WPI

Goat Cart
The Autonomous Golf Cart

Major Qualifying Project Report
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Abstract

The Goat Cart is an autonomous vehicle that will be summoned via mobile app and safely drive around Worcester Polytechnic Institute's campus. In order to accomplish this multiyear goal, this year's team worked on the essentials of the golf cart. The primary subsystems of steering, braking, throttle, power and sensors were all improved and updated so the cart can drive-by-wire. The 2017-18 team worked to create a solid electro-mechanical base that future years can build off.

Acknowledgments

- Friends and Family of all of the team members
- Professor Wyglinski
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Chapter 1. Introduction

1.1 Motivation

Safety has been the motivating force for engineers to investigate and develop automated driving technologies. It is estimated that 1.25 million people die every year due to car accidents worldwide [1]. Out of the 32,367 fatal car accidents in the United States per year, 93% of these accidents were caused by human error, be it through alcohol, speeding, sleeping, or simple driver distraction (Figure 1) [2]. Autonomous vehicles have the potential to reduce these accidents by 40% given the fact that they are programmed to eliminate human error from the equation [2]. With the introduction of autonomous vehicles to the market, it is expected that car crash fatalities will no longer be the primary cause of death for people ages 14 through 24 [2]. However, reducing car crashes is expected to be only one of the positive impacts that will come along with the introduction of autonomous vehicles.

Additionally, there will be a decrease in traffic congestion, fuel consumption, and gas emissions [2]. Autonomous vehicles are going to have access to information never available before, such as the driving intentions of the cars surrounding it, leading to a smoother flow of traffic and the prevention of crashes in congested areas. The average speed in congested cities can be as low as 20mph, causing people to spend hours sitting in traffic [3]. Depending on the scenario, autonomous vehicles are expected to decrease traffic by 8-13% and economize fuel by 23-39% [2]. Along with the introduction of autonomous vehicles to the market, there are many projects regarding autonomous car sharing programs. These are expected to transform cities and commuting behaviors. Nowadays, there are three parking spaces for every car owned and it is expected that autonomous car sharing systems could reduce the parking demand by 90% [4]. All

of the reasons mentioned above serve as motivation to use all the technologies and knowledge available to create a safer, greener and more efficient transportation experience.

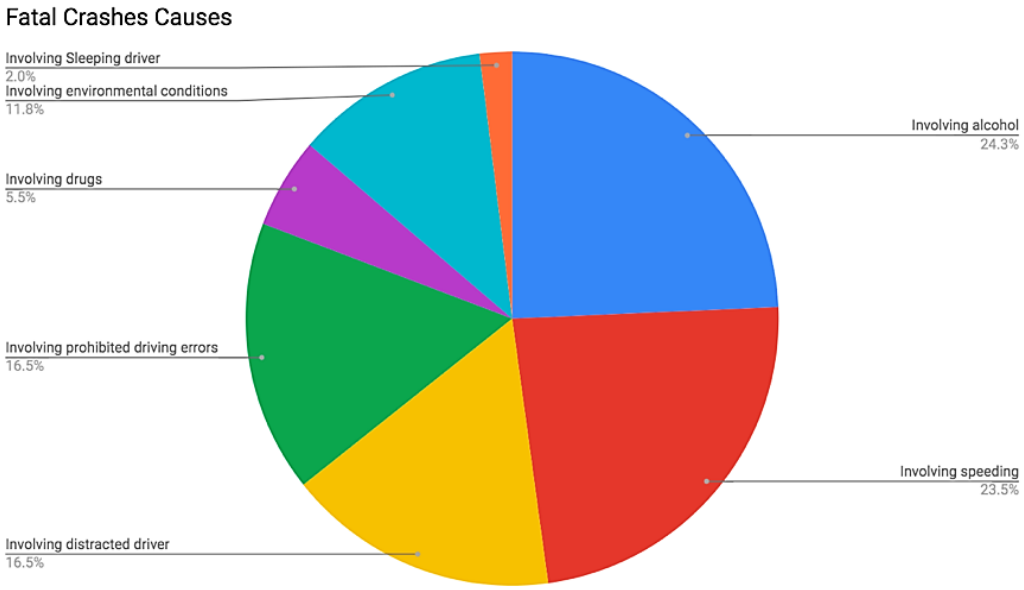


Figure 1: This figure represents in a Pie Chart the different causes of fatal crashes in the United States, the biggest one involving alcohol. It is worth to notice that almost 90% of the causes involve human errors that can be prevented with autonomous vehicles [2]

1.2 Previous MQP's Work

Motivated by the impact autonomous vehicles (AV) have on society; this MQP was created many years ago under the direction of the Professor Alexander Wyglinski. The main idea was to develop a simpler, smaller and affordable version of an autonomous vehicle: an autonomous golf cart. Many ideas came along during the years of work in order to automate the

golf cart. From using multiple robots (drones) that collected data for path planning, to several iterations of image processing design and object detection. The 2014-2015 MQP report written by Prateek Sahay [5], and the 2015-2016 report written by Robert Crimmins and Raymond Wang [6] talk about how essential is to create a drive by wire system in order to transform the cart into an autonomous vehicle. Designs were proposed to improve the throttle, breaks, steering and vision so these systems could be controlled by microcontrollers. However, these designs were not entirely successful, and they were isolated designs without any integration system. Finally, important improvements to the power and safety systems of the cart were recorded in the 2016-17 MQP report [7]. After four iterations of this project and many lessons learned from the past, this year's MQP team came with the intention and energy to work towards getting closer to the initial goal of this MQP.

1.3 Initial Conditions of the Goat Cart

Upon receiving the project in August, the team read the previous years' reports and took full diagnostics of the different subsystems of the Goat Cart. From the reports, it was discovered that many of the systems were continually replaced year to year. This made it difficult to determine which documentation corresponded to each component on the cart. The power system was revamped in the 2016-2017 school year. The throttle, steering and braking systems were completed in 2015-2016. Unfortunately, many components that the previous reports described were either not found on the Goat Cart or were non-functional. It was necessary for this year's team to take time to complete a full diagnostic check before deciding the direction of this year's iteration of the project.

The team determined that the steering system required extensive work due to its poor condition. Previously there was a gear mounted directly to the drive shaft. This gear was controlled by a 60A motor through a drive chain along with a 10-turn potentiometer. The potentiometer was used to determine the position of the gear and thus know where the front wheels were directed. This entire system was exposed and was a major safety concern, for it was mounted in the passenger's seat. Additionally, the steering system was simply poorly mounted. Finally, the drive shaft was at an angle that did not line up with the dashboard component's geometry on the golf cart. In order to connect to the drive shaft, a previous team fabricated a metal plate that held the gearing and motor. While this might have worked in theory, the execution was sorely lacking. The metal plate was improperly attached to the frame of the cart, via hinges with washers as spacers, in an unsuccessful attempt to bring the plate perpendicular to the drive shaft. As a result of the mounting being unstable, there was also a significant amount of room for movement in the gearing, so much so that two of the gears would actually interfere and prevent each other from turning. The major problems with the steering system meant that, in order to steer the cart, the entire subsystem would have had to be fixed or replaced. The software for the steering was undocumented and impossible to decipher. The program lacked descriptive variable names and comments. The steering controls were combined with the braking controls, and because of the lack of comments, it was unknown which motor controlled which subsystem. Instead of wasting time deciphering the program it was determined that it would be simpler to write new, separate programs for the steering and braking that were properly commented.

The hardware of the braking system was disconnected when the cart was received in August. The only sign that such a system had previously existed on the cart was through the documentation from previous years. Unfortunately, the documentation only included the fabrication process used to create the braking hardware. Luckily, the pieces of the braking system found were basic enough that this year's team could figure out how the braking subsystem was supposed to work. However, once the braking was reassembled and tested it was found that the braking system did not work as thought. The location where the motor was initially mounted required more torque to pull the brakes then the motor could provide.

The one fully working system on the cart was the throttle. It was found in good condition and worked successfully. The motor and motor controller were working, despite the motor controller having an output pin removed from the device. The throttle was controlled via an Arduino that used a digital potentiometer. The program for the throttle was commented and easily understood. However, it was later discovered there were no safeguards against going over the recommended resistance for the throttle input.

The Controller Area Network (CAN bus) which was supposed to be used to connect the different subsystems was not found on the Goat Cart. The original CAN bus was developed by Keshuai Xu (Cosine) in 2016. It was a proof of concept that had a Teensy outputting to a laptop connected via USB. CAN was never implemented for communicating messages between the subsystems, and the message library was done arbitrarily with no documentation. It was

determined that the CAN bus would need to be overhauled and implemented so that the different subsystems could receive or send commands to a master Teensy.

Initially, the power system appeared to be in working order. There is a set of four 12V batteries in series that were used to power the throttle at 48V, and a set of two 12V batteries in parallel to power the remainder of the cart. The power system was sufficient to operate the cart for short periods; however, the battery life was unknown. Calculations made last year stated that both systems would run for 1.5hours. Upon inspection, the batteries were not charged with proper float chargers as the reports stated. Continuously charging lead acid batteries like this causes the battery acid to evaporate, and potentially explode.

1.4 Current State of Art in AV

Motivated by the impact autonomous cars will have on society, the 2017-2018 Goat Cart team worked to ensure the functioning of all fundamental elements necessary to build an autonomous golf cart. According to an article in Mckensy&Company written in 2017, to design the software required to automate a vehicle, some fundamental systems of the car need to be in robust shape (Figure 2). Among these elements found: actuation (steering, braking and acceleration), perception (vision and object detection sensors), sensors that will help gather important data, drive control (sends signals to the actuator), and decision making (data path planning) [8]. The team had to undergo mechanical, electrical and software challenges to ensure the robustness of each systems, while keeping the project realistic and cost effective.

By the end of the Major Qualifying Project, the team was able to transform several subsystems of the cart. Among the actuation subsystems, the team redesigned and rebuilt the steering system, replaced the rack and pinion, and added controllers that will be crucial when automating the golf cart. The breaking system was redesigned, and the throttle motor controller was replaced. The team was able to integrate ultrasonic sensors and is currently working on the vision sensors. Another sensor added to the system was the odometery sensor, which tells the distance traveled and speed of the cart. Finally, the team also developed and added the CAN (Control Area Network), which made communication between subsystems possible. In the future, the cart will be able to make decisions upon the data being communicated in the network.

Table 1: Overall team contributions during this year's MQP.

Communication	Designed Hardware and Software Structure and integrated with Odometry
Steering	Redesigned and rebuilt steering system
Braking	Redesigned automated breaking
Throttle	Replaced
Sensor	Odometry and Ultrasonic sensors included

In terms of autonomy, the golf cart is in a drive by wire state; the team worked primarily on the systems that are fundamental to control the cart remotely. However, the team was able to display basic levels of autonomy by creating a program that tracked the cart's distance traveled and sent a break signal once a certain distance was reached. Afterwards, it would automatically send a signal to the steering to turn right and start driving again. This was a simple demonstration of autonomy; the team hopes that in the future the cart will have more capabilities.

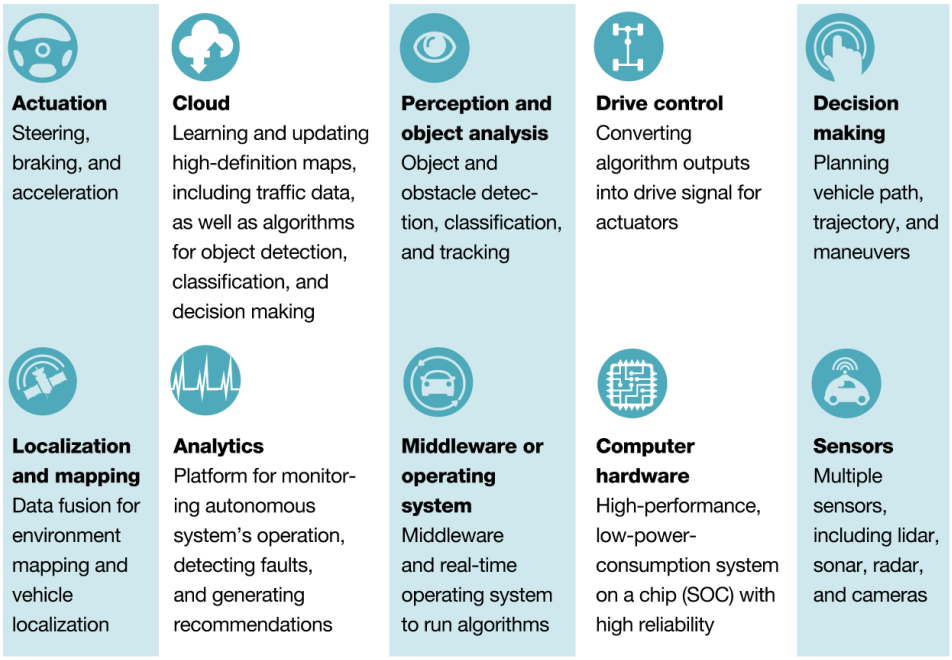


Figure 2: Fundamental systems of autonomous driving cars [8].

1.5 Report Organization

The report is structured to provide insight into the different systems that the team worked on during this MQP. The team's goal is defined in Chapter 2, and the logistics regarding how to

accomplish that goal. Chapters 3-8 discuss about the communication system, steering redesign, the breaking system, the throttle system, power system and the sensors implemented on the cart, respectively. Finally, Chapter 9 presents the team conclusions regarding the lessons learned during the MQP and the recommendations for the future.

Chapter 2. Project Objectives and Organization

In order to complete the MQP, the team needed to set an overarching goal and break it into manageable sections. It proved most efficient to take the time and plan how best to use the finite resources of time, manpower and money. This allowed the team to set realistic expectations and give everyone a defined role in completing the overall task.

2.1 Objectives and Goals

The ultimate goal of the Goat Cart MQP is to create a fully autonomous vehicle that can be summoned to specific points on the WPI campus via a mobile app. The large scope of this goal means that no one team can accomplish a task this massive in its entirety within the one year to work on it. As such, each year the new team must focus on a particular piece of the overall objective as their goal for the year.

The metric of success chosen at the start of this year's project was to have the cart successfully drive around the WPI track with only a laptop or pre-programmed instructions to guide it. After the evaluation of the initial state of the cart, the steering, braking, and CAN subsystems were identified as most in need of improvements.

In order to further subdivide the team's goal into smaller and more easily accomplished pieces, each subsystem had a specific objective to complete. This allowed the team members to work in parallel and accomplish more in a limited time. The goal for the steering subsystem was to create a new functional and reliable design that could be controlled by wire. The existing

braking system needed to be replaced with a reliable and remotely controllable replacement while retaining the ability to manually activate the brakes. In order to have the different subsystems communicating, the team needed to create a system that used a CAN bus to send messages. The team needed to create a message library that would be used and easily added to, as future years of the project add more complexity to the Goat Cart. Additionally, the team set a goal of having basic sensors added to the Goat Cart so that it could begin collected data about the cart and its surroundings. By having an effective team of six, the goals stated above was doable within the time given.

At the beginning of B term 2017, the team was given an intermediate goal to present a proof of concept presentation at WPI-IEEE Spark Party. Spark Party is an annual event at WPI of comedic and serious presentations by students and faculty within the Electrical and Computer Engineering department. Spark Party 2017 was held in early November, which gave the team a mere two weeks to have a working design. To successfully demo the Goat Cart, the team needed to get the new steering system installed, and get a prototype control system integrated with enough time left to move the cart and create a presentation. Luckily, this aligned with the team's original plans, though it required a highly accelerated timetable.

2.2 Division of Labor

Each member of the team gravitated towards a different area of the project based on his or her previous experience and skills. Jade took on the role of project manager as well as

working on the software side of the steering system. David's interest hands on electrical and hardware work lent itself to designing and installing the new steering system. He also helped design, assemble, and debug the circuit boards for the CAN bus. Camila became the working expert on the CAN bus system for the cart and worked on both the hardware and software parts of the subsystem. Jared devoted the bulk of his time to the new braking system. Alex worked on the throttle as well as ordering parts and budgeting through the department. Matt spent his time adding odometery and ultrasonic sensors to the cart to improve the amount of environmental data available for making decisions. Though each team member had one particular system they were in charge of, team members also assisted each other as needed.

Table 2: Visual summary of division of labor

Name	Responsibilities	
Jade	Team Leader	Steering Software
David	Steering Hardware	CAN Hardware
Camilla	CAN Software	
Jared	Braking	
Alex	Throttle	
Matt	Sensors	

2.3 Timeline

The intended duration of the project was three terms, approximately 6 months. During this time, the team had to do all work on the cart and generate the report, with minor cleanup and demonstration work to be finished in the final term.

The first seven weeks were dedicated to evaluating the existing state of the cart and creating plans for how to proceed. Through late August and September of 2017, the team identified which systems were most urgently in need of upgrading or repairing. For each subsystem, several options were considered and compared until an initial plan was decided upon. Only then could the team begin its work in earnest. Then from October until the Spark Party presentation, major overhauls to the cart were begun. These changes were primarily focused on redesigning and improving the steering and braking drive-by-wire systems. Parts were ordered and installed with the looming Spark Party deadline acting as a driving force. A major issue confronted was the batteries in the 48V array dying.

After the successes and failures of Spark Party, the team began to feel burned out and took the following week to pause and reevaluate the state of the cart. The new steering and braking hardware was found to be adequate. New problems appeared when the motor controller burned out the day of Spark Party 2017. This prompted the team to refocus their efforts on the throttle system, as well as expanding the software of each systems. Meanwhile the CAN bus boards were being debugged.

2.4 Budget and Resources

Each student in the project was allocated $200 from the Electrical and Computer Engineering department's project fund. With six students working on the project, this gave the team a total budget of $1200. Additionally, the team's advisor, Professor Wyglinski, offered to leverage several of his own independent funding sources for any additional needs beyond what the department was already providing. This fund was used for purchasing a replacement motor controller, which was later reimbursed when the team received sponsorship from Curtis for the part. Additionally a few of the students contributed funds towards small parts orders that were obtained on Amazon or Home Depot.

Most of the tools and equipment needed for working on the cart had already been purchased by previous teams. Both mechanical and electrical tools and a collection of wires and fasteners were already available in the lab. This allowed the team to focus its spending on new and replacement parts for the cart. The primary expenses of this project were parts for the steering, power, and embedded communication systems. Each required approximately $400 worth of parts. A summary breakdown of the budget can be seen in Table 3. The full cost breakdown can be found in the appendix.

Table 3: Budget breakdown by each subsystem summary

System	Total Spent
Steering	$470.63
CAN	$476.77
Power	$454.79
Sensors	$14.87
Throttle	$0.00
Braking	$0.00

2.5 Chapter Summary

The goal of this year's project was to return the cart to a drivable state. However, most of the systems on the cart needed varying levels of attention and repair or replacement before this could happen. Each member of the team specialized in one of these systems to provide individual attention. The team's budget was channeled towards the systems that were most in need of new hardware: steering, CAN and power. The team was spurred to heightened productivity by the intermediate deadline of presenting at Spark Party.

Chapter 3. Control Area Network (CAN)

CAN (Control Area Network) is a real-time communication protocol that provides fast, simple, efficient and robust communication among different subsystems. It is widely used in the automobile industry; in fact, it is mandated by the Environmental Protection Agency that every car should be equipped with CAN bus communication technologies [9]. The CAN bus is designed to operate at high speeds, from 500 Kilobits per second up to 1 Megabits per second and send messages containing up to 8 bytes of content [10]. The idea behind CAN is to connect and communicate state information through messages and signals between the different Engine Control Units (ECUs). These signals can be temperature of the car, odometery, oil, steering wheel position, speed, among others. These signals can be transmitted periodically or sporadically.

CAN networks consists of at least two nodes connected through a bus of twisted pair of wires and terminated with two resistors of 120 ohms (Figure 3). The maximum number of nodes depends on the frequency at which the network operates. Some important features that CAN contains: every message that enters the bus is visible to every node in the network, there is prioritization of messages, and the twisted differential pair provides noise immunity [11]. The differential pair will measure the voltage difference of the pair of wires instead of the voltage in relation to ground, allowing communication to be clear in hostile environments.

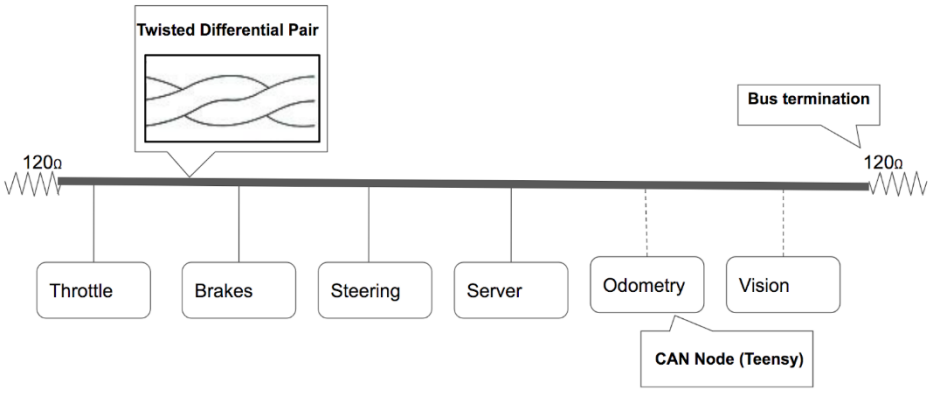


Figure 3: CAN bus Architecture: The most important hardware components are the Microcontroller, connected through a CAN controller to the differential pair of wires that terminate with a 120 ohms.

A CAN node is comprised of a microcontroller, a CAN controller usually embedded in the microcontroller and a transceiver attached to the CAN bus line. The microcontroller is in charge of data gathering and processing of data in a certain subsystem of the car. The CAN controller converts signals from a common microcontroller protocol (SPI and serial are popular) to the CAN protocol. Attached to the Microcontroller a transceiver is placed, which performs the conversion between the single-ended CAN controller CAN Tx and CAN Rx signals to the bi-directional differential pair of the CAN bus called CANH and CANL (CAN High and CAN Low). The differential pair provides excellent noise immunity and some bus fault protection. In a differential pair, one line will switch from a common state to a positive voltage state during a logic 1; the other line will switch from a common state to a negative voltage state during a logic 1. During a logic 0, both lines will switch from their respective voltage states to a common state (Figure 4) [11].

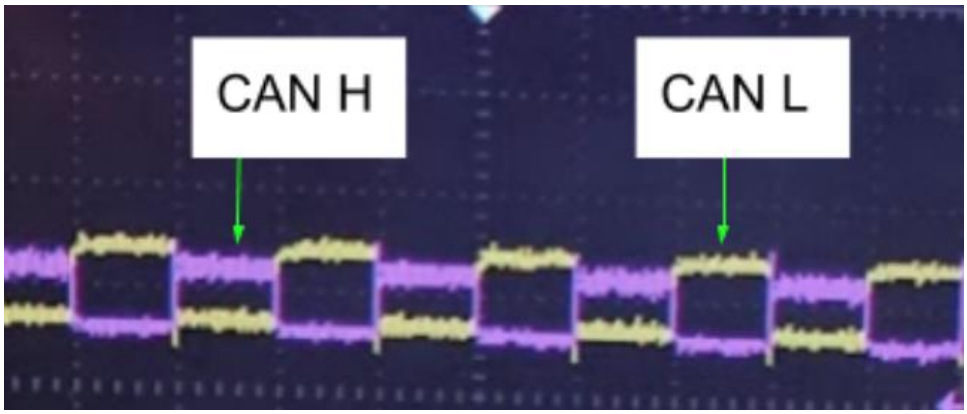


Figure 4: CAN high and CAN low signals are shown in this picture. The CAN controller responds to the electrical differences between the two signals, rather than a single signal and ground.

The CAN messages, which can be sent periodically, irregularly and on demand, have different fields that can contain information. The most relevant fields for this project are:

- The Message ID: Is the first field of information that goes after the Start of Field (SOF) bit marks. The message ID can occupy 11 bits or 29 bits (Extended Identifier) and it can be prioritized. The smallest number has the highest priority message and the largest the least. If two nodes are put on the bus at relatively the same time, the message with the highest priority is going to be read first and the other messages will wait in a queue. There is a byte that will be set to 0 if the 29-bit-identifier is not used, and 1 if used [12].
- The Data Length Code (DLC): The Data Length Code occupies 4 bits and represents the length that the message body is going to take. It can be from 0 bytes to 8 bytes if information [11].

- The Data: It can contain any type of data, including none. It is possible that the Data field is not used and the ID is used as a command [12]. Conversely, if the Data field is used it is composed of an 8 byte buffer.

There are other fields in the 16-bit Cyclic Redundancy Check (CRC), which contains the checksum for error detection, the 2-bit acknowledgement flag that states the integrity of the data, and the 7 bits that state the End of Field (EOF). These fields are not used in Goat Cart yet, but can be implemented in the future [12]. In Figure 5 it is represented the CAN message structure.

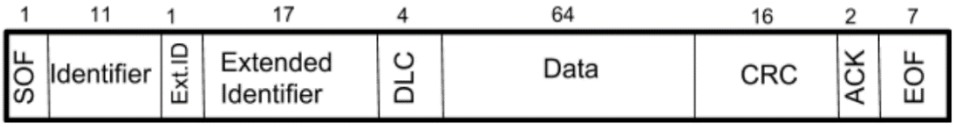


Figure 5: This figure represents the structure of a CAN message. The numbers in the upper part of each field mean the number of bits assigned to them. The most relevant fields for this project are the message identifier, the Data Length Code (DLC) and the data.

3.1 CAN Hardware Design Process:

Embedded devices are necessary for each of the different subsystems so that they can be controlled remotely. The previous teams used the Arduino and the Teensy platforms as their primary embedded devices. The Teensy used had a PCB board designed by a Ph.D. student named Kesuai Xu (Cosine) as proof of concept for using CAN bus on the Goat Cart. Figure 6 depicts the circuit diagram of the original CAN PCB from the 2016-17 MQP team. Figure 7 shows an Altium drawing of the PCB for that circuit.

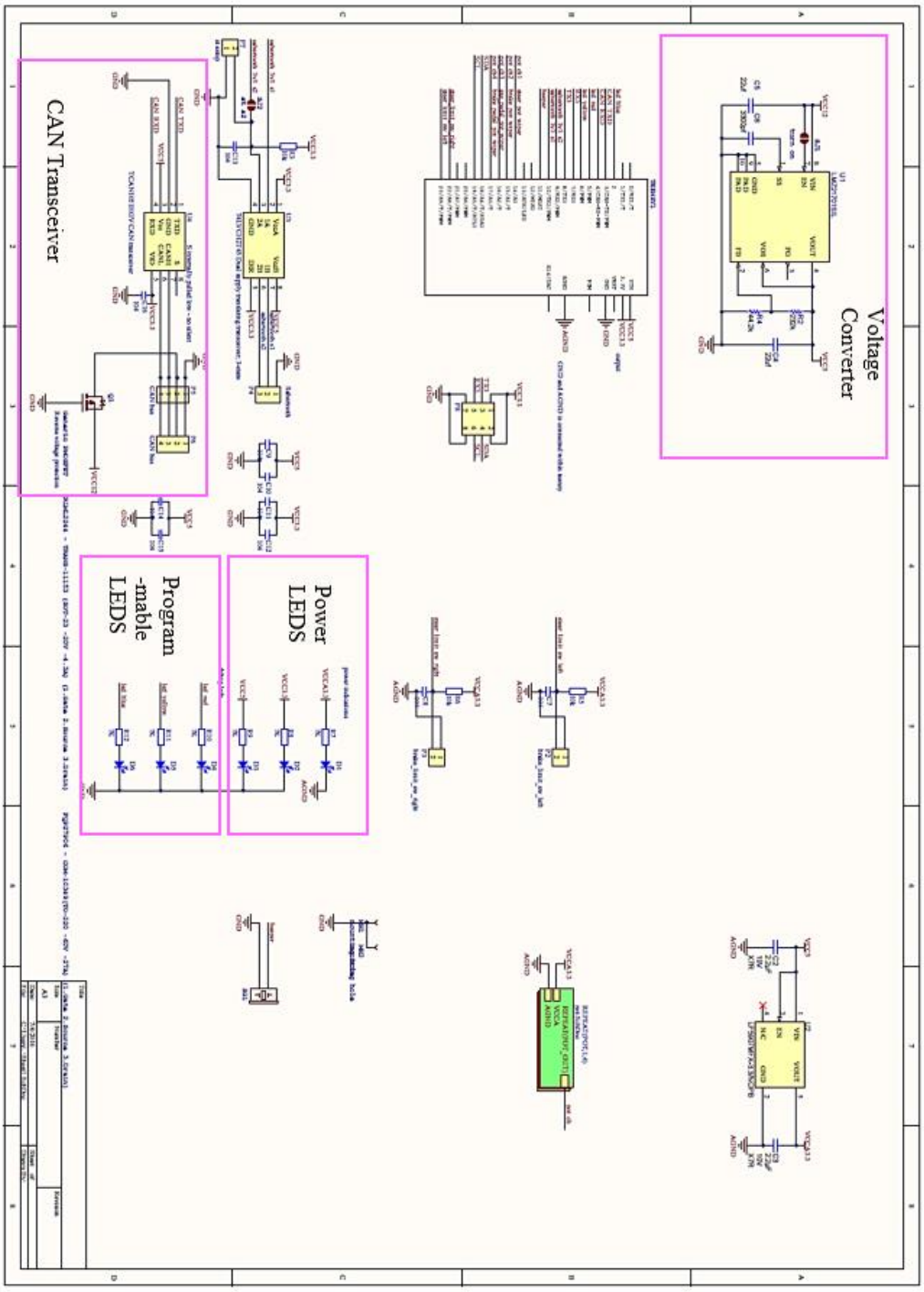


Figure 6: Circuit diagram of the original CAN PCB from the 2016-17 MQP team.

