Robocart: Autonomous Ground Vehicle
Electromechanical Foundations Design

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Abstract

Networked autonomous vehicles have long been a dream, promising traffic-less cities and safer roads. This MQP laid the foundations for a vision-based autonomous ground vehicle. The team this year outfitted a 1995 golf cart with sensors and motors to automate the steering and brakes to lay a strong foundation for future teams. Additional work was done mounting of two stereoscopic cameras and a display for computer feedback as well as foundational work on the controls algorithms.

List of Acronyms

ALV Autonomous Land Project

CAD Computer-aided design

CAM Computer-aided manufacturing

CMU Carnegie Mellon University

CNC Computer Numerical Control

DARPA Defense Advanced Research Projects Agency

DRC DARPA Robotics Challenge

EBS Electronic Braking System

ECU Electronic control unit

GPS Global Positioning System

LIDAR Light image detection and ranging

MQP Major Qualifying Project

RALPH Rapidly Adapting Lateral Position Handler

ROS Robot Operating System

WPI Worcester Polytechnic Institute

Acknowledgments

My heartfelt thanks go out to everyone who made this project possible. To those who helped me in times of need as I tackled a project like none other before, Matthew Forman, Kevin Arruda, and Professor Stafford: your generosity and patience were a godsend. Words are beyond me as I attempt to thank Joe St. Germain from the RBE lab and Bob Boisse from the ECE shop for endlessly lending me their tools and expertise. Additional thanks to Tracey Coetzee in the RBE department for all her help with budgeting and preparations for Project Presentation Day. Lastly, I'd like to thank Professor Wyglinski for his unwavering guidance and enthusiasm, and for his dream, without any of which I could never have grown as much as I did this year. I wish him the best of luck with this ambitious project.

Executive Summary

Motivation

Autonomous vehicles have long been a dream. The motivations behind them are clear; the promise of saving 1.2 million lives a year [1] and solving traffic congestion problems [2] has struck a chord with scientists, engineers, and programmers around the world.

With the price of sensors and computing steadily decreasing year after year, affordable self-driving automobiles are starting to become a reality. This MQP aims to imagine a divergent take on autonomous vehicle technology by challenging modern vision algorithms combined with affordable sensing technology.

Sensors are a big part of autonomous navigation. Although sensors like LIDAR have dominated recent ventures, their price, bulk, and vulnerable location atop autonomous vehicles could hinder their uptake in the future. As a result, this project sought instead to pursue vision-based object-recognition and navigation.

Proposed Approach

For this project, a 1995 electric golf cart was also acquired for prototyping with. Significant upgrades had to be made to its design in order for it to become autonomous. Because of the large scale of this project, the project was broken down into separate subsystems, each of which was worked on separately to be combined sometime in the future. The different

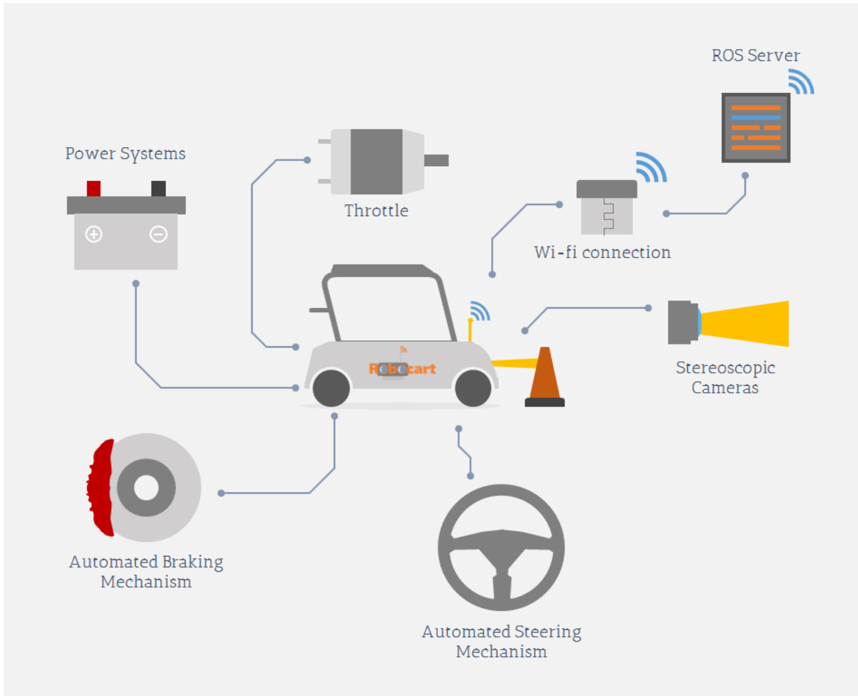


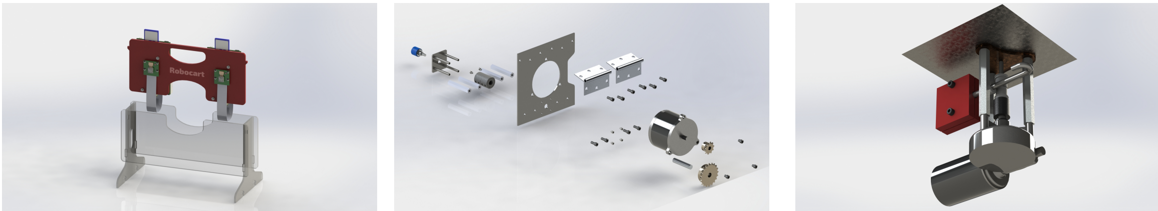
Figure 1: Overview of the different systems involved in making the golf cart autonomous.

systems requiring modifications are shown in Figure 1.

The scope of this paper involves the three mechanical subsystems—the stereoscopic cameras, the automated steering mechanism, and the automated braking mechanism. Each of these subsystems posed their own unique challenges and were dealt with very differently.

Raspberry Pi cameras were used for the steroscopic cameras, since they were cheaply available and readily able to be connected to a wireless network through Raspberry Pi computers. A mounting solution was required for the Raspberry Pi cameras and computers which needed to fulfill the following requirements:

- Hold two Raspberry Pis
- Hold two Raspberry Pi camera modules
- Ensure the two cameras face the same direction
- Allow the the Raspberry Pi's and cameras to be easily removable (to allow the Raspberry Pis to be debugged more easily off the cart)



(a) Raspberry Pi mount. (b) Automated steering. (c) Automated braking.

Figure 2: CAD prototypes of the three mechanical subsystems in Robocart.

- Protect the cameras without obstructing the view of the cameras
- Allow access to all necessary ports of the Raspberry Pi

Next, the steering system needed to undergo some major changes to allow the computer to control it. The requirements for the system were listed as follows:

- Supply at minimum 9.19 ft-lbs of torque to the steering column
- Allow the wheels to be turned from fully left to fully right in about 1 second
- Must be back-drivable

Finally, the brakes on the golf cart also needed to be automated in order for the computer to control them. The requirements of the new system were:

- Fully engage in under 0.5 seconds
- Supply a force of 100 lbs to the brake cables
- Must be back-drivable
- Negative braking

Part of the approach involved drafting CAD prototypes for each of these three systems to ensure the different parts would fit together and function without issues. Different iterations of the designs for each system are shown in Figure 2.

Discussion and Results

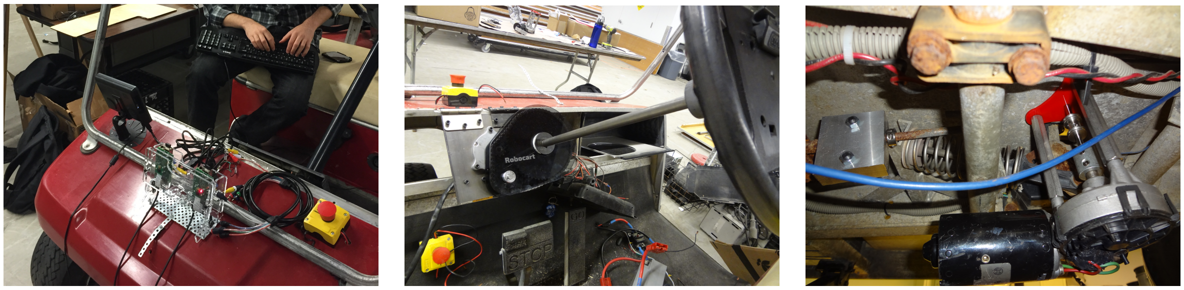
The Raspberry Pi mounting system took a unique approach to the design. Once the design was drafted in CAD, the parts were individually laser-cut from acrylic and assembled together. A spring-loaded mechanism ensured the electronic components would stay together, but also be easy to remove to be worked on elsewhere. All of the listed requirements were successfully met.

The steering system was more difficult to implement. A motor was added to the dashboard area of the golf cart with a chain-and-sprocket system to supply the steering column with sufficient torque and speed to turn it from fully left to fully right in 0.9 seconds. A rotational sensor was added with its own sprocket for position feedback data. The torques were also determined such that a person of average strength could overpower the motor, thereby making the system back-drivable. All of the listed requirements of the system were successfully met.

Finally, the braking system was tackled. Since it had been decided the system should be back-drivable, a new mechanism was developed for this system whereby the motor could actuate the brakes, but a human passenger could also apply the brakes at any time without having to fight the motor at all. The brakes could be fully actuated within 0.2 seconds. Unfortunately, it seemed, even after much design work, that it was impossible to meet the requirement of implementing negative braking—the only viable way of including this feature was by converting the brakes to a hydraulic system, which was deemed too costly for this MQP. Thus, this requirement had to be dropped. However, out of the remaining listed requirements for this system, all of them were successfully met.

Conclusions and Recommendations

This project is a very ambitious one, and it is regretful that more of the subsystems could not be completed this year, and that the team never got to see the golf cart run. Before



(a) Raspberry Pi mount. (b) Automated steering. (c) Automated braking.

Figure 3: Final mounted designs of the three mechanical subsystems in Robocart.

Robocart can begin to drive autonomously, however, there is still plenty of work to be done on the various subsystems. For one thing, more sensors are required for the computer to be able to intelligently allow Robocart to navigate autonomously. Not only would some cheap LIDAR or ultrasonic distance-sensing be useful, but also possibly encoders on the wheels, and limit switches on the steering and braking systems for safety reasons. There still remains plenty of work to be done on the software side of the robot, as well. Faster and more accurate algorithms for object-recognition and navigation will continue to evolve, and Robocart should be allowed to evolve with them. Some mechanical improvements would also make Robocart function better, such as replacing the brake system with a hydraulic one. A hydraulic system would also fulfill the requirement of implementing negative braking, which was unfortunately unable to be done this year due to its sheer cost.

All-in-all, however, the mechanical upgrades done to Robocart this year can be considered a success. I'm very grateful for the help I received not only from Professor Wyglinski, but also from other professors around campus, staff at Washburn, and lab managers. Finally, I'm also very grateful for the collaborative and nurturing environment at WPI, without which this project would not have been possible.

Chapter 1

Introduction to Autonomous Vehicles

Autonomous vehicles have been in development for over 65 years—in fact the first cruise-control systems were introduced in 1948 [3]. Multiple car manufacturers estimate the first commercial driverless cars to be released by 2020 [3][2]. The promise of saving 1.2 million lives a year [1] and solving traffic congestion problems [2] has struck a chord with scientists, engineers, and programmers around the world. Thanks to quantum leaps made in computing technologies in the past 30 years—cheap sensing, reliable object recognition, and real-time, portable, large-scale data analysis—automated vehicles are becoming a reality. Inspired by ongoing research today from around the world, this MQP aims to imagine a divergent take on autonomous vehicle technology by challenging modern vision algorithms combined with affordable sensing technology.

The path the industry will take to evolve autonomous vehicles is generally agreed upon by large automobile manufacturers and market analysis groups alike [2][4]. As shown in Figure 1.1, this consists of beginning with features like adaptive cruise control, automated emergency braking, and park assist technologies, which exist today, and passing through intermediary features such as highway and traffic jam assistive features before arriving at fully autonomous vehicles.

Several other labs have demonstrated the viability of autonomous cars in general, such

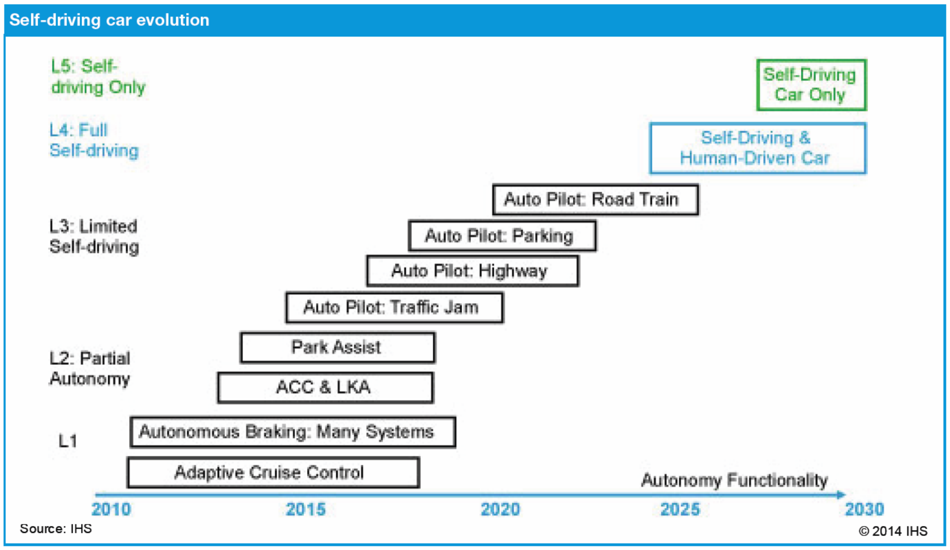


Figure 1.1: IHS's prediction of the evolution of self-driving cars.

as those of Google and the Autonomous Systems Laboratory at the University of California, Santa Cruz, as well as several major car manufacturers including Toyota, Nissan, Cadillac, and Audi [2], but many of these systems rely on expensive, bulky, and ungainly roof-mounted LIDAR detectors [5]. A unique part of the mission of this MQP is to achieve the same or better results using vision only—clearly it is possible because humans do this already.

Autonomous vehicle research has exploded in past decades, due to increased fascination with driverless vehicles and the impact they can have on society. Cars today come with options for adaptive cruise control, lane detection, and automated parallel parking—all features that rely on sensors and computing. Further advanced autonomous vehicles blend human-control with autonomous systems, and as result, have the ability to activate brakes in emergencies or alert drivers of dangers [5]. Tracing the origins and historical discoveries of autonomous vehicle technologies leads us to the basis for the Robocart MQP.

1.1 Major Milestones in Autonomous Vehicle History

Early on, fully-autonomous vehicles, (ones that did not rely on devices embedded into roads), were few and far between [5] before Martin Marietta, in conjunction with some research facilities and funded by DARPA, introduced the Autonomous Land Vehicle Project in 1985 [5][6]. Martin Marietta's ALV used computer vision and laser scanning for sensing and six server racks for path correcting. It successfully traveled a half mile on an empty road in 1985, but was notoriously fickle and easily tricked by shadows and small variations in lighting [7]. In the same time period, Ernst Dickmanns in Munich introduced saccadic vision and Kalman probabilistic filters for use in autonomous vehicles [5].

A decade later, in 1995, Carnegie Mellon developed the Rapidly Adapting Lateral Position Handler (RALPH) which used computer vision to determine the location of the road ahead to autonomously steer a car as two researchers controlled the throttle and brakes [5][8]. Dean Pomerleau was able to "teach" an artificial neural network to drive the car (it learned to use the grass as boundaries) and was able to successfully drive on a highway at 55mph [9]. Researchers from Carnegie Mellon were able to use this software to drive an autonomous car from Pittsburgh, PA to San Diego, CA for over 98% of the journey [5][8], a project called computer vision and No Hands Across America. By this point, autonomous path planning was somewhat solved to a degree, but there were still many issues to be resolved before a car could actually drive itself.

DARPA's Grand Challenge in 2005 challenged universities to make driverless cars to traverse a 132 mile-long off-road driving course in the Mojave Desert. The competition was actually the second of its kind—the first DARPA Grand Challenge in 2004 had been quite a disaster [9]. The competitors again took a wide number of approaches, utilizing combinations of GPS, radar, LIDAR, computer vision, sonar, and machine learning to navigate a trafficless desert course at speeds up to 25 mph [5]. The winning autonomous car, Stanley of Stanford University, used machine learning to distinguish errant sensor readings from the bumping around of the car and differing light conditions, and accounted for them using probability distributions. Essentially, it was able to reason about the accuracy of its readings and make fewer errors—only about 1 in 50,000 [9].

