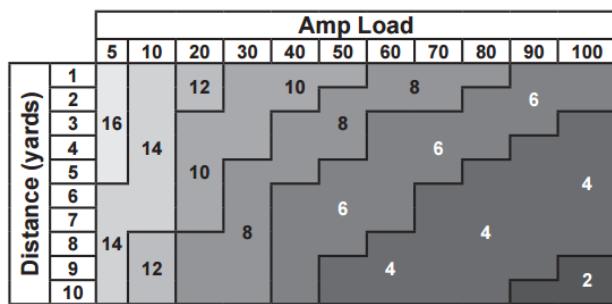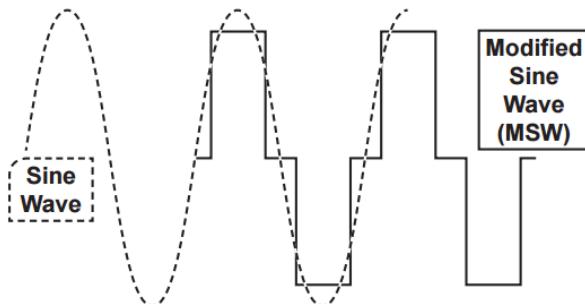| Input Voltage	12 VDC (nominal)
Output Voltage	115 V~ / 60 Hz
Continuous Power	750 W
Surge Power	1500 W
Operating Conditions	32° - 104° F
Receptacles	Two 3-prong grounded polarized AC outlets One 5 VDC 500mA USB outlet
Fuse Type	One 35 Amp Internal Blade-type Fuse (professional replacement only)
Overall Dimensions	9-1/4" L x 5-1/4" W x 2-1/2" H

Distance (yards)	Amp Load										
	5	10	20	30	40	50	60	70	80	90	100
1	16	14	12	10	10	10	8	8	8	6	6
2	16	14	12	10	10	8	8	8	6	6	6
3	16	14	10	10	8	8	6	6	6	6	4
4	16	14	10	10	8	8	6	6	6	4	4
5	16	14	10	8	8	6	6	6	4	4	4
6	14	14	10	8	6	6	6	4	4	4	4
7	14	14	10	8	6	6	6	4	4	4	4
8	14	12	8	8	6	6	4	4	4	4	4
9	14	12	8	8	6	4	4	4	4	4	2
10	14	12	8	8	6	4	4	4	4	2	2

Distance (yards)	Amp Load										
	5	10	20	30	40	50	60	70	80	90	100
1			12		10		8			6	
2			12		10		8			6	
3	16					8			6		
4		14				8			6		
5		10									4
6						6					4
7				8		6			4		
8	14			8					4		
9		12				4					2
10						4					2