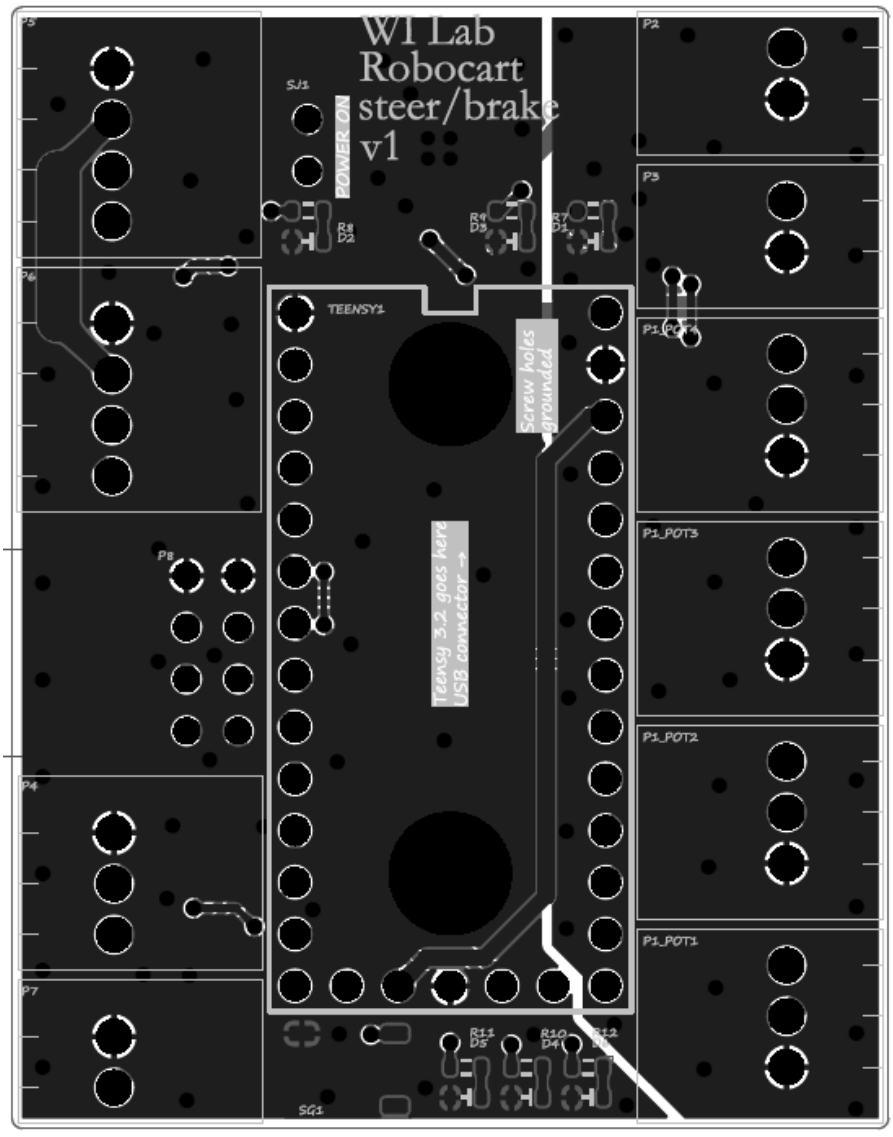


Figure 7: Altium drawing of the PCB for the 2016-17 circuit

When the 2017-18 team received the cart, the Teensy embedded device was not working properly. Additionally, the team wanted to add more to the CAN interface board and not have it specialized for a single subsystem. This would improve upon the 2016-17 CAN interface board

which was dedicated for the steering system. This lead to the decision to upgrade and standardize the embedded devices on the Goat Cart.

The best embedded device for the project would be a member of the Teensy family. The Teensy has a few very nice features that make it a good fit for the Goat Cart; they are inexpensive, compact, CAN capable, and have full documentation. The Teensy 3.5 was chosen over the Teensy 3.2, which the team already had because it has a much faster processer. A full comparison can be viewed in Table 4. [13]

Table 4: Comparison of the Teensy 3.2 and 3.5 [13]

Feature	Teensy 3.2	Teensy 3.5
Price	$19.80	$24.25
Processor	MK20DX256VLH7	MK64FX512VMD12
Core	Cortex-M4	Cortex-M4F
Rated Speed	72 MHz	120 MHz
Overclockable	96 MHz	-
Flash Memory	256 kB	512 kB
Bandwidth	192 MB/s	192 MB
Cache	256 B	256 B
RAM	64 kB	192 kB
EEPROM	2048 B	4096 B
Direct Memory Access	16 Channels	16 Channels
Digital I/O	34 Pins	58 Pins
Breadboard I/O	24 Pins	40 Pins
Voltage Output	3.3V	3.3V
Current Output	10mA	10mA
Voltage Input	5V Tolerant	5V Tolerant
Interrupts	34 Pins	58 Pins
Analog Input	21 Pins	27 Pins
Converters	2 Pins	2 Pins
Usable Resolution	13 B	13 B
Comparators	3 Pins	3 Pins

Analog Output	1 Pin	2 Pins
DAC Resolution	12 B	12 B
Timers	12 Total	17 Total
PWM, 16 bit	3 Pins	4 Pins
Total PWM Outputs	12 Pins	20 Pins
RTC	1 Pins	1 Pins
Communication		
USB	1	1
Serial	3	6
With FIFOs	2	2
High Res Baud	3	6
SPI	1	3
With FIFOs	1	1
I2C	2	3
CAN Bus	1	1
Digital Audio	2	2
SD Card	-	1
Ethernet	-	1

However, the Teensy 3.5 only has a built-in CAN controller and not a CAN transceiver. To enable proper CAN communication on the cart, it was necessary to create an additional PCB that had a CAN transceiver. The breakout board was designed in September 2017 (Figure 8 and Figure 9). It contained the following:

- 12V-to-5V regulator (LM317)
- 3.3 output voltage from the Teensy
- power LEDs for +3V3 and +5V
- 3 LEDs for debugging
- CAN transceiver (MCP2551) with operating voltage of 5V
- 2 SPI Ports
- 2 I^2C Ports
- 3 Serial Ports
- 7 PWM pins

- 18 Digital pins
- 12 Analog pins.

The voltage regulator was included so that the 5V could be used for sensors, such as the encoder used in steering, and for powering the Teensy. The LM317 is a simple component that has been used in many WPI ECE courses, so the team had experience with its function and capabilities. [14] The power LEDs are a useful feature for determining if the PCB is receiving power. The debugging LEDs are useful for testing programs as a visual check that the code is working as expected. The CAN transceiver is necessary translating the Teensy's mono bus CAN communication to a differential bus and vice versa. The MCP2551 was chosen because it is commonly used as a CAN transceiver for Teensys. [15] This led the team to believe that the MCP2551 would work flawlessly with the Teensy 3.5. The pins from the Teensy that were included in the CAN interface board's connecters were chosen based on versatility. The goal was to have access to at least five Analog, Digital and PWM pins. These are the most needed pins for the basic sensors that were used on the 2017-18 Goat Cart. The CAN interface board had SPI, I^2C and serial communication included in its connectors so that sensors supporting more complex communication methods could be used. The Teensy can be powered via the USB or through the +5V on the board, which in turn will get power from the 12V power system on the Goat Cart. The PCB was designed using Eagle; the circuit schematic and PCB layout can be seen in Figures 8 and 9 respectively.

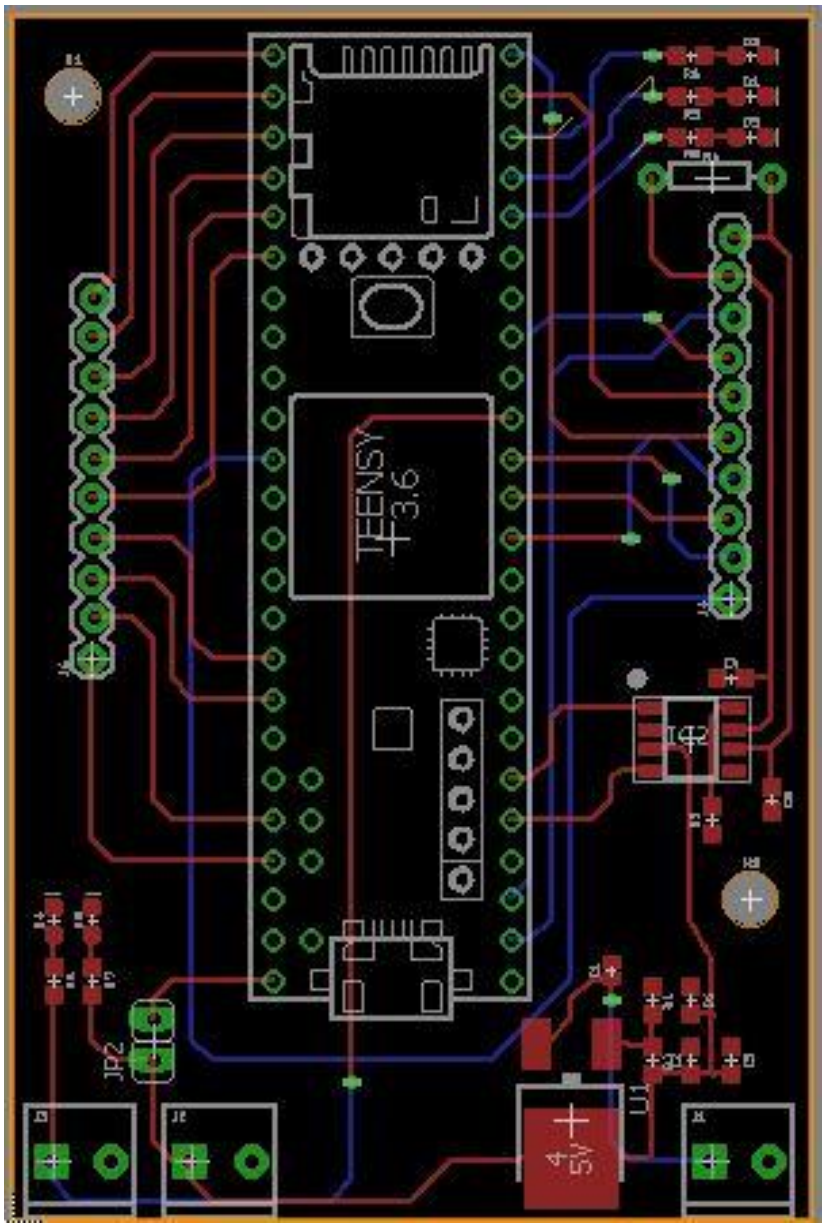


Figure 8: CAN interface board version 1 PCB from September 2017. The interface board is to be the generic board for the Goat Cart and can be used to control any subsystem and use the CAN to communicate with other subsystems.

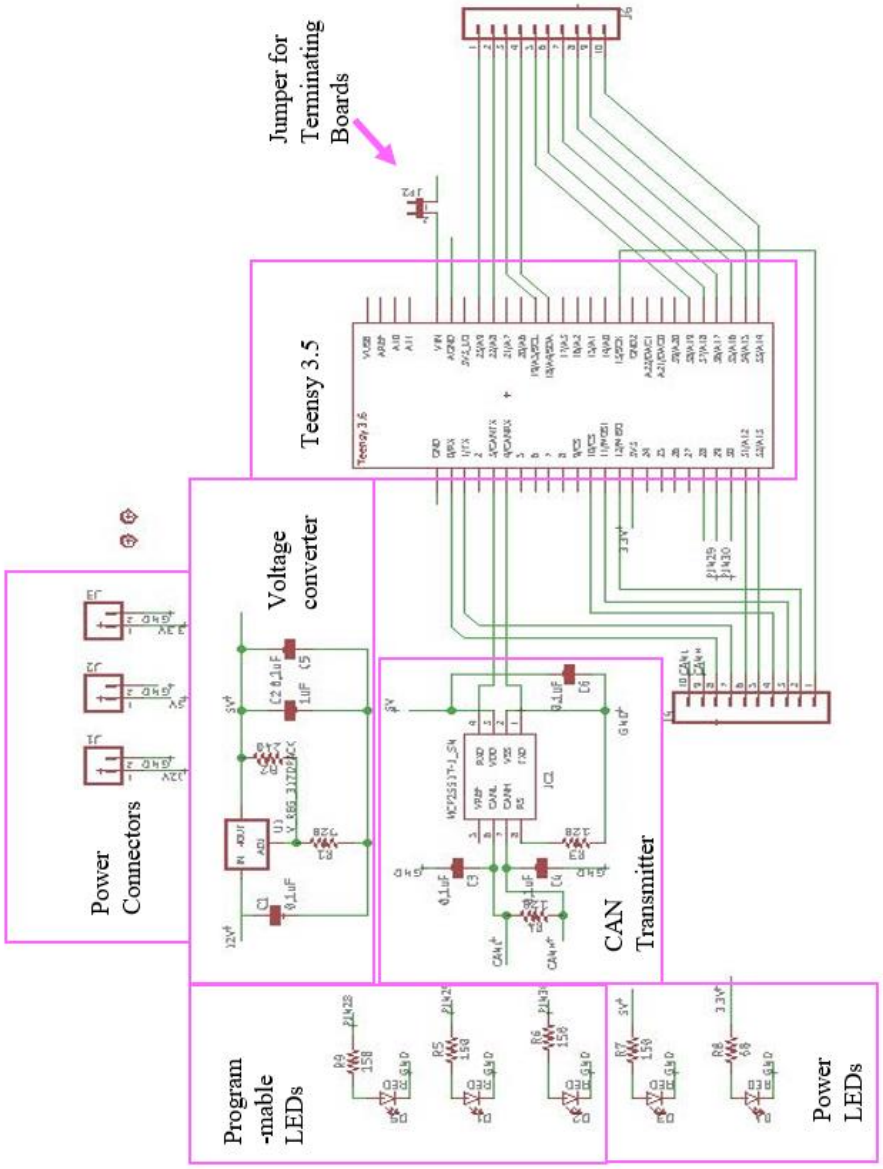


Figure 9: CAN interface board version 1 schematic from September 2017. The interface board is to be the generic board for the Goat Cart and can be used to control any subsystem and use the CAN to communicate with other subsystems.

The process of implementation and debugging of this first design was very intense. Several design mistakes were encountered and tackled. With some external advice and arduous work, the team was able to debug the board. The issues found include the following:

- Reversal of Tx and Rx signals: The first major obstacle that was encountered was the reversal of the Tx and Rx signals between the Teensy and the CAN transceiver. This problem was a design error on the CAN interface boards. The Teensy CAN transmit (Tx) pin was connected to the receiver (Rx) pin of the transceiver and the Teensy CAN Rx pin was connected to the Tx pin of the transceiver. The team was able to temporarily fix this issue by utilizing breadboards to remotely socket the Teensy and connect the Rx pin of the Teensy with the Rx pin of transceiver, and the Tx pin of the Teensy with the Tx pin of the transceiver using jumper wires (Figure 10).

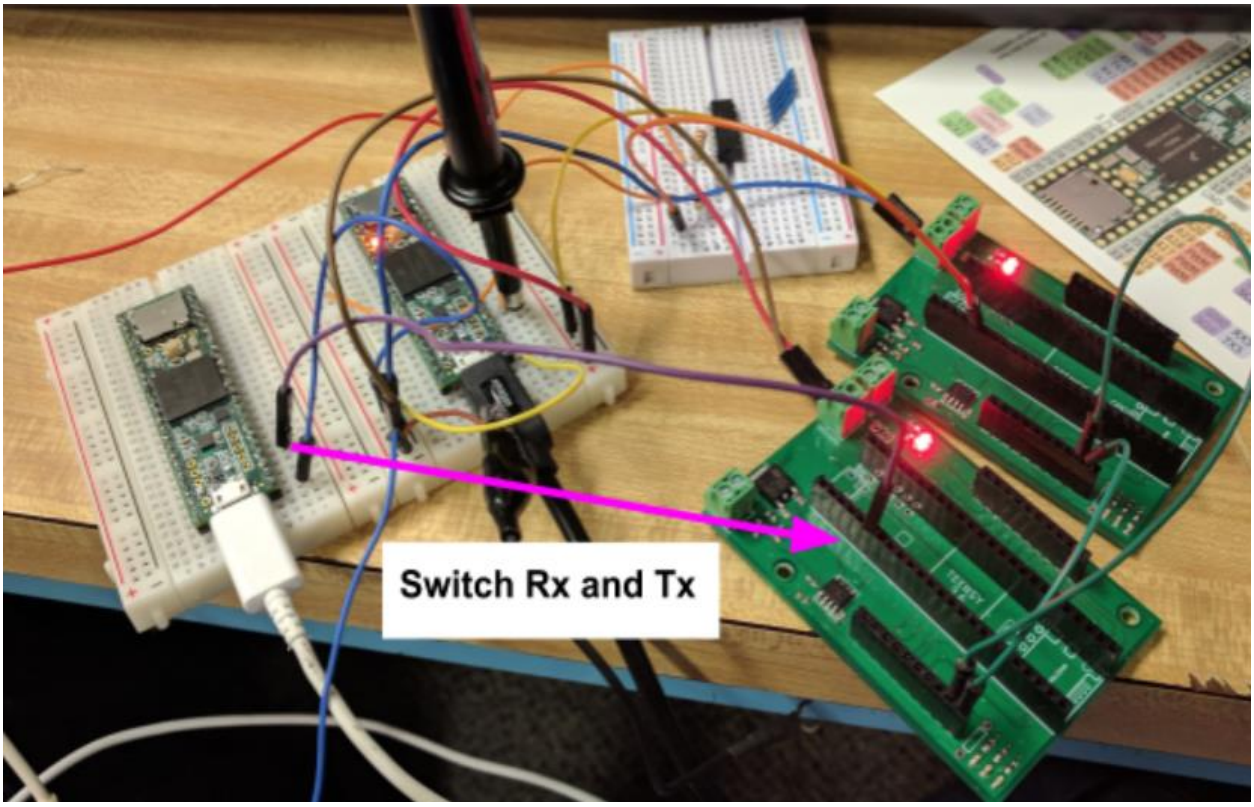


Figure 10: The first problem was solved by wiring the Tx Pinout with the Tx input in the transceiver

- CAN bus always high, never low: During the debugging process, it was noticed that the CAN signal would always hold high and never drop low. This signal response was solved by removing improperly placed filter capacitors that connected the CAN_HIGH and CAN_LOW bus lines to ground (Figure 11).

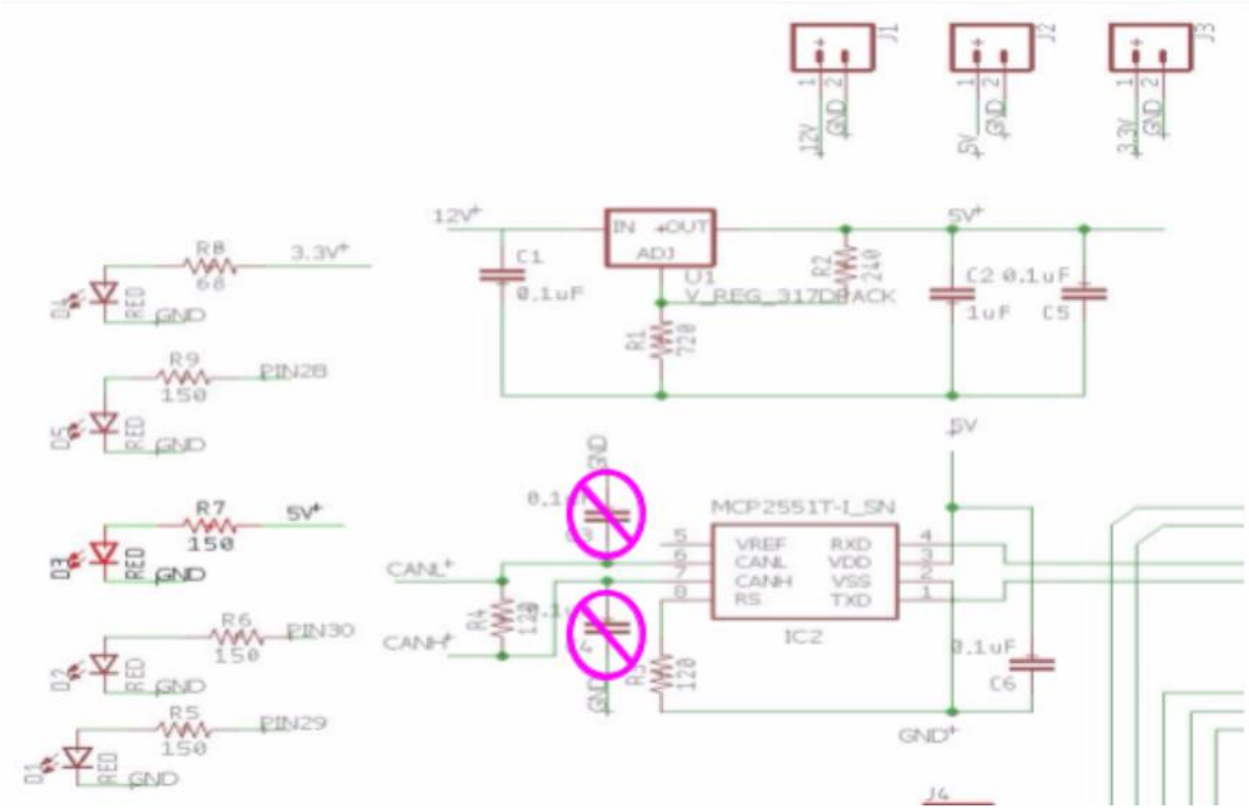


Figure 11: Signaled in pink are the two filter capacitors that were disrupting the CAN signal.

- Transceiver Operating Voltage: Another hardware problem encountered was the lack of a signal appearing on the CAN bus. By disconnecting the Teensy from the transceiver and using a signal generator as a substitute, it was discovered that the CAN transceiver MCP2551 would not operate on the +3V3 that the Teensy output. This was due to the MCP2551 having a hardware requirement of +5V.
- CAN Transceiver Signal Voltage: Due to the CAN transceiver only functioning on +5V the signal it output would swing from ground to +5V, which was beyond the input

capability of the Teensy's CAN inputs. As a result, a voltage divider had to be used to step down the signal voltage.

Some other problems were encountered, but they were linked to the software implementation of the CAN system. By the end of the debugging process, a stable CAN signal was viewed at the output of the receiving transceiver (Figure 12), leading to the conclusion that the design errors of the first version was found and the team was ready to design and build a second generation of the PCB.

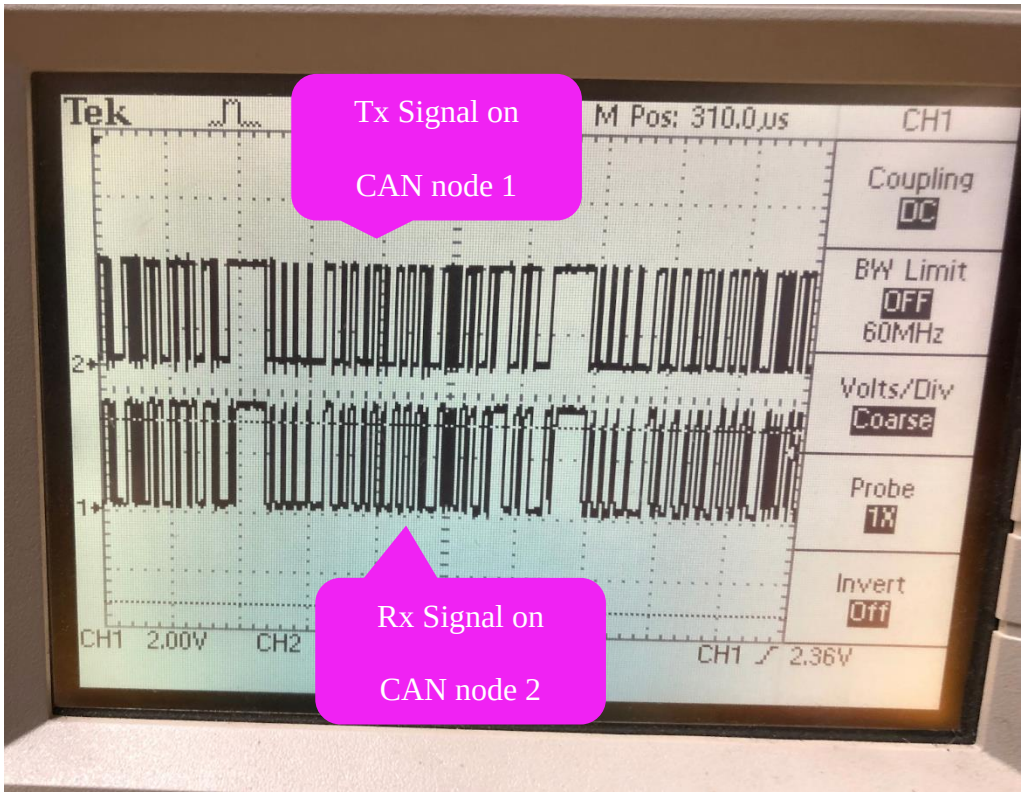


Figure 12: These two waveforms represent the same CAN signal from the transmitter side of one Teensy, to the receiving side of the other Teensy. The signal being transmitted, which looks like a normal CAN signal is successfully transmitted to another CAN node. However, the Arduino program still cannot detect any signal being

The second version of the board fixed the errors found in the first PCB and further optimized the layout. The CAN transceiver was replaced with a SN65HVD23x 3.3-V CAN Bus Transceiver. [16]

The second board has:

- Voltage regulation
  - +12V to +5V
  - +5V to +3V3 (Teensy)
- 2 Power LEDs
  - +5V
  - +3V3
- 3 Programmable LEDs
- 2 differential CAN ports (link together via daisy chain method)
- 2 SPI Ports
- 2 Serial Ports
- 2 I^2C Ports
- 16 Digital Pins
- 10 Analog Pins
- 5 PWM Pins

The primary goal of this design was to have many different methods of communication from the Teensy so that it could communicate to any type of sensor that a future team might use on the Goat Cart. Another reason for having numerous pins available was to allow a single Teensy to be used to control multiple subsystems. The only problem with the design was that, since the pins are software programmable, using a pin for a certain function could limit the

availability of its other functions. An example of this is using pin 10 for PWM prevents its use as one of the SPI channels. The list of connector pinouts can be seen in Table 4. Figures 13 show the circuit and PCB of the second version of the CAN interface board.

Table 5: Pinouts of the Teensy used in the CAN Interface Board

Pinouts for the CAN Interface Board	
1. GND 2. 3.3V 3. CAN L0 4. CAN H0 5. CAN L 6. CAN H 7. Pin 32 - D/A/RX4/CS1 8. Pin 31 - D/A/TX4/SCK1 9. Pin 12 - D/MISO0 10. Pin 11 - D/MISI0 11. Pin 10 - D/PWM/TX2/CS0 12. Pin 13 - D/SCK0	13. Pin 33 - D/A/TX5 14. Pin 34 - D/A/RX5 15. Pin 37 - D/A/PWM/SCL1 16. Pin 38 - D/A/PWM/SDA1 17. Pin 18 - D/A/SDA0 18. Pin 19 - D/A/SCL0 19. Pin 22 - D/A/PWM 20. Pin 23 - D/A/PWM 21. Pin 1 - D/TX1/MISO1 22. Pin 0 - D/RX1/MOSI1 23. 3.3V 24. GND

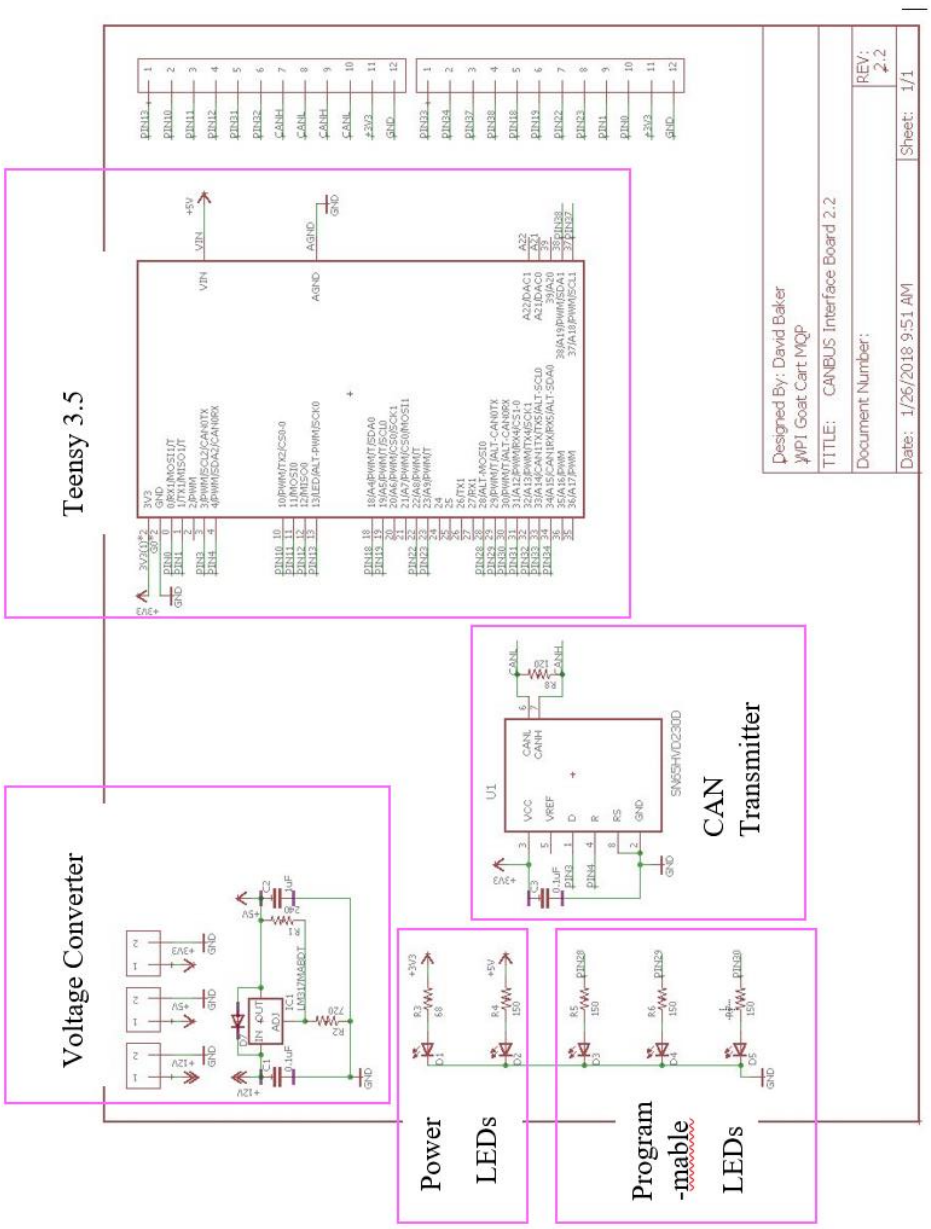


Figure 13: CAN interface board version 2 schematic from December 2017. The interface board was fixed based off the results of testing of the first version.