Four years later, in 2010, the Vislab from the University of Parma in Italy constructed a fully-electric autonomous vehicle that embarked upon and completed the VisLab Intercontinental Autonomous Challenge: an 8,000 mile road trip from Parma to Shanghai [1]. Throughout the journey, the vehicle encountered a variety of traffic, road, and weather conditions [5]. Unlike cars from the DARPA Grand challenge, the Vislab vehicle largely relied on image processing for local mapping. Other sensors onboard included laser-scanning and GPS, but the lasers were mainly used for detecting terrain [1]. Vislab proved the reliability and viability of vision algorithms rather than the use of complex sensors.

Beginning in 2011, Google started a self-driving car project that leverages their mapping technology in order to navigate roads. This prompted the Nevada Department of Motor Vehicles to issue the first driver's license for an autonomous vehicle. Along the way, Google has discovered more challenges involved in autonomous driving, including having to program aggressive behavior for moving through a four-way intersection.

In 2014, Volkswagen implemented the AdaptIVe Project with the objective of creating autonomous vehicles that can function in various levels of traffic and driving scenarios. Specific goals include navigating a traffic jam, parking in a parking garage, and eventually creating a robotic taxi.

1.2 Sensors in Autonomous Vehicles

Even though sensors like LIDAR are becoming more affordable and their use more widespread, they still cost tens of thousands of dollars in today's market. The Robocart MQP aims to direct its research toward LIDAR-less navigation, citing Vislab's Intercontinental Autonomous Challenge and other progressions in sensing analysis algorithms as evidence. Thus, it was decided to use standard Raspberry Pi cameras because they were cheaply available and could relay information over a network easily through a Raspberry Pi module.

1.3 Report Structure

The following chapter, Chapter 2, lists some of the topics that are relevant to this project which may not have been covered before in classes at WPI. Chapter 3 covers the thought processes behind the designs of the Raspberry Pi mount, electronic steering, and electronic braking systems. Chapter 4 discusses the actual implementation of these ideations: the steps followed and the challenges encountered. Chapter 5 includes a definitive analysis of whether or not the requirements of each system were met, as well as bond graphs for the steering and braking mechanisms. Finally, Chapter 6 discusses some more of the work that needs to be done, as well as recommendations and brief notes that could help teams in the future.

Chapter 2

Project Fundamentals

This chapter explains the background of this project and its short history, as well as some foundational knowledge necessary to understand much of the electromechanical aspects of this report.

2.1 About this MQP

The MQP described in this report is the second in a series of a much larger project conceived by Professor Wyglinski to wirelessly network together multiple autonomous vehicles, including aerial drones as well as ground vehicle. Last year's team was the first to begin work on this project; they had a large team of five engineers working on both the aerial drones as well as the ground vehicle. Although they made significant progress, they found the project was too large for one MQP. As a direct result, this year the project was split into one ground vehicle MQP and two aerial drone MQPs.

This year, the ground vehicle MQP originally consisted of three members—Liz Miller (RBE), Gabe Isko (RBE), and myself (RBE/ME). Because I was the only dual-major on the team, I wanted to try to overload in C-term and finish at the same time as Liz and Gabe. Partway through the year, however, I realized I would not be able to finish in time, so it was decided that the MQP would again be split into Liz and Gabe's part and my part so that we

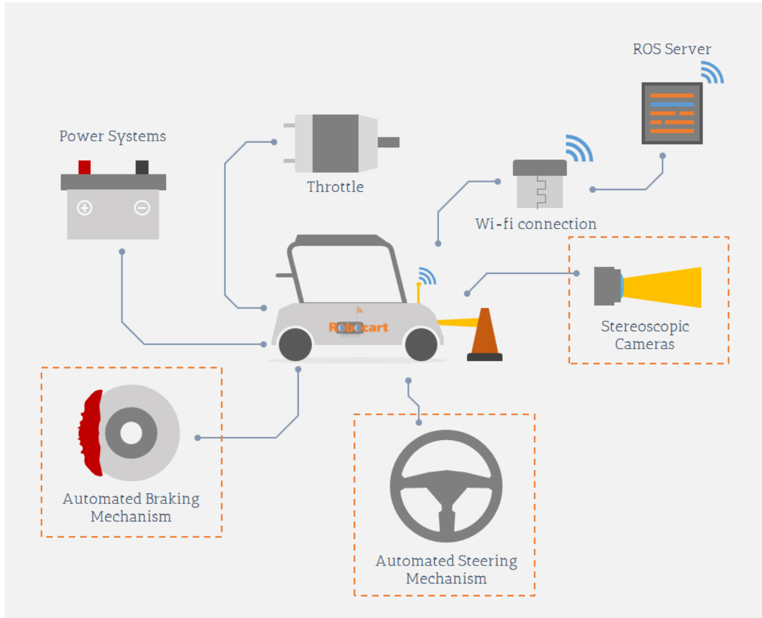


Figure 2.1: The three main mechanical components with respect to the overall system.

could submit in different terms. Thus, Liz and Gabe focused on the ROS programming and networking side, while I focused on designing and installing the mechanisms and sensors necessary for automating the golf cart. The different components of the overall system focused on in this report are outlined in orange in Figure 2.1.

As a result, this report focuses mainly on the electromechanical aspects of the ground vehicle project. For the networking aspects of the ground vehicle, please see Liz's project report on the WPI Electronic Projects Collection page here. The networking and ROS aspects of this project were pursued separately, and at some other time can be joined together with the mechanical aspects.

2.2 Sensors

Autonomous cars are only as good as the sensors and algorithms behind them. Affordable sensing technology has been a significant challenge for the robotics community.

Common sensing techniques include rudimentary sensors, best characterized by SONAR emitter/detectors. SONAR rangefinders work by emitting high-frequency sound waves and recording the amount of time until the sound returns. Because the sound wave travels at a near-constant and known speed, the time it takes to return can be used for determining distance to the obstacle. SONAR is generally known for its use in underwater use in submarines, but nowadays is also a common method of range-finding in robotics in the form of ultrasonic sensors, which use inaudible frequencies instead [10]. The issue with ultrasonic sensors; however, is that their readings cannot always be trusted because the sound wave grows at it leaves its point of origin and is prone to bouncing back to the sensor early. For example, a series of refractions can result in an emitted wave that reaches the sensor too early or too soon, resulting in errant data.

Nowadays, highly sophisticated sensors are commercially available which are able to sweep across a wide area and create entire maps on their own, reliably, rather than mapping a single distance at a single point. For example, LIDAR, (light detection and ranging), sensors, are beginning to see wide use in cars today. Although they may be better-known for their infamous appearances at autonomous vehicle grand challenges, LIDAR sensors are also used in cars with adaptive cruise control today, such as Mercedes' 2013 SL550. The SL550 uses two bumper-mounted LIDAR sensors for accurate range-finding at single points [11].

Prototype autonomous vehicles; however, tend to have roof-mounted LIDAR scanners. The Google Car for example, has a roof-mounted Velodyne scanner consisting of 64 different sensors that spin at several hundred rotations every minute and are able to create a 3D map of the environment in real-time [12]. The issue with these sensors, however, is the cost. Google's top-of-the-line LIDAR costs $70,000, with the price only beginning to come down [12].

Millimeter-wave radar sensors are relatively affordable sensors popular in cars today for range-finding. By sending high frequency wavelengths, using a multitude of these sensors placed around the front, sides, and rear of a vehicle, an autonomous vehicle can detect obstacles in the vicinity. Lexus uses such sensors in its Advanced Pre-Collision system found on some models. Ultrasonic sensors are also used for similar purposes, including assisted parking features [10].

Generally, GPS units are used in autonomous vehicle research for global mapping and path-planning. Because commercially available GPS units have fairly low resolution, they are reserved exclusively for global localization, while other sensors are used for local positioning [10]. This project aims to serve as a proof-of-concept of the effectiveness of stereoscopics for local positioning, and therefore a GPS unit or ultrasonics will not be a part of the Robocart's sensor system this year.

Google's autonomous Toyota vehicles also feature encoders on the wheels to track odometry as the car moves. Similar, but much less reliable results can also be achieved through an accelerometer and gyroscope or digital compass for measuring the car's six-dimensional pose in space. Generally, these sensors are reserved for vehicles, such as submarines, which don't have wheels and can't make use of encoders or GPS. Digital compasses tend to be affected by metal objects and are used in other, highly specialized cases. Inertial measurement units (IMU) can be used to detect and attempt to minimize forces on the passengers, such as those used in the Google Car. Google's autonomous cars have collectively driven over 190,000 miles with minor human intervention [12].

We believe that LIDAR is unnecessary and a step in the wrong direction due to its high cost and other affordable, reliable alternatives. We plan to implement robust algorithms with an appropriate selection of sensors. For this reason, the Robocart MQP intends to rely solely on stereoscopic vision and a complementary software suite. Cameras offer incredibly cheap sensing, even at low resolutions. One study, by Goncalves and Sequeira, supports our concept through their use of a single, low-resolution camera and an array of ultrasonic sensors. Goncalves and Sequeira were able to combine the readings from both types of sensors into an occupancy grid and perform edge-detection. As a result, the vehicle was able to perform lane-tracking. The ultrasonic array was used to detect vehicles in the vicinity of the car on the highway when passing or being passed [13].

Because no single sensor can be 100% consistent or reliable, the best course of action is to correct for mistakes in perception by combining data from multiple sensors to best take advantage of the strengths of each sensor. For example, a vision system may be fooled easily by shadows, but a radar array will not [14].

The future of sensing will reveal even better-suited systems for autonomous vehicle research. Faster-spinning and cheaper LIDAR sensors will allow for low-cost, high fidelity, and high accuracy for understanding the vicinity of the vehicle. Even more exciting are the promise of new types of sensors, such as the event-based sensor developed at MIT in May 2014. This type of sensor, which consists of a simple camera backed by a novel algorithm, is able to record changes, or events, in individual pixels, and report these changes. This type of sensor is exciting for autonomous vehicle technology because it replicates the way our own eyes perceive objects while navigating—by using information from changes in the system in front of us rather than focusing on the whole image we see [15].

There are a whole host of other sensors used in autonomous vehicles, however, not just those used for navigation and object avoidance. Relevant to this report, for example, are the sensors used for position feedback on the steering and brakes, so research was conducted on common sensors used in these applications.

2.2.1 Steer-by-Wire

Steer-by-wire is a common technology used in cars today. It consists of replacing the fully mechanical steering steering mechanism with a host of sensors, which detect the rotation of the steering wheel, an actuator, which actually turns the wheels on the car to face the desired direction, and a force-feedback actuator on the steering wheel, which gives the driver feedback from the road [16]. Generally, a sensor is also used at the output and a closed-loop control algorithm is implemented for greater reliability, as well [17]. For safety, three electronic control units (ECUs) are placed inside the body of the car. In the event that all three fail, a clutch can activate a temporary backup mechanical steering mechanism. The advantages of steer-by-wire over traditional power-steering mechanisms are numerous, so many cars on the road today use this technology—for example, the response is much improved, and extraneous vibrations from the road need not be transmitted back to the steering wheel, making operation much more comfortable for the driver [18]. However, of interest to this project, steer-by-wire solutions make driver-assistive technologies where the car intelligently maneuvers for the driver in some cases, such as lane-assist, much better to implement [18]. Traditional lane assist technologies would engage the brakes to assist the driver, resulting in an uncomfortable ride [16]. Thus, steer-by-wire solutions were drawn upon for this project for automating the steering system, even though a full steer-by-wire system was not implemented.

Existing steer-by-wire cars seem to use rotational potentiometers complemented with encoders placed at multiple points along the steering mechanism; for example one could be placed on the steering column and another at the pinion [17]. The potentiometers supply absolute position data, but their data are supplemented by the non-absolute encoder information [17]. The reason for using multiple sets of these sensors is for safety and reliability.

2.2.2 Brake-by-Wire

Brake-by-wire is a similar technology applied to brakes, but is much more widespread and was developed much earlier than steer-by-wire today because of its use in truck trailers [19]. Because it has been in use for so long, much of the systems have been standardized already, including force sensors in the brakes as well as temperature sensors to both compensate for shrinkage or expansion of parts and detect overheating [20]. The main sensors used in these mechanisms tend to be potentiometers in the foot pedals and resolvers in the brakes [20].

2.2.3 Rotational Sensors

Specifically for this project, rotational sensors were used in the steering and braking systems to convey rotation information back to the computer. The two main types of rotational sensors I considered were potentiometers and encoders. There are other types sensors that can be used, such as resolvers or accelerometers, but would not be as cheap nor straightforward to program as a potentiometer or encoder.

There are many different kinds of potentiometers on the market—linear, rotary, multiturn, etc. Most of them rely on a simple voltage divider-type circuit, where the potentiometer has a long resistive material such as ceramic, which is connected to power on one end and ground on the other with a wiper in between. Moving the wiper back and forth on the resistive material effects changes the voltage divider and results in a voltage across the wiper and ground proportional to the distance away from the power node. However, most rotary potentiometers have wipers that can only make about 3/4 of a turn. This posed a problem in the steering mechanism in this project because the steering wheel makes multiple turns. To get around this, there are also *multiturn* potentiometers, which are simply a regular potentiometer with gearing inside to get multiple turns out of the same-size resistive material.

There are many different types of encoders as well. Optical encoders rely on a disk with an alternating pattern which passes and blocks light at specific intervals, which a sensor picks up and relays; a computer can determine the angle and speed at which the encoder's shaft is spinning by counting numbers of 'ticks'. Magnetic encoders perform in a similar way but with a magnetic disk, which makes them less prone to dirty environments where the optical encoder could face issues if its disk got dirty. Quadrature encoders have two sets of patterns printed on the same disk where one pattern is rotated slightly. With some clever programming, quadrature encoders can be used to not only tell speed and angle traveled, but also direction of rotation. One feature that potentiometers have over encoders, however, is that potentiometers know their 'absolute' position or angle, whereas encoders can only tell relative angle. This means, in practice, that if the power is lost on two robots, using an encoder and one a potentiometer, and someone bumps into both robots and changes the angle of the shafts on each, when both robots turn back on, only the robot with the potentiometer will know how much its shaft has moved by. To resolve this, there are also *absolute* encoders on the market. Some of these work by using Grey's binary code to assign a specific pattern of blacks and whites on the disk to each angular position. However, these are unreasonably expensive and so are seldom used. Another issue with these types of encoders is that if the shaft makes more than a full rotation, the encoder will have no idea how many rotations have passed if it lost power in between. To get around this issue, there are also *multiturn* encoders which output two numbers: the number of revolutions the shaft has made and the current angle of the shaft within its current revolution. For the steering mechanism, an *absolute multiturn magnetic encoder* was considered at one point, but eventually discarded due to its overwhelming price.

2.3 Mechanisms

2.3.1 Racks and Pinions

Rack and pinions are fairly straightforward mechanisms consisting of a gear, called a pinion, and a rack, which resembles an 'unrolled' gear with teeth arranged linearly. They are commonly used for translating between rotational motion and linear motion, and are commonly associated with steering mechanisms. The rotational motion of the steering column on the golf cart, shown in Figure 2.2, goes through a rack ① and pinion ② to move the Ackermann steering mechanism left and right to cause the wheels to turn.

Figure 2.2: The rack and pinion steering mechanism in the golf cart.

2.3.2 Universal Joints

Universal joints are a type of joint that allow rotary-to-rotary transmission of motion across rods at different angles. They tend to work best at angles less than 45°, otherwise they can start to get jammed. Upon close inspection, it also becomes clear that using a single universal joint results in uneven speeds at the output shaft because of the nature of universal joints. To resolve this, two universal joints are generally found placed at 90° offsets to one another on the same shaft. By making this small change, the speed of the output shaft would now match that of the input. Universal joints are strongly associated with automobile steering mechanisms and the wheel suspension systems. The universal joints in the steering mechanism of the golf cart are shown in Figure 2.3, where the input shaft ① connects to the steering column and the output shaft ② holds the pinion of the rack and pinion mechanism.