Output Waveform
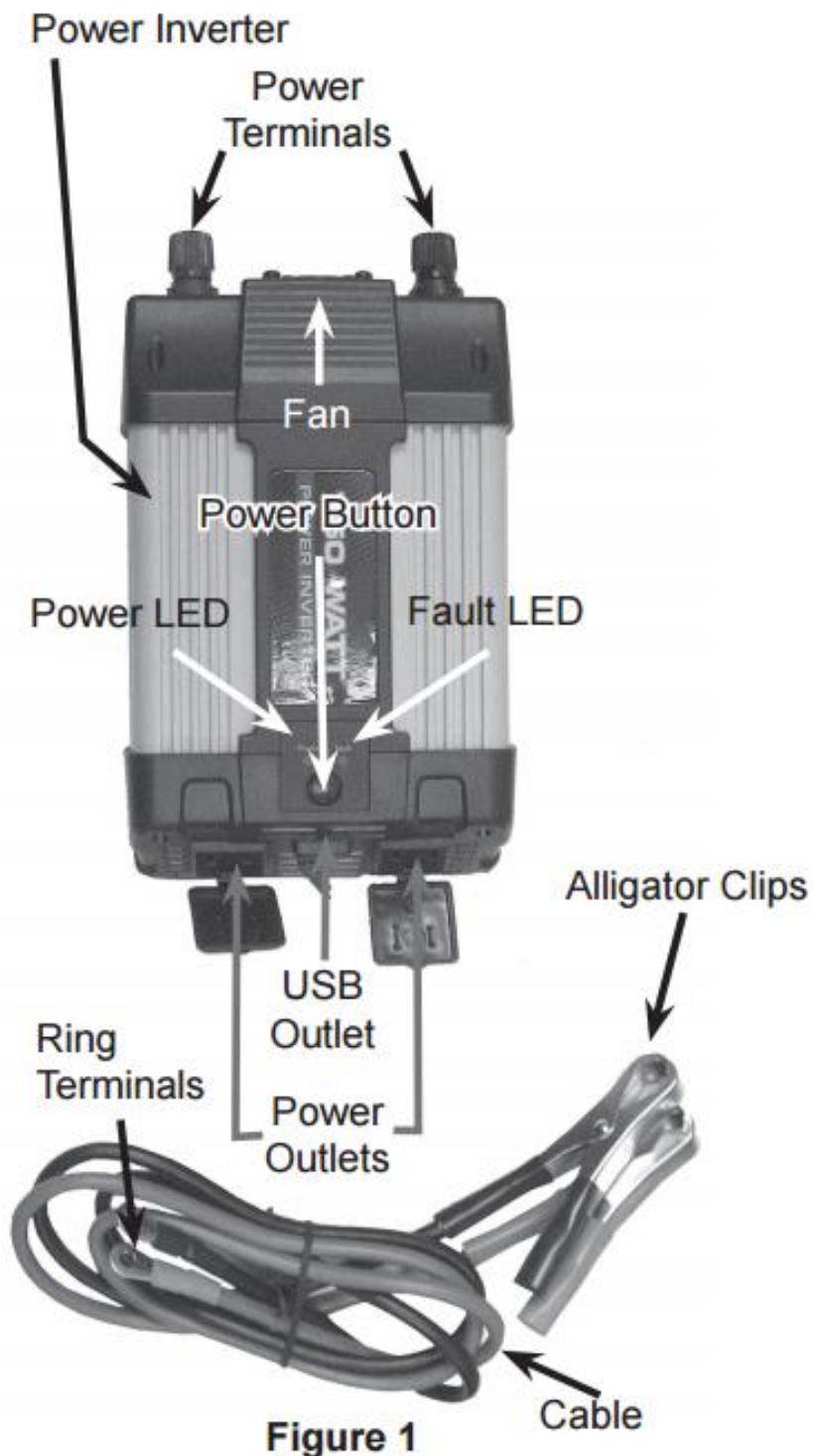

Sine Wave

Modified Sine Wave (MSW)

1. This inverter's output is a Modified Sine Wave. Power from most electric utilities is a Sine Wave.

Note: Only multimeters identified as "TRUE RMS" will read Modified Sine Wave voltage accurately.

2. **Modified Sine Wave (MSW)** power is suitable for most AC devices and power supplies used in electronic equipment, transformers, and motors. Do not use to power sensitive devices such as medical equipment or computers. Some audio equipment may perform poorly if run on Modified Sine Wave power.

3. **Sine Wave** inverters provide power that is identical to, or even better than, the power supplied by your power company. Motors start easier and run cooler under Sine Wave power. Certain devices, such as laser printers, variable speed motors and digital clocks, require sine wave power to operate properly. Sine wave inverters are typically more expensive for their capacity than other inverters.

Functions

Power Inverter

Power Terminals

Fan

Power Button

Power LED

Fault LED

Alligator Clips

USB Outlet

Ring Terminals

Power Outlets

Cable

Figure 1

Appendix G

Golf Cart Dimensions

Source: ClubCar.com

SPECIFICATIONS	DS 36 VOLT ELECTRIC
DIMENSIONS	
Overall Length	232 cm (91-1/2")
Overall Width	120 cm (47-1/4")
Overall Height at Steering Wheel	122 cm (48")
Wheelbase	166 cm (65-1/2")
Ground Clearance	11 cm (4-1/2")
Front Wheel Tread	88 cm (34-1/2")
Rear Wheel Tread	98 cm (38-1/2")
Weight...Electric (without batteries)	203 kg (448 lbs.)
Weight...Gasoline (dry)	
Forward Speed	19-24 KPH (12-15 MPH)
Clearance Circle (diameter)	533 cm (17' 6")
Braking Distance at 19 KPH (12 MPH)	427 cm (14')

Appendix H

Golf Cart Owner's Manual

Source:

Club Car

Owner's Manual

**1996 DS Golf Car
Gasoline/Electric**

Manual Number 101883801
Edition Code 0895F0196A

Appendix I

Golf Cart Maintenance Manual

Source:

Club Car®

1995-1996 MAINTENANCE SERVICE

**DS GOLF CARS
GASOLINE/ELECTRIC**
MANUAL NUMBER 101905101
EDITION CODE 1196H0799C