The CAN interface boards were placed on the cart and daisy-chained together. This allows the different subsystems to communicate between each other. They are connected via twisted pair wires, for this, the team deconstructed an Ethernet wire to use. This can be seen in Figures 14 and 15.

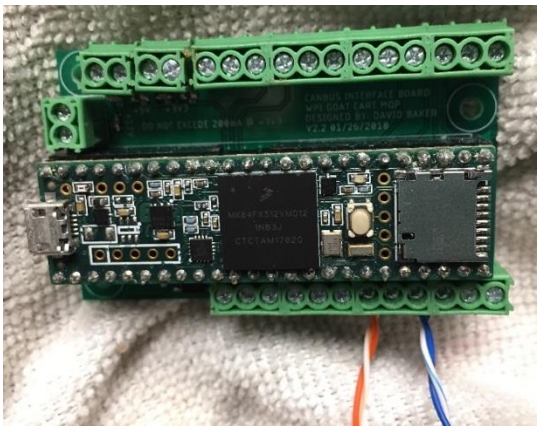


Figure 14: CAN interface board with CAN in the middle part of a daisy chain so that it can connect to others in the network. The orange and white wires is one twisted pair and blue and white is another.

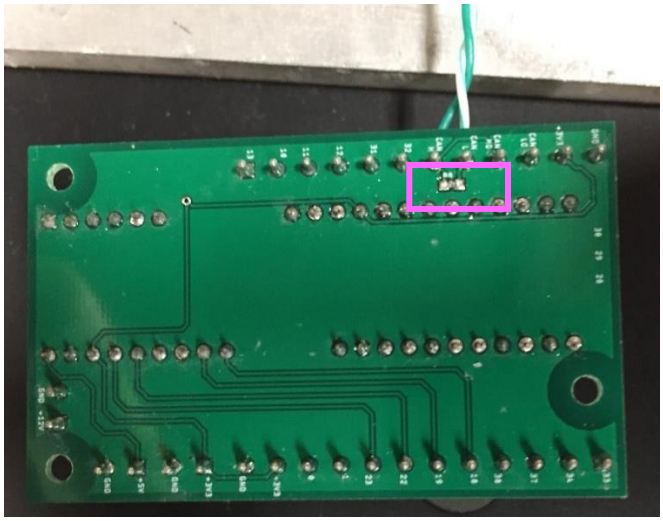


Figure 15: CAN interface board that is at the end of the daisy chain. It has a 120Ω terminating resistor, which is highlighted.

3.2 CAN Software Design Process:

When receiving the cart and previous CAN software programs in a GitHub, the team decided to use a more standardized method to build the CAN Network rather than use the CAN library the team was given by Cosine, the PhD student. Teensy microcontrollers can be programmed in C with any program editor; however, the team decided to use the Arduino IDE with an extension called Teensyduino. Libraries to control the CAN capabilities of the Teensy can be found on the internet. The FlexCan is the most standardized library found for working with CAN on the Teensy. There were several versions of this Library on GitHub, one of them being a built-in version within Teensyduino. Teensyduino's built in FlexCan library was written by Collin Kidder and the team decided to trust this version because according to research this library is commonly used and reliable. [17]

To create a CAN network, the team had to design a database of the messages that each subsystem sends and receives to create useful and efficient communication within the cart. The messages along with the message's ID had to be planned. Eventually, prioritization of messages will be needed in the Goat Cart.

The intended goal with the CAN bus is to connect the subsystems that the team has been working on for the past year: the throttle, the brakes, the steering system and the sensors. The plan is that there will eventually be a server connected to the system that will receive all crucial information, process it, and send commands to the respective subsystems. The team created a list

of the messages that are important to send and receive between the different nodes. Refer to Table 5 to find a summary of the database of messages described below:

- Speed Increase: The Speed Increase message represents a command message. Receiving this message makes the throttle increase the speed at a fixed rate. The message ID is **0x14 (20)** and does not contain any message in the body.
- Slow Down: Slow Down represents a command message that every time received, it decreases the speed by a fixed amount. The message ID is **0x12 (18)**.
- Breaks On: When received the breaks actuate and stop the cart. It is important that in terms of priority breaking have a lower message ID (more important) than Speed Increase and Slow Down for safety reasons. The message ID chosen is **0x0A (10)**.
- Turning Degrees: A turning degrees message with an ID number of **0x25 (37)** that contains in the specific amount of degrees to turn left or right. In the first character of the message buffer contains either a 'P' or 'N' to dictate direction. The second character contains the value of degrees to turn to.
- Center the Wheels: A command message with ID number **0x24 (36)** is sent to center the wheels. It will have a lower ID than the Directions' message ID since it is considered to have higher priority.
- Calibrate Steering: When starting the Goat Cart, wheel calibration must be done to accurately map the steering wheel angle. The message ID is **0x23 (35)** and it

will represent a command message; whenever received, the steering is calibrated. This message is expected to be sent every time the golf cart is turn on.

- Distance traveled: This message sends information collected by the odometery sensor. It is represented by the message ID **0x28 (40)**. The body of the message contains the amount of feet traveled since the cart was turned on. The idea is to restart the counter every time the machine is turned on and store the total miles traveled in the server.

Table 6: Summary of all messages created by Goat Cart 2017-2018 group.

Message	Message ID [HEX-DEC]	Message Body
Speed Increase	0x14h - 20	-
Slow Down	0x12h - 18	-
Breaks On	0x0Ah - 10	-
Center Wheel	0x24 - 36	-
Turning Degrees	0x25h - 37	Msg.buf[0] = 'N' or 'P' Msg.buf[1] = 0-90
Calibrate Steering	0x23 - 35	-
Distance Traveled	0x28 - 40	Sum of all the buffer positions being used is the total distance traveled since it was turned on.

The diagram found in Figure 16 represents the flow of these messages in the network. The odometery node constantly sends messages through the CAN bus representing the distance

traveled and the only node accepting the distance-traveled message is the server. The server transmits commands to the different actuators (breaking and throttle, and steering). In the future, these commands are going to be a result of data processing, vision and path planning programs inside the server.

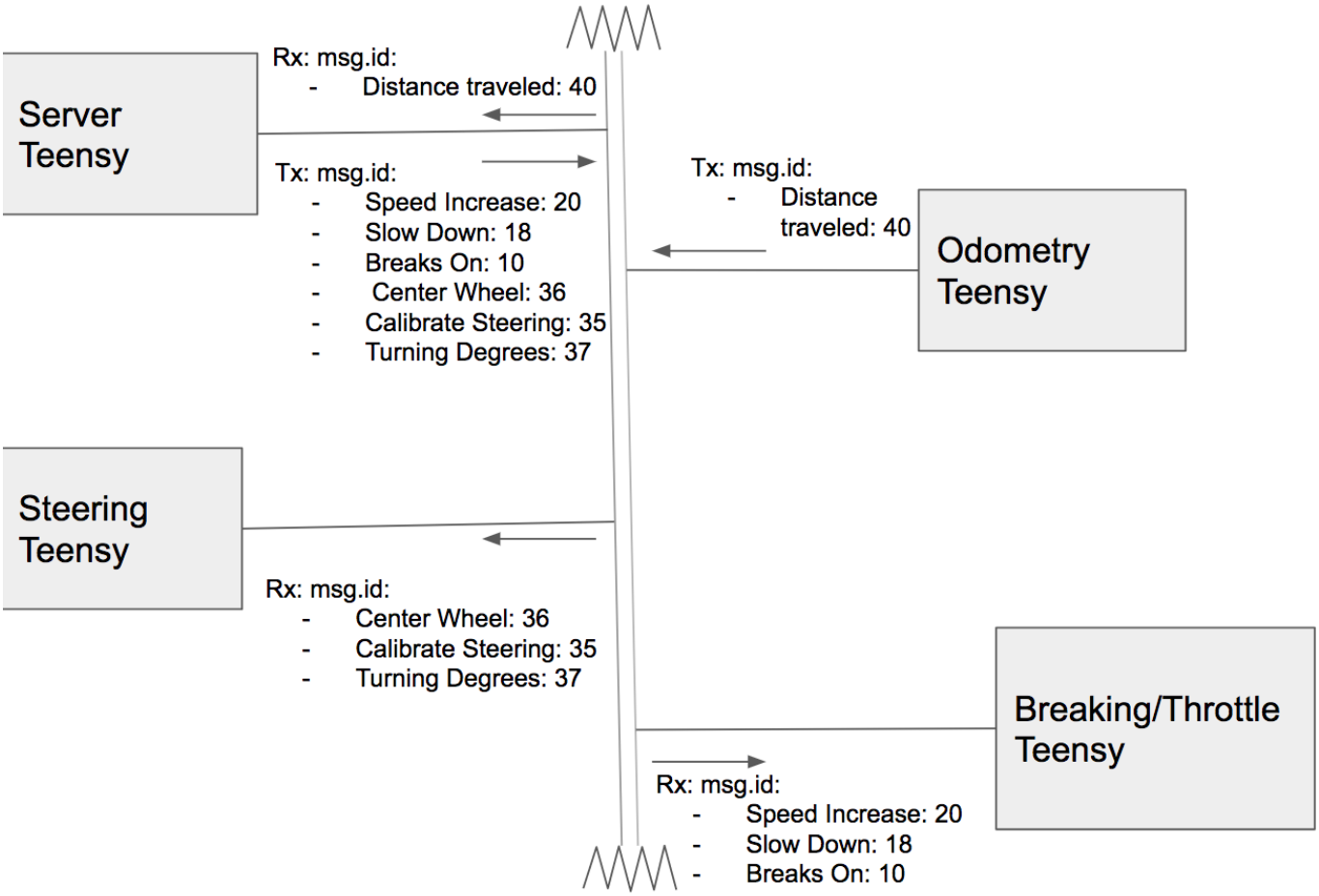


Figure 16: Network representation of all 4 systems implemented as for now. It is described what messages are transmitted and received in each CAN node. Each CAN node is composed mainly by a Teensy microcontroller that owns its own database and only receives messages that their ID matches with one on its database

Once the hardware was ready for testing and a message database was created extensive debugging occurred to send and receive a CAN message. The main software problem encountered when debugging was a register setup problem that apparently was very common when implementing Collin Kidder's FlexCan Library. [17] After researching this issue, it was concluded that the best solution was to switch to library written by a GitHub user called Teachop instead. [18] The new FlexCan library had to be downloaded from GitHub and included on the Libraries folder of the Arduino IDE. With the new library, the team was able to send and receive CAN messages, filter out messages by ID and send information in the message body (Figure 17).

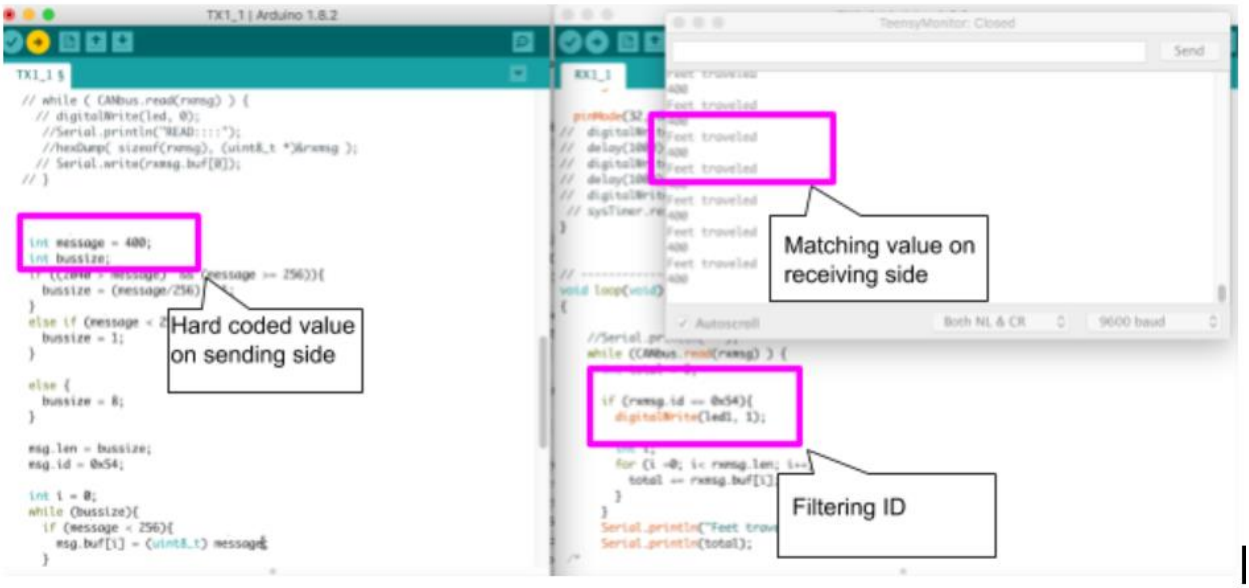


Figure 17: Program created to send distance traveled. The correct outputs were given and we were able to proof filtering of messages.

Different software tests were performed to simulate the different messages that the systems are sending and receiving can be seen in the Appendix. The first test consisted of sending a message from one node and having a receiving program on the other node, which lit up

an LED when it received a message. After testing the LED upon Message program, a message filtering was then tested and implemented successfully. This test consisted of having the receiving side lighting a LED if the message was of a specific ID number. The third test performed consisted of sending a message with data in the message body. An odometery program was written so if the distance to be sent in feet was bigger than the capacity of one position in the buffer (255) it would split the number so fill the maximum value in one position and the remainder in the next position. Consequently, having the length of the data buffer vary depending on the number to be sent. For example: if the total distance traveled was 400ft., the program would store in the first position of the buffer 255 and in the second position of the buffer 145, which when added equal to 400. The fourth test simulated sending two different messages that would be linked to two different LEDs on the receiving side. Whenever one ID was received it would lit up its respective LED. The test number five simulated the format of steering messages, and the sixth test was a complete simulation of three systems together: the throttle and braking system, and the steering system. This test communicated three Teensies and would send commands to the respective Teensy via a serial port. For more information, refer to the MQP's GitHub.

The 2017-18 team has implemented CAN bus tests consisting of two nodes communicating with each other, and merged the odometery program with CAN. However, is expected that by the end of the D term 2018 the team will have had integrate all the four systems this information would be discussed in an appendum to the project.

3.3 CAN Chapter Summary

Overall, this year's MQP was able to study in depth the structure and characteristics of the CAN network. The team had to understand the requirements of the communication system to be built and come up with a design that was robust, but at the same time straightforward for future groups. By going through two design iterations the team was able to tackle some problems, report the root because so future groups do not commit the same mistakes, and instead, keep working on merging as much subsystems as possible. Throughout the rest of this MQP report, the team writes in detail about the different subsystems that are to be integrated, starting from steering subsystem.

Chapter 4. Steering

The steering on the cart presented a number of challenges that were primarily due to the original design of the cart, the age of the cart, and previous MQP teams. Since the original cart used a manual steering system, controlling it with a computer proved to be no simple matter. Both the steering hardware and steering software had their own unique challenges that had to be overcome. In this MQP, the hardware work turned out to be more challenging than the software work because the team was made up of six electrical and computer engineering (ECE) students and no mechanical engineering (ME) students that were working on a mechanical engineering project. The software part ended up being a simpler process; however, it too was plagued with problems. Despite the issues, the 2017-18 MQP team managed to redesign and rebuild the steering system to allow for drive-by-wire operation.

4.1 Steering Hardware

The steering hardware encompasses all of the mechanical and electromechanical components of the steering system. This is where all of the retrofit from the old system to the new occurred. There were numerous options for how the steering could be controlled, and therefore a lot of research and consulting work had to be done before a design could be created and implemented.

4.1.1 History of Goat Cart Steering

When the 2017-18 Goat Cart MQP team received the cart, the steering system was in a non-functional state. The system that was in the cart was originally designed and built by the 2014-15 MQP team. It was later revised by the 2015-16 and 2016-17 MQP teams to result in the state seen in Figure 18. It consisted of a sixty-amp motor mounted to a support plate that was attached to the dashboard frame on the cart. The motor had a sixty-tooth gear directly attached to it, which drove a chain that connected to a ten-tooth gear. The ten-tooth gear was attached to the original steering shaft, which supported the steering wheel in the original cart. A ten-turn potentiometer was also driven off the chain.

The chain drive system failed for two reasons. The first is that the plate supporting the motor was not firmly mounted in a way that allowed the chain drive system to maintain proper alignment. It was set up with an adjustment system that consisted of standoffs and hinges. This system, shown in Figure 19, was meant to allow for adjustments while the alignment was still being figured out. However, this mounting method caused the alignment to shift when the steering motor was powered.

Figure 18: Photo showing the location of the steering system in the cart. The photo features the steering system that was in the cart at the beginning of the 2017-18 MQP.

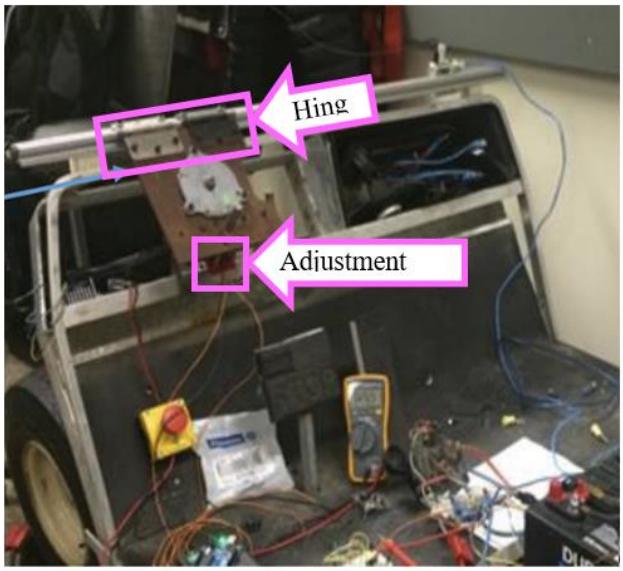


Figure 19: Photo showing the hinges and the adjustment system that was used on the steering mounting plate. This is part of what caused the misalignment of the old steering system.

The other problem with the steering system that existed in the cart, when the 2017-18 MQP team received it, was the steering shaft itself. The mounting of that shaft, which was being driven by the chain drive system, was insufficient for maintaining proper alignment. The steering shaft was floating in a single bearing mounted to the dashboard frame that was worn from years of service. It completely lacked any linear support because of a set of universal joints that had been installed by the factory to correct a misalignment at the steering rack. This lack of support allowed the steering shaft to move independently of the plate, which in turn prevented consistent alignment of the chain drive system.

When the 2017-18 MQP team checked the status of the cart at the beginning of the school year, they found that, when the steering motor was running, the chain would jump off its drive gears. This, combined with extreme amounts of wear and other damage to the factory steering components meant that almost no part of the steering system, as it was configured at the start of A-term 2017, would be usable in future, autonomous functions of the cart. In order to fully understand the steering system and then to make it functional, the 2017-18 MQP team needed to first understand what was on the cart when the Goat Cart MQP first acquired it.

The team did not have much in the way of reference material to work off when they received the project. Information was limited to what was available in the previous year's reports. The 2016-17 MQP team had stated that the model of the cart was a 1995 Club Car Powerdrive System 48. It was discovered after a lot of research that this was not the case. The particular golf cart that the Goat Cart MQP is using is a 1995 Club Car DS. Club Car puts different model numbers on their golf carts and their powertrains, [19] that allows Club Car to

put the same powertrain in different carts and different powertrains in the same cart. The model of the powertrain, not the cart, is a 1995 Club Car Powerdrive System 48. Once this discovery was made, manuals and parts for the steering system became a lot easier to find. Below in Figures 18-21 are the various explosions of the steering system in a 1995 Club Car DS.

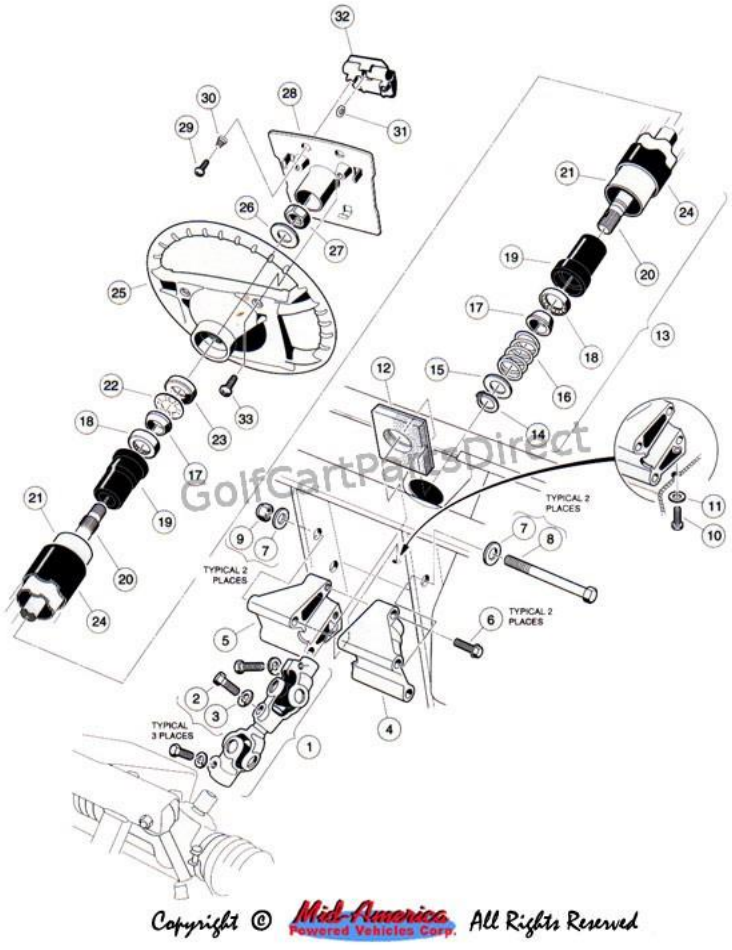


Figure 20: Explosion of the upper steering system and steering column in a 1995 Club Car DS [20]

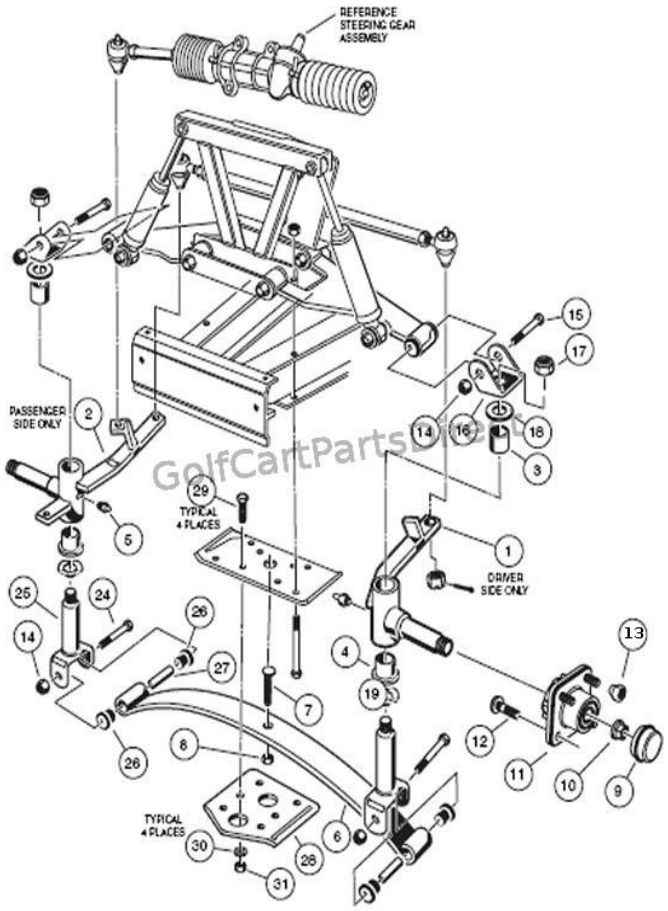


Figure 21: Explosion of the lower steering system and the front end in a 1995 Club Car DS [21]

In the original cart, the steering wheel (Figure 20, Item 25), connects to the steering shaft (Figure 20, Item 20), which is supported by bearings (Figure 20, Item 18) inside the steering column (Figure 20, Item 21). The steering column is attached to the dashboard frame by the steering column-mounting bracket (Figure 20, Items 4 & 5). The steering shaft connects the steering wheel to the double U-joint (Figure 20, Item 1) [20], which connects to the steering rack (Items 1-21 in Figure 22). This transfers the rotational motion of the steering wheel to linear motion that

can be used to turn the wheels. This linear motion is transferred through the drag link and drag link end (Figure 22, Items 30 & 24) [22] to the passenger side steering knuckle (Figure 21, Item 2). This is connected to the driver's side steering knuckle (Figure 21, Item 1) [21] via the tie rod ends and the tie rod itself (Figure 23, Items 6, 11, & 13) [23].

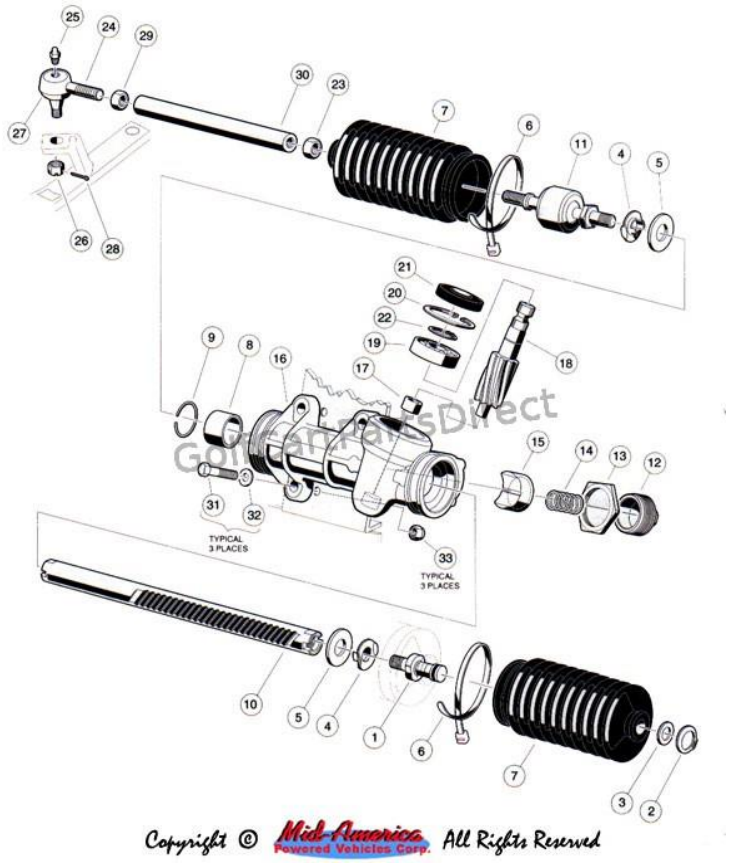


Figure 22: Explosion of the steering rack system in a 1995 Club Car DS [22]

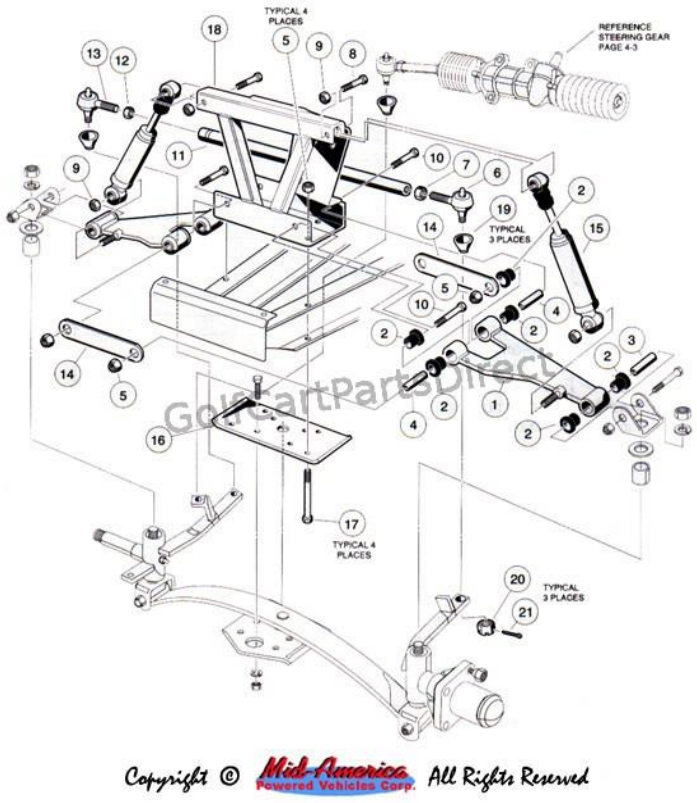


Figure 23: Explosion of the lower steering system and upper front-end suspension in a 1995 Club Car DS [21]

When the previous teams removed the steering wheel and attached the gear drive system to the steering shaft, they removed the steering column. This inadvertently removed all the support for the bearings, which caused the instability in the shaft.

When the 2017-18 MQP team received the cart, the entire upper steering system, including the steering column, was worn out and nonfunctional. The steering rack, drag link, and drag link end were also severely damaged and worn out. This put the team in a position where they needed to redesign and rebuild the steering system.