2.3.3 Sprockets and Chains

Sprockets and chainsets are relatively simple and robust ways of moving rotary motions from one place to another without changing the direction of rotation. One can use different

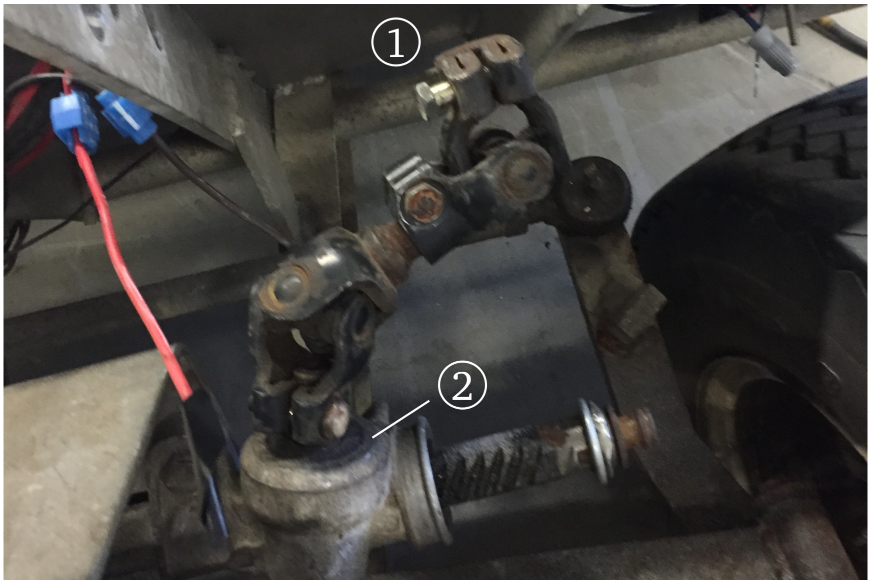


Figure 2.3: The pair of universal joints in the golf cart steering mechanism.

sprocket ratios to transform the torque and velocity at the output shaft. They can be more useful than gears sometimes because of the flexibility of the roller chain and the ability to flex. Sprockets are capable of shifting or being mounted a few degrees off. Gears, on the other hand, will grind each other down if not fitted properly.

Chains and sprockets are categorized into several different sizes, including 25, 35, 40, 50, and 60. The first digit of the size is for the pitch of the chain (in eighths of an inch) and the second digit is either zero, for a standard chain, or five, for a rollerless chain. Adding links to a chain is done by adding a two links at a time—an adding link and a connecting link. It is possible to purchase something like a half-link, which is a single link that can be used to extend the chain by just a single pitch of the chain, but these are generally weaker and more expensive so are generally avoided.

Sprockets can be categorized as either internal or external, depending on the way the chain wraps around them. When a chain wraps around a series of sprockets, they are all considered internal. However, if a sprocket lies outside of the area of containment of the chain, it is considered external.

2.3.4 Drum brakes

There are a variety of different kinds of brakes used in wheeled vehicles, but the golf cart used in this project used drum brakes. Drum brakes are generally activated by tugging on a cable, and, in the golf cart's case, are connected to the brake pedal. Springs are used to keep the brakes disengaged by default. When the brakes are engaged, two or more brake shoes extend outward from the center and put pressure on the drum, which rotates with the wheel, causing the drum to slow down from friction.

2.4 SolidWorks

SolidWorks is a 3D CAD software that was used extensively in this project. I used 3D modeling software to make sure that pieces would fit as intended before they were ordered or built. Additionally, SolidWorks is compatible with the Computer Aided Manufacturing (CAM) software Esprit, which is used in the machine shop for generating the machine code for the CNC machines. Additionally, the files generated by SolidWorks are compatible with the laser-cutter for cutting custom acrylic or wooden parts.

The golf cart was modeled to scale in SolidWorks for the purpose of designing the steering, braking, and Raspberry Pi mounting systems with all of their relevant details in order to make sure everything would fit. Initially, only parts of the golf cart were modeled as they were needed, but Liz and Gabe requested a model of the full cart for use the in simulation software Gazebo. However, they later discovered that the transition from SolidWorks to Gazebo is a very difficult one to make, so efforts were abandoned. Fortunately, the full model of the golf cart later became useful for making visually pleasing renderings, such as the one in Figure 2.4, for materials for Project Presentation Day. Perhaps a future team will find a way to import the model into Gazebo or another simulation package since the measurements of the model are fairly true to the actual golf cart.

On the whole, however, this project would have been much longer and more expensive

Figure 2.4: A SolidWorks Photoview rendering of the golf cart CAD model.

without the use of SolidWorks. Having the CAD model made visualizing assemblies, checking clearances, and finally fabricating parts much simpler. Many of the photos contained in this document are actually SolidWorks renderings because they are easier to arrange or show cross-sections of.

2.5 Chapter Summary

The purpose of this chapter was to introduce fundamental concepts perhaps not taught in classes, but very relevant to this project. Although the long-term project is to build wirelessly connected autonomous vehicles, the scope of this year's project was to continue work on the 1995 electric golf cart acquired last year. This paper, specifically, focuses on the mechanical upgrades made to Robocart.

Fundamental concepts that were involved in this project include detailed information about sensors, such as LIDAR, radar, ultrasonic, potentiometers, and encoders; mechanisms, such as racks and pinions, universal joints, sprockets and chains, and different kinds of brakes used in automobiles; and finally 3D computer-aided design software such as SolidWorks, without knowledge of any of which this project would not have been successful.

Chapter 3

Project Approach

Since the Robocart platform is centered around a golf cart, the mechanical upgrades necessary in order to meet the system requirements of delivering a mobile, autonomous ground vehicle were focused on. Significant mechanical upgrades were made to the original golf cart using sensors, motors, and parts modeled in SolidWorks.

Because the system was somewhat large and complex, it was broken down into individual subsystems. While Gabe tackled the ROS algorithms handled on the server and Liz handled the wireless connectivity aspect, I focused on the three mechanical subsystems of Robocart, namely, mounting the stereoscopic cameras and implementing automated steering and braking systems. Unfortunately, because there was not much overlap of talents in our small team, we found ourselves unable to work together on much of this project.

The golf cart had already been acquired by the previous team—a 1995 electric golf cart, shown in Figure 3.1. The space we worked in had already been reserved in the loading dock area in the second level of the Rec Center, also by the previous team.

3.1 Raspberry Pi Mount

A mount was needed to both protect and hold the Raspberry Pi cameras at a fixed angle and position on the hood of Robocart in order to implement vision. It was found that the

Figure 3.1: The physical golf cart we worked on.

only way to implement stereoscopic vision with Raspberry Pi cameras was to have two Raspberry Pi cameras each connected to its own Raspberry Pi chip, i.e. two cameras and two Raspberry Pis. Because the only cable for connecting them was so short, the Raspberry Pi chips had to be in close proximity to the Raspberry

The previous year's team had constructed a mount, as shown in Figure 3.2, but it was decided early on that the team would require a more adequate mount for the Raspberry Pi modules and cameras than the existing solution. The previous team had simply mounted the Raspberry Pis and cameras to a piece of wood held together with duct tape and Vex metal pieces, and it was decided a much more permanent and elegant solution would be needed.

In order for the software programming of the Robocart to begin, it was decided the Raspberry Pi mount should be the first mechanical challenge to be tackled. The previous design had several weaknesses, such as not being sturdy enough to hold the cameras without wobbling, not being able to be fastened securely to the golf cart, and not protecting the camera lenses from debris. Additionally, it was decided that it would be convenient if the mount itself could remain attached to the golf cart while the Raspberry Pis and cameras

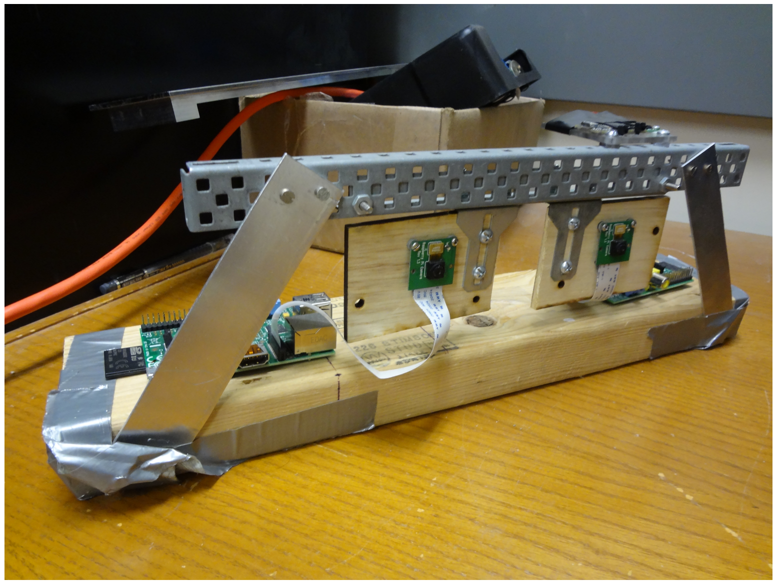


Figure 3.2: Last year's Raspberry Pi mount design.

could be removed and taken somewhere else; this way, there would be less variation in the way the Raspberry Pi cameras were mounted back on the golf cart, removing some error between trials involving the cameras. Thus, the requirements of the design were as follows:

- Hold two Raspberry Pis
- Hold two Raspberry Pi camera modules
- Ensure the two cameras face the same direction
- Allow the the Raspberry Pi's and cameras to be easily removable (to allow the Raspberry Pis to be debugged more easily off the cart)
- Protect the cameras without obstructing the view of the cameras
- Allow access to all necessary ports of the Raspberry Pi

With these requirements in mind, a new design was created. It consisted of a much more robust and rigid design made of laser-cut acrylic with a plate

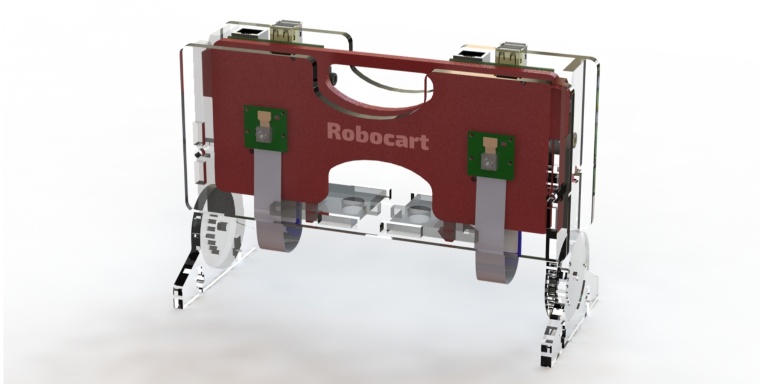


Figure 3.3: The new design drafted in CAD.

The CAD prototype, shown in Figure 3.3, was mocked up using measurements from the mounting holes of the Raspberry Pis themselves as well as the RPi cameras. It was decided that the most elegant solution would involve mounting the two Raspberry Pis on one side of a removable plate and the cameras on the other. Because the middle plate was removable, the bottom of the mount could stay attached to the body of the golf cart while the Raspberry Pi modules and Raspberry Pi cameras could be detached for working on somewhere else. This way, the Raspberry Pi modules and cameras could be reattached to the golf cart while ensuring that the cameras had not moved to a different location between trials. A rigid, clear, acrylic box was constructed around this plate with legs whose angle could be adjusted to allow the team to try attaching the mount on different locations on the Robocart before a final location was selected. A handle was created on the removable plate for easy removal. Finally, holes were cut into the sides of the clear box for access to the HDMI and component-out ports on the Raspberry Pis. The rest of the ports were either on the top or bottom of the Raspberry Pi and therefore did not require access holes in the mount.

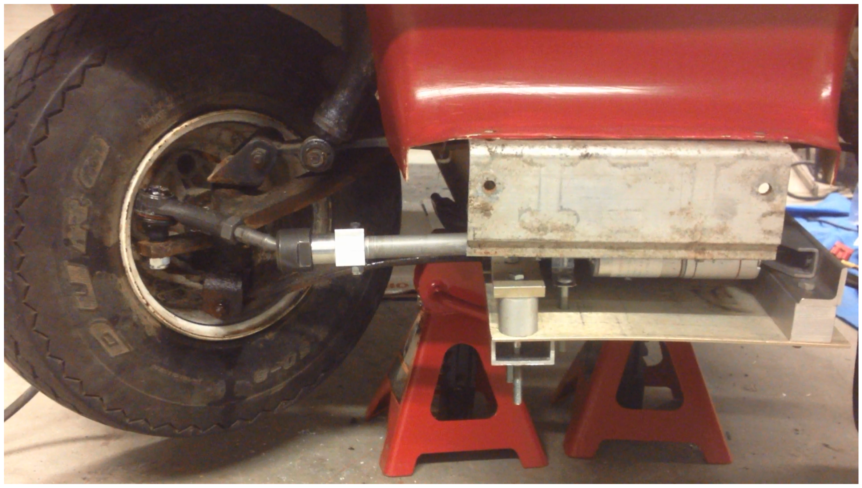


Figure 3.4: Last year's design was a linear actuator which pushed against one of the wheels.

3.2 Automated Steering Mechanism

Next, the steering on the golf cart underwent major modifications to allow the computer to control it. The previous year's solution was again deemed inadequate—it consisted of a linear actuator which pushed directly against the front wheel of the golf cart in order to turn it, as shown in Figure 3.4. The main issue with this solution is that it did not make use of mechanical advantage, which caused an inordinate amount of stress on the system since it is specifically designed to be actuated from the steering column end. Additionally, because the actuator was not mounted properly and not attached to the wheel at the same height from the ground on both ends, the entire actuator itself flexed as it extended. Finally, the actuator was not back-drivable, which posed serious risk to the passengers of the golf cart in the event that the golf cart needed to be veered away from danger.

To solve this, the torque needed at the steering wheel was first measured. It was known that the torque would be highest when the golf cart was not driving, but held stationary. The torque required on the steering wheel was measured experimentally using a force gauge and a measuring tape. It was found to require a minimum of 21 pounds of force at 5.25" away, or 9.19 pound-feet of torque, to turn the steering wheel while the golf cart was stationary. Next, it was decided between the student and the adviser that it would be much safer if the steering, once automated, was back-drivable in order to ensure the safety of the passengers. Finally, from watching some videos of the previous team's solution, it was also decided that the steering mechanism needed to be much quicker in order to be a successful autonomous vehicle. About one second to turn the wheels from fully left to fully right seemed to be fast enough, in fact even quicker than a human. Thus, the essential design requirements for the steering wheel modifications were as follows:

- Supply at minimum 9.19 ft-lbs of torque to the steering column
- Allow the wheels to be turned from fully left to fully right in about 1 second
- Must be back-drivable

Design ideas were then discussed among peers and Joe St. Germain from the robotics lab. The final revamped design proposed involved using a rotary motor attached directly to and driving the steering column. This solution allows for back-drivability, as a human in the driver's seat could seize control of the steering wheel and overpower the motor, and also makes much better use of mechanical advantage than the previous year's design. Upon inspection of the steering mechanisms of the cart, it was discovered that there was nowhere else to mount a sprocket or gear other than in the passenger area. This was unfortunate, but no other viable choice presented itself. We hope that in future iterations of this project, perhaps some of the internal mechanisms of the golf cart can be gutted and replaced with better-hidden self-driving machinery.

Additionally, another challenge presented itself when we realized the front dashboard was not perpendicular to the steering column, as shown in Figure 3.5. To compensate for this, it was decided to mount the motor on a plate whose top was hinged from the top of the dashboard, but whose bottom was distanced from the dashboard using standoffs. In doing this, the motor could be mounted such that the motor shaft was almost exactly parallel to the steering column. Because of the tolerance issues involved, which could result in the motor shaft being a few degrees off from being exactly parallel to the steering

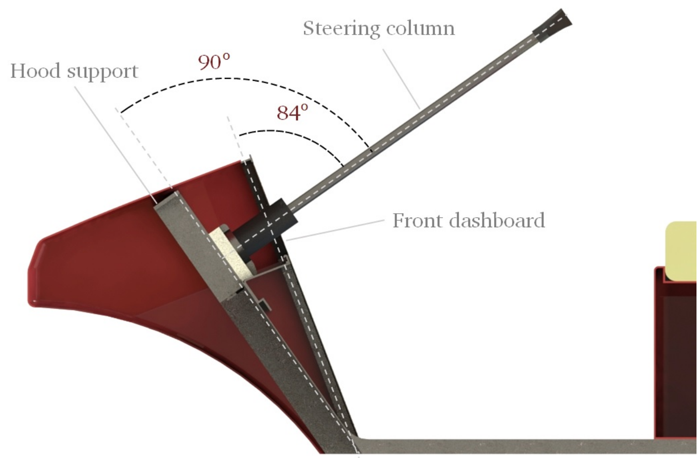


Figure 3.5: The steering column is perpendicular to the hood support, not the dashboard.

column, it was decided to use a sprocket and chainset rather than gears. Gears can have trouble meshing properly if not mounted on close-to-exactly parallel shafts. Sprockets and chainsets, however, can tolerate some wiggle.