4.1.2 Steering System Redesign and Rebuild

As the team began to redesign the steering system, it became obvious that there were a number of different methods that could be used, and deciding on one would be very challenging. The team had a few resources that were available at the beginning of the steering redesign. The 2013-14 MQP team had previously tried to use linear actuators for steering and breaking. Although this attempt was unsuccessful, it left the linear actuators in the project's inventory for the team to use. The team also had the remnants of the gear drive system available. This put the idea of using a linear actuator steering system or a system that made use of the factory steering rack high on the list of possibilities. A few other potential ideas that were examined included an electric over hydraulic system and a pneumatic system. The latter two were similarly impractical; they both required systems that did not already exist on the cart. These systems, hydraulic and pneumatic, were both extremely costly in not only monetary expense, but also in power expense. The power expense was the major drawback to these methods, as the support systems they required needed to run constantly.

The other two options, a linear actuator or a modification to the carts original steering system, both had their advantages and disadvantages. The linear actuator would have eliminated the manufacturers steering system, but it would cost a lot, would have a few fabrication challenges, and would require complex testing. Utilizing the original steering system would have eliminated the need to do complex testing, but would still cost a lot and require complex fabrication. The cost of the linear actuators would be caused by the fact that the ones already available were either too small or too big, so a new linear actuator would have to be purchased.

Since the steering did not originally use a linear actuator, some fabrication would have needed to happen to allow for its installation. The linear actuators that were being considered would have required an interface to the eyelets they used for mounting, shown in Figure 25. It was unclear how this would be accomplished, so the team decided to consult the WPI Formula SAE Team. They were able to recommend a type of fastener that would easily be able to interface between the cart and the actuator. This fastener is known as a Heim Joint. They recommended that the MQP team have them welded to the ends of the linear actuator. Figure 26 shows what a typical Heim Joint looks like.

Figure 24: Linear actuator that was previously used for steering the Goat Cart.

Figure 25: Typical Heim Joint for steering which features eyelet mounting. [23]

The last major issue for the linear actuator came from choosing specifications for the new one. The 2017-18 MQP Team had no information available on what amount of force would be required to turn the wheels on the cart. This presented the challenge of either calculating it or measuring it. The team brought up this calculation while consulting with the Formula SAE Team, who stated that, while there was a calculation for it, it was very complex, and that they had four mechanical engineering students working for six months to calculate the force required for their own vehicle. They recommended that the goat cart team set the cart on the roughest surface that it was likely to encounter, deflate the tires slightly, and put the maximum load it was likely to carry on the cart. The SAE team then recommended that we attach the steering knuckle arm to a force gauge and use this to turn the wheels. This would give us the maximum linear force required to turn the wheels in a worst-case scenario. The 2017-18 Goat Cart MQP Team contemplated doing this; however, they decided to consult another expert first and mock up the two options. The mock up presented one mounting option for using the carts original steering system, which is shown in Figure 9. However, with the linear actuator, there were two mounting

options: The first option, shown in Figure 27, would place the linear actuator in the location that the carts steering rack had been mounted in, while the second option, shown in Figure 28, would put the actuator in front of the rest of the cart.

Figure 26: Possible mounting location if the motor is used to drive the original steering rack of the can

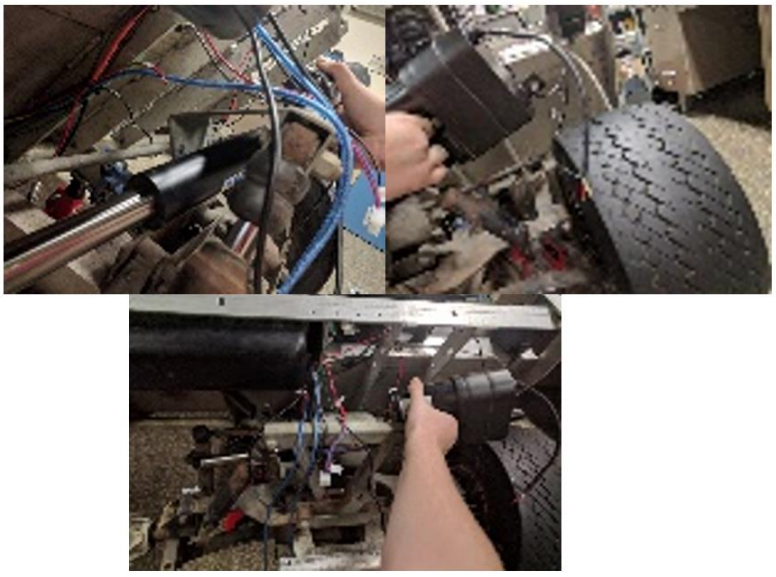


Figure 27: Possible method of using the linear actuator for steering seen from three angles. The linear actuator would be located where the steering rack was originally.

Figure 28: possible mounting of linear actuator in front of the Cart's suspension. This would not require the removal of the original steering rack.

A motor driven steering rack would have required a belt or chain drive system of some kind. The first option for mounting a linear actuator would have allowed the actuators force to be more effectively used, however the actuator's range of motion would have been limited. The second mounting option for a linear actuator would have given plenty of room for a full range of motion, but the applied force would be reduced. A challenging decision of which option to use needed to be made.

The team needed the input of an expert to assist with its decision. The team made several attempts to contact WPI Robotics Professor, Ken Stafford, after WPI Robotics' Associate Director of the Robotics Resource Center, Brad Miller, recommended him. When the team finally made contact with Ken Stafford, he suggested taking the route of using the carts original

steering system. Professor Stafford had previously advised a mechanical MQP that had devoted its entire project to designing a drive-by-wire steering system for a vehicle. He was able to tell the team that a human is able to produce a maximum of around one hundred fifty watts of power with their arms. This, he stated, would mean that a three hundred watt motor would be more than enough to replace the power a human would be able to apply to the steering wheel. Professor Stafford recommended the team use a CIM motor. According to him, this motor had an unloaded speed of 5300 RPM and a full load speed of 2600 RPM. He further informed the team that a human would turn a steering wheel at a rate of approximately 60 RPM. This meant that the CIM motor would have to be geared down to this speed. Professor Stafford informed the team that the maximum reduction a gear or chain drive system is capable of is seven to one. He recommended that a planetary gearbox be used for an initial reduction and a timing belt drive be used from there on. He recommended that an overall reduction of nine to one be used. He informed the team that the necessary components would be readily available from the company Andymark. When the question of how accurate positioning information could be obtained came up, Professor Stafford recommended inserting an absolute encoder or a ten-turn potentiometer in the system. After the team acquired expert consultation, there were many answered questions and there was a clear path to follow, however it also left more unknowns for the team to find solutions to.

In order to utilize the cart's original steering system to turn rotational motion into linear motion, it required at least a portion of that system to be functional. The biggest issue with this was that the team did not know how or where to acquire parts for this cart. The team considered

purchasing a new cart, however taking into consideration what was available on the market and the budget we had to work with, this proved impractical. The team decided to contact the local dealer for Club Car. After several unreturned voice messages, this method was abandoned. The team then thought to consult someone who works with golf carts on a regular basis. The team ventured to a local golf course, the Wachusett Country Club, where they went to the maintenance garage. The maintenance personnel were able to point the MQP team to a website-based parts warehouse located in Florida. This company, Buggies Unlimited, was capable of supplying all the manufacturer and aftermarket parts that the team would need to make the steering system functional. The decision was made to remove the upper steering system entirely, including the very problematic double universal joint at the bottom of the steering shaft. This resulted in the decision to purchase a new steering rack, drag link, and drag link end to replace the unusable components that would remain from the original steering system. The team researched the CIM motor and accessories that would be used to turn the input shaft of the steering rack. They discovered that Andymark was not capable of supplying what was needed, but another company, VEX Robotics, was more equipped to serve the needs of the team. VEX Robotics sells a planetary gearbox that is capable of up to a one hundred to one gear reduction [24]. Since the nine to one gear reduction was an available option, the team chose to perform all of the driveline reduction in the gearbox and to have no belt drive reduction. Due to this decision, a one to one belt drive system was purchased, which allowed the planetary gearbox to interface with the steering rack. The chosen planetary gearbox, which was a part of the VersaPlanetary Gearbox product line, had an option for an adapter that would allow it to attach directly to a CIM motor. It

also contained provisions for adding an encoder, which was another option that the team chose to purchase. As parts began to arrive, the team began to realize that the connection between the steering rack and the gearbox as well as the mounting of the CIM motor would be very difficult.

The challenges of mounting and connecting the CIM motor were largely due to the input geometry of the steering rack. This geometry is the reason why the factory had to include a double u-joint at the bottom of the upper steering system. As the parts that were ordered for the steering system were beginning to arrive, the team started to mock together how the parts were going to fit together. Figure 30, below, is a photo of them laid out on a lab bench, showing the connections that would need to be made.

Figure 29: Lay out of the new steering components on table prior to instillation.

One thing that became obvious as time went on is that mounting the CIM motor would be very challenging. As no one knew exactly how that was going to happen, the team made the decision to work on the interface between the steering rack and the timing belt. They went to WPI's Higgins Machine Shop, and were informed that they were not allowed to use the machines. Following this incident, the team visited a machine shop, Sandy Hill Locomotive Works, in Georgetown, MA. The owner, Dick Boucher, and his son, Michael Boucher, advised the group to abandon the timing belt drive, and instead directly mount the CIM motor with the gearbox to the steering rack input. This would allow the entire driveline to remain in one axis and it would prevent any issues with maintaining alignment of the timing belt. Following this, the machine shop advised the team to create a collar that would grab the custom spline on the input to the steering rack. This could then be attached to one of the pulleys from the timing belt setup that was no longer being used. Using the pulley would be necessary, as the gearbox output was a half-inch hexagonal shaft, which required a half-inch hexagonal hole to firmly connect the gearbox to the collar. The first thing produced was the collar. This was made out of a piece of steel round stock measuring one inch long by one and a half inch diameter. It was then trimmed down to seven-eighths of an inch in length. A hole, measuring ten thousandths of an inch smaller than the outside diameter of the input spline, was bored in the center. Then, four holes were drilled and counter bored to accept 10-32 machine screws. One of the pulleys was then drilled and tapped to match the 10-32 clearance holes. This was all accomplished in one night while being designed on the fly, meaning that poor design decisions were made, and the final product did not work. The tapped holes blew out the side of the pulley, which meant that the collar and

the pulley could not be connected. When the team regrouped, learned from their mistakes, and realized a design was needed, they decided to review what was made, and to discover what needed to be done differently. They then realized that the collar needed to be pressed onto the steering rack input spline. This meant that the pulley could not be attached to the collar while the collar was being installed, and the cap screws had to be screwed in from the pulley side, not the collar side. It was further discovered that instead of using a purely press fit system, it would be better to slit the side of the collar and use a retaining screw to clamp it together. The last major design decision was to include a setscrew on the pulley with which to firmly attach the gearbox. Following this, the team drew up a set of designs, which can be seen below in Figures 31 and 32.

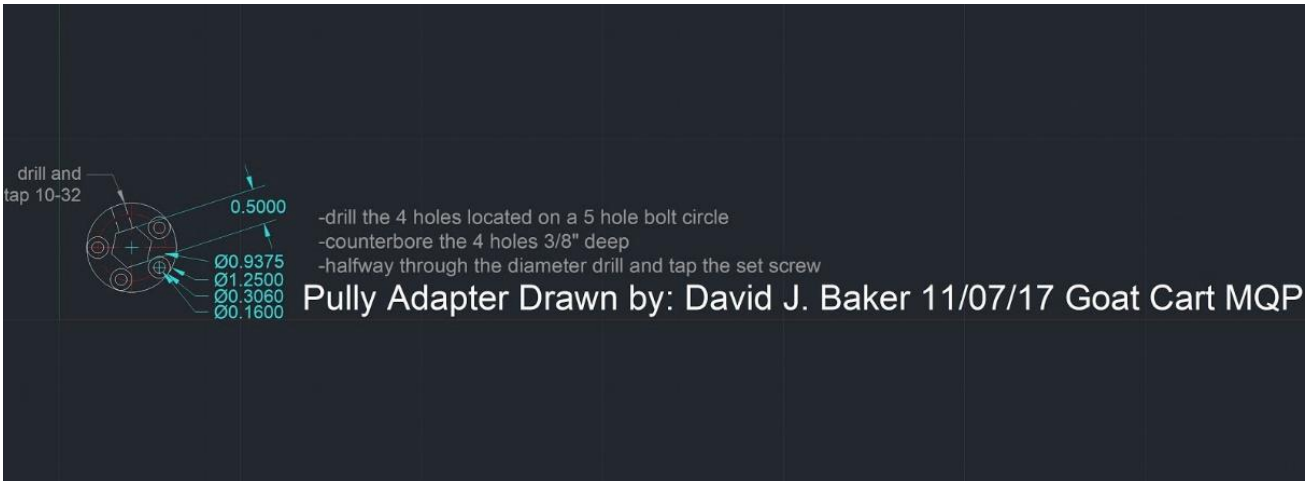


Figure 30: Pulley Adapter CAD Drawing

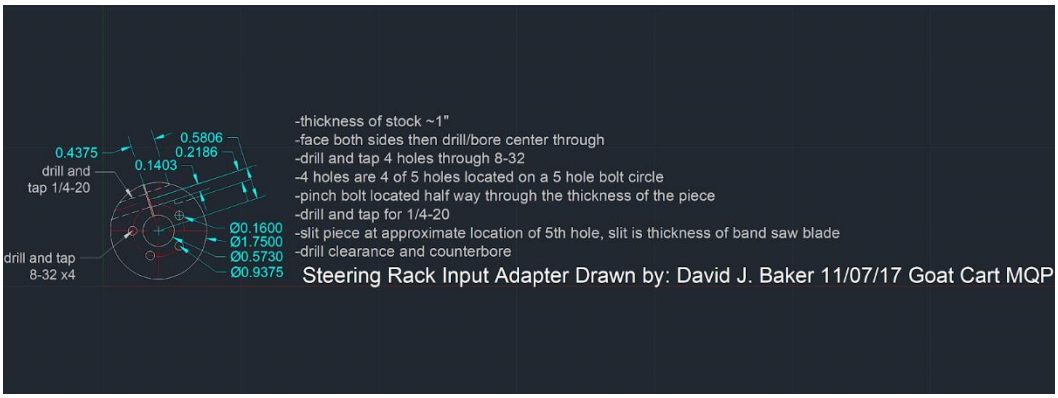


Figure 31: Steering Rack Input Adapter CAD Drawing

The steering rack input adapter is the component being referred to as the collar. There were a few other minor design changes, including the decision to switch to 8-32 screws to connect the two adapters together, and to use one and three quarter inch diameter stock for the collar. Armed with these designs and the remaining pulley, the team returned to Sandy Hill Locomotive Works. The stock for the collar was cut out and trued up. The center hole was then bored out to a press fit on the steering rack input spline. Next, the counter bore for the Pinch bolt was milled, and the hole was drilled and tapped for ¼-20. The slit was cut in the side followed by the clearance drilling of the pinch bolt. The collar was finished by drilling and tapping the four 8-32 connecting screw holes. Then the pulley adapter was created. As the team began to work on the pulley, they realized that the flanges of the pulley were separate from the pulley itself. These flanges were press fit onto the sides of the pulley. The team then cut them off, as they would be weakened in the process of drilling holes in the pulley. The pulley then had clearance holes and

counter bores for the 8-32 connecting screws drilled. Below in Figure 33 is a photo of one of the team members working on the pulley adapter.

Figure 32: Team member working on machining the pulley adapter.

The last process performed was drilling and tapping the 10-32 set screw hole. The collar was then pressed onto the input spline of the steering rack. The pulley adapter was screwed to the collar and the pinch bolt on the collar was tightened. The final procedure was to securely attach the CIM motor and gearbox to the pulley adapter using the setscrew.

Figure 33: Finished coupler attached to the steering rack.

Above in Figure 34 is a photo of the final coupler attached to the steering rack. This was accomplished rather easily, but the team had little clue what was waiting for them in terms of mounting the whole setup.

Due to deadlines set by the Spark Party Presentation, the steering system mounting was completed entirely in one night. This began with mounting the factory replacement parts. This was a simple process given the fact that all of the components were direct replacement parts. The only challenge presented was the need to replace the attachment hardware because the old hardware had been destroyed by a previous teams work. Once the cart's lower steering system was functional again, the team began work on the secure mounting of the CIM motor. The first challenge was that the motor would not fit in the cart due to the geometry of the steering rack's input spline pushing the CIM motor into the dashboard. The team rectified this issue by first

removing the speaker system and the LED underglow, as both of these systems were run through the area of the dashboard that the CIM motor would occupy. The next issue was to remove the driver's side of the plastic insert that supported a glovebox and previously the ignition switch. This was rather easy, as it was only held in with a couple of screws and some rivets that were easily drilled. Then the metal kick pan that ran from the dash to the floor pan needed to be notched in the area that the CIM motor would occupy. The notch, made in the kick pan where the motor exists, can be clearly seen in Figure 35. One concern the team had was that dash supports would need to be cut, and that this would weaken the structural integrity of the dashboard. Fortunately, however, the CIM motor fell cleanly between the two adjacent supports. The clearance between the dash frame and the motor is shown in Figure 36.

Figure 34: Notch cut into kick pan to accommodate the CIM motor.

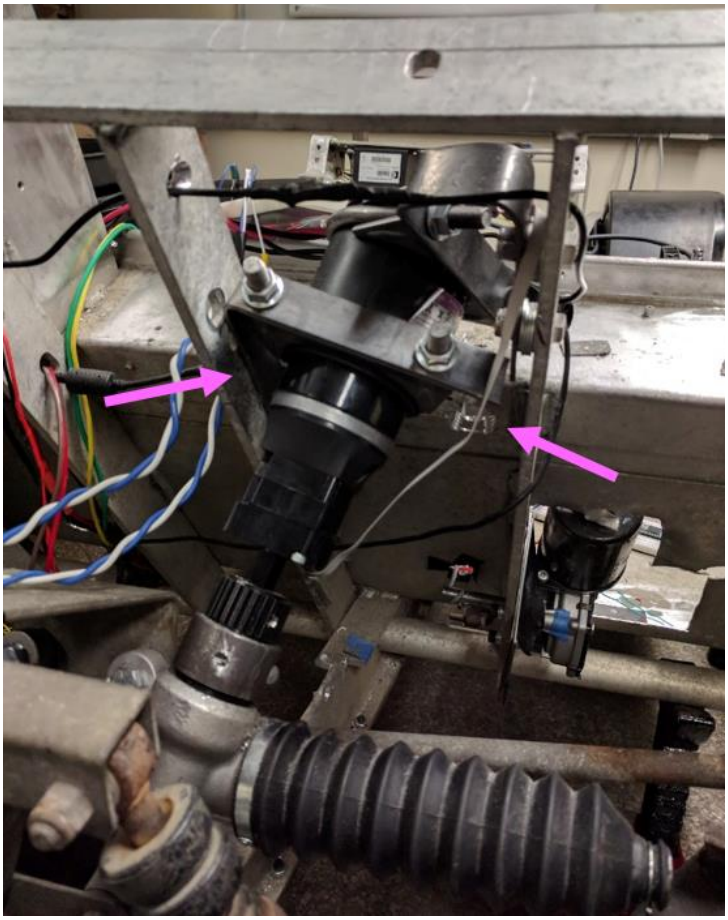


Figure 35: CIM motor clearing the two-dash frame supports. The arrows point out the mounting points of the motor.

This conveniently meant that they could be used for supporting the CIM motor. The next big question was how the mount that would be created would connect to the CIM motor. The team decided to head to the hardware store and look through the plumbing hangers and clamps. The outside of the motor was close to, but not quite as large as the outside diameter of a standard pipe size. This meant that none of the options would securely hold the motor. The team did find one

Fernco coupling that the team was able to stretch over the CIM motor. However, there was still no clamp that would grab onto the outside of the motor with the coupling. After several unsuccessful trips through the hardware store, one team member suggested the idea of using exhaust clamps. The team then headed to a local auto parts store, where they found a U-Bolt exhaust clamp that grabbed the motor snugly around the Fernco coupling. In Figure 37, is a photo of the clamp around the Fernco coupler on the CIM motor. It also details the exhaust clamp, which will help explain how the exhaust clamp was fastened to the frame of the golf cart

The 2017-18 MQP team then made a trip back to the hardware store to purchase a piece of steel strapping that would get used to secure the exhaust clamps to the golf cart frame. Two of

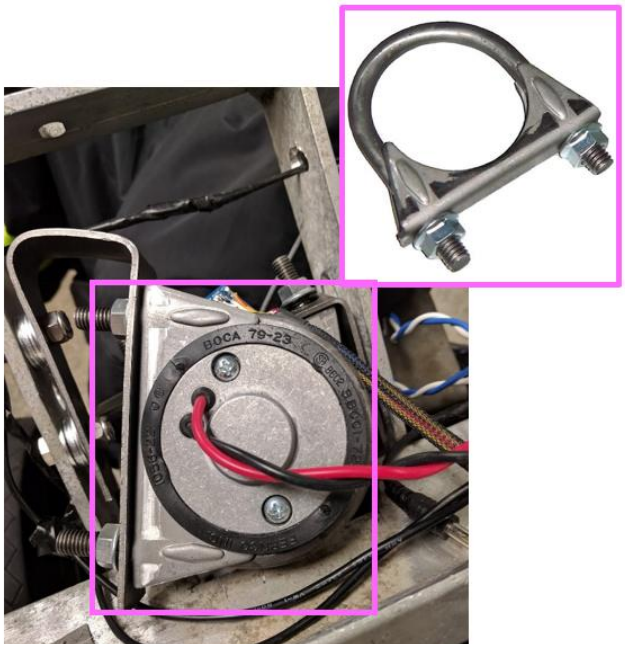


Figure 36: Exhaust clamp holding the CIM motor through the Fernco Coupling. [25]

the exhaust clamps were then secured to the motor with the Fernco coupling on it. As shown in Figure 36, each exhaust clamp is made out of a U-bolt and a strap. The U-bolt provides two sections of threaded rod with nuts that serve as great places to attach a support. [25] The team used this attachment place to add a piece of the strapping that was bent to match the profile of the nearby dash frame supports: one strap for each of the two exhaust clamps that each ran to one of each of the adjacent dash frame supports. Holes were then drilled in each of the straps and in each of the dash frame supports to allow the exhaust clamps to be securely bolted to the dash frame supports through the straps. The straps running between the motor exhaust clamps and the dash frame can be seen below in Figure 37.

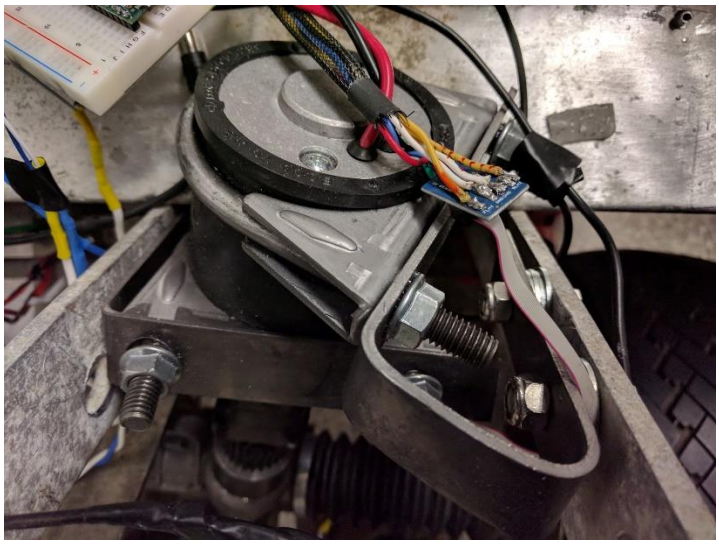


Figure 37: Steering CIM Motor Wrapped in Fernco Coupling Clamped by Two Exhaust Clamps Attached to Dash Frame Using Steel Straps

4.1.3 Steering System Testing

With the mounting of the steering system complete, the focus switched to testing the steering system. At first, the team decided to directly touch the leads of the motor to a battery to "bump" the steering from the left, to the right, and back again. This worked perfectly, and proved that there was not any binding in the steering components. The team then attached the motor to the Sabertooth, and proved that the cart could be steered using drive-by-wire. In Figure 38, is a photo of the front of the cart, including the steering system during its initial testing.

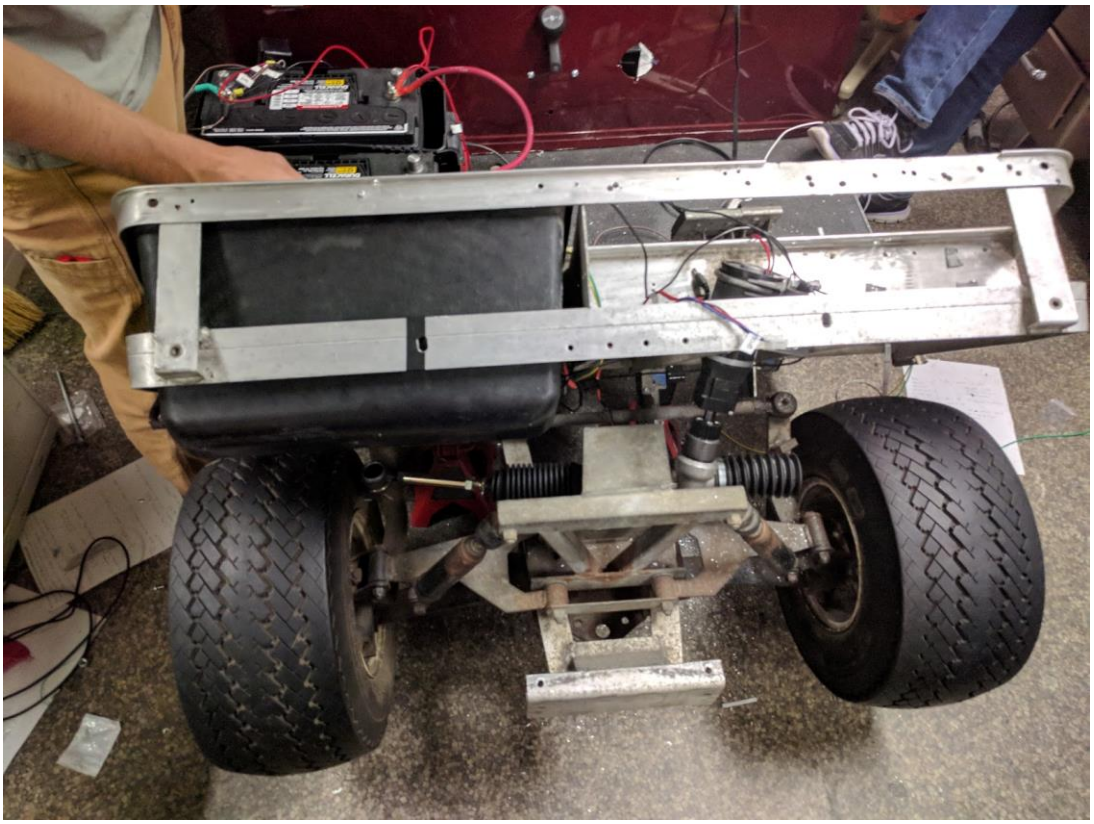


Figure 38: Front End of Cart Including Steering System During Testing

A few problems presented themselves during testing. The major ones were software related; however, there was a non-critical design mistake discovered. This design mistake was that the calculation for the gearbox reduction was never performed. The team had assumed that Professor Stafford's recommendation of a nine to one reduction would be correct. However, if the reduction had been calculated using Equation 1 below, the team would have found that they wanted a much greater gear ratio:

Equation 1: Gear Ratio Equation

$$Gear\ Ratio = \frac{Input\ Speed}{Desired\ Output\ Speed}$$

Using the loaded speed of the CIM motor, 2600 RPM, as the Input Speed and the Desired Output Speed of 60 RPM, the team calculated the required gear ratio to be approximately forty to one. The consequences of using nine to one instead of forty to one was first that the maximum torque was lower, which wasn't an issue and second that the ability to control the steering speed was significantly lowered. This meant that under worst-case scenarios the motor speed had to be limited in software to 11% of full speed to obtain the desired speed. With the testing of the mechanical components of the steering system completed, the team moved on to work on the software and controls design of the cart.

4.2 Steering Software

The steering software controls a motor that turns the rack and pinion, moving the angle of the wheels. The code was built in a way that it started simple and thoroughly tested, then more complex parts that built on the original were added in and tested. The software is on a Teensy

3.5 and receives inputs from the CAN bus telling it what amount of degrees the wheels must be at. For the system to act intelligently there are sensors that are used to determine the location that the rack and pinion is at, mainly and encoder and two limit switches. The circuit for the steering system was simple but used a few complex components.

4.2.1 Steering Controls Circuit

In order to control the steering CIM motor was used with a Sabertooth motor controller was used. This motor controller fits the specifications needed plus a margin of error to control the steering motor. The Sabertooth 2x60 is able to be powered by 6V through 30V, meaning that even if the 12V batteries are draining, the steering motor will still be powered. In addition, it can take up to 60A continuous per channel, and a spike of 120A. The motor used has a free current, the current drawn when the motor has no load, is 2.7A, even when the cart is on the ground the amps drawn should remain below 60A. However, the stall current, the maximum current drawn when applying maximum torque, of the CIM motor is 131A. Though the stall current is above the abilities of the Sabertooth, the cart should never be in a position when this is occurring. If the stall current is reached, there is a larger problem occurring that needs to addressed [26].

For the wiring of the Sabertooth, motor controller the gauge of the wire is important so that it is not overheating. The expected continuous amp draw is at most 45A. According to the datasheet, the battery lead size should be at minimum 8 gauge and the motor lead size should be 10 gauge. This is important because if not complied with the Sabertooth can overheat and fail [26].

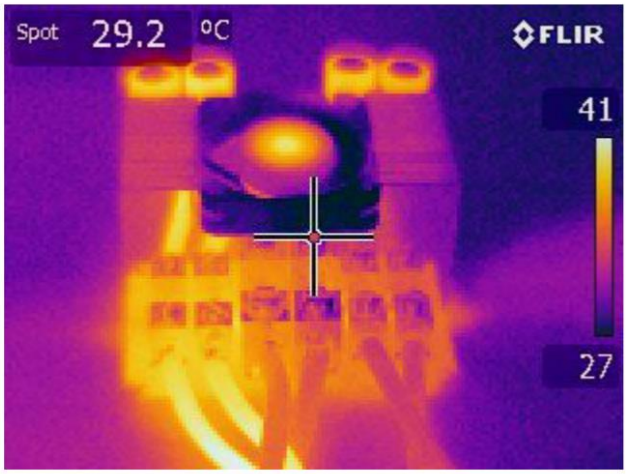


Figure 39: Sabertooth Heat Map showing Incorrect Gauge Motor Leads vs Correctly Sized Leads. The left two wires are to small and are causing the overheating of the Sabertooth Motor controller, this can cause fatal and unpredictable errors. [26]

Figure 39 shows what occurs if the motor leads are too small when 40A is continuously running. The wires on the left are 12 gauge, instead of being at least 10 gauge, causing the left to overheat and effect the center of the Sabertooth where the battery leads are. The issue of overheat could potentially lead to dangerous errors that the cause of are not obvious at first glance.

The Sabertooth is controlled by the Teensy 3.5 output of a pulse width modulated (PWM) signal. The datasheet suggests putting the PWM signal through a low pass R/C filter. Following the suggestions, a 10k ohm resistor was used with a 0.1uF capacitor as seen in Figure 40. [26]

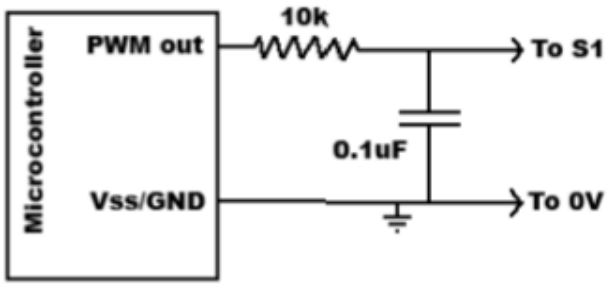


Figure 40: Circuit for Filtering the PWM Signal before Connecting to the Sabertooth. This circuit smooths the PWM output from the Teensy removing any high frequency spikes in the signal. [26]

A quadrature encoder is used on the motor so that the angle of the wheels is known. An encoder is an electromechanical device that can determine rotational motion; the one being used for the steering is a magnetic encoder. A magnetic encoder has permanent magnets with altering poles spaced around a disk that moves with the motor shaft, a Hall Effect sensor stays in place and picks up the alternating magnetic field, as the magnets pass. For a quadrature magnetic encoder, a second Hall Effect sensor is placed at 90 degrees offset from the first (Figure 41) [27].

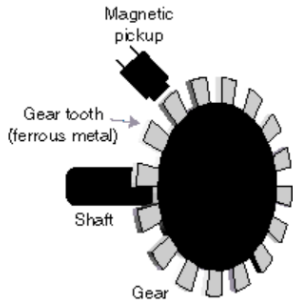


Figure 41: Magnetic Encoder Construction. The shaft with the gear is connected to the motor shaft and rotates at the same speed so that the magnetic pickup receives input for each tooth and uses that to produce a value that represents the amount the motor has spun [27]

The offset of the two sensors allow there to be two channels, A and B that are 90 degrees out of phase. Having the two channels out of phase, it is possible to know which direction the quadrature encoder is turning. If channel A is leading B then the disk is rotating clockwise; else, if channel B is leading A then the disk is rotating counter-clockwise (Figure 42). [28]

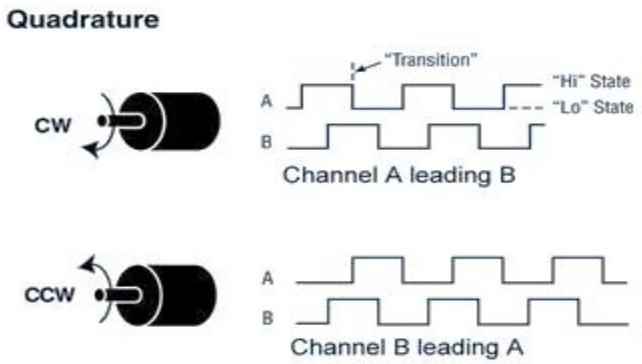


Figure 42: The direction the encoder is turning changes which channel is leading. This allows the program to know which direction the encoder is turning. [28]

For the Goat Cart a quadrature encoder is used to determine what angle the front wheels currently are. The motor's rotational movement moves the pinion in the rack and pinion system, which moves rotationally along the linear rack, causing the wheels to angle. The quadrature encoder attached on the gearbox picks up the movement of the steering motor, and because the movement originates with the steering motor, the angle of the wheels can be calculated from the quadrature encoder values. Unfortunately, since the quadrature encoder loses power when the cart turns off, the location of the steering motor is lost, requiring calibration every time the cart is started.

The quadrature encoder used requires 5V and GND, and outputs signals A and B (the quadrature channels). [29] The power comes from the Teensy breakout board that has a 12V to 5V voltage converter. The outputted signals connect to pins 22 and 23 on the Teensy via the breakout board.

The encoder does not know where the ends of the steering rack is, for this reason; the limit switches were added so to not overrun the rack. The limit switches are attached to the A frame and are hit by hard stops that are built into the steering arms as seen in Figures 43 and 44.

The limit switches do not have a shared ground, most likely because of the liberal use of epoxy attaching them to the Cart. One of them had to be reattached using JV Weld, which is conductive, so it connects the ground to the A-frame. The circuit for them is very simple because the Teensy has internal pull-up resistors, so the signal wires plug directly into the Teensy breakout board.

4.2.2 Software Design

The program for the steering was built in steps, going from basic human controlled, to automated using the different sensors. Initially, the program only had the wheels turn left and right based off when the human presses the buttons for left, right and stop. This is what was used for Spark Party in November 2017, because there was limited time for development and testing.

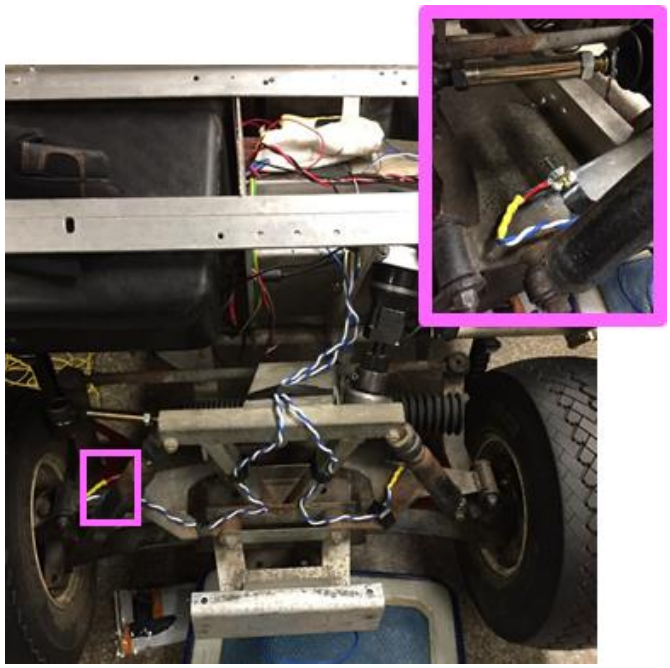


Figure 43: The right limit switch attached to the A-frame of the steering rack. The hard stop hits the limit switch signaling it has reached the end of the rack.

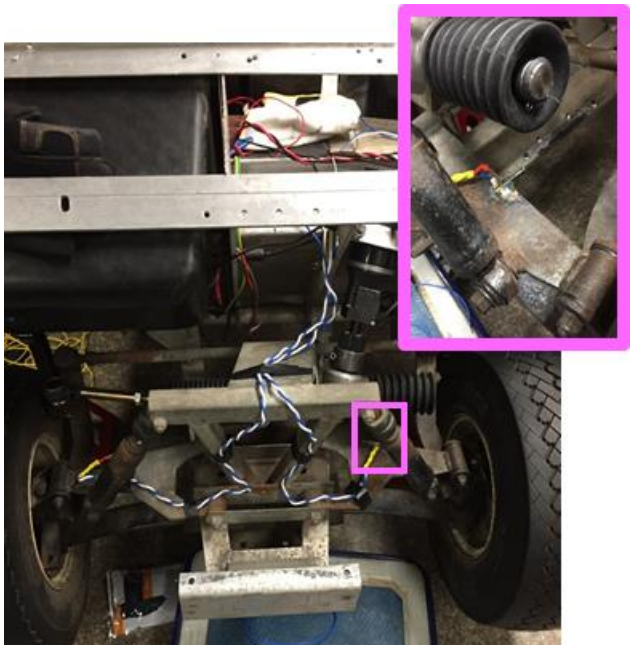


Figure 44: The left limit switch attached to the A-frame of the steering rack. The hard stop hits the limit switch signaling it has reached the end of the rack.

The next version of the program had the program turning left and right based off human button presses, and having the steering stop at the ends of the rack. This is the first implementation with the limit switches being used to detect the end of the rack. Adding the limit switches eliminates the possible issue of the steering not stopping before the end of the rack. It is better than having just a hard stop because with just a hard stop the motor will continue trying to turn the rack while it is hitting against it. The logic of this version of steering can be seen in Figure 45.

The next iteration of the steering program was to include a calibration mode. The calibration is necessary because upon the startup of the cart it is unknown where straight is in the steering. To determine the center of the steering rack, which is the straight position, the quadrature encoder and the limit switches were used. The process for calibration is simple. The cart turns left as far as it can, hitting the left limit switch and getting the encoder value at that position. Then the cart turns right as far as it can, hitting the right limit switch and getting the encoder value at that position. Then the average of the two values is found and then the cart goes to the value within a small range of tolerance and then zeros the encoder value at that location, which is then called 0 degrees or straight. This process can be seen in Figure 46.

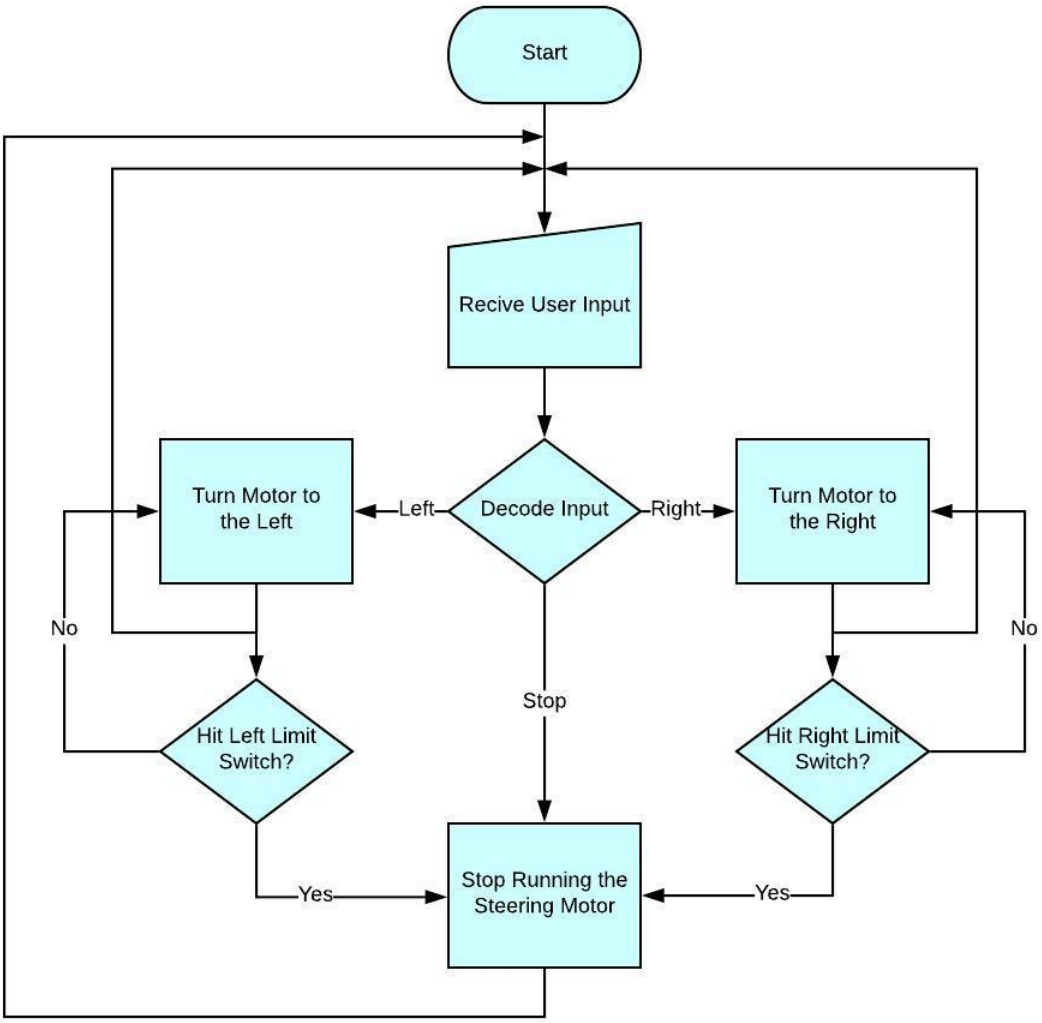


Figure 45:Flow chart depicting the process of the steering program with just limit switches. Based upon user input the steering turns left or right till it hits a limit switch and stops.

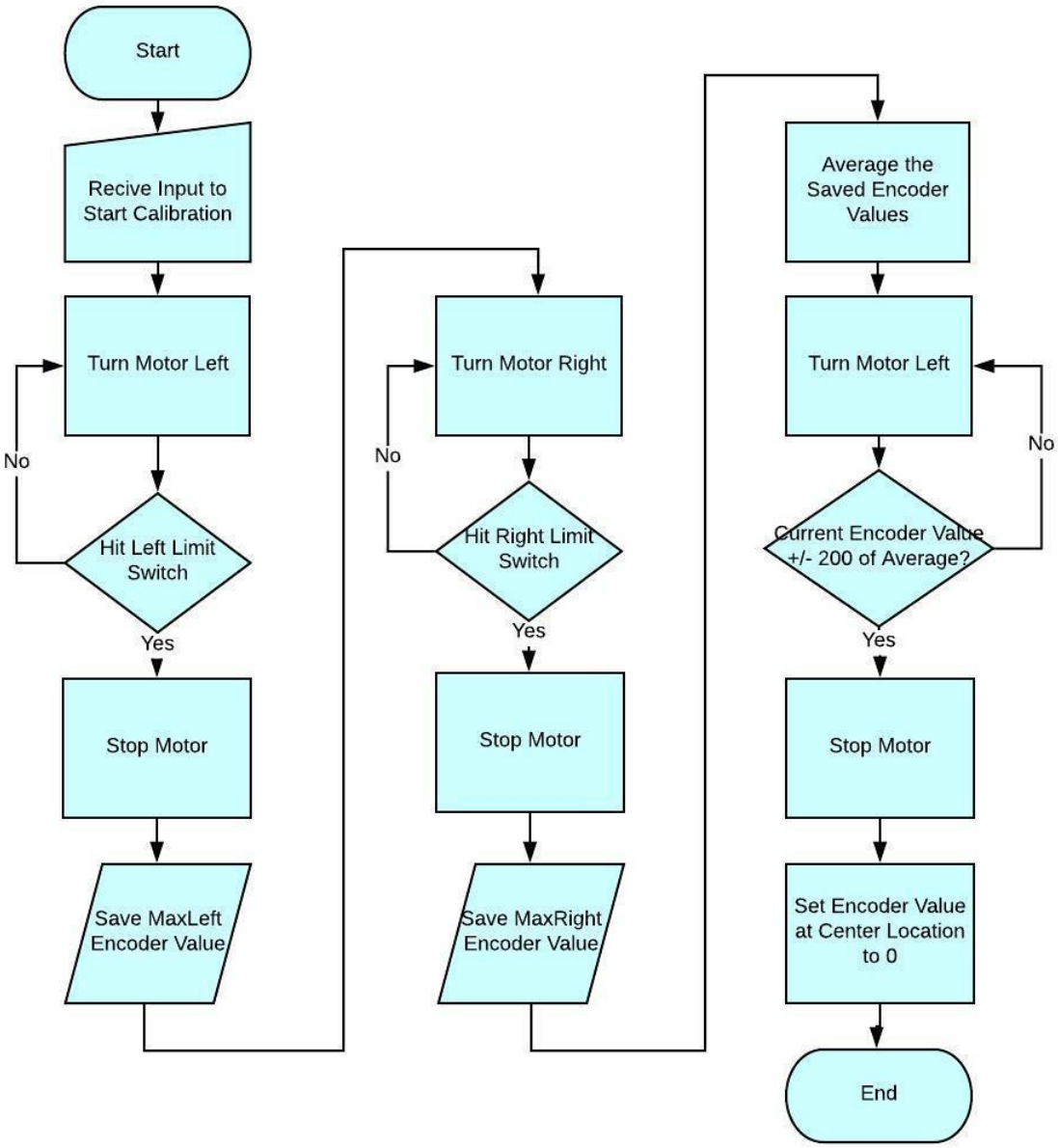


Figure 46: The program for calibration runs at start up so the cart knows what position it begins at. The cart turns full right and left grabbing the extreme encoder values, and then averages the values to find center.

The last addition to the steering software is adding a function that receives an input that takes a character ‘N’ or ‘P’ followed by a number between 1 to 90 and then turns to said degrees. The character input signifies positive or negative, where 0 degrees is straight, as seen in Figure 47. This scheme was chosen because it is logical and simple for the CAN bus to send and for the steering Teensy to decode.

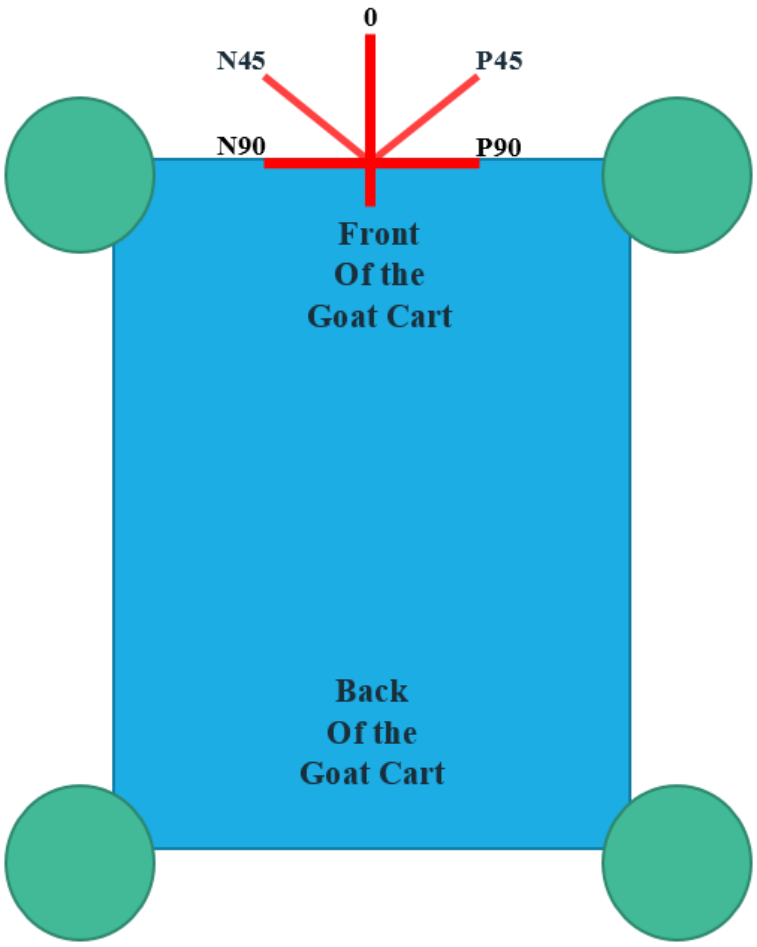


Figure 47: Diagram of Goat Cart with steering degree code inputs. Straight is 0, while -1 to -90 degrees is N##, and 1-90 is P##, these codes are chosen because they are somewhat self-explanatory.

Once the message is received and decoded. The program finds out where the steering initially is. Then it determines which direction it must go to get to the desired location. Once it starts turning the desired direction, the program continuously checks if the steering has hit the correct location by checking the current encoder values with the desired encoder value with in a tolerance. Once the steering has hit inside the tolerance for the correct range it stops. Figure 48 shows this process

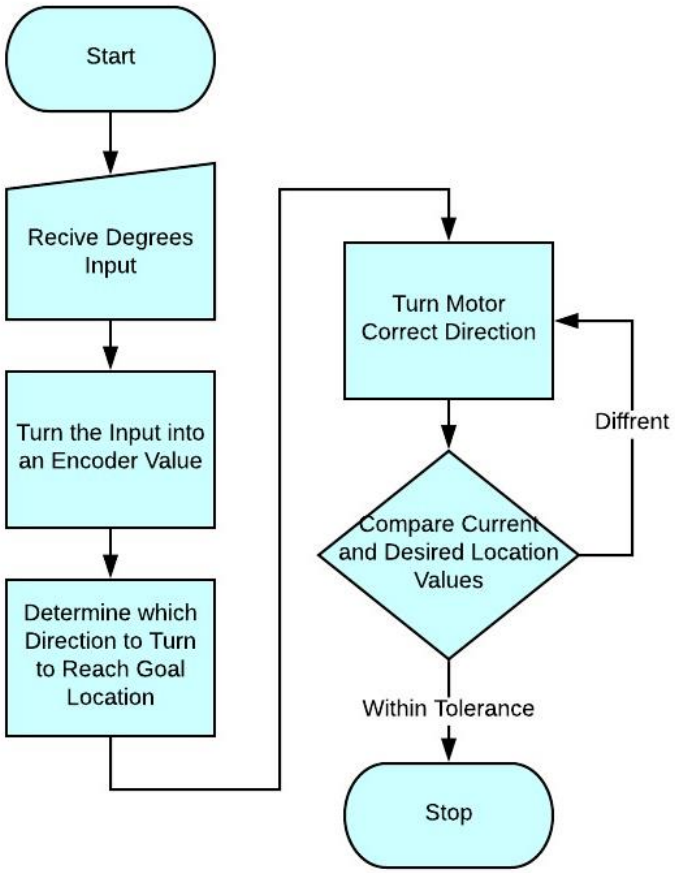


Figure 48: Steering program that receives an input of degrees. Then based off the current location the steering turns left or right to reach the desired location within a range of tolerance.

4.2.3 Steering Software Implementation/ Testing

The program was implemented in stages, as discussed above. Each subsequent part builds off the previous, making it easy to keep adding additional functionality. Every part is further broken down into multiple functions that complete a section of the desire part that are then called. This process was done so that every part can be thoroughly debugged and tested. The logic is kept straightforward, so that there will be few exception cases that need to be handled. In addition, by keeping the logic simple, ideally future years of this project will understand how steering works and can build upon it.

There were a few minor issues when testing the steering programs. The basic steering program worked well at the first try, the only complication was getting the Teensy to communicate to the Sabertooth. After checking the switches on the Sabertooth (Figure 49) and placing it into PWM mode, it worked properly. [30]

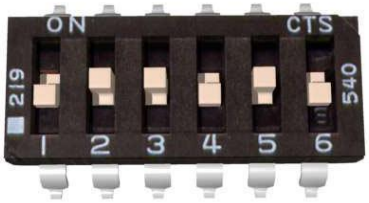


Figure 49: Sabertooth switches are used to tell the controller what mode it should be in. The mode shown is for non-lithium batteries, microcontroller PWM input, independent motor one and two mode with linear control. [30]

Adding the limit switches added another layer of complicity, but was quickly up and running. The most bothersome part while testing was keeping track of which limit switch is left

or right, and if it was on or off, this required a chart to be made describing the limit switches (Table 7).

Table 7: Logic chart used for debugging the limit switches, while seemingly simple as a chart, it was much more difficult when the switches were off the cart.

Limit Switch Logic Chart			
	Teensy Pin	Output 0	Output 1
Right Limit Switch	34	Not at end of rack	At end of rack
Left Limit Switch	33	Not at end of rack	At end of rack

After that was completed and debugged, the calibration was tested. The calibration system worked perfectly since the first time it was implemented. The encoder was simple to use properly because there is a working Teensy library for encoders. Then during later tests, the limit switch broke off and had to be reattached to the frame twice. The limit switch was then attached with JV Weld instead of the originally epoxy. The switch that was connected with JV Weld to the cart would be grounded to the A-frame because JV Weld is metallic. If both switches were grounded out then only one ground wire would be necessary.

Then when testing resumed C term 2018, the steering was not functioning properly. The code did not change, nor did the hardware so it was assumed that something broke. This meant it was necessary to go through the entire steering circuit and debug. The first step was to test the initial version of code that had no sensors, just the motor turning and stopping based upon user inputs. This test was successful, so it was concluded that the issue was with one of the sensors.

The second test had the limit switches added into the circuit; this did not work as it should have. From the second test it was determined there was an error with the limit switches. From this, the limit switch testing had to be redone and compared to the chart shown in Table 7 above. Oddly enough, the limit switches values were not changing. This led to the conclusion that a wire was broken. The wires were then tested using a multimeter, from this it was found that two wires in the harness were broken and another one that was connected to the limit switch. The latter was replaced and the limit switches were disconnected from the harness and plugged into the Teensy. In addition, to simplify the circuit, the pull up resistors for the limit switches were removed and replaced with the internal pull up resistors in the Teensy. Once the steering circuit was repaired and improved the steering calibration code worked as expected.

4.3 Steering Summary

The steering system was completely redone by the 2017-18 team. The previous steering was out of alignment and damaged. Instead of wasting time fixing the old system, a new steering method was devised after consulting with professors and professional machinists. The new steering system has a new steering rack that is controlled by a CIM motor. The steering motor was solidly mounted to the front of the cart. When driving the motor will not shift out of alignment, and excluding a major crash the mechanical steering should not be changed in the future.

The steering circuit and software was redone and improved. The circuit was simplified to include the motor controller, two endstop limit switches and a quadrature encoder. By having the

limit switches and encoder it is possible for the steering system to know where the end of the rack is and where the steering is currently pointed. The final 2017-18 version of the steering program has a calibration mode that must run at the once the cart turns on, so that way the Goat Cart knows where it is. Then to turn when driving about, the steering can receive a command of how many degrees it needs to turn from -90˚ to +90˚ with 0˚ being straight. The steering program does not have any self-correction, which should be added in the future.

Chapter 5. Braking

The braking on the car was supposed to be complete from previous team's work. Unfortunately, that was not the case and a new design had to be implemented. The existing motor was repositioned so that it provided enough force to apply the brakes while maintain the manual functionality of the brake pedal. The final version of this design is very solid and should last many years of testing and experimentation.

5.2 Braking Design

As stated in the initial conditions, the braking system was installed but was not connected to anything. In the original design, the brake motor pulled a cable by wrapping the cable around the motor shaft. The cable, in turn, connected to a lever (Item 3) that attached to the braking axle (Item 2) as shown in Figure 50.

The brakes are activated when the brake axle (Item 2) turns and wraps another cable around itself pulling on the brake mechanism. When testing the system, the team found that it did not activate the brakes. Going back to the data sheets of the motor and doing some basic math, the team discovered that the brake motor could not provide enough force in its current position to activate the brakes.

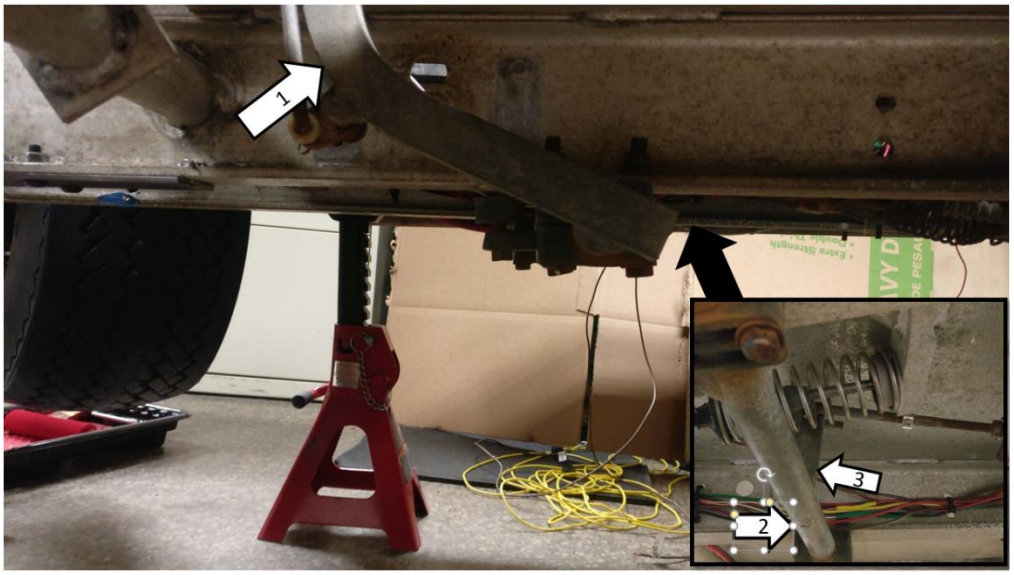
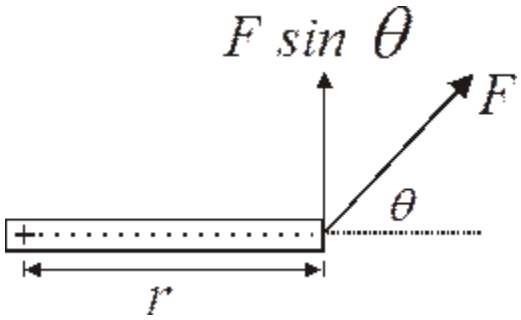


Figure 50: Shows a side image of underneath the cart. Item 1 is the bottom part of the level that is the brake pedal. Item 2 is the brake axle. Item 3 is the lever where the previous team attached the cable to the brake axle.