Once the motor mounting design was complete, work was begun on choosing a sensor. Because the steering column was designed to make almost two full rotations to turn the wheels from facing fully left to fully right, a regular potentiometer was not a viable option, though it would have been the cheapest one. Next, encoders were looked into that would be a good fit for this application. Part of the complication was that, first of all, the encoder needed to know the absolute orientation of the steering column, and second of all, how many turns the steering column had made when it was booted on. For example, it is possible that when Robocart is turned off, someone could come by and turn the steering wheel to some arbitrary angle. Then, when Robocart is turned on again, it would need to be able to know the absolute angle θ of the steering column as well as if the steering wheel is on its first or second turn, n, in order to know which way the wheels are facing now. Otherwise, the computer could give the motor a command to turn past the limits of the steering mechanism and possibly break something. One way around using an absolute rotational sensor was to use a generic quadrature encoder, but use limit switches inside the steering mechanism itself to know when the rack had reached its limit and also to calibrate the steering system. However, this idea seemed inelegant, since Robocart would have to recalibrate its steering system every time it was turned on again by turning its wheels all the way to one side until it hit one of the limit switches before Robocart could be used.

There are absolute encoders which can know their absolute angle (as a potentiometer can). However, most of these cannot count how many full rotations have been made when the encoder is powered off. Upon further research, multuturn absolute encoders were discovered. Encoder Products Company helped over the phone with picking an encoder. However, the cheapest multiturn, absolute, magnetic encoder that they had was $532 after a student discount. The specifications sheet for the encoder found as well as the price quote are attached in Appendix A.

Finally, it was decided to simply use a multiturn potentiometer, which is both absolute and multiturn by its nature, and also much, much cheaper. It was decided to attach this to the existing chain and sprocket system. Because the steering column was found to turn a total of approximately 840 degrees (2.33 revolutions) and had a 60-tooth sprocket, it was decided to use a potentiometer with the maximum number of turns possible, which was found to be a 10-turn potentiometer, thus requiring a 15-tooth sprocket. In reality, the potentiometer would only be making 9.33 rotations instead of 10 because of the nature of the system, but it was decided that this would be resolved later in circuitry by scaling the signal from the potentiometer to mimic making 10 full rotations, thereby not losing any resolution. From modeling the system in SolidWorks, it was found that the best way to attach the potentiometer to the system would be as an external sprocket, since adding it internally would require a 26” chain, while the only ones commercially available had options of 24” and 36” lengths of chains.

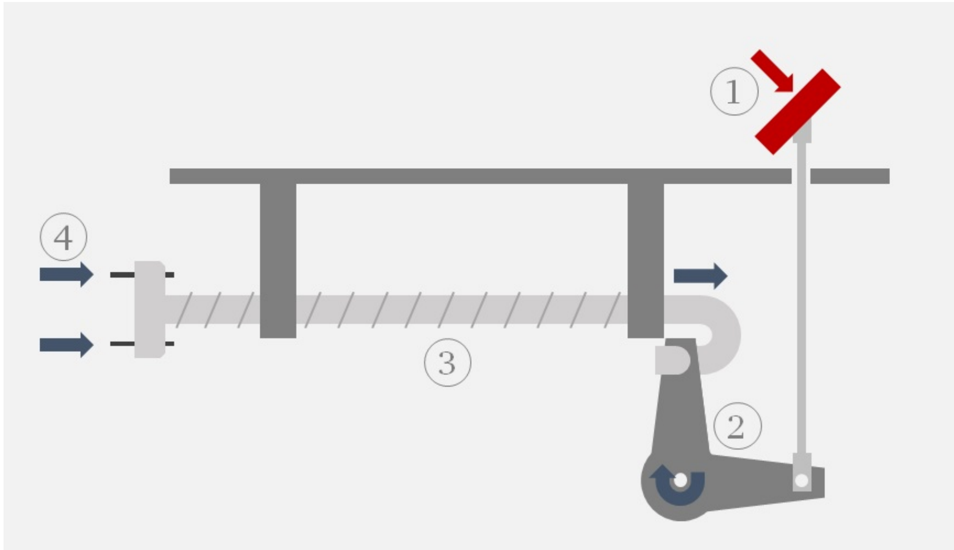
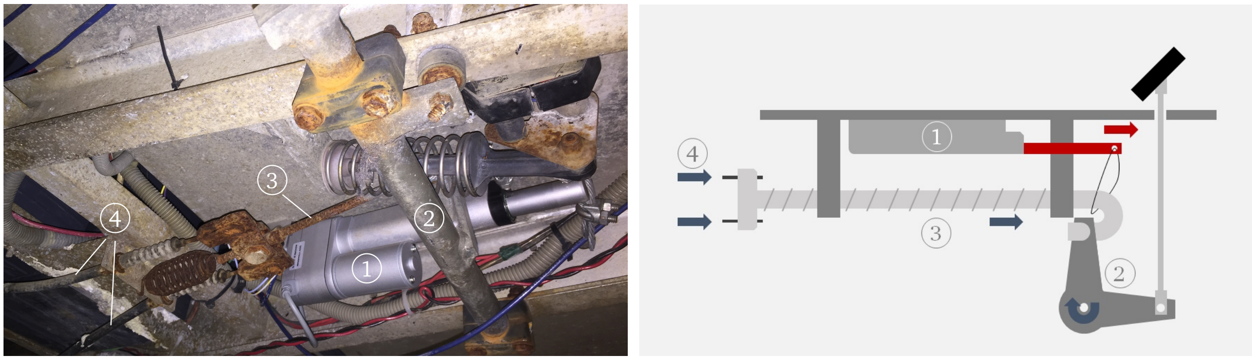


Figure 3.6: Simplified diagram of the normal functioning of the brakes.

3.3 Automated Braking Mechanism

Finally, work on the braking system was begun. Upon inspection, the brakes on the golf cart as it was originally built worked as shown in Figure 3.6. When the driver presses the brake foot pedal ①, lever ② is turned about its fixed center of rotation, which in turn pulls the hooked rod ③ towards the front of the golf cart. This threaded rod is directly connected to the two brake lines ④ which extend all the way to the two rear wheels. Pulling on these two brake cables engages the drum brakes inside the wheels.

The previous year's team had installed their own motor-actuated braking system on the golf cart. A photo of last year's design is shown in Figure 3.7a. A simplified diagram of their computer-controlled braking system is shown in Figure 3.7b. A linear actuator ① is attached to the underside of the golf cart. A small length of steel rope is tied from the end of the actuator to the hooked rod ③. As the actuator extends towards the front of the golf cart, it also pulls the hooked rod towards the front of the golf cart, thereby pulling on the brake lines ④. In this setup, the lever mechanism and brake pedal ② are made irrelevant; pressing the brake pedal will have absolutely no effect on the brakes themselves because the brake system is now attached to the linear actuator, which cannot be back-driven. However,



(a) Last year's motor-actuated braking design. (b) Simplified diagram of last year's design.

Figure 3.7: Before and after comparison of Raspberry Pi mount designs.

extending and contracting the linear actuator will moved the brake pedal up and down.

Although the design is stable, robust, and long-lasting, it was deemed inadequate for several reasons. First and foremost, the design is not back-drivable, which raises several safety concerns. Secondly, the speed of the linear actuator means that it takes about three seconds for the brakes to be fully pressed down. Thirdly, because the actuator is not attached to the brake system rigidly, but instead by a loose steel rope, it experiences hysteresis, which would cause problems down the line when a control system is added.

It was decided that a new system should be installed in place of last year's. It was also decided that a new feature should be added for safety: the brakes should engage if the golf cart ever loses power—we named this feature negative braking. Upon measurement using multiple force gauges, it was found that the brake cables required over 50 lbs of force to engage; the exact force couldn't be determined because not enough force gauges could be found, so a force of about 100 lbs was tentatively estimated. From these, the main requirements for the revamped braking system were set as follows:

- Fully engage in under 0.5 seconds
- Supply a force of 100 lbs to the brake cables
- Must be back-drivable
- Negative braking

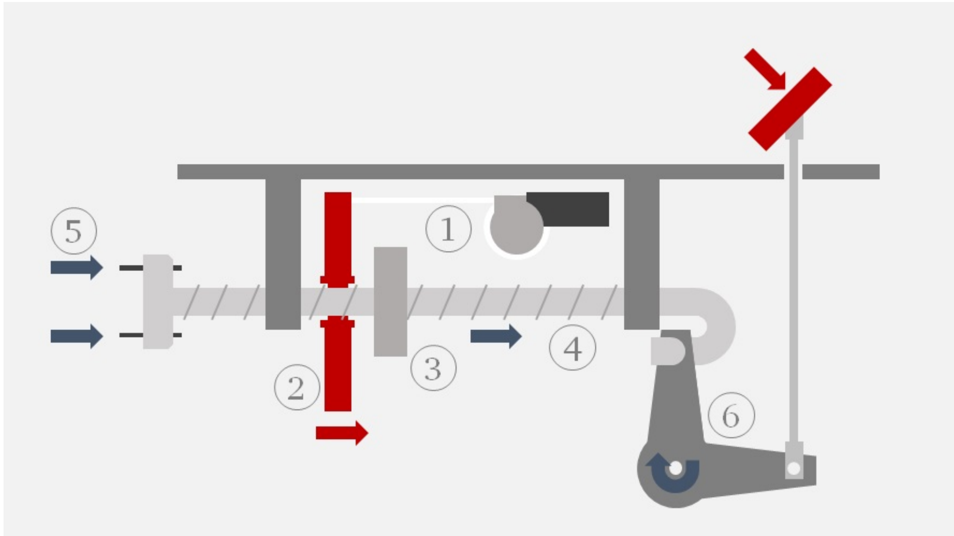


Figure 3.8: Simplified diagram of the revamped brakes design.

Because the back-drivability and negative braking requirements made the design difficult, Professor Stafford was consulted for his expertise in mechanical, especially automotive, designing. With his help, two systems were designed, but the upshot was that there was no real good way of getting around using solenoids and installing a hydraulic system, which would require compressors, cylinders, regulators, and other parts to setup. The design was deemed too expensive for this year's budget, so after much deliberation it was decided to drop the negative braking requirement since it made the design economically infeasible.

With the new set of requirements, a new, very straightforward concept for the braking system was created, shown in simplified form in Figure 3.8. A non-back-drivable motor called a van door motor ① pulls a bearing ② along the threaded rod until it collides with a shaft collar ③ clamped onto the threaded rod ④. When this happens, the threaded rod is pulled toward the front of the golf cart, pulling on the brake cables ⑤. However, a passenger in the car is free to push on the brake pedal in the golf cart and actuate the lever ⑥, which will be able to pull the threaded rod ④ towards the front of the golf cart and activate the brakes. As a result, this design is back-drivable.

A Bosch van door motor was acquired from Professor Stafford, who found one with a

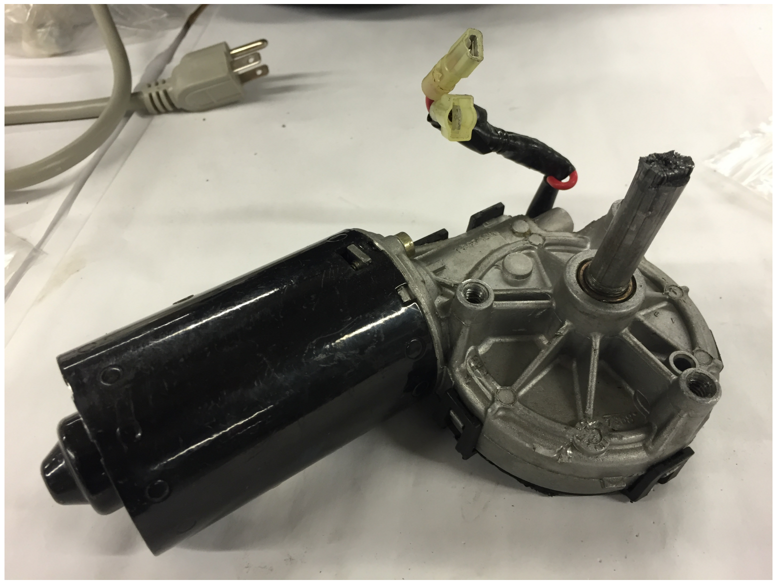


Figure 3.9: The Bosch van door motor chosen for the automated braking system.

broken shaft that the FIRST team had discarded and generously donated it to the team, shown in Figure 3.9. A CAD model for this motor was found online at firstcadlibrary.com; it seems it is a commonly used type of motor in FIRST Robotics Challenge competitions. The datasheet for the motor was also found online and is attached in Appendix C.

Next, work was begun on designing the actual mechanism in CAD. It was found that the diameter of the hooked shaft was 5/16" and that it was situated 2" underneath the floor of the golf cart. The datasheet for the van door motor listed the stall torque as 34 N-m, or 25 ft-lbs. To achieve a force of 100lbs, the pulley used on the motor had to be 1/2" in diameter, since $\tau = F \times r$.

The first iteration of the design in SolidWorks is shown in Figure 3.10. The van door motor ① is hung from the bottom of the golf cart floor by a steel plate and a bracket, which can't be seen. A small pulley attached to the motor shaft has a steel rope (not shown) used to pull on the metal bearing-type piece ② which slides along two railings ⑤ on either side of the hooked rod ④ and hung from two Y-shaped support pieces ⑥ also hung from the bottom of the floor. The shaft collar ③ is clamped onto the hooked shaft ④. The two railings ⑤ and custom steel Y-shaped pieces ⑥ are placed to keep the bearing-type piece

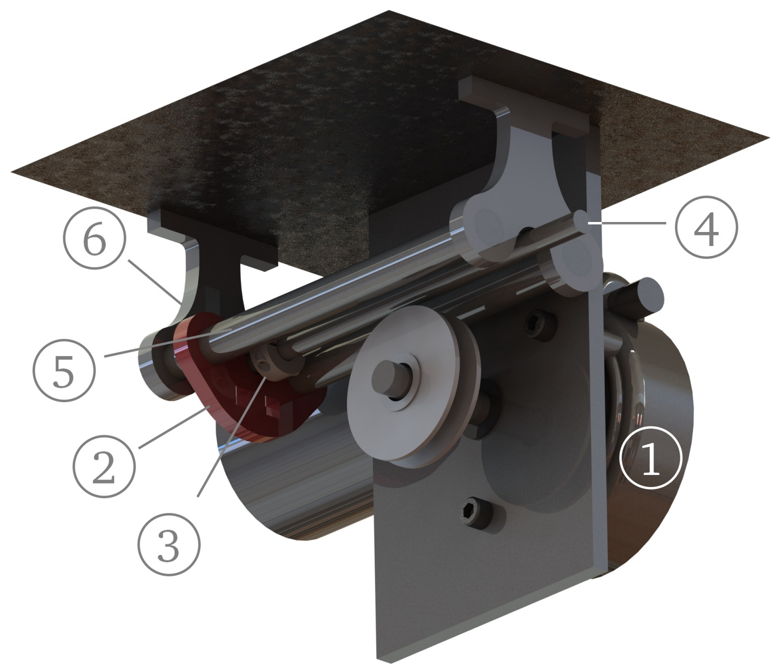


Figure 3.10: CAD model of the first design of the automated braking system.

② from experiencing uneven forces and becoming jammed on the hooked shaft ④ and not being able to be moved. The two railings ⑤ are placed on either side of and at the same height as the hooked shaft ④ in an effort to reduce the chance of the bearing-type piece ② from accidentally jamming. Unfortunately, the only way to attach the steel rope coming from the motor was off-center from the bearing-type piece, meaning there would be an additional torque on the part, making jamming more likely.

The next iteration replaced the bearing-type piece with two actual bearings and a simpler metal piece, as shown in Figure 3.11. It was realized that since the hooked shaft ① could not be removed from the golf cart to slide parts onto it, the bearing-piece ② and shaft collar ③ had to be made as two pieces that would be fastened together around the hooked shaft. Thus, a two-piece shaft collar was ordered from McMaster and the bearing-piece was designed to be bolted together from either side through the two slider bearings ④. It was discovered later that the two slider bearings were actually roller bearings—slider bearings

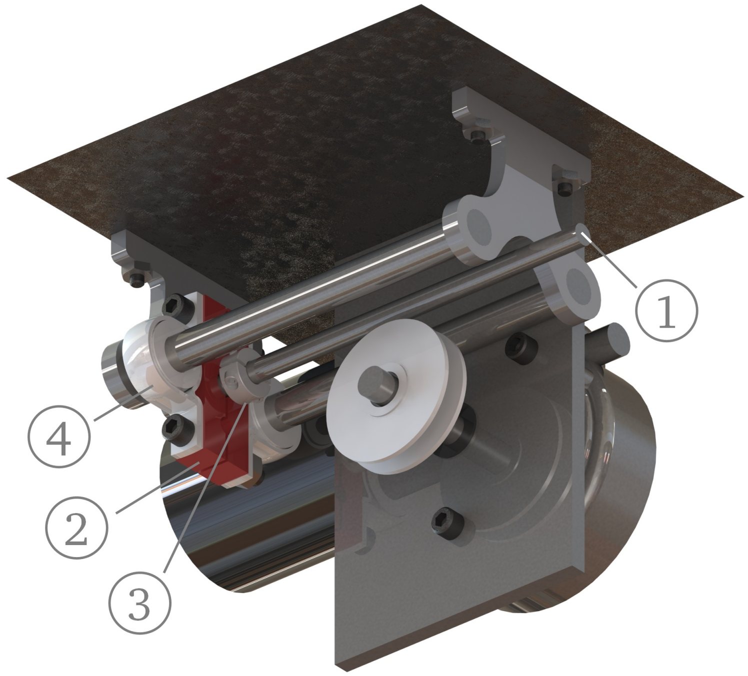


Figure 3.11: CAD model of the second design of the automated braking system.

are generally longer.