Performing some basic math using the torque equation (Equation 2) the team found that the previous team's location of the brake motor was inefficient. The equations shows that the main factors of torque are the force (F) and the distance from the axis of rotation (r). The sine component is used to find the vector of the force that is perpendicular to the lever extending out from the axis and acts as a scaling factor for the force. For rough math, the sine component was ignored as all of the forces being dealt with acting at or very close to 90 degrees.

Equation 2: $T = F*r*\sin(\theta)$



Using this information the team analyzed the current position of the brake and the forces involved in activating the brake manually. To activate the brakes manually, the operator would push on the pedal, which would turn the brake axle and activate the brakes. Rough measurements found that the top of the brake pedal was approximately sixteen inches away from the brake axle whereas the brake motor cable was only mounted two inches away. Using the torque equation it can be determined that the brake motor needed to exert eight times as much force in this configuration as the manual use of the brake pedal does. Looking at the data sheet for the brake motor, it can output 19.2N*m at peak power. Solving the Equation 2 for torque and converting inches to meters, the brake motor can apply 208Nm of torque on the brake axle, where for the same amount of force the pedal can exert 1864Nm of torque.

Several options were considered to fix this problem. While buying a more powerful motor was possible, the team decided to attempt repositioning the existing motor to a location that would give it more torque. Attaching the motor cable directly to the braking mechanism was considered, but this had two flaws. The first is that it the motor would still not have enough torque, the second issue is that it would remove the manual functioning of the brake pedal in an emergency.

Alternatively, mounting the motor to pull the brake pedal itself would avoid all the previously mentioned problems. This configuration would provide an eight times increase in torque compared to the previous implementation and would maintain the functionality of the brake pedal in emergencies. Another factor in choosing to keep the old motor was that it was a

worm drive. A worm gear motor does not require any power to hold its position, only to change position.

The ideal location for the motor to connect to the brake pedal would have been directly under the dashboard of the cart as seen in Figure 51.

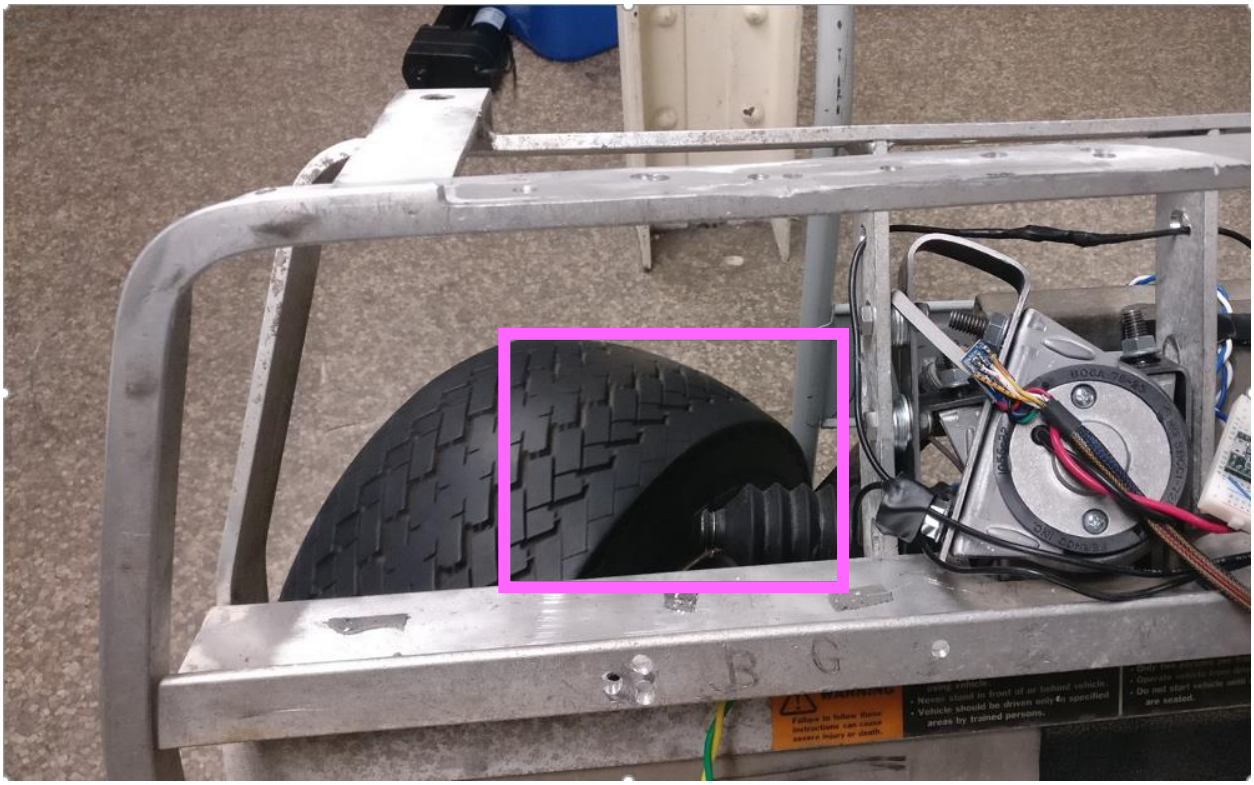


Figure 51: Shows the ideal mounting location for the braking motor as it could be hidden away under the shell when finished. Also, show the interference that would occur with the steering it was located there

Unfortunately, this was not possible, as it would have collided with the new steering system, which took precedence. The only other option was to mount the motor to the floor panel directly behind the brake pedal (Figure 52).

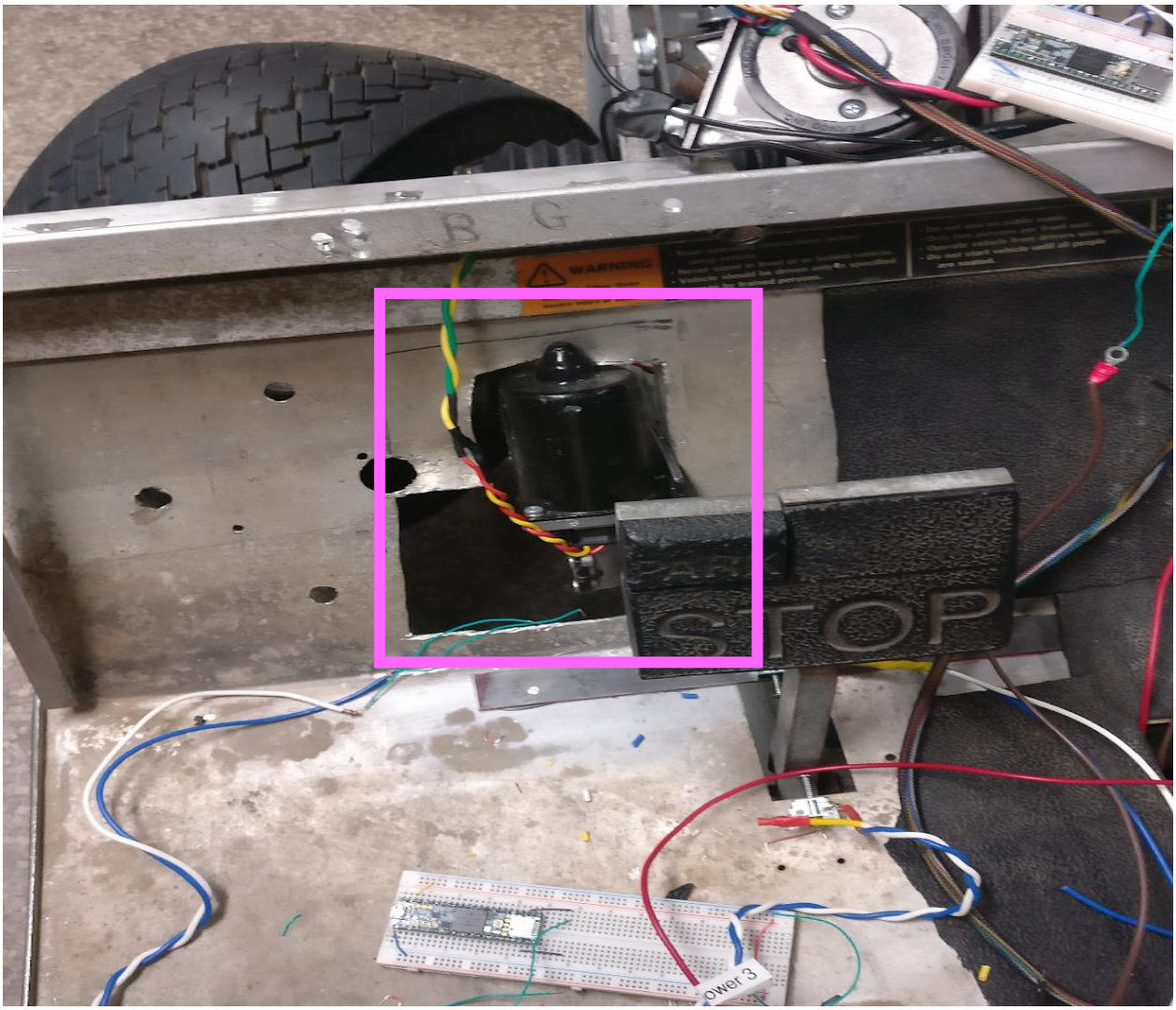


Figure 52: Shows the final mounting location of the braking motor directly behind the brake pedal. The brake cannot be push far enough down for it to interfere the brake motor.

This option gave the team a mounting point directly on the frame and would require the least amount of additional structural support.

A brief testing of the electronics in the original brake setup seemed sufficient. The motor controller, a Sabertooth, can output a maximum of 60A and the brake motor stalls out at 40.9A. Therefore, the previous team's selection of a motor controller is sufficient for this motor's needs. Additionally the Sabertooth motor controller can be directly controlled with a Teensy 3.5 via PWM control, which is the standard for this project.

5.3 Braking Implementation

To mount the motor, a portion of the floor panel needed to be cut away. The team started cutting with a handheld dremel and several small abrasive cutoff wheels. This method of cutting ended with the job half way done, after several cut off wheels were used up and the dremel was melted. To finish cutting the hole, the team used metal shears and pliers to bend, cut, and move the thin aluminum flooring out of the way. This process of cutting the flooring was crude but the team was on a very tight timeline because of Spark Party 2017. A proper handheld grinder or metal saw is advised for any future endeavors to cut the flooring. However, the final hole created was in line with the brakes and good enough for fitting the motor in place.

After the flooring was cut out, the team drilled a hole through the frame where the motor shaft needed to go. This hole was positioned such that, when the brake was fully depressed, the angle between the cable and the brake shaft would be as close to 90 degrees as possible to maximize the torque under maximum load.

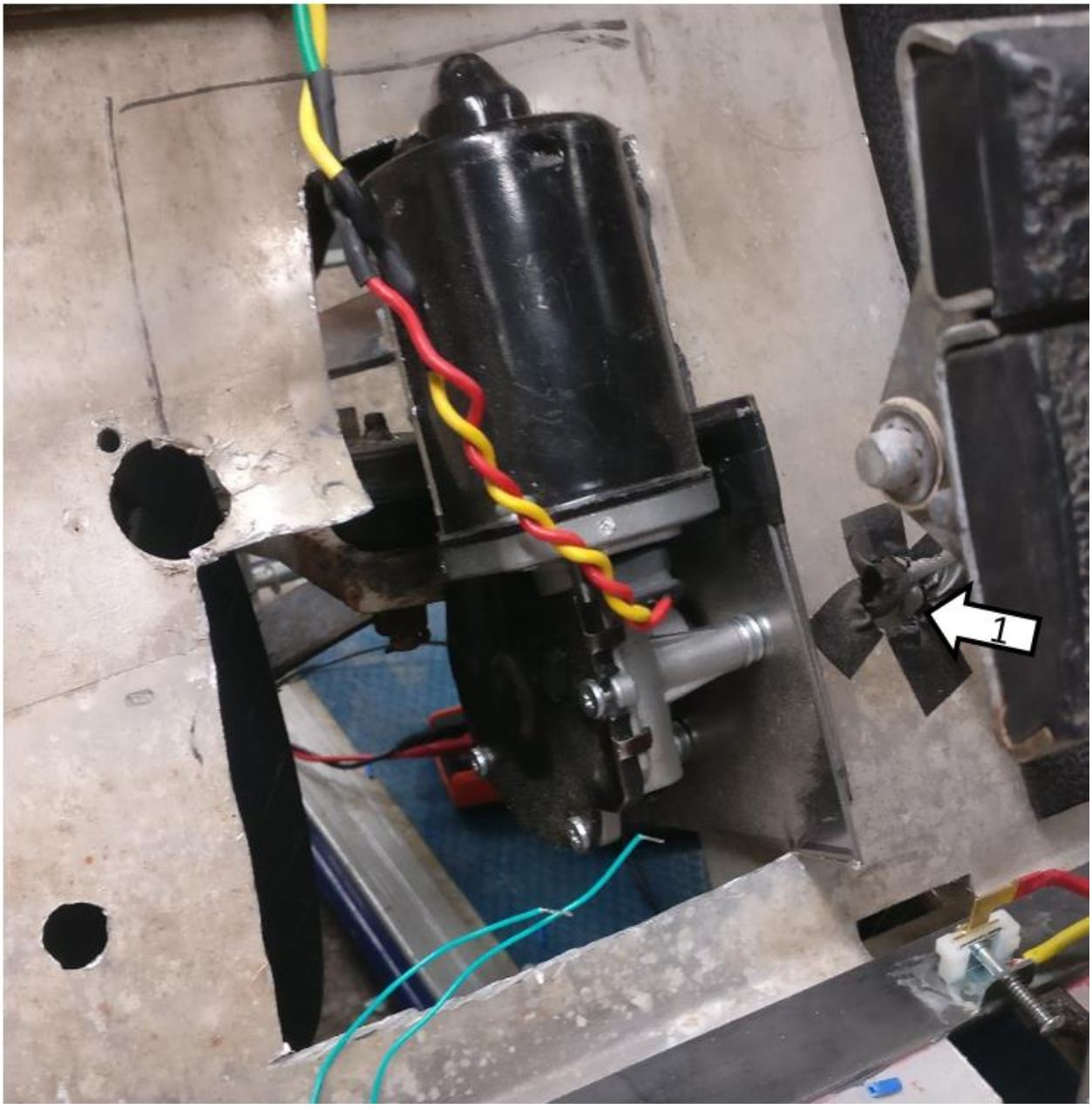


Figure 53: Shows the hole that was cut to allow the brake to be mounted behind the brake pedal. Item 1 shows the additional hole that was need to be cut for the cable to be run from the motor to the brake pedal.

Once the position of the motor shaft was selected, created the motor was dry fitted in place. One team member held the motor in place while another team member marked the positions of the mounting holes. Due to the time crunch, proper measurements to locate the mounting holes for the motor were not taken. Additionally, because of the location of the holes it was difficult to place the drill inline. One of the holes was in the correct location, but the other was slightly off and needed to be widened. Only having two mounting points left the motor slightly wobbly when the bolts were fully tightened. To remedy this instability, a piece of sheet metal was added between the motor and the frame of the golf cart to allow a third mounting bolt to be used. Due to the thickness of the metal sheets available, two plates were stacked for maximum stability. The sheets of metal stuck out into the front of the cart more than expected and later became a problem during testing. The result can be seen in Figure 54.

The next step was to hook up the cable from the brake motor shaft and the brake pedal. The team got 6 feet of steel cable and crimps to secure it on each end. The cable was crimped in place because there was excess cable and it could be replaced if it needed to be modified. The brake shaft already had a hole drilled through it from the previous system design. The cable was threaded through the hole in the motor shaft and crimped back on itself so that it was secure.

The other end of the cable was then threaded through the hole in the flooring and around the brake pedal (Figure 55, Item 1). It was secured with a crimp and eye loop to prevent the motion of the brake pedal from wearing through the cable over time (Figure 55, Item 2). The

length of cable between the brake pedal and the motor shaft does not have to be exact because any excess would be would up on the brake motor shaft.

Figure 54: Shows the brake cable (Item 1) wrapping around the shaft of the brake motor. Item 2 is the crimp on the end of the cable keeping it secure.

The first circuit that the team designed used voltage to control the Sabertooth and by extension the motor. One of the input modes of the Sabertooth takes in a voltage value of 0-5 volts. 0V would be full reverse, 2.5V would be stop, and 5V would be full forward. To achieve this input a MCP4131 digital potentiometer was used as a voltage divider.

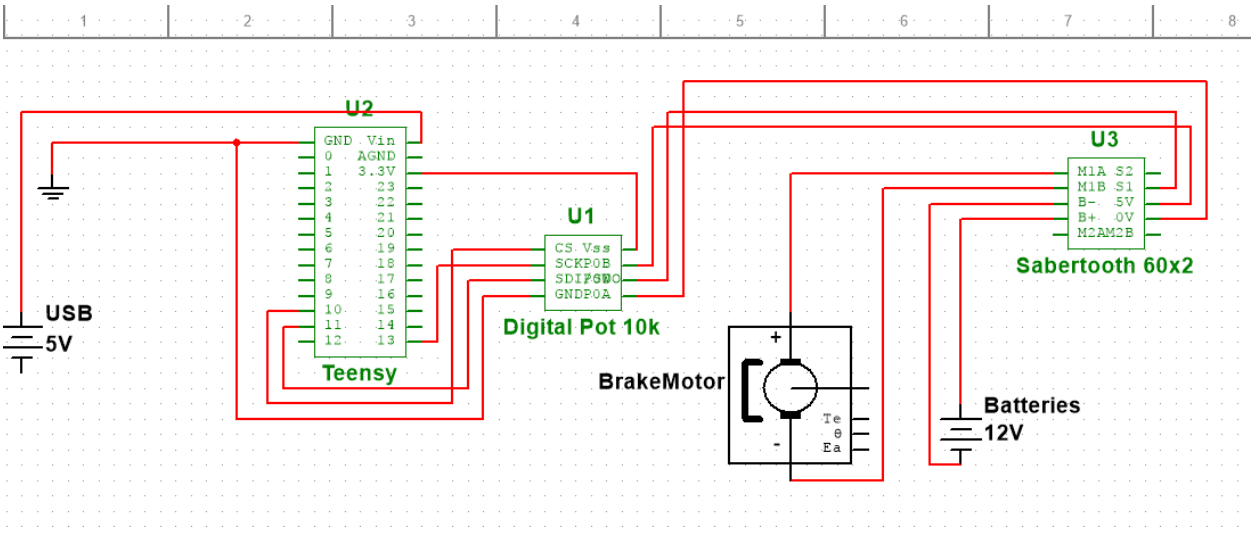


Figure 55: This figure shows the circuit diagram for the first method of control of the Sabertooth. The 10k digital potentiometer is control through SPI from the Teensy. The Sabertooth then reads the digital pot output and powers the motor.

As seen in Figure 55, the MCP4131 is controlled by the Teensy using the SPI library and sending control bits ranging from 0 to 255. These control bits change the resistance of the potentiometer from roughly 300Ω to 10kΩ. The MCP4131 has three output pins, a high, a low, and the wiper. By hooking up the high to 5V, the low to ground, and reading from the wiper a variable voltage divider is created. The Sabertooth supplies the 5V and ground reference for the MCP4131, reads back the wiper voltage, and uses that to control the brake motor. In addition to taking in the wiper value, the Sabertooth is hooked up to a 12V DC supply and the motor itself.

After testing, this first method did not work. The second attempted method of controlling the Sabertooth used pulse width modulation (PWM) control. The Teensy can directly output PWM signals to the Sabertooth. In this mode, the Sabertooth control pin is directly wired to the

output pin on the Teensy. This method allowed for much finer and more reliable control of the brake motor.

After the first round of testing, the team added end stops to the brake pedal (Figure 56). These were placed at the extremes of motion of the brake pedal to tell the cart if the brakes are on or off.

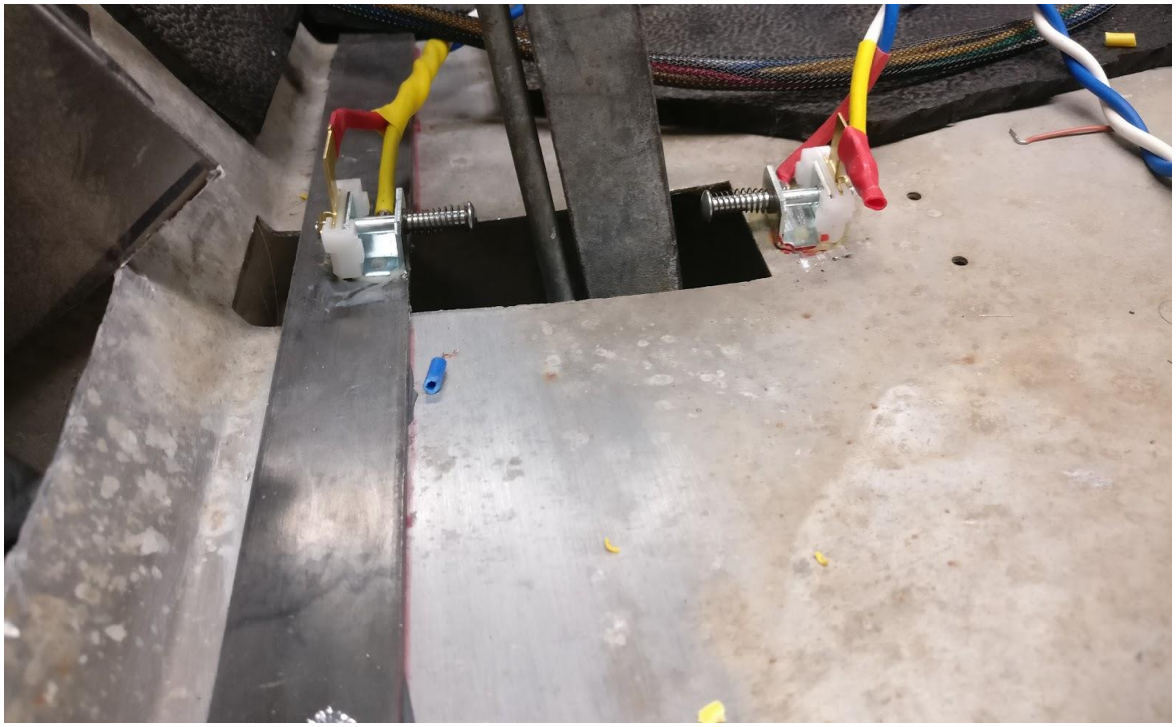


Figure 56: This image shows the location and mounting of the endstops. These are active low endstops originally intended for car emergency brake detection.

Since, the limit switches sense the movement of the brake pedal and not the activation of the brake motor, the end system will still trigger if the operator manually engages the brakes. One of the endstop was directly epoxied to the flooring of the cart such that it is pressed when

the brake is in the off position. When this endstop is released, the system knows that the brake is engaged. The other endstop is epoxied onto a spare strip of metal across the hole in the flooring for the brake pedal shaft. The purpose of this endstop is to detect when the brake pedal is fully engaged in order to prevent the brake motor from pulling the brake pedal too far. There are two different ways to modify this system for finer control. One is that shims can be added to the ends of the endstops so that they activate quicker. Additionally, the actual brakes themselves can be adjusted by tightening the clamps within the wheel wells or the cable that runs from the brake pedal axle to the brakes themselves.

5.4 Braking Testing

The braking system required several stages of testing. The stages alternated between having the cart up on jack stands and driving it through the hall. The brake motor was hooked up to the Sabertooth motor controller, which was connected to the 12V system and a Teensy 3.5. The first attempt to use the Sabertooth was with the MCP4131 voltage divider. This method did not work because the digital potentiometer did not operate correctly when driven by the Sabertooth. The proper functioning of both the Sabertooth and digital potentiometer were verified by testing each component individually using a bench power supply. When the digital potentiometer was driven from the 5V pin on the Sabertooth, it ceases to work properly. The team believes that there was some problem using the Sabertooth's own 5V and reference ground for the voltage divider. This was done because of the Teensy operating on 3.3 volts instead of 5 volts. The Teensy's 3.3V output prevented it from controlling the Sabertooth directly with voltage. As a work around, the team found that the Sabertooth could accept PWM control signals

directly. This method proved effective and remained the main method of Sabertooth control currently used.

The initial braking program was contained very basic logic. A counter ranged from 0 to 180 to describe the speed and direction of movement. During testing it was discovered that the off signal for the Sabertooth was not the expect 90 but instead 91.This method proved effective for testing but was not viable to use moving forward as it could not be easily controlled via the CAN bus.

To help create a CAN friendly code, a function was created to set the motor at a set value to wind in the cable for a set amount of time. This function is called brake on and is quite simple.

```
void brakeOn() {
       myservo.write(135); // turns on one direction
       delay(1000);
       myservo.write(91); //stop motor
}
```

This function tells to motor to turn on at a specific speed and wind up the cable for 1 second then turn off. The motor is treated as servo because there are predefined libraries for sending out PWM signals to a servo. Additionally, a reciprocal function was created to turn off the motor.

```
void brakeOff() {
     myservo.write(46); //turn the other direction
     delay(750);
     myservo.write(91); //stop
}
```

This function tells the motor to unwind at a set speed for 750 microseconds and then turn off. The BrakeOff function is activated for less time because there is no load on the motor unlike when it is activating the brakes. These times were what we estimated to be equal amounts of winding and unwinding of the brake cable. However, it was not perfect and cable would slowly become more wound after each cycle of BrakeOn and BrakeOff. This would be fixed later by the endstops, but at this point, it was good enough to test with the cart on the ground.

It was assumed that there would be no addition load with cart on the ground because the weight of the cart on the wheels should not affect how much force is needed to apply the brakes. Because of the drifting of the BrakeOn and BrakeOff function for full cart testing, it was decided to add granular control of the brake motor to the code. This created the ability to manual increment the value of the servo so that we could set the start position of the brake to start the test. The cart was brought out of the lab and down into the largest hallway in the building for testing. The team proceeded to drive the cart up and down the hall for two days testing, modifying, and retesting everything. During these full cart tests, the BrakeOn and BrakeOff functions worked perfectly after some slight timing changes.

When endstops were added to the braking system, the code had to be modified to consider the limit switches. The general logic of brake on and off remained the same; the only addition was checking if the limit switches were pressed. This was done by making the braking independent from time, instead having the braking motor stopped if a limit switch was pressed. The logic of this is very similar to the second iteration of the steering software.

When debugging the version of the code with the limit switches there was one major issue. The limit switches were not working as expected, instead of changing states they remained single state. This was not the expected result, and had to be tested to see what the problem was. The limit switches were tested individually and were found to work properly, but when used together they did not. This lead to the conclusion that the two switches shared a ground. Using a multi-meter with the limit switches, this was confirmed. The solution was to use a single ground wire for the two switches instead of one for each switch.

5.5 Braking Summary

This year's team managed to salvage existing hardware and create a functioning design while spending minimal amounts of the budget. We took the existing motor and repositioned to get an eight times increase in torque compared to the previous implementation. The new implantation was augmented with endstops to detect what state the brake was in. Additionally, this design maintained the functionality of the brake pedal for manual use in an emergency. Using the states, we created a state machine that can cycle states for use with CAN bus commands and have the state overwritten in an emergency. This current design for braking should last for the rest of the golf carts life spans barring any unforeseen circumstances.

Chapter 6. Throttle

The throttle system on the cart was functional yet isolated. The team initially left it alone to work on other, less initially functional, systems. However, the burnout of the motor controller forced it to be reevaluated and eventually reconstructed.

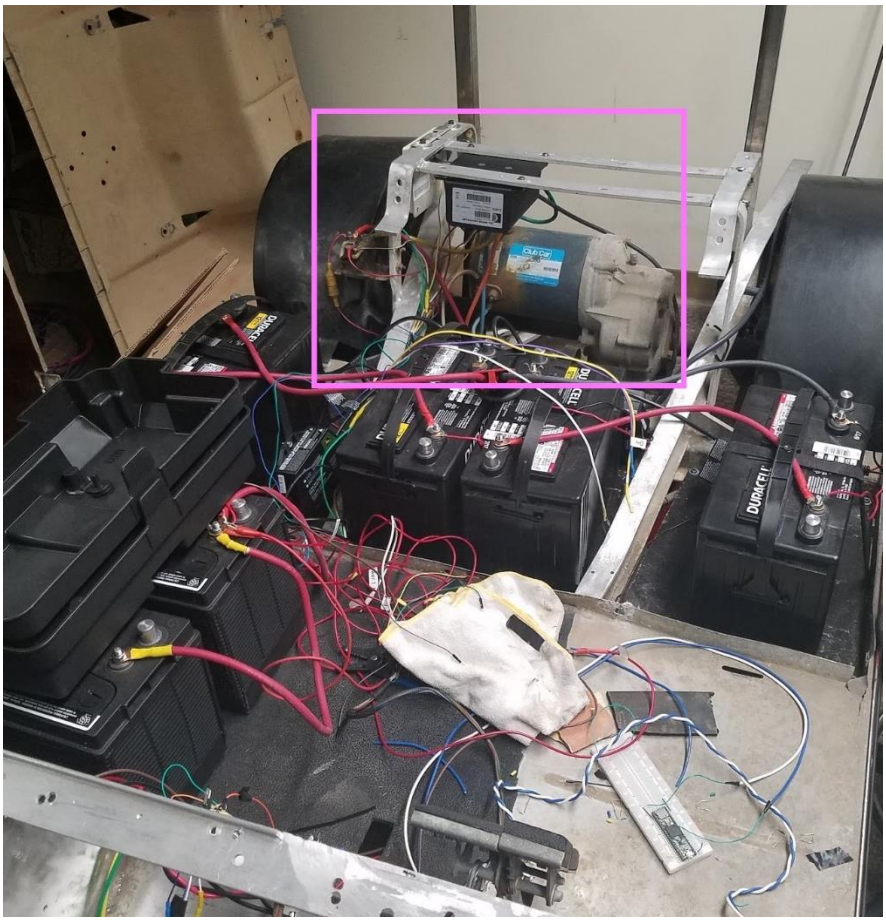


Figure 57: Location of throttle system on the cart

6.1 Throttle Circuit Design

The throttle system on the cart is composed of five components: a digital potentiometer, motor controller, drive motor, solenoid, and forward/reverse switch. Each piece needs to be working in order for the cart to drive. In the original system designed by the 2016-17 team, the digital potentiometer was used as the input for the motor controller and was, itself, controlled by an Arduino that was intended to be connected to the CAN bus. The motor controller that was on the cart when received was a Curtis 1204-410 with the A2 pin missing. The drive motor is a Club Car 48V electric motor, which was original from when the cart was first acquired for the MQP. The solenoid works in concert with the original onboard computer to act as a breakpoint for most of the kill switches. The two direct kill switches are the key switch on the dashboard of the car and the wireless kill switch receiver near the batteries. The third kill switch is an Anderson power connector located under the seat of the cart that allows the 48v battery array to be disconnected from the rest of the cart without any disassembly or disconnection of wires. The forward/reverse switch is a physical switch in line with the main power cable and is used to change the polarity of the DC motor inputs. The full wiring for the throttle system is described in Figure 58.

The bulk of the wiring work for the project involved wiring to or from the motor controller directly. The motor controller has four main power fins, four control fins and a 4-pin connector as seen in Figure 59.

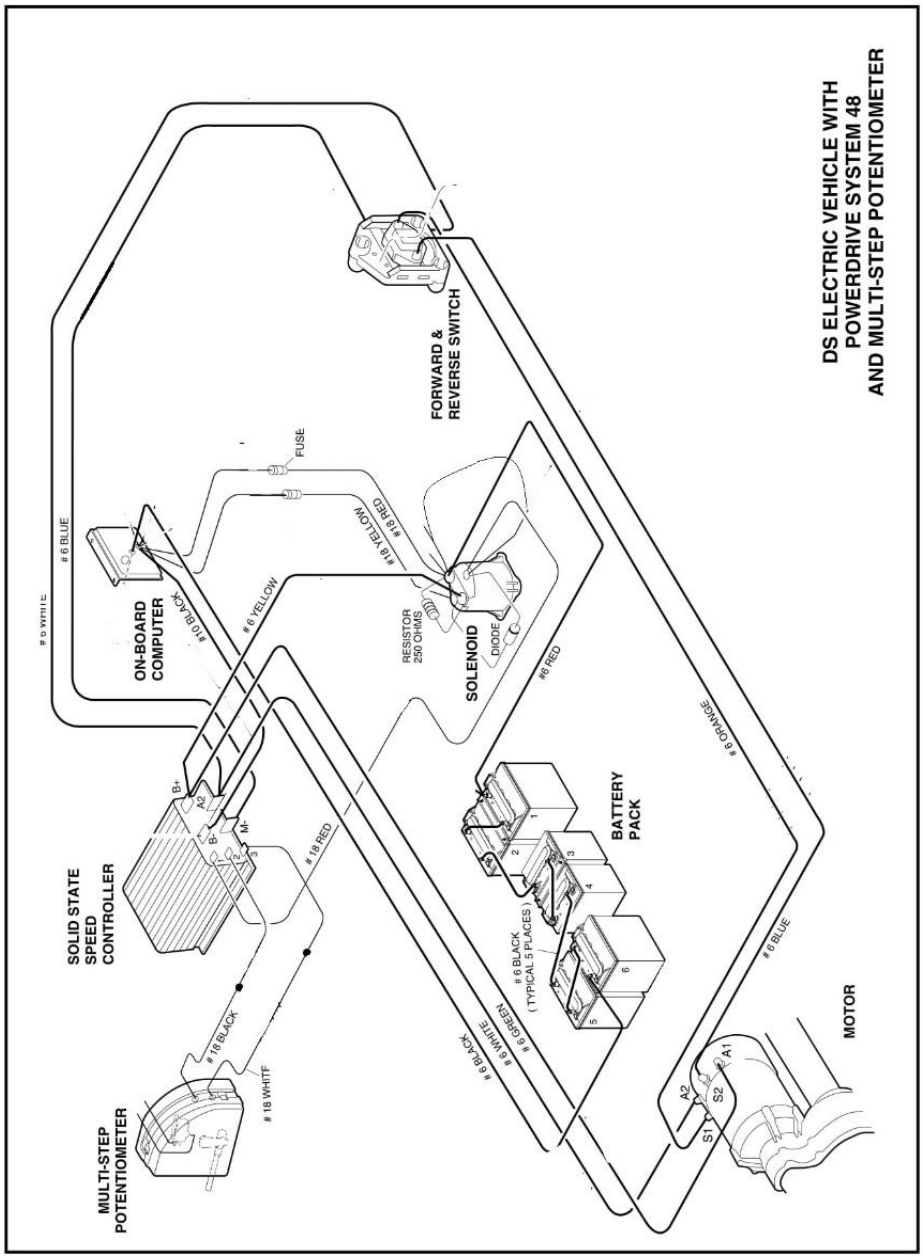


Figure 58: Wiring diagram of throttle system and wire colors [19]

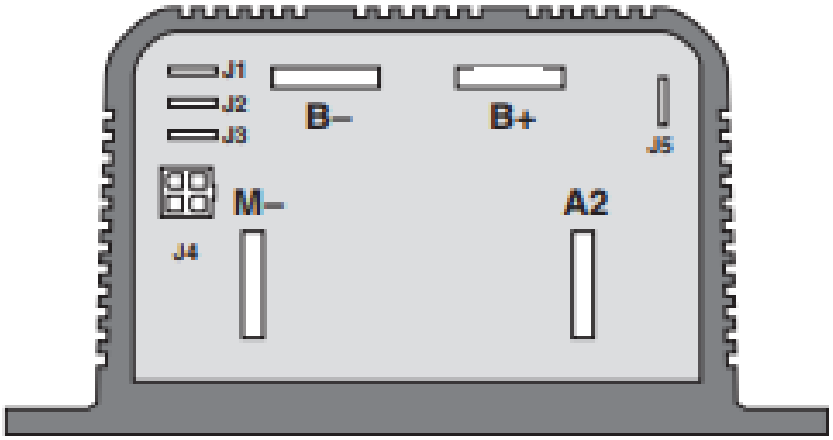


Figure 59: Pin layout on motor controller face [31] The following Tables, 8 and 9 elaborate on the different pinouts

The main power fins are significantly thicker and require cables to be bolted to them. The control fins are smaller and have header cables to attach to them.

Table 8: Power fin descriptions [31]

B+	Battery+ and motor armature. (plug diode -)
B-	B-.
A2	Motor armature and field (plug diode +).
M-	Motor field (controller output).

Table 9: Control fin descriptions [31]

J1	Keyswitch.
J2	Wire 1 of 2-wire throttle; Pot High of 3-wire or ITS throttle.
J3	Wire 2 of 2-wire throttle; Pot Wiper of 3-wire throttle; Pot Low of ITS thottle; or electronic throttle input.
J4	4-pin connector
J5	Reverse signal output / main contactor coil driver.

The 4-pin connector is a new feature of the 1204M controller and is primarily used for interfacing with the programmer (Figure 60). It can, however, be used with an external status LED for diagnostic purposes.

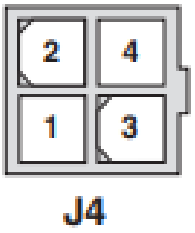


Figure 60: Diagnostic pin cluster diagram for use with programmer or external LED. Table 10 elaborates on the different pinouts. [31]

Table 10: Diagnostic pin cluster descriptions [31]

PIN	PROGRAMMER	STATUS LED
J4-1	Data input from programmer (Rx).	Status LED enable.
J4-2	Ground.	Ground.
J4-3	Data output to programmer (Tx).	Status LED output.
J4-4	+15 V.	+15 V.

The motor controller is mounted on the underside of the engine housing causing all the pins to appear reversed relative to the wiring diagram as seen in Figure 61.

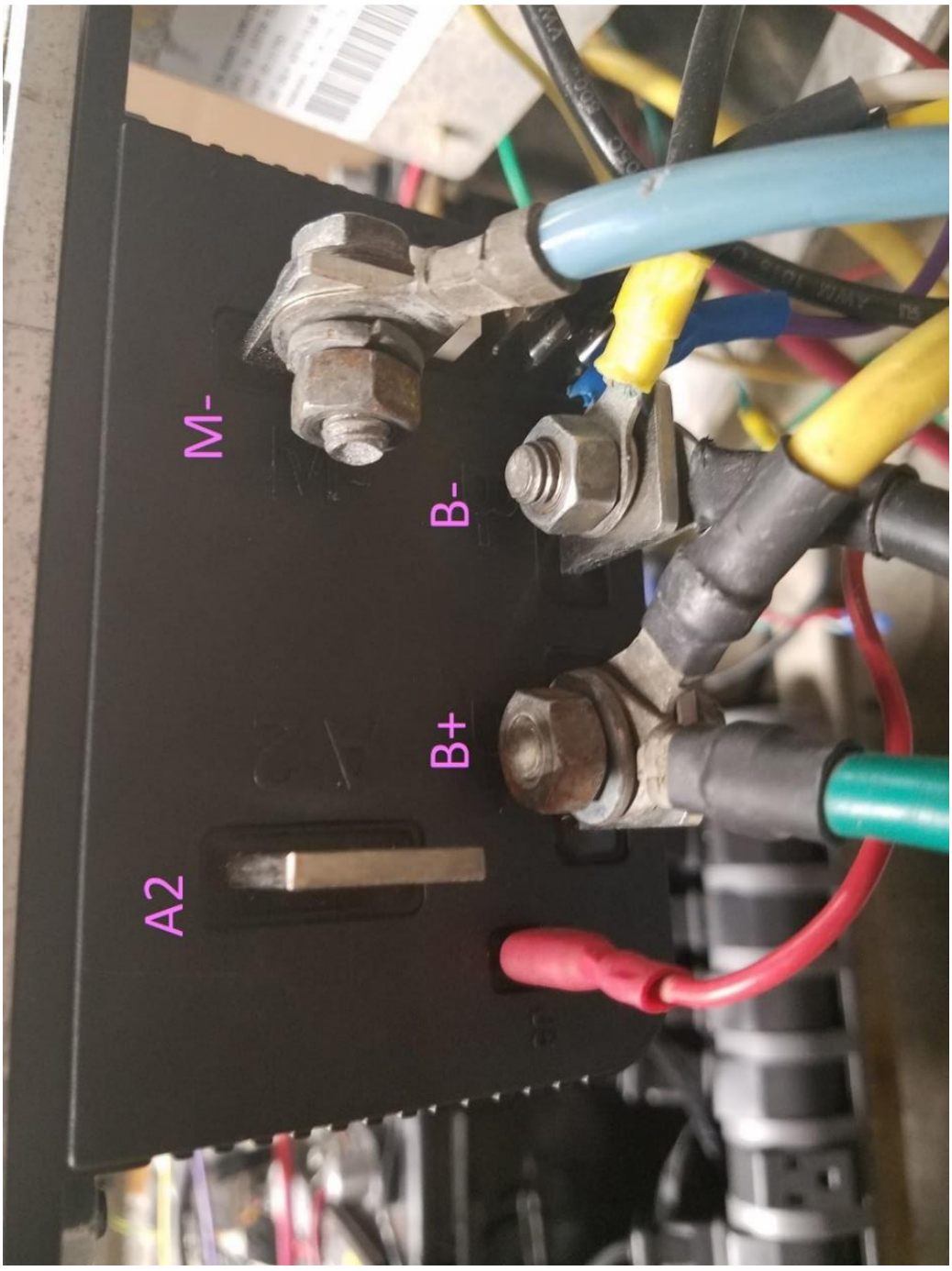


Figure 61: Motor controller face close-up with main pins labeled

6.2 Throttle Implementation

The code for the system was found on the server (which is actually a UNIX computer). The comments were sufficient to make the code understandable. However, no wiring diagram existed to explain how the digital potentiometer and motor controller were configured together. Multiple pinouts had to be referenced via their data sheets to identify them and understand the circuit.

The throttle code found on the server was in much better condition than most of the other code for the cart. The comments were sufficient to make the code readable; however, no wiring diagram existed to explain how the digital potentiometer and motor controller were configured together. Multiple pinouts had to be referenced via their data sheets to identify them and understand the circuit.

In order to integrate the throttle system with the CAN bus control network, the Arduino needed to be replaced with one of the team's CAN interface board that contains a Teensy 3.5. This required changing references to Arduino pins into references to the correct teensy pins, which took the bulk of the necessary work time. At the same time, the team decided to integrate the braking code onto the same Teensy. This hardware level unification allowed the team to prevent the throttle and brakes from engaging at the same time without having to worry about signal delay from the CAN bus.

After reviewing all the disparate elements of the throttle system, the team was successfully able to engage and control the throttle. They then begin to test the capabilities of the system through a range of speeds. The cart appeared to perform well on the tests until the digital

potentiometer suddenly burned out. It was determined that the throttle system had originally been designed for an analog potentiometer tied to a physical pedal. The key difference between analog and digital potentiometers is that, though digital potentiometers can be remotely controlled, they have a much lower maximum current threshold. The resistance of the potentiometer was continually lowered to increase the speed the cart was tested at causing higher currents through the potentiometer until it burned out. This was replaced by a higher rated potentiometer and no further high-speed tests were performed. The code was also altered to include speed limiters at a software level to prevent this from happening during future testing.

6.3 New Motor Controller

The throttle system remained functional during system level testing but the motor controller broke down just before the team's demonstration for spark party. There appeared to have been a loose connection to the motor controller that caused an intermittent disconnection and current spikes into the controller. This caused the motor controller to fry internally and rendered it unrepairable.

The team reached out to Curtis, the motor controller manufacturer, about the possibility of them sponsoring the team for a new motor controller. Curtis agreed on the condition that they first receive confirmation of the team's affiliation with WPI in the form of a full letter of request on school letterhead. They also asked that this letter contain an explanation of what had led to the problems and what was being requested from Curtis. A letter meeting these conditions was quickly drafted and signed by both Professor Wyglinski as the team's advisor as well as by

Professor McNeill as the head of the department. A scan of this document plus both professors business cards with contact information were sent back to the point of contact at Curtis.

A week later, a second point of contact from Curtis reached out to the team and offered to sponsor the team for the same model of motor controller that burned out the 1204. The only catch was that they were made to order from a factory in Bulgaria and would take 10-11 weeks to assemble and ship. Another series of emails were exchanged where the team asked if Curtis could send them one of their newer models of the same controller and upgrade rather than just replacing the old design that was over 20 years old. The Curtis representative said that he was happy to provide a newer motor controller but that the newer models were also made to order and would take an even longer 13-14 weeks of lead-time. Additionally, a separate programmer kit was also needed to run diagnostics or to use some of the new settings available in the upgraded controller. This had a similarly long lead-time but Curtis was generous enough to donate both the motor controller and programmer kit in exchange for officially sponsoring the project. The team agreed to this but also wanted to begin work on the cart as soon as possible.

A second motor controller of the same model was purchased from Buggies Unlimited with the intention of using it until the Curtis controller arrived. However, the Buggies Unlimited was delayed in shipping around the Christmas season and was unable to be processed through the ECE department during winter break meaning that it was received only two weeks before the Curtis controller arrived. The team determined that a burnout of the new controller was unlikely and so, rather than keep one controller as a spare, decided to return the Buggies Unlimited controller for a refund.

The new motor controller was mounted in the same location as the previous controller as seen in figure 55. One of the features of the new motor controller is that there are now nine different accepted types of input. Unfortunately, changing between input types requires the programmer, which was further delayed in its arrival so input mode 0, was used. In this mode, the controller tries to read a 0Ω to 5kΩ resistance between two of its input pins. It uses this to determine what percentage of total power to send to the motor. The behavior of infinite resistance when the terminals are disconnected has not yet been determined. This input method is similar to the previous motor controller with the only difference being the resistance range decreased from 10kΩ to 5kΩ allowing the adaptation of the replacement digital potentiometer with minor software changes to halve every output.

Another feature of the new motor controller is a functional A2 pin. This pin is exclusively used for resistive braking on the new motor controller. Resistive braking is a throttle based braking system that automatically engages whenever the throttle is not actively driving the motor by putting a load across the motor causing it to both slow down and regenerate a small amount of power.

Chapter 7. Power

When the 2017-18 MQP team received the golf cart at the beginning of A-term, they were told that power had been taken care of by the previous year's team. There is a +48V system that powers the throttle (Figure 62). The +12V system powers the peripherals, which for the current 2017-18 setup is composed of CAN interface boards and a Sabertooth. The +12V system can be viewed in Figure

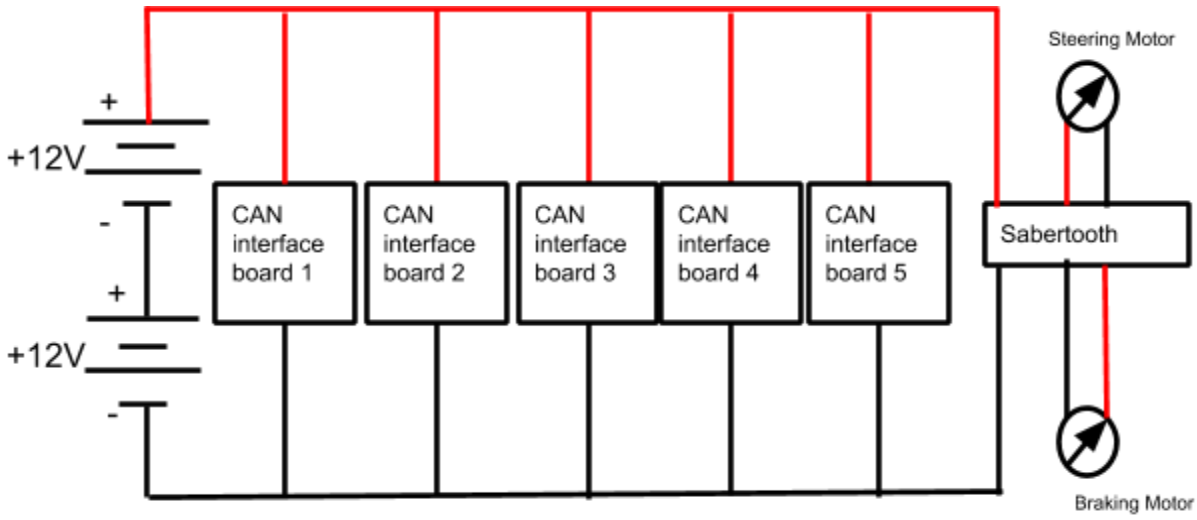


Figure 62:Depicts the +12V power system of the Goat Cart.

The 2016-17 report stated that there were automatic chargers on the batteries. This led the team to assume that leaving these plugged in to a wall outlet, as this is generally an acceptable way of maintaining batteries. In the middle of B-term, it was discovered that the cart would no longer drive.

When trying to diagnose the issue the team found the voltage across the +48 volt battery bank was +0 volts. The individual battery voltages were checked to see if the issue was loose connections. Of the four batteries in the bank, only one had a reasonable voltage for a +12V battery. The other three, had voltages ranging from a negative voltage to approximately four volts. This led the team to believe that the batteries might have shorted internally due rough handling.

The team researched rugged, agricultural batteries from John Deere. These batteries, sold under the name StrongBox, feature plates that are potted in epoxy at the bottom and include spacers to prevent shorting even in tough conditions. [32] It was believed that this was the best solution to prevent this issue from occurring again.

Then to confirm that the batteries were incorrectly chosen and that it was not a different issue, a professor that was knowledgeable about batteries was consulted. It was discovered that WPI does not have a professor that specializes in battery technology. After asking whom would know the most, they determined that Professor O'Rourke might be able to help. Professor O'Rourke made his own assessment of the batteries. He decided to open the battery cells to determine the water level in each of them. It was discovered that the three batteries with unexpected voltages were low on water. The remaining working batteries were also low on water. In fact, when the cells were opened the water that was left inside them could be seen boiling. Professor O'Rourke advised the team that the three batteries that were not showing normal voltages were not going to be recoverable. He also stated that the other three batteries

would be fine as long as the water was refilled with distilled water. The cause for the boiling off the water was the charger.

Once this was discovered, the team investigated the capabilities of the charger that was attached. The charger, the NOCO genius GEN4 (Figure 63), claimed to be able to maintain a battery after charging it. [33] In reality, it appeared that this claim was meant more as an automatic shut off after the battery was charged and not that it was suitable for long-term battery maintenance. This meant that the batteries went through numerous, and unnecessary 10A charge cycles, when the batteries were only slightly drained, leading to the water to be boiled out of the cells. It was discovered that the three remaining batteries that showed an acceptable voltage were also low on water.

The replacement chargers were Automatic 1.5-Amp Battery Charger/Maintainer, is capable of float charging which is exactly what is needed in the application of the cart (Figure 64). One of the team members had experience with these battery chargers and knew these chargers would work perfectly in this application. Five Automatic 1.5-Amp Battery Chargers were purchased, one for each of the batteries in the forty-eight volt system and one for the two batteries in parallel for twelve-volt system. [34]

Figure 63: NOCO genius GEN4 battery charger that was used on the Goat Cart and was replaced by the 2017-18 team. It had automatic shut-off, but it is not a float charger. [33]

Figure 64: New float battery charger that was installed. There is one for each battery of the 48V system and another for the 12V system.

Three, Duracell 27DC batteries were purchased from SAMS Club to replace the dead ones. The new battery can be seen in Figure 65, and one of the old batteries can be seen in Figure 66.

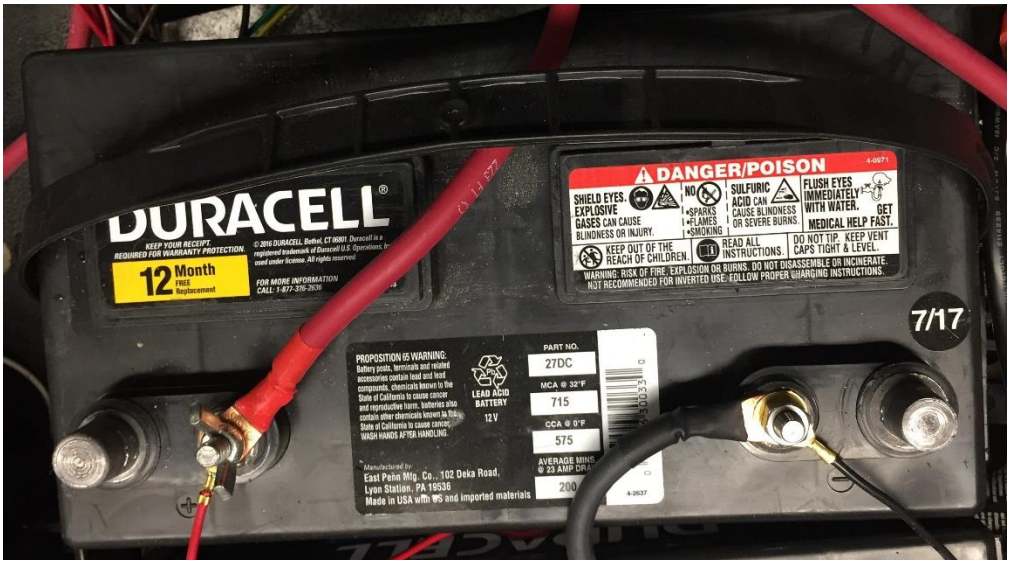


Figure 65: New 12V battery from the 48V system.

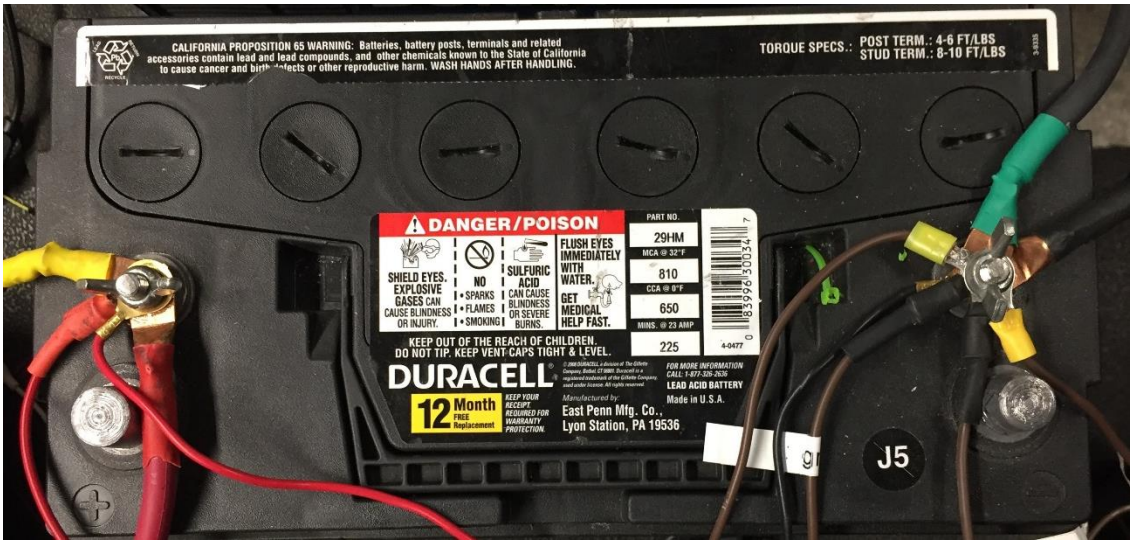


Figure 66: Older battery from the12V system. It is near identical to the newer ones except for the battery cell covers.

7.1 Power Summary

The power system was repaired by the 2017-18 team. Three of the batteries of the +48V system died and new ones were bought. The cause of death of the batteries was found to be from being continually charged with the NOCO genius GEN4 battery charger. The battery charger was replaced with a float battery charger, the Automatic 1.5-Amp Battery Charger/Maintainer. This new charger can be continually plugged into and outlet and left in the power system. The only maintenance that needs to be done is that the water level in each of the cells should be checked and topped off twice a year.

Chapter 8. Sensors

A sensor is a device that detects events or changes in its environment and sends the information to other electronics to be processed [35]. Changes in physical properties (i.e. temperature, speed, light, pressure, etc.) can be detected and converted into electrical signals. These signals can then be processed by other electronics in order to provide a response or report a measurement. Control system-based applications often utilize sensors. A control system typically comprises of a computer or microprocessor and a control program that handles data from sensors and sends signals to output devices [36]. Computers or microprocessors are used for their processing speed, consistency, adaptability and stamina. Along with a properly configured control program, a control system can process data and make appropriate decisions faster and more efficiently than a human ever could. Today's applications of sensors in control systems include manufacturing and machinery, airplanes and aerospace, automobiles, medicine, robotics and many other aspects of day-to-day life. In an autonomous vehicle, like the WPI Goat Cart, sensors are a necessity for making real-time decisions.

8.1 Assessment

After the initial assessment of the pre-existing project, the 2017-2018 WPI Goat Cart Team elected to allocate time and resources to areas of greatest interest/concern, one being sensors. It was quickly determined that the project's previous teams had not seen sensor implementation as an immediate priority. The only integrated sensor was an infrared sensor used to operate a wireless kill switch. Matthew Mahan was delegated to head up the 2017-2018

sensors team and received assistance from other team members when need be. To begin, it was agreed upon by the team that incorporating a way to measure speed and distance traveled was the top priority.

8.2 Odometer/Speedometer

To begin the process of engineering a solution to measure speed and distance traveled, research on prior technologies was conducted. The modern-day vehicle measures speed and distance traveled with the use of a computerized speedometer/odometer [37]. A computerized speedometer/odometer is generally comprised of a magnet, a pickup and a computer with a specialized program (Figure 67) [38].

The magnet is attached to the rotating drive shaft and a pickup is attached to a stationary point in close proximity of the magnet. Once per revolution of the wheel, the magnet passes by the pickup, generating a brief pulse of electric current and a corresponding voltage. The computer records these voltage spikes, or pulses, and uses the specialized program to calculate the instantaneous speed and distance traveled [38]. Being the most common, effective and reasonable method, the team approved and proceeded with this generalized design.

To begin the project, it was agreed upon by the entire team that the Teensy 3.5 microcontroller unit would serve as the cart's universal programmable device for consistency purposes. Furthermore, the Teensy 3.5 microcontroller unit met all the requirements for the task. For these reasons, the Teensy 3.5 microcontroller unit was chosen as the computer component to the speedometer/odometer system.

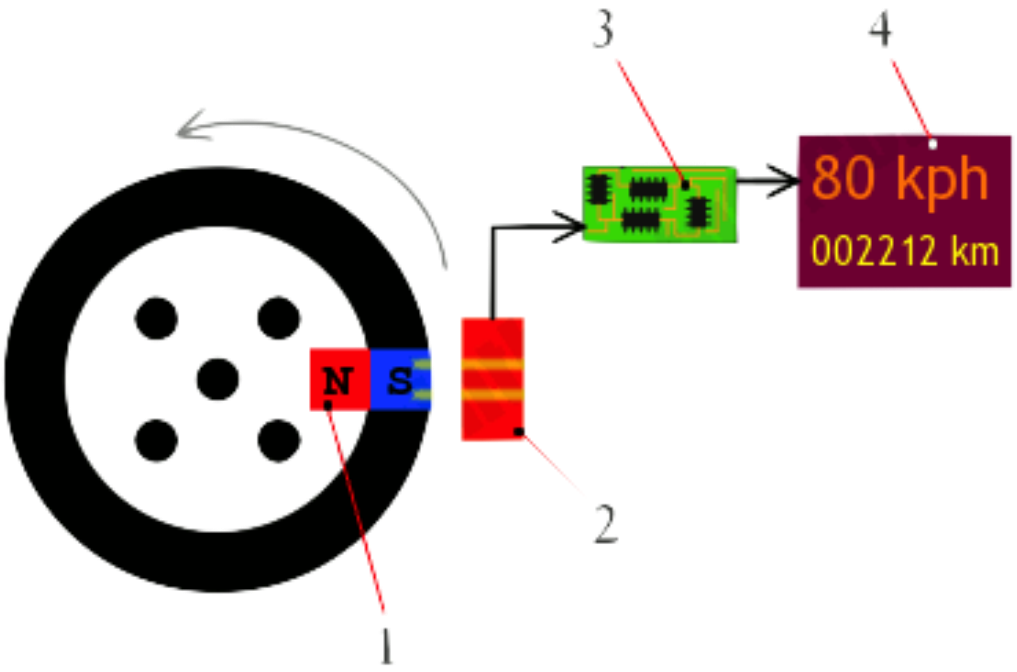


Figure 67: How an electronic speedometer works: 1) A magnet connected to one of the wheels (or more likely to a driveshaft attached to one of the wheels) rotates at high speed. 2) Every time it makes one complete revolution, it passes a Hall-effect (or other magnetic) sensor and the field from the magnet triggers the sensor. 3) A circuit amplifies the signals from the sensor and translates them into your instantaneous speed and distance traveled. 4) A digital display on the dashboard acts as both a speedometer and odometer, displaying the speed and distance side by side.