Finally, the third iteration of the design was an attempt to shrink the design so that fewer pieces would have to be machined. The result is shown in Figure 3.12. The van door motor was turned upwards with three standoffs (1) to obviate the need for the large and somewhat delicate steel plate hanging vertically from the golf cart. Because no pulleys could be found with a 7/16" bore diameter, a 7/16"–1/4" shaft coupling (2) was added. Two pulleys (3) were added instead of just one for extra strength and for ensuring the force on the bearing-piece (4) was even so there wouldn't be any extra torques exerted on it. The bearing-piece (4) was also made longer to make it less likely to jam on the hooked rod, as well. A new acrylic piece (5) was added to the top of the assembly to support the 1/4" axle from above. Finally, two acrylic rings (6) were placed on the 1/4" diameter steel rod. These two rings had a hole for passing the steel rope through and holding in place. Because the 1/4" rod had a D-profile, these two acrylic pieces would rotate with the axle.

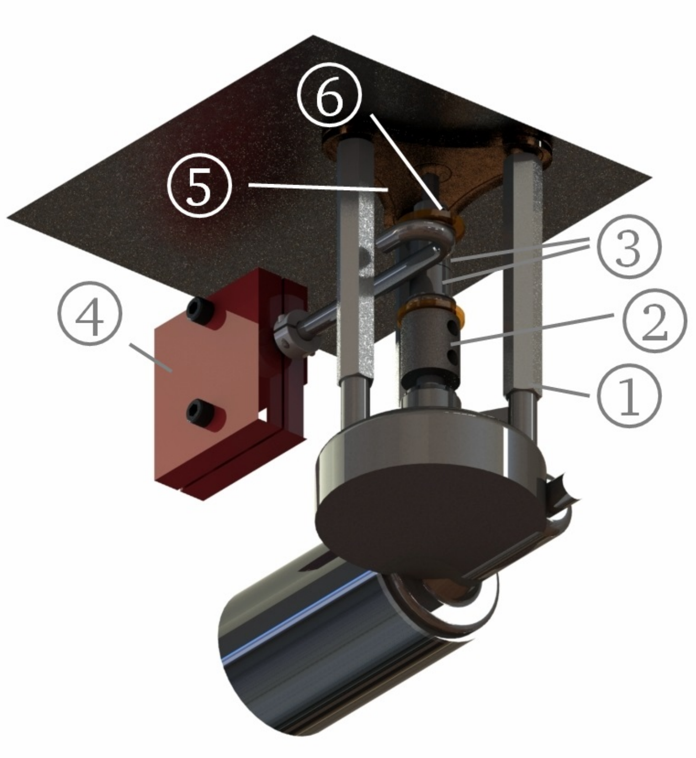


Figure 3.12: CAD model of the third design of the automated braking system.

3.4 Chapter Summary

Because the project was so large and complex, it was broken down into smaller subsystems. The three subsystems focused on in this paper are the Raspberry Pi mount system, the automated steering mechanism, and the automated braking mechanism. For each, a set of distinct requirements was listed out and initial prototyping begun in SolidWorks. A few different designs were created for each system, one was chosen, and the chosen design was then taken through a few iterations in CAD before starting the actual building of the system. This saved a lot of time and money later on in the project. Unfortunately, the requirements of the braking system had to be adjusted because the only solution that fit the original requirements would have been too costly for this MQP. It is hoped that future teams, perhaps having more funds, will be able to implement a solution which meets all of the requirements in the future.

Chapter 4

Project Implementation

Work began on the Robocart with the mechanical outfitting of the cart. This involved smaller tasks, such as creating a mount for properly mounting and protecting the Raspberry Pi cameras, as well as larger tasks, such as body work on the internals of the golf cart to prepare the steering and braking for computer control.

4.1 Raspberry Pi Mount

The Raspberry Pi mount design went through four iterations. When the design of the first prototype was completed, it was laser cut out of clear 0.125" acrylic to allow the cameras to see through the material. The first iteration involved forcing the 0.125”-thick side plates of the "box" to flex to make the removable plate lock into place, but this solution made the mount prone to cracking and was difficult to use. The second iteration was cut out of 0.22" acrylic for greater durability, but it was found the acrylic could no longer flex, awkward to use, and potentially dangerous for the Raspberry Pi cameras if they were forced in at awkward angles. The third iteration had cuts that allowed the removable plate to be slid in through the top and then locked into place by passing bolts through the front plate and tightening nuts on the other side, as shown in Figure 4.1. However, this was deemed inelegant; when the bolts were tightened, it was found that the removable plate would

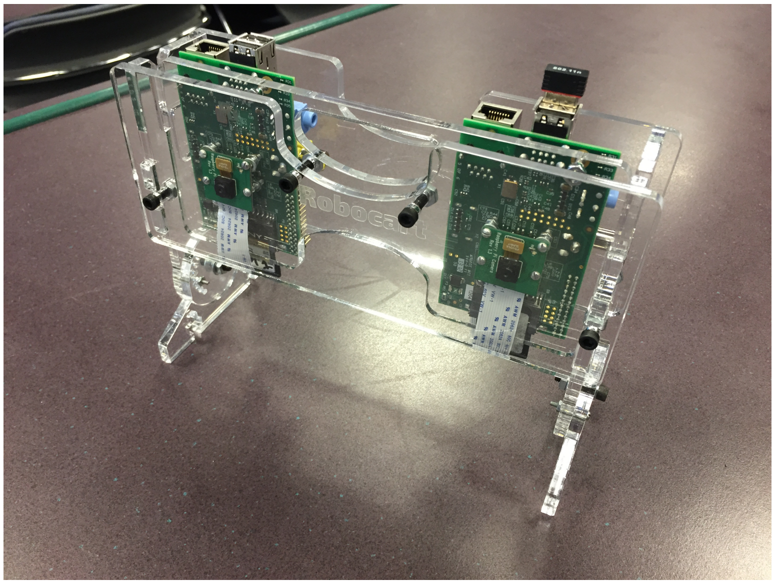


Figure 4.1: The fourth iteration of the Raspberry Pi mount design with locking bolts.

flex under the pressure and change the angle between the cameras. The fourth iteration involved a spring-lock mechanism which allowed the removable plate to lock into place when inserted. Finally, after being carried around in backpacks and rough-handled, it was found that the feet of the fourth design could break easily, as shown in Figure 4.2. A simple fix was done to this piece by adding more material above the cut for the mounting bolts, and thus the final design was arrived at, shown laser-cut, assembled, and attached to the golf cart in Figure 4.3. The mount was temporarily attached to the golf cart with pieces of Vex so that different locations on the hood could be tested once the vision algorithms were implemented. Once a specific location is determined, the four mounting holes can be drilled into the hood of the golf cart and the Raspberry Pi mount can easily be attached to the hood with four bolts.

4.2 Automated Steering Mechanism

The first issue which raised itself involved the mounting of the motor. Because of the way the golf cart was designed, the dashboard was not perpendicular to the steering column,

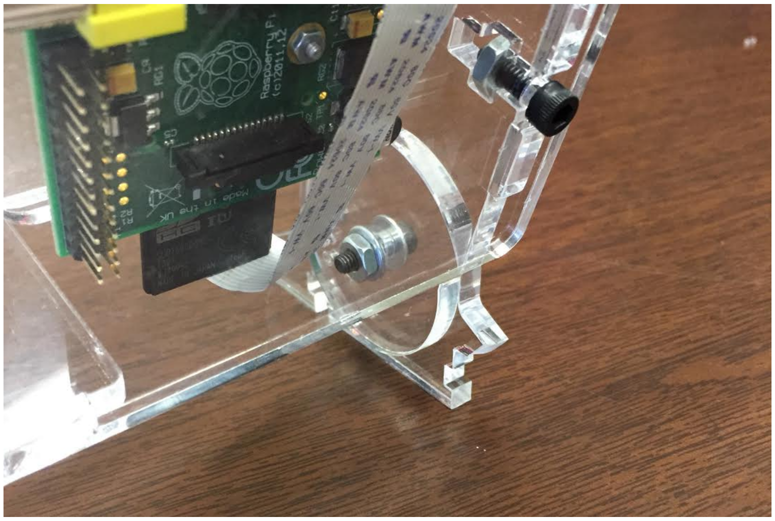


Figure 4.2: The foot was identified as a break point and fixed for the final design.

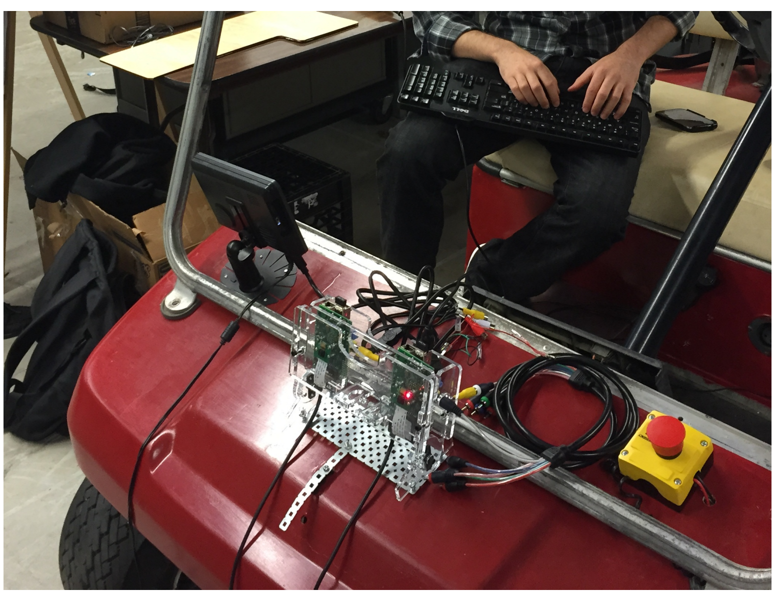


Figure 4.3: The final Raspberry Pi mount design attached to the golf cart.

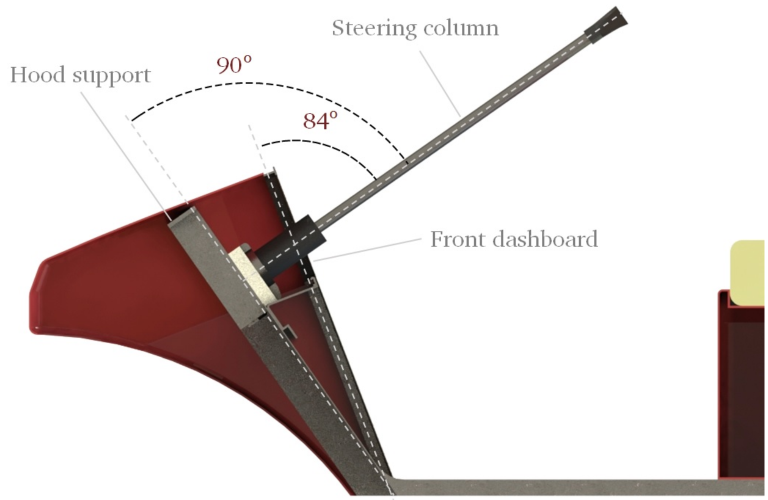


Figure 4.4: The steering column was not perpendicular to the front dashboard of the cart.

as shown in Figure 4.4. As a result, the motor controlling the steering column could not be directly mounted to the dashboard. Instead, it was decided a separate steel plate had to be mounted to the dashboard with hinges and then angled correctly using offsets. The motor could then be bolted directly to this steel plate and be parallel to the steering column.

Next, it was decided that using a chain and sprocket would be more favorable than using gears for this application. This was decided because the steel plate had to be manually mounted to be perpendicular to the steering column, there is going to be some error, such as a few degrees between the axis of the motor and that of the steering column. If gears were used for this scenario, even a small amount of error in the angle could result in a lot of grinding and wearing down of the gears over time, leading to slippage and dangerous situations while driving. However, using sprockets and a chain affords much more room for error and was much more preferable for this case.

Joe St. Germain generously provided the MQP with a Currie Technologies XYD-13 900-Watt motor. From the motor chart found online for the XYD-13, shown in Figure 4.5, it was found that the peak efficiency of the motor occurred at around 1.5 N·m. Since it was known that 9.19 N·m of torque were required at the steering column, it was decided that a gear ratio of 6:1 would be needed provide adequate torque to turn the steering wheel

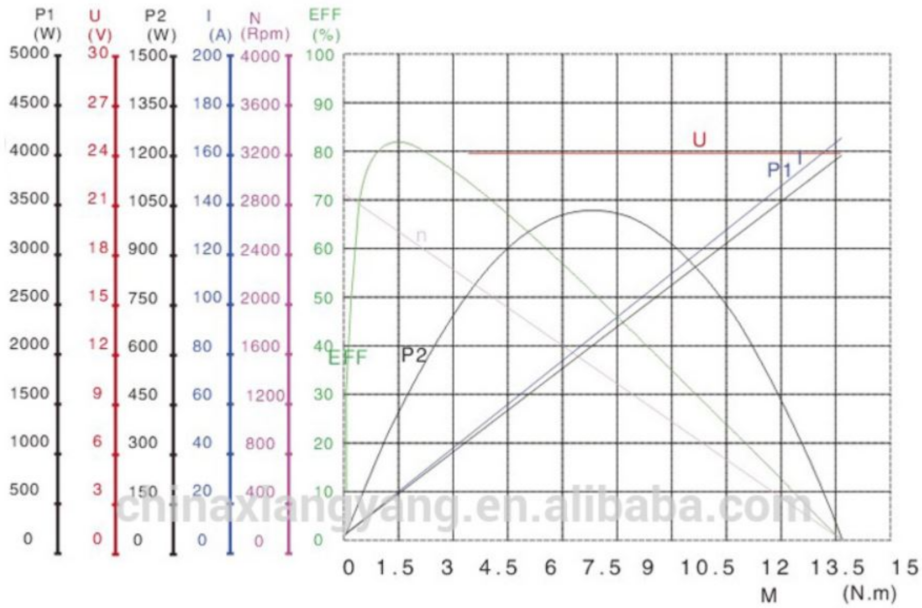


Figure 4.5: Motor chart for the motor used in controlling the steering mechanism.

at the peak efficiency of the motor. One 10- and one 60-tooth sprocket each were chosen because the 10-tooth was small enough that there was a gear that was six times larger but large enough that a chain would fit around it.

Next, the correct type of chain had to be chosen to ensure that the forces from the motor and steering column wouldn't break the chain. The largest force on the chain would occur at the intersection of the chain and the smaller sprocket. The magnitude of this force would be $\tau/r = 9.19$ N·m/0.0763 m $=$ 120.4 N $=$ 27 lbs force. The weakest standard, #25 chain with a 1/4" pitch, was found to have a working load of 88 lbs, which made it more than satisfactory. However, the #35 chain with a 3/8" pitch and working load of 199 lbs was chosen because it was 25% cheaper on the McMaster website. Once the pitch was selected, the corresponding 10-tooth (McMaster 6793K117) and 60-tooth (McMaster 6793K139) sprockets were chosen. The entire length of chain needed is 26.49 inches, so two feet of the #35 chain were ordered as well. It came with a connecting link included. Orders were placed for the steel plate and sprockets at the same time.

While the parts were on their way, the essential pieces of the golf cart frame were modeled in SolidWorks and a CAD model of the steel plate was designed with the proper

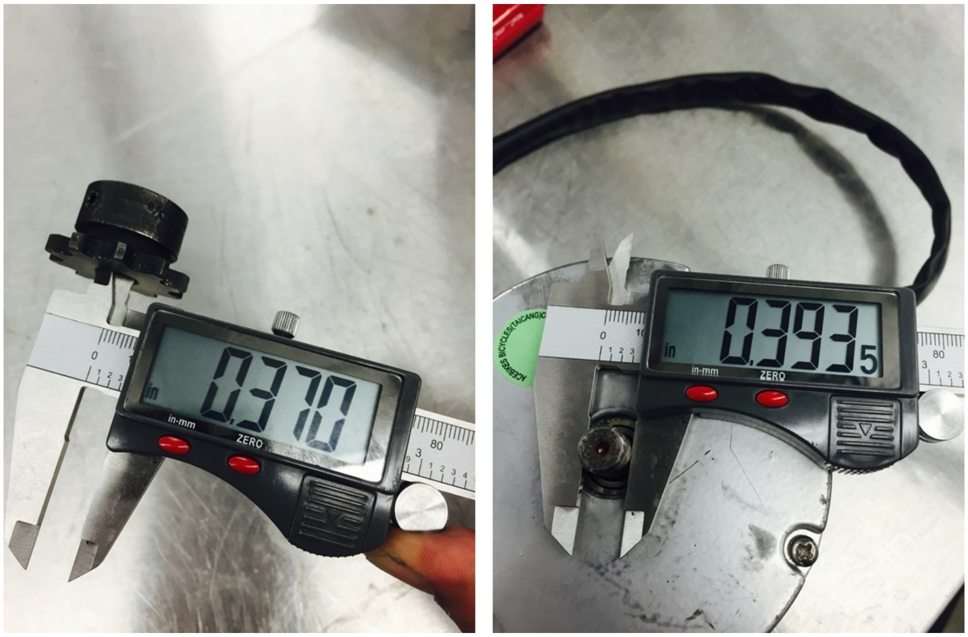


Figure 4.6: The 10-tooth sprocket was found to not be an exact fit for the motor shaft.

mounting holes for the motor. Once the parts arrived, it was discovered that the 10-tooth sprocket in fact did not fit on the motor shaft. Upon further research, it was discovered that the motor had been constructed with metric measurements, but the datasheet being used listed the measurements in approximate ANSI measurements instead, and the actual motor shaft was 10mm in diameter, not 3/8” as expected. The parts were taken to the machine shop and measured with calipers, as shown in Figure 4.6.

As a result, the sprocket was taken to a lathe and bored out with a drill of size ‘X’, or 0.397” since that was the closest available one in the HL 104 machine shop. Although the motor shaft diameter was 0.002” less, it was decided that the diameter did not need to be so exact in this case. Care was taken to remove the set screws from the sprocket before drilling into it.

Once this was resolved, the first thing to do was machine the steel plate. The part had to be machined with a CNC mill because the large hole in the middle of the plate for the motor could not be simply drilled out. The team asked Matthew Forman for his help and expertise in machining. Unfortunately, even with his help, the steel plate was machined

Figure 4.7: An error in the CNC machine resulted in a badly cut plate.

incorrectly, as shown in Figure 4.7, as a result of some tampered settings on the machine.

Since there was no way to recover the plate, a new plate was ordered. This time, the plate was machined correctly. Next, two hinges were needed for attaching the plate to the golf cart frame. Fortunately for us, the Collablab in Higgins happened to have two lying around of the perfect size and strength that they generously donated to us. The hole pattern of the hinges was manually drilled out of the steel plate using 9/32" holes with pilots holes using a drill press, as shown in Figure 4.8.

The motor-mounting steel plate had to be attached to the frame of the golf cart. However, the frame of the golf cart was such that there was a lip preventing the direct attaching of the hinge to the golf cart. Two possible solutions to this problem were to either simply grind down the lip using an angle grinder or to use washers and attach the hinge at a vertical offset from the frame. However, as shown in Figure 4.9, using the solution with the washers (Idea #1 in the figure) would result in high torques on the frame as varying forces from the motor carried through the steel plate and to the ends of the hinges. Over time, this would result in deformation and weakening of the portions of the frame where

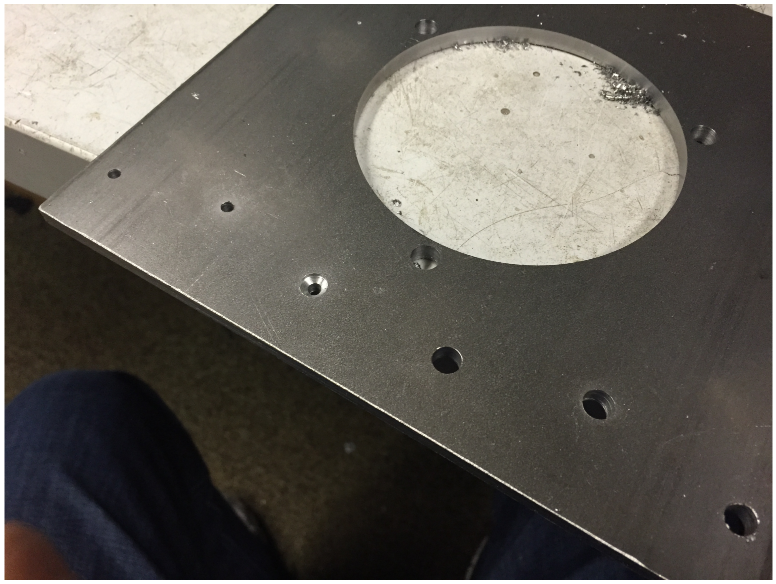


Figure 4.8: Drilling the hinge hole pattern in the correctly cut steel plate.

the hinges were attached, so it was decided to grind the steel frame down instead (Idea #2 in the figure).

Joe St. Germain was generous enough to lend the MQP his personal angle grinder from home and the frame was ground down at two locations large enough for the hinges, as shown in Figure 4.10, although it is somewhat difficult to see. Once this was done, six holes were drilled into the golf cart frame to attach the hinges.

Finally, the steel tube covering the steering column had to be cut down to accommodate the 60-tooth sprocket that was now mounted to it. The steel tube and plastic cover were simply taken to the machine shop and cut down to a 7" piece on the horizontal bandsaw, as shown in Figure 4.11.

Next, some 1/4-28 nuts and bolts were acquired. It was decided to use 1/4-28 instead of 1/4-20 since more more threads per inch were desired; this way the bolts are less likely to become loosened over time due to vibrations in the golf cart during operation. However, when the motor mount was assembled and the steering column steel cover tube inserted, it was found that the steel plate intersected with the steel tube. To resolve this, a cutout had to be made in the steel plate.

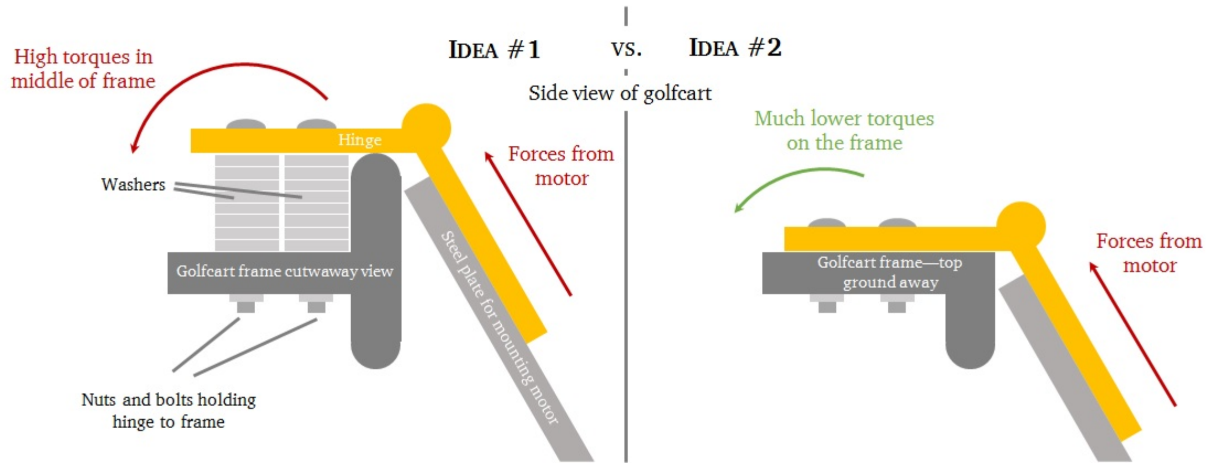


Figure 4.9: Using washers would result in torques and deformations on the frame.

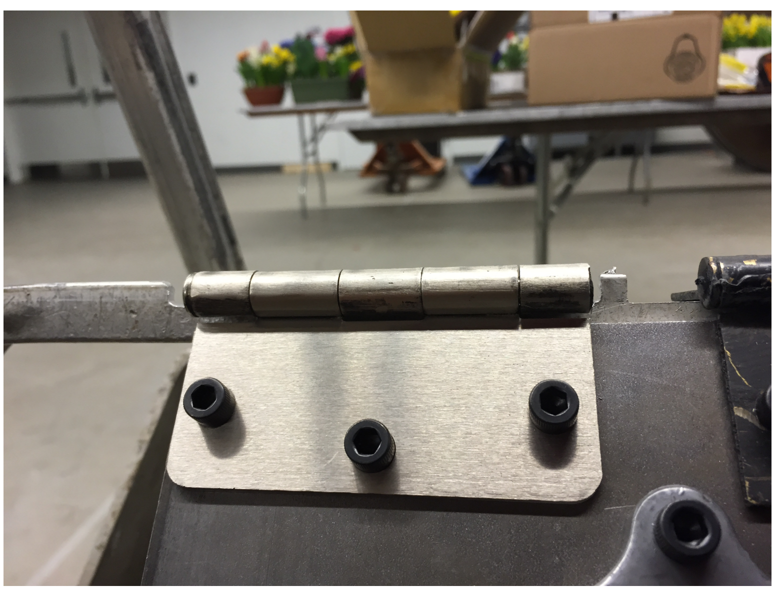


Figure 4.10: An angle grinder was used to grind down the lip of the frame of the golf cart.

Figure 4.11: The steering column mounting tube had to be cut on a horizontal bandsaw.

The cutout was designed in SolidWorks with gentle 3/8" radii to minimize shear forces in the plate. The plate was machined in a CNC mill in the machine shop. The bad plate which had been incorrectly machined earlier was used as a test this time to make sure the machine settings were correct before performing the cut on the actual plate. Now, finally, all the pieces fit together correctly and could be mounted to the golf cart. The partially installed plate is shown in Figure 4.12.

However, upon installation and assembly, it was found that the sprockets were so close together, as shown in Figure 4.13, that any wobbling of the steering column would result in grinding of the sprockets' teeth. To resolve this, additional plates had to be made to hold the motor shaft and steering column apart. The first prototype of this plate, laser-cut from a scrap piece of acrylic, is shown in Figure 4.14.

After an iteration of this plate where another hole was added so as not to intersect with the bolt holding the motor to the steel plate, the parts were installed. It was found

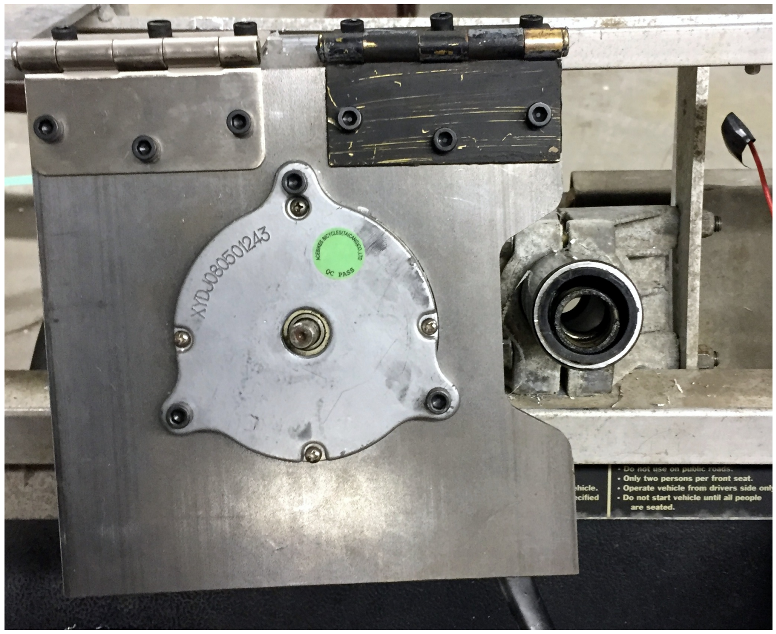


Figure 4.12: The steel plate had to be machined in a CNC mill to avoid the steering column.

Figure 4.13: The clearance between the sprockets was small so extra measures were taken.

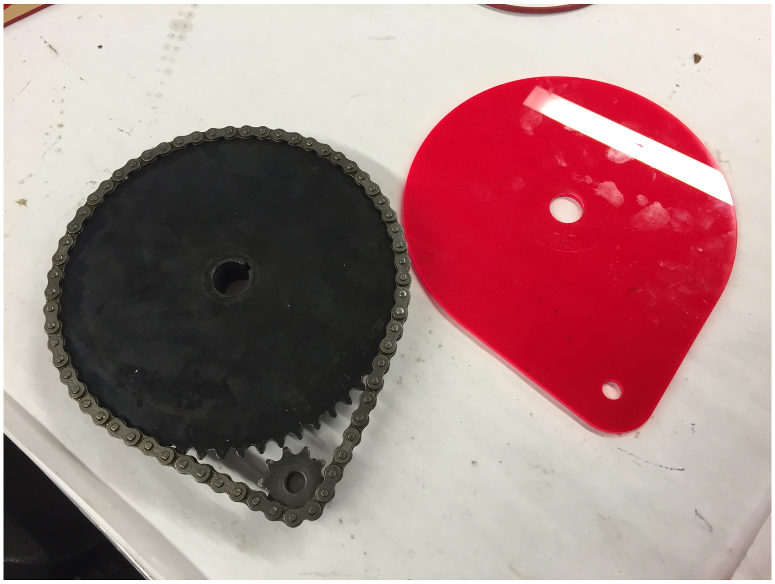


Figure 4.14: A plate was laser-cut from acrylic to hold the two sprockets apart.

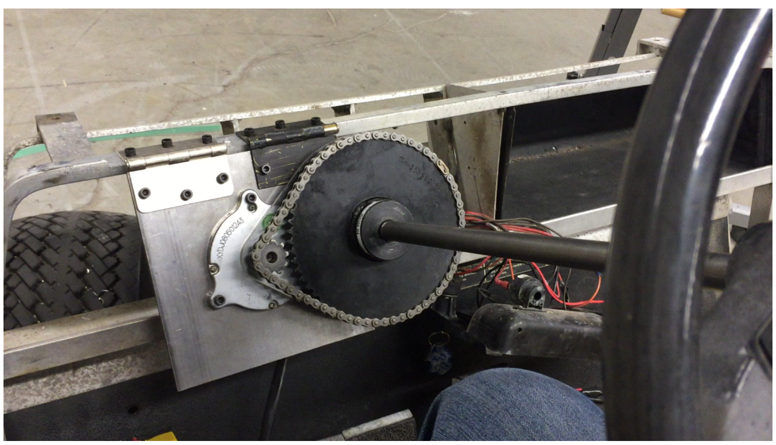
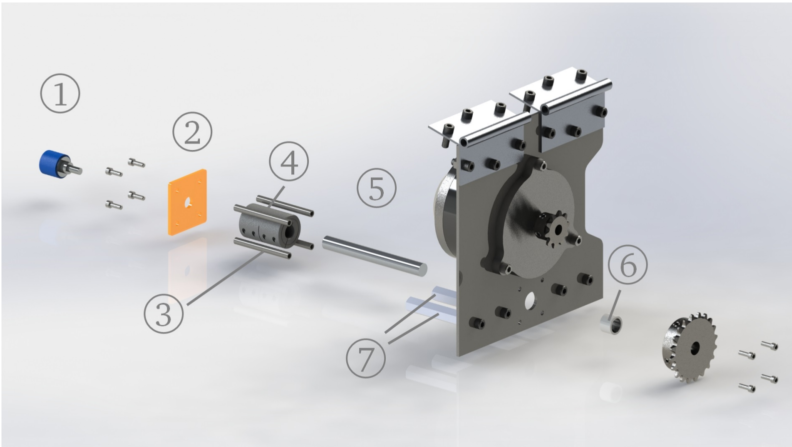


Figure 4.15: Final assembly.

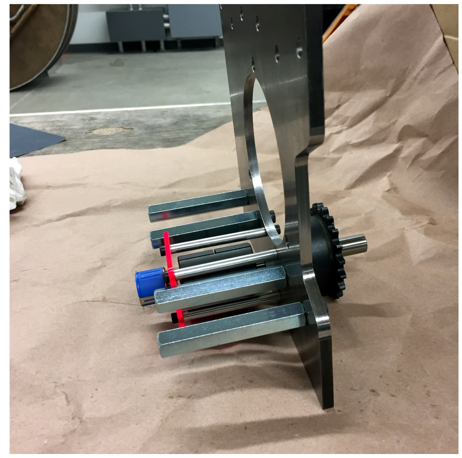
that holding the two shafts apart at 4.4375 inches seemed to keep the the sprockets from grinding each other while allowing them to rotate freely. The assembly of the motor, chain system, and clear plate is shown in Figure 4.15.

Once this was complete, work was begun on attaching the multiturn potentiometer to the system. Although the 15-tooth sprocket had seemed to just barely fit in the SolidWorks model, there didn't seem to be enough room on the chain to securely add it to the actual system. Thus, it was decided that there was no choice but to move the potentiometer system and attach the sprocket internally by buying additional chain links and extending it to accommodate. The SolidWorks model indicated that this would require about 26.5" of chain. Since the pitch size of a #35 chain is 3/8", this equated to about 6.5 additional links, which was rounded up to 8 links since it needs to be an even number, as explained in Section 2.3.3.

Next, it was also discovered, after much searching online, that 15-tooth sprockets are not available with 1/4" bore diameters—the smallest had bore diameters of 1/2". This was a problem because the potentiometer's shaft was 1/4" thick. The initial idea was to search for a bore reducer on SDP-SI to reduce the shaft diameter, but no 0.50" to 0.25" version was found on the website. It was possible to use a shaft coupling, but then the potentiometer would have to be mounted a few inches behind the steel plate to accommodate. The only other idea that came to mind was producing a custom bore reducer which would fill the gap between the 1/4" shaft and 1/2" hole, but this was deemed to be too much work because of how accurately the piece would have to be machined and then drilled to insert set screws. The design chosen for extending the potentiometer behind the steel plate is shown in Figure 4.16a. As seen in this figure, the potentiometer ① is inserted into a laser-cut acrylic sheet ② and offset with four standoffs ③. The potentiometer ① and shaft coupling ④ were ordered first to make sure they would fit in the actual golf cart behind the steel plate. Unfortunately, once again no shaft coupling was found that translated between the potentiometer's and sprocket's differently sized shafts, so a machinable-bore coupling ④ was found on McMaster. Thus, once the parts were ordered, the first order of business was machining the smaller end of the 0.50"-0.235" coupling to 0.25". After it was ensured that there was enough space in the dashboard for the assembly, the 0.5" diameter shaft ⑤ and 11/16" diameter needle bearing ⑥ were ordered. Four 1/4"-20 standoffs ⑦ were also ordered for supporting the steering assembly. The ten holes were then drilled accordingly using the Bridgeport milling machine in the ECE shop and the potentiometer mount assembled, shown in Figure 4.16b. The placement of the hole for the potentiometer was placed such that, in SolidWorks, the length of the chain going around



(a) Exploded view of potentiometer assembly.



(b) Assembled pot mount.

Figure 4.16: The potentiometer assembly.

the three sprockets was an exact multiple of the 3/8" pitch of #35 chain in the hope that the chain would fit over the sprockets without too much or too little slack. In practice, however, there was somewhat more slack in the chain then desired.

Lastly, a new design for the the plate from Figure 4.14 was laser-cut from gray, translucent acrylic. The purpose of this plate was not only to hold the sprockets, but also to protect the greasy chain from collecting debris, protect the passengers from the moving parts, and also help keep the chain from falling off the sprockets when too much strain was put on it.

Finally, everything was assembled and mounted on the actual golf cart. An 0.50" shaft collar was purchased and attached to the potentiometer shaft to keep the front acrylic guard plate attached. The final assembly is shown in Figure 4.17.

4.3 Automated Braking Mechanism

The braking system was somewhat simpler to implement than the steering system had been because there were fewer parts and because much of the designing had been done before the implementation was begun, contrary to how the steering system had been implemented with some of the design work being done during the implementation phase.

The first order of business, once the parts were ordered, was to cut the shaft of the

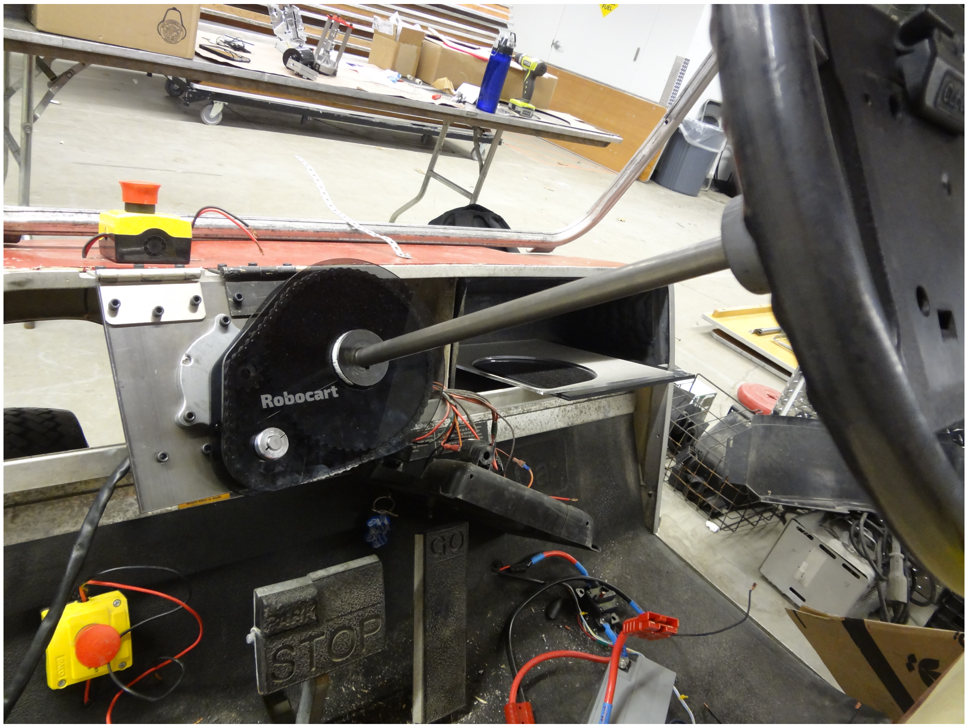


Figure 4.17: Completely assembled steering system.

van door motor shorter, since the damage to the shaft had caused the end of it to become frayed, making the shaft coupling unable to be mounted. It was assumed that this would be a difficult task since the shaft was most likely hardened steel, but it was found after two minutes with a hacksaw that this was not true. Perhaps the weak metal had even been the reason it had become so badly damaged in the first place.

Once the shaft was cut down to size, the shaft coupling was tightened to it and the rest of the axle components mounted and assembled. The supporting acrylic plate was cut out of a scrap piece of 1/8" acrylic. It took two tries on the laser-cutter because the three mounting holes on the van door motor are actually slightly further apart than they are in the CAD model found on the FIRST website.

Next, the bearing-type piece was created. Because the holes in this piece didn't have to be very exact, they were measured by hand and then hand-drilled. Finally, the piece was cut in half using a bandsaw and then assembled, as shown in Figure 4.18.

The two acrylic rings were then laser-cut, attached to the shaft, and had the steel rope

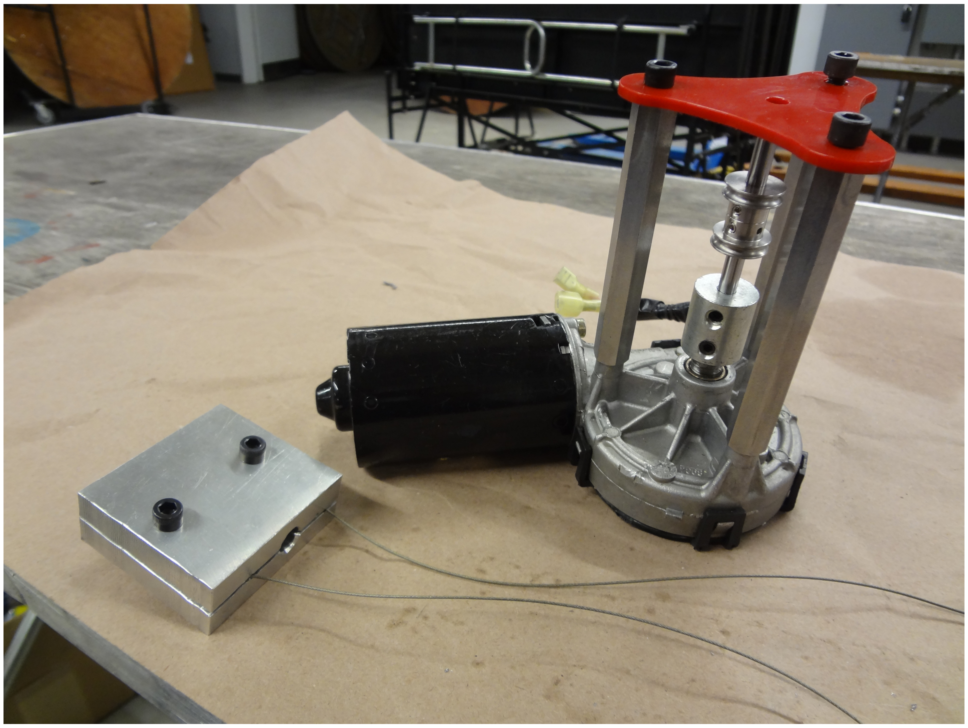


Figure 4.18: Brakes.

knotted securely on both ends. Finally, the motor was held underneath the golf cart in different positions until one was found where the pulley could pull on the bearing-type piece head-on. Using a Sharpie and the triangular acrylic piece, the three screw holes were drilled, very painstakingly, from underneath the golf cart. With the help of some Facilities members, the screws were inserted and tightened into the three standoff pieces. The final assembly attached to the golf cart is shown in Figure 4.19.

4.4 Chapter Summary

The implementation for each of the three subsystems was found to be very challenging. In the case of the Raspberry Pi mount, for example, extensive testing of the design through multiple iterations kept finding small errors in the design, though almost all of these were winnowed out in the final design. In the case of the automated steering system, it was found that the design kept having to be changed on-the-fly in CAD and then re-implemented until

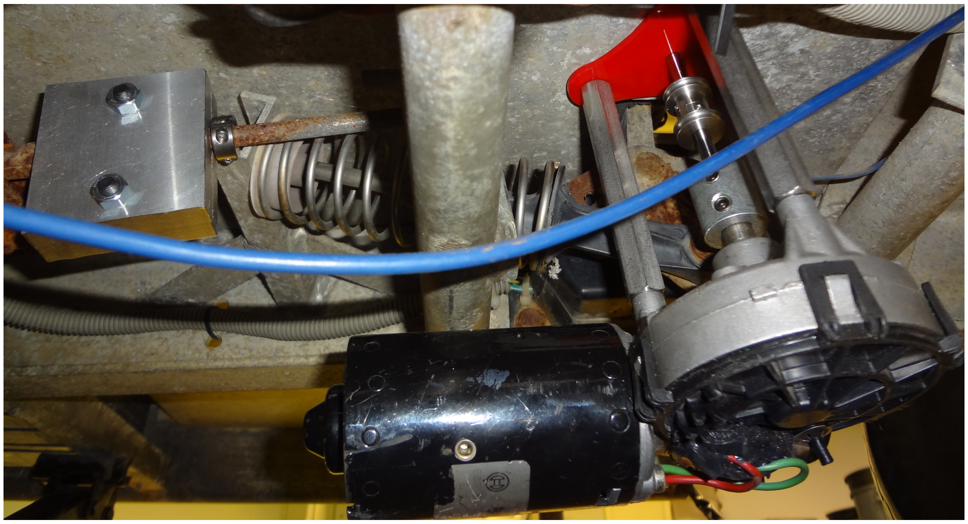


Figure 4.19: The completed brake design mounted to the underside of the golf cart.

a successfully-functioning design was found. Because the braking system was tackled last, many of the design flaws were weaned out before the design was implemented, so the implementation actually went fairly smoothly. All of the three subsystems successfully met all of their stated requirements.

Chapter 5

Discussion and Analysis

5.1 Raspberry Pi Mount

The full list of requirements of the Raspberry Pi mounting system can be found in Section 3.1. Looking at the final design, it is clear all of the requirements were met. The system is able to hold two Raspberry Pi modules and cameras on a rigid plate, ensuring the cameras will always face the same direction. The mount offers protection to both the cameras and the modules while allowing access to all the ports. Finally, the detachable plate gives more freedom to the software developer to remove the Raspberry Pi modules and cameras from the golf cart and place it back in while ensuring the cameras haven't moved between trials.

Given some more time, a few more refinements would have been made to the design. For instance, there is still some play in the spring-lock mechanism, to the point where the supposedly spring-loaded pieces move around. Also there is some play in the sliding plate when it is inserted, which may lead to issues later on.

5.2 Automated Steering Mechanism

The requirements of the automated steering mechanism are listed in Section 3.2. All of these requirements were met, as well. Although our systems engineer was unable to acquire motor controllers for the XYD-13 motor used in the steering mechanism, a 12 volt battery was used for testing the mechanism. Although the motor was designed to work at peak efficiency at 24 volts, it was found that the 12 volt battery still supplied enough torque to turn the steering mechanism from fully left to fully right in about 0.9 seconds. The current draw was unfortunately not measured because it would have required another pair of hands. Finally, the steering wheel motor can be overpowered by a person, making the system back-drivable.

Had there been more time, some more refinements would have been made to the steering system. For example, the two laser-cut guard plates in front and behind the sprockets don't line up quite exactly, so the sprockets are pushed into awkward angles, leaving the 10-tooth and 15-tooth sprockets in a different plane from the 60-tooth sprocket. This leads to the chain not being able to move smoothly around the sprockets and very nearly coming off the 60-tooth sprocket. Also, the steel plate holding the motor should be moved slightly further away from the steering column to relieve some pressure the steering column as well as some of the slack in the chain.

5.2.1 Bond Graph of the Automated Steering Mechanism

The bond graph of the system can be modeled since the masses and lengths of the different linkages are known. This can later be of use when designing the control algorithms for the steering mechanism. The free body diagram for the steering system is shown in Figure 5.1. The relevant inertias are the mass of the rack, inertia of the steering column and motor, and inertias of each of the two coupler links in the four-bar linkage.

In the diagram, several assumptions are made:

- The XYD-13 motor draws a current of 4 amperes
- The motor has a negligible inductance and resistance
- The inertias of the steering column, steering wheel, and motor are lumped into one inertia, J_{steer}
- The friction at the motor and steering column bearings are lumped into a single friction factor at the steering column bearings, b_{steer}
- The inertia of the two coupler links are lumped with those of each of the wheels into J_L and J_R
- The friction in the Ackermann system is lumped into two locations at the pins holding the two coupler links to the ground link (not shown)
- The stiffnesses of the shafts can be neglected

From this diagram and the stated assumptions, the causal bond graph can be constructed as shown in Figure 5.2. It becomes apparent from this bond graph is that all of the inertial elements possess derivative causality. This is to be expected since it implies that all the inertial elements of the system rely directly on the motion of the motor to move. Because some of the variables, such as the gyrator constant, could not be easily determined, the solving of this bond graph is left to future teams.

5.3 Automated Braking Mechanism

Finally, upon inspection, it can be seen that the automated braking mechanism met all of its requirements, except for the negative braking aspect, which was dropped from the list in Section 3.3. Upon testing, it was found that the brakes can engage in about 0.2 seconds while supplying the necessary force on the brake lines to pull them tight. The brake pedal

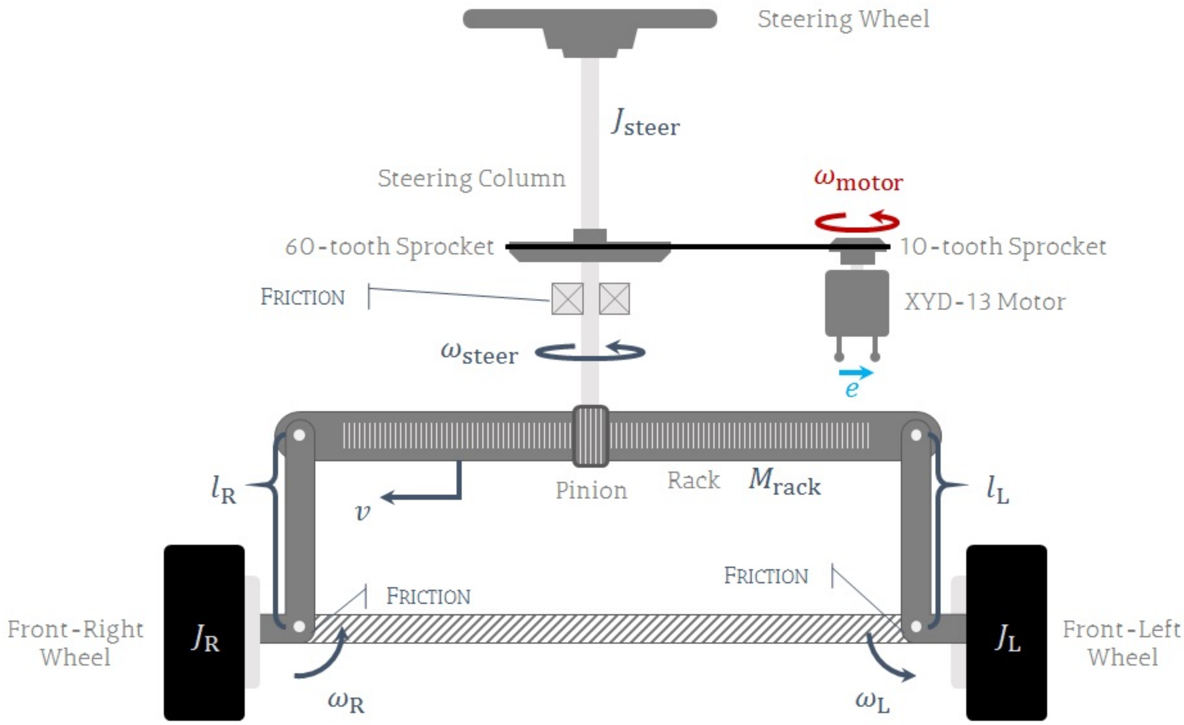


Figure 5.1: Free body diagram of the automated steering mechanism.

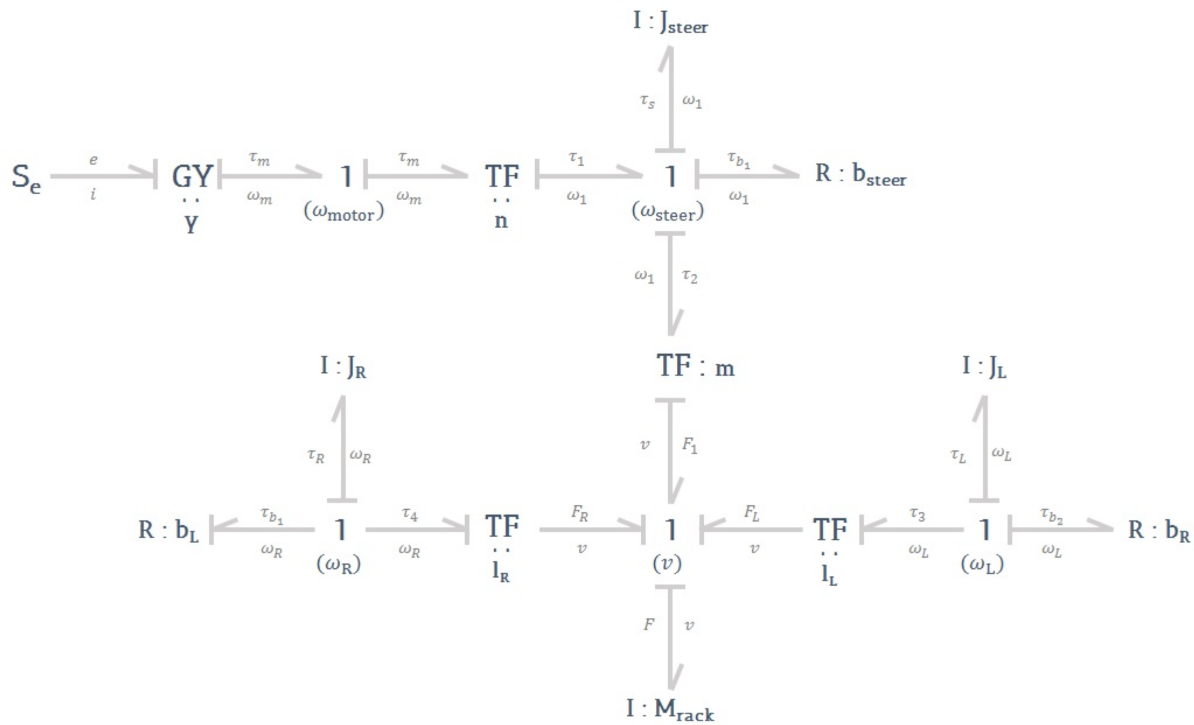


Figure 5.2: Bond graph of the automated steering mechanism.

can still be used to engage the brakes as well without fighting the motor, so the system is considered successfully back-drivable.

Unfortunately, the negative braking aspect could not be included this year; hopefully a future team will be able to implement a hydraulic system which would include this feature. Additionally, because the system was found to be very difficult to attach to the golf cart body with only one pair of hands, the system has been left partially incomplete. That is, the steel rope and D-profile axle have not been added to the system. Instead, a regular round shaft is currently in the shaft coupling attached to the body of the golf cart, so the braking system will not work at the moment.

5.3.1 Bond Graph of the Automated Braking Mechanism

From the fully constructed system, a free body diagram of the system was created, as shown in Figure 5.3. Several assumptions were made in the diagram:

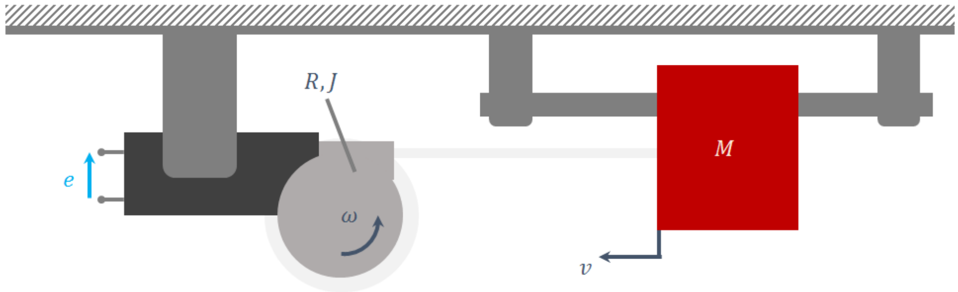


Figure 5.3: Free body diagram of the automated braking mechanism.

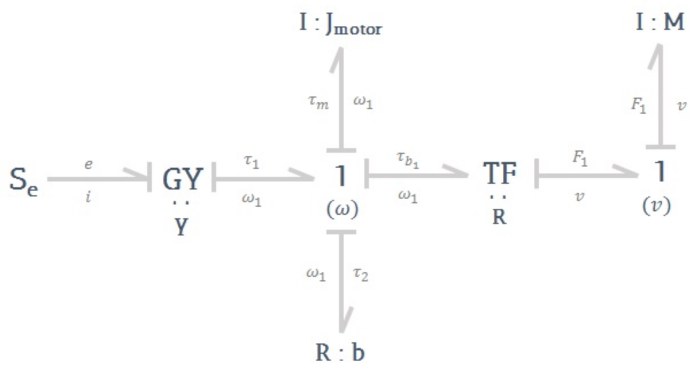


Figure 5.4: Bond graph of the automated braking mechanism.

- The inertia of the motor, D-profile shaft, pulleys, and shaft collar were collapsed into a single inertia, J_{motor}
- The mass of the bearing-piece was lumped with the mass of the screws holding it together and the steel rope into a mass M
- The effects of gravity were ignored since the system is only moving in a horizontal place
- The friction throughout the motor was lumped into one variable, R_b
- The friction from the bearing-piece sliding along the shaft is non-negligible and represented by R

Because of the way the causal bond graph was constructed, all the inertial elements in the system have derivative causality. This is reassuring because it again proves that the moving elements in the system move as a direct result of the motion of the motor. Again, because some of the variables are missing and liable to change in the future, the solving of this bond graph is left to future teams.

5.4 Chapter Summary

A comparison of the three subsystems worked on in this MQP to the original requirements of each shows that this project was very successful. Further analysis through bond graphs shows that the efforts and flows of the different inertial elements are all dependent on the sources of effort in the automated steering and braking mechanisms.

Chapter 6

Conclusions and Future Work

This project is very ambitious and the work very challenging. Unfortunately much of the mechanical work could not be integrated in the end with the wireless systems and ROS server, but it is hoped that future teams will be able to combine the different subsystems of Robocart together as they are completed and bring the project to fruition. Given more time, the proper motor controllers would have been purchased so that the control systems could have been designed for the steering, braking, and throttle systems. It is unfortunate that the golf cart never got to run this year.

For future teams, a larger team is recommended with multiple people working on the different subsystems of the golf cart—for example, having multiple mechanical engineers would be very helpful for getting measurements or for helping while someone is working on the brakes underneath the golf cart. Additionally, having multiple engineers would be very helpful in making good design decisions or coming up with intelligent design concepts for modifying the golf cart. To make up for a lack of experience and teammates, I often had to consult with different professors or Joe St. Germain in the RBE lab or Bob in the ECE shop on my designs and for help using machinery. Thus, a larger team would be very beneficial to the project.

There is still plenty of work to be done on the golf cart itself beyond what was done in this year on this MQP. For example, power systems was unfortunately never tackled, much in part due to lack of experience in the area. My understanding is that distributing power to the different motors and microcontrollers around the golf cart is a difficult task itself. Thus, I recommend also bringing on someone in a following year who is experienced in power distribution systems to begin completing Robocart.

Additionally, I hope that another team in the future with a larger budget than ours can purchase sensors and motors perhaps more appropriate to this project. For example, a potentiometer was used in the steering system. Although it works for now, because potentiometers rely on a wiper making electrical contact with a resistive material, over time friction will wear down the resistive material and start giving errant readings. Therefore, an encoder is probably more suited to this application since it relies on light passing through a clear disk rather than physical contact. Perhaps a team with more funds can afford something like the encoder shown in Appendix A. Limit switches are also recommended for applying to the ends of the steering system and brakes to make sure the computer knows not to overreach its limits. Encoders on the wheels of the golf cart may also be helpful for localization of Robocart. Ultrasonic sensors could also be useful for use during navigation. Lastly, a stepper motor may be better suited to the steering system for better control of the steering mechanism, and a hydraulic system might be better-suited for the braking mechanism since it can fulfill the negative-braking requirement.

In changing out the motor, perhaps one with a higher torque could be found, since as a result, a sprocket smaller than the large 60-tooth one could be used since this large sprocket intrudes somewhat into the passenger compartment, although not enough to make sitting uncomfortable.

Finally, it is recommended that the golf cart be moved to a dedicated facility. With all the people moving through, sometimes parts can get lost in the loading dock area. Additionally, because the FIRST competitions require the use of the space, the golf cart unfortunately becomes temporarily inaccessible for part of D-term. A space dedicated to the Robocart would very much benefit the project, especially if it were in the Atwater-Kent building, since the ECE and RBE shops are so nearby.

Many other components of this project ran very smoothly, however, allowing a great deal of this project to be completed in the limited amount of time available. I'm very grateful for the help I received not only from Professor Wyglinski, but also from other professors around campus, staff at Washburn, and lab managers. I'm also very grateful for the collaborative and nurturing environment at WPI, which should not be overlooked for having made this project possible.

Bibliography

[1] J. L. Kent, “Driverless van crosses from Europe to Asia,” 2010. [Online]. Available: http://edition.cnn.com/2010/TECH/innovation/10/27/driverless.car/index.html?iref=allsearch

[2] C. Albanesius, “Prepare for Self-Driving Cars by 2025,” 2014. [Online]. Available: http://www.pcmag.com/article2/0,2817,2428935,00.asp

[3] KurzweilAI, “Fully Self-Driving Cars Expected by 2030, Says Forecast,” 2014. [Online]. Available: http://www.kurzweilai.net/fully-self-driving-cars-expected-by-2030-says-forecast

[4] IHS, “Self-Driving Cars Moving into the IndustryâĂŹs DriverâĂŹs Seat,” 2014. [Online]. Available: http://press.ihs.com/press-release/automotive/self-driving-cars-moving-industrys-drivers-seat

[5] J. Schmiduber, “Professor Schmidhuber’s Highlights of Robot Car History,” 2011. [Online]. Available: http://people.idsia.ch/~juergen/robotcars.html

[6] L. Martin, “Driving Forces: Lockheed Martin’s Autonomous Land Vehicles,” 2012. [Online]. Available: http://www.lockheedmartin.com/us/100years/stories/alv.html

[7] M. Novak, “DARPA Tried to Build Skynet in the 1980s,” 2013. [Online]. Available: http://paleofuture.gizmodo.com/darpa-tried-to-build-skynet-in-the-1980s-1451000652

[8] D. Pomerleau, “RALPH: Rapidly Adapting Lateral Position Handler,” *IEEE Symposium*, no. September, 1995. [Online]. Available: http://www.cs.cmu.edu/∼tjochem/nhaa/ralph.html

[9] J. Davis, “Say Hello to Stanley,” 2006. [Online]. Available: http://archive.wired.com/wired/archive/14.01/stanley.html?pg=1&topic=stanley&topic_set=

[10] A. Iliafar, “LIDAR, Lasers, and Logic: Anatomy of an Autonomous Vehicle | Digital Trends,” 2013. [Online]. Available: http://www.digitaltrends.com/cars/lidar-lasers-and-beefed-up-computers-the-intricate-anatomy-of-an-autonomous-vehicle/

[11] H. Fountain, “Yes, Driverless Cars Know the Way to San Jose - NYTimes.com,” 2012. [Online]. Available: http://www.nytimes.com/2012/10/28/automobiles/yes-driverless-cars-know-the-way-to-san-jose.html?pagewanted=1&_r=0

[12] E. Guizzo, “How Google’s Self-Driving Car Works - IEEE Spectrum,” 2011. [Online]. Available: http://spectrum.ieee.org/automaton/robotics/artificial-intelligence/how-google-self-driving-car-works

[13] A. Goncalves and S. Joao, “Low Cost Sensing for Autonomous Car Driving in Highways.” [Online]. Available: http://welcome.isr.ist.utl.pt/img/pdfs/1663_hans_icinco07.pdf

[14] P. Stenquist, “On the Road to Autonomous, a Pause at Extrasensory,” 2013. [Online]. Available: http://www.nytimes.com/2013/10/27/automobiles/on-the-road-to-autonomous-a-pause-at-extrasensory.html?pagewanted=all

[15] L. Hardesty, “Think fast, robot,” 2014. [Online]. Available: http://newsoffice.mit.edu/2014/think-fast-robot-0530

[16] K. Nice, “The Future of Power Steering - How Car Steering Works,” 2001. [Online]. Available: http://auto.howstuffworks.com/steering5.htm

[17] P. Yih, “Steer-by-Wire: Implications for Vehicle Handling and Safety,” Dissertation, Stanford University, 2005. [Online]. Available: http://www-cdr.stanford.edu/dynamic/bywire/dissertation.pdf

[18] A. Davies, “Infiniti’s New Steering System Is a Big Step ForwardâĂŤUnless You Love Cars,” 2014. [Online]. Available: http://www.wired.com/2014/06/infiniti-q50-steer-by-wire/

[19] Knorr-Bremse, “Electronic Systems,” 2015. [Online]. Available: http://www.knorr-bremse.de/en/commercialvehicles/products_1/electronicsystems/electronicsystems.jsp

[20] J. Laukkonen, “What Is Brake-By-Wire?” 2014. [Online]. Available: http://cartech.about.com/od/Safety/a/Brake-by-wire.htm

Appendix A

EPC's Magnetic Absolute Encoder

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.

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/40 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: 38, MA — Electrical: 12, 10, V3, P2, C1, A

MA63S – 38 MA – 12 10 V3 P2 C1 A – SMJ – ____ – ____

MODEL
MA63S Absolute Series

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

MOUNTING
MA 2.50" Flange
MC 2.50" Servo Mount

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

MULTITURN RESOLUTION
18 18 Bit (CANopen)
40 40 Bit (CANopen)
00 to 40 Bit (SSI Only)[4]
Price adder for Bit > 18

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

COMM PROTOCOL
P1 CANopen
P2 SSI

OUTPUT CODE
C1 Binary
C2 Gray[1]

SOFTWARE REV
A Revison A

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

TEMP
0-80° C Std
T5 -40-80° C

SEAL
IP50 Std
S3 IP66
S4 IP67

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).

Appendix B

Steering Motor Specifications Sheet

Source: alibaba.com

Welcome t Product Description Company Information Our Services Packaging & Shipping

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

7YR

Con

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

Serv

See larger image

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

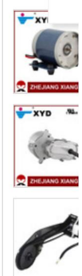
Start Order Add to Inquiry Cart Add to My Favorites

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 ›

You M



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.

Minis
Surv

Appendix C

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 $\pm$ 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.