The pickup component was required to be compact, durable and be able to interface with a computer. Based off the generalized model, the pickup component would ideally be a magnetic sensor such as reed switch or Hall-effect sensor [38]. Examples of both a reed switch and a Hall-effect sensor were ultimately purchased in order to conduct testing and gain understanding of their operation. The test for the components was designed to be able to control magnet proximity and compare the component's effectiveness as a switch. For this test, a circuit with a single LED, power supply and resistor was constructed (Figure 68). Each sensor was then inserted into the

circuit as a switch. A magnet was then brought into close proximity of the switch. When in close enough proximity, the switch would close, and the LED would light up.

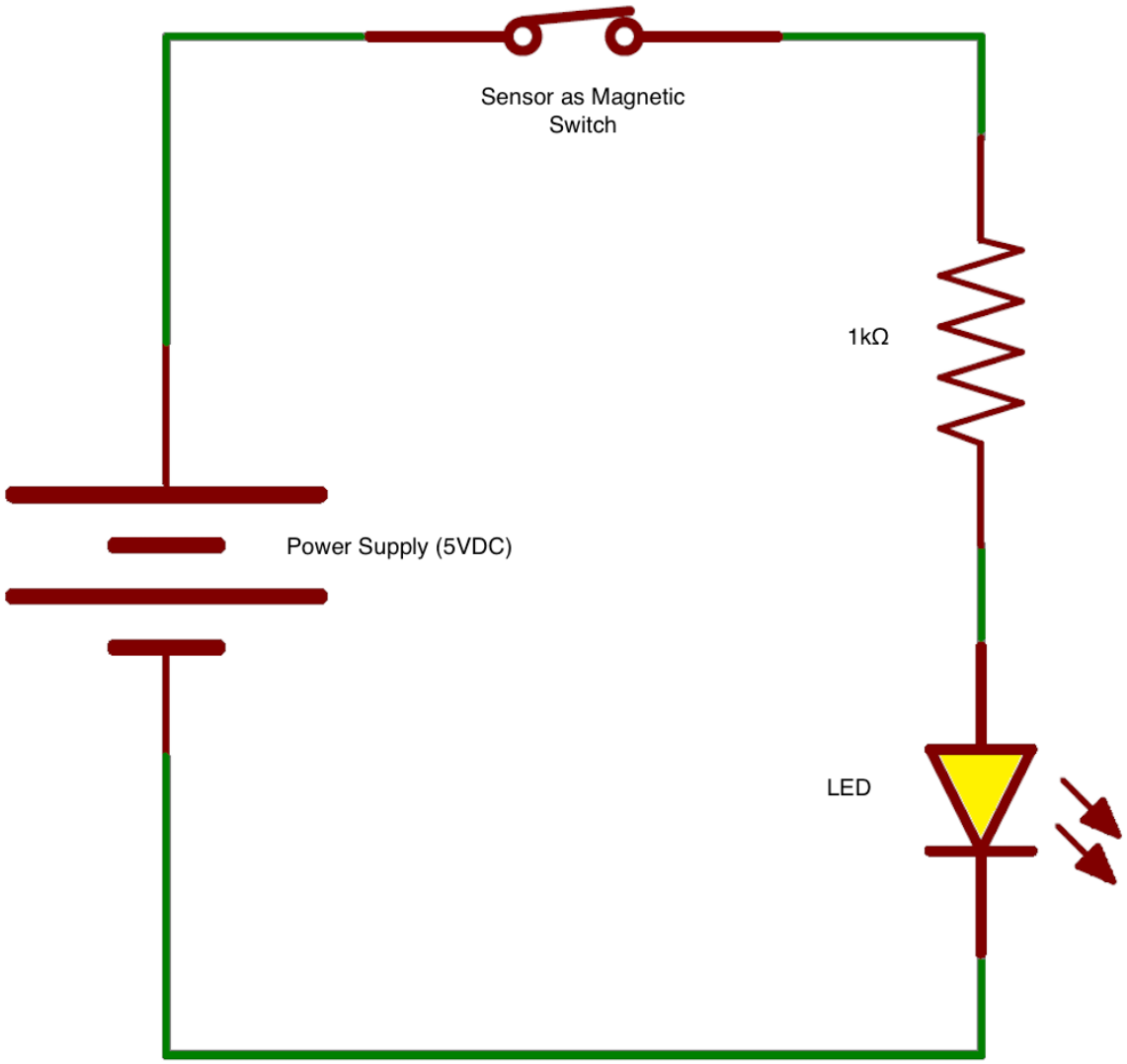


Figure 68: The diagram of the test circuit with an LED, resistor, and a magnetic switch. When the switch is closed, current flows and the LED can illuminate. Otherwise no current flows, and the LED receives no power. This circuit was used to determine the advantages and disadvantages of each magnetic circuit element in regards to the speedometer/odometer application [39].

This test type of test provided a best estimate as to what type of range and accuracy each sensor had. After testing was completed, it was determined that the most appropriate solution was a single-pole-single-throw, normally open, plastic-coated reed switch with wire leads as seen in Figure 69 [40].

Figure 69: The reed switch used as the pickup component of the speedometer/odometer system. This product by Littelfuse is a single-pole-single-throw, normally-open, plastic-coated reed switch with wire leads [6].

This choice was based upon the sensor's ability to detect a magnet effectively within the dimensions of the wheel well of the golf cart. The magnet component was required to be compact and be able to trigger the pickup within close proximity. An inexpensive, effective and convenient solution were the ½-inch neodymium rare-earth magnet discs from a local hardware store. Once approved by the team, each component was purchased.

Once purchased, the next step was to assemble the system and design a program to accurately measure speed and distance. To assemble the system, one of the sensor leads was attached to the ground terminal of the microcontroller unit and the other was attached to an analog input pin. The remainder of the circuit was completed within the program by configuring the analog pin with an internal pull-up resistor (Figure 70) [41].

In this configuration, the circuit has two states. The first state is when the switch is closed and in the presence of a magnet. In this closed state, the analog input pin is connected directly to ground and reads as low. The second state is when the switch is open and unaffected by a magnetic field. In this open state, the analog input pin is biased by the internal pull-up resistor and reads as high. The first program was designed around detecting the changes between these two states. In theory, the passing of a magnet by the pickup would result in a high state, followed by a low state, followed by a high state. This series of events corresponds to one revolution of the wheel, when a single magnet is being used. Using this information, both the speed and distance can be calculated when a single revolution is detected. The distance traveled during a single revolution of the wheel is simply the wheel's circumference, 20.995 centimeters. Upon each detected revolution, the total distance is incremented by the wheel's circumference. The speed is simply distance traveled divided by time. By keeping track of the time elapsed between revolutions using a specialized program, the instantaneous speed of the cart can be calculated. Using these principles, a program was developed to meet the needs of the task at hand.

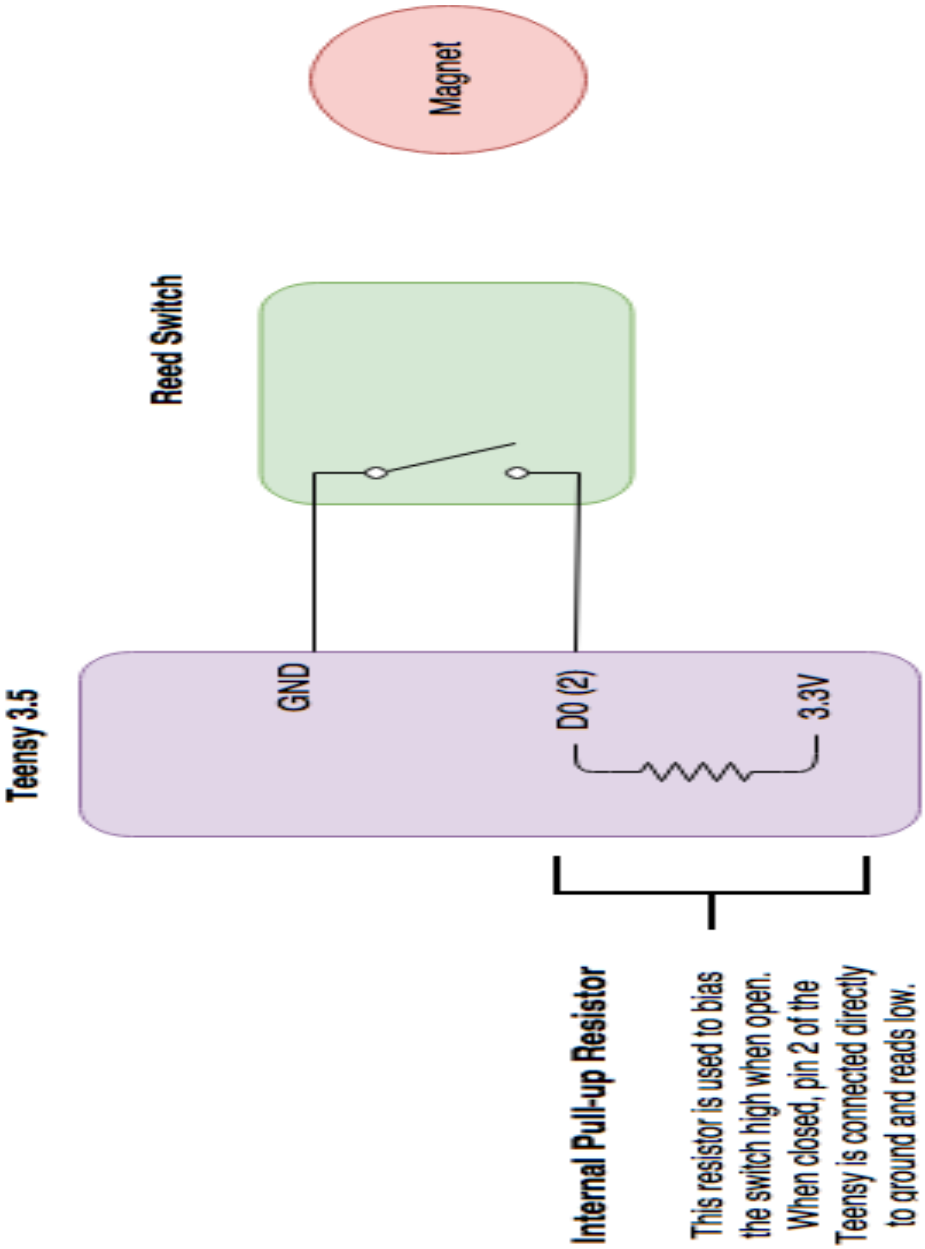


Figure 70: The circuit diagram of the speedometer/odometer system installed on the WPI Goat Cart. The system is comprised of the Teensy 3.5, reed switch and magnet. The circuit includes an internal pull-up resistor that is used to bias the switch high when open. When closed, the digital pin of the Teensy is connected directly to ground and reads low.

Upon assembly of the corresponding circuitry, a series of program modifications were designed, tested, troubleshot and improved until the final program version met all accuracy requirements and suffered zero errors. The final result is a program that will measure speeds up to approximately 30 mph, measure distance in intervals of approximately 13 inches, and transmit values of speed and distance to the cart's main server using CAN communication. In order to achieve this level of accuracy, four magnets were required to be used. The four magnets were positioned 90 degrees apart from one another along the circumference of the wheel of the cart. In this configuration, the passing of a magnet would signify one-fourth of a complete revolution of the cart's wheel. The final program is designed to first run the setup() function. The setup() function is used to initialize variables and configure the microcontroller pins, serial data transmission, CAN communication and interrupt timer. Upon configuration, an interrupt is attached to the timer with a period of one millisecond. The interrupt service routine, or readSensor() function, is called every interrupt. The readSensor() function is used to detect a valid pass of a magnet by the sensor as well as execute an algorithm for calculating the instantaneous speed and total distance traveled by the cart. In order for an input from the sensor to be valid, the signal must transition from high-to-low, remain low after a 2-millisecond period, transition from low-to-high and remain high after another 2-millisecond period. This is successfully achieved through a series of conditional statements that keep track of a set of five variables that determine the current state of system (Figure 71).

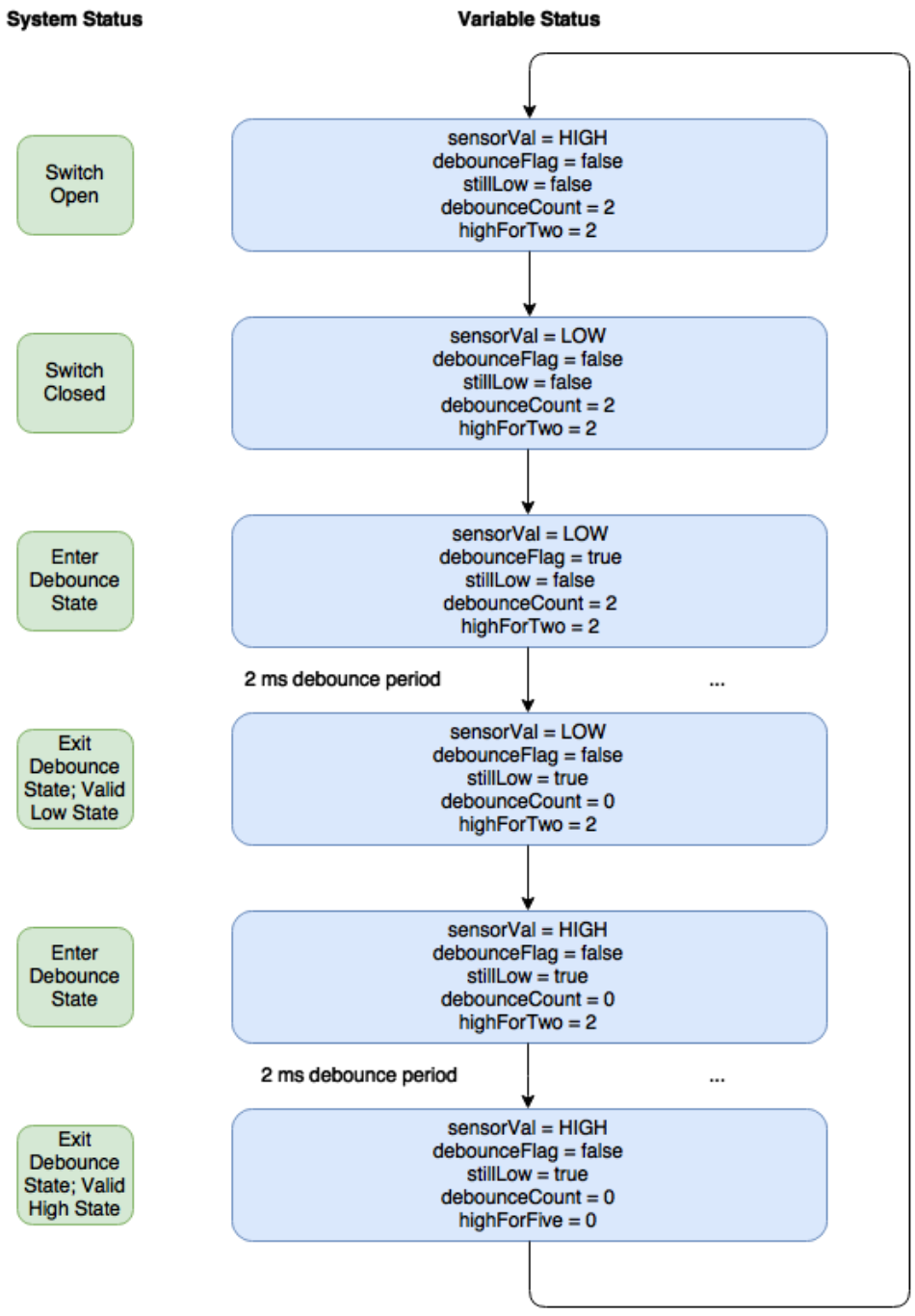


Figure 71: A flow chart documenting the changes in the status of the speedometer/odometer system and the corresponding status of the changes in the variables of the associated specialized program. The code that this flow chart represents can be found in the appendices of this paper.

The transition in states represent the passing of a magnetic presence causing the switch to close and open. The periods after the transition in states are put in place to allot enough time for the switch's operating and release times to pass. The operating and release times represent the amount of time it takes for the switch to open and close, respectively, including the state in which the signal tends to bounce. The switch using in this system is rated for an operating time and release time of 1 millisecond [40]. In allotting a buffer of 2 milliseconds for these times to pass, it is ensured that the switch position indeed changed and is not the result of a noisy signal. This method of solution is known as debouncing and is depicted in Figure 72.

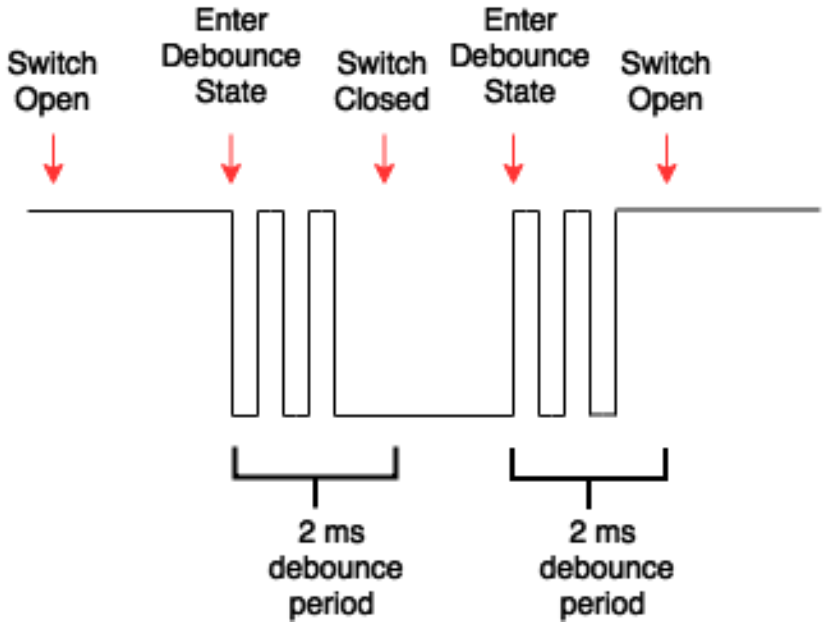


Figure 72: The signal visualization of the passing of a single magnet by the pickup of the speedometer/odometer system. When the magnet passes, the microcontroller unit sees changes in state from high to low and back to high again at one of its digital input pins. During these changes in state, a phenomena known as bouncing occurs where noise becomes present in the signal. This signal visualization also represents the strategy of how to deal with this phenomena known as debouncing.

Once a valid input is confirmed, the instantaneous speed and total distance traveled are calculated and stored in variables. The total distance traveled is calculated by multiplying the circumference of the cart's wheel by the number of revolutions by a conversion factor (to convert to feet). The number of revolutions is incremented by 0.25 with every valid input from the sensor.

```
revolutions += 0.25;
feet = circumference*revolutions*toFeet;
```

The instantaneous speed is calculated by dividing 0.25 of the circumference of the cart's wheel by the time elapsed between valid inputs from the sensor. Additionally, this value is also multiplied by a conversion factor (to convert to miles per hour).

```
mph =
toMPH*((circumference*0.25)/float(revTimeDelta));
```

The time elapsed is kept track of in the readSensor() function and is also used to reset the speed to zero if there are no valid inputs for an interval of two seconds.

```
if (revTimeDelta > timeout){
  mph = 0;
}
else{
  revTimeDelta++;
}
```

After the setup() function is called, the loop() function is continuously run. The loop() function is used to format the speed and distance data to be transmitted over CAN. The formatting of the data is completed in three steps. First, the size of the buffer used store the data is determined. The buffer has a maximum length of eight, with each element in the array consisting of 8 bits, or 1 byte. That being said, under the current implementation the maximum distance value that can transmitted over CAN is 2047 feet.

```
if ((feetCopy < 2047)  && (feetCopy >= 256)){
    bussize = (feetCopy/256) + 1;
  }
  else if (feetCopy < 256) {
    bussize = 1;
  }
  else {
    bussize = 8;
  }
  dist_msg.len = bussize;
```

Second, the buffer is filled element by element, starting with index 0. When the first element is filled to its max value, that value is subtracted from the data attempted to be transmitted and the remainder is stored in the next element. This is continuously done until the speed/distance data is completely broken up and stored in the buffer.

```
int i = 0;
while (bussize){
  if (feetCopy < 256){
    dist_msg.buf[i] = (uint8_t) feetCopy;
  }
  else {
    dist_msg.buf[i] = 255;
    feetCopy -= 255;
    i++;
  }
bussize--;
}
```

Lastly, the message is sent to the CAN bus using a pre-existing library function. Using this program, the team was successfully able to transmit distance and speed values wirelessly over CAN with zero known errors.

The final steps in the process of engineering a solution were to install the speedometer/odometer system onto the cart and prepare future teams for successful operation. The magnets and sensor are currently being held into place by heavy duty Velcro. There are four magnets positioned 90 degrees apart from one another on the inside of the back-right tire's wheel well. The sensor is attached to the frame of the cart in close proximity of the magnets. The wire leads of the sensor have been extended for convenient placement of the microcontroller unit. Future teams should approach this system from two points of view: hardware and software. From

the hardware perspective, continue to ensure that the magnets, sensor and microcontroller are in place and in working order. Improvements could be made to how the components are secured onto the cart in order to increase durability and longevity. From the software perspective, the system should be further integrated with CAN. The current code only transmits distance, not speed. Additionally, the distance data is received over CAN, but no further actions are taken as a result by other systems. In other words, the system is standalone and makes no interaction with braking, throttle, etc. It should be known that the current code is adaptable to any change in the physical parameters of the cart such as change in tire radius.

8.3 Ultrasonics

The team's next priority regarding sensors was to incorporate a way to detect objects and measure their associated distance to the cart. To begin the process of engineering a solution, research on prior technologies was conducted. Similarly, to the odometer/speedometer, an object detection system is typically comprised of a sensor and a computer with a specialized program. The types of sensors used in object detection applications can be classified into three different groups: 1) proximity sensors, 2) motion detectors, and 3) image sensors [42]. Proximity sensors can be comprised using one of several sensor technologies including ultrasonic sensors, capacitive, photoelectric, inductive, or magnetic. Motion detectors are based on infrared light, ultrasound, or microwave/radar technology. Image sensors are typically digital cameras, camera modules and other imaging devices based on CMOS technology [42]. During the research process, the team refined the intended solution to be to detect the presence of any object in close proximity to the cart and signal the cart to stop, regardless of the object's position. With this goal

in mind, image sensors were ruled out due to their number of unnecessary features and associated cost. Consequently, proximity sensor and motion detector technologies were chosen to be the potential product pool for our intended solution.

The next step in the process of engineering a solution was to determine component requirements and choose the appropriate corresponding product. For consistency purposes, the Teensy 3.5 microcontroller unit was chosen to satisfy the computer component of this system. When choosing an appropriate proximity sensor the following factors were taken into consideration: accuracy, resolution, range, control interface, environmental condition, calibration and cost [42]. A potential option from the motion detector group of object detection sensors was an infrared sensor. An infrared sensor measures the infrared light that is transmitted in the environment to find objects via an infrared LED. Infrared sensors are inexpensive, can operate in real-time, use non-visible light for detection and can detect infrared light over a large area. For these reasons, this type of sensor is very popular in navigation for object avoidance and distance measuring applications. However, infrared sensors are very sensitive to infrared lights and sunlight [42]. For this reason, infrared sensors are best used in applications designed for low light areas. A potential option from the proximity sensors group was an ultrasonic sensor. Ultrasonic sensors are designed to generate high frequency sound waves and receive the echo reflected by the target, without the need for direct contact. One advantage of ultrasonic sensors is high accuracy, including the detection of small objects. The response of these sensors is not dependent on the colors, transparency of objects, optical reflection properties, or by the surface texture of the object [42]. They are also functional in critical conditions such as dirt and dust.

Ultrasonic sensors are also suitable for use with a microprocessor. The output value of these sensors is linear with the distance between the sensor and the target, easing the task of data processing. For these reasons, ultrasonic sensors are used in a wide range of applications and are very useful when it is not important for the detection of colors, surface texture, or transparency [42]. Some disadvantages of ultrasonic sensors are that the response of the sensor can be sensitive to changes in the environment (i.e. temperature, humidity, pressure) and loud noises. Additionally, these sensors typically have a response time with a fraction less than some similar sensors. Ultimately, ultrasonic sensor technology was chosen for the task at hand based on their capability of performing at a high level for each of our considered relevant factors. Shortly after this decision was made, it was recalled that a previous team had purchased two ultrasonic sensor modules from LV-MaxSonar as seen in Figure 73. These LV-MaxSonar-EZ3 modules are narrow beam ultrasonic sensors with good side object rejection, low power consumption, easy to use interface, large object detection and can be powered by many different types of power sources [43]. They can detect objects from 0 to 254 inches and provide sonar range from 6 inches out to 254 inches with 1-inch resolution. Objects from 0 inches to 6 inches typically range as 6 inches [43].

Figure 73: The LV-MaxSonar-EZ3 ultrasonic sensor module used in the ultrasonic system. This sensor module is a narrow beam ultrasonic sensor with good side object rejection, low power consumption, easy to use interface, large object detection and can be powered by many different types of power sources [9].

Additionally, they are rated to detect people up to approximately five feet and are suggested to be used with autonomous navigation by the manufacturer. These modules were never used by the previous team. Although purchasing other modules was considered, it was determined that the modules in the team's possession met the needs of the application at hand.

With the products in place, the next step was to assemble the system and design a program to accurately measure speed and distance. To configure a single sensor module for operation, three connections are needed (Figure 74). The first connection is from the ground terminal on the sensor to the ground terminal of the microcontroller unit. The second connection is the supply voltage terminal of the sensor to the 3.3V supply voltage terminal of the microcontroller unit. The third connection was from the analog output terminal of the sensor to the analog input terminal of the microcontroller unit [43].

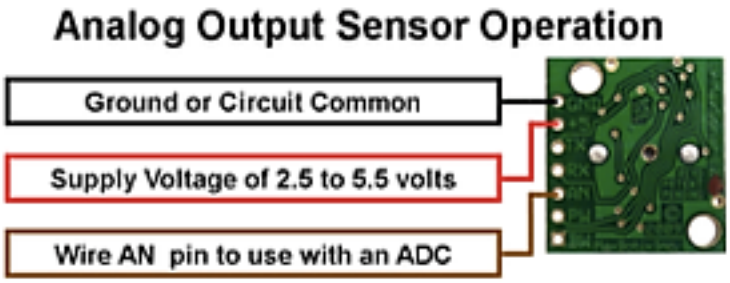


Figure 74: The manufacturer's suggested wiring guide for independent sensor operation. For this project the supply voltage supplied by the Teensy 3.5 is 3.3V and within the suggested range. An ADC, or analog-to-digital converter, is equipped on the Teensy 3.5 microcontroller unit for each of the analog pins to access [9].

For the needs of our application, two ultrasonic sensor modules were used in a single system. One is to be positioned on the front left or back left of the cart and the other is to be positioned in the front right or back right of the cart. This type of setup is often prone to interference (cross-talk) from other sensors when connected individually [44].

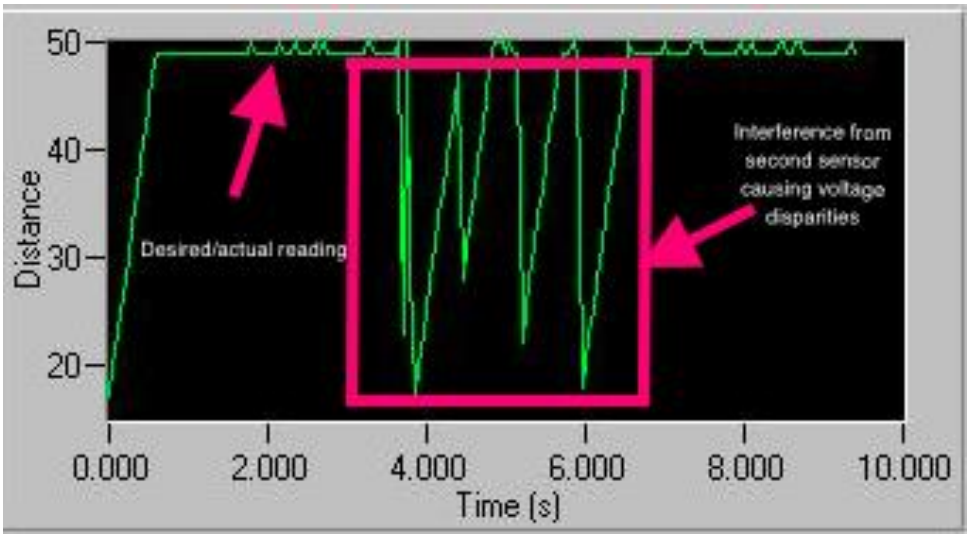


Figure 75: A visualization of an ultrasonic sensor signal with interference. As seen in the visualization, when two sensors are operating at the same time within close proximity to one another, interference may occur that is seen as voltage noise causing disparities in the data [10].

To avoid interference, a strategy known as continuous loop chaining was implemented. In this loop, the first sensor will range, then trigger the next sensor to range and so on for all the sensors in the array as shown in Figure 76 [44]. Once the last sensor has ranged, it will trigger the first sensor in the array to range again and will continue this loop indefinitely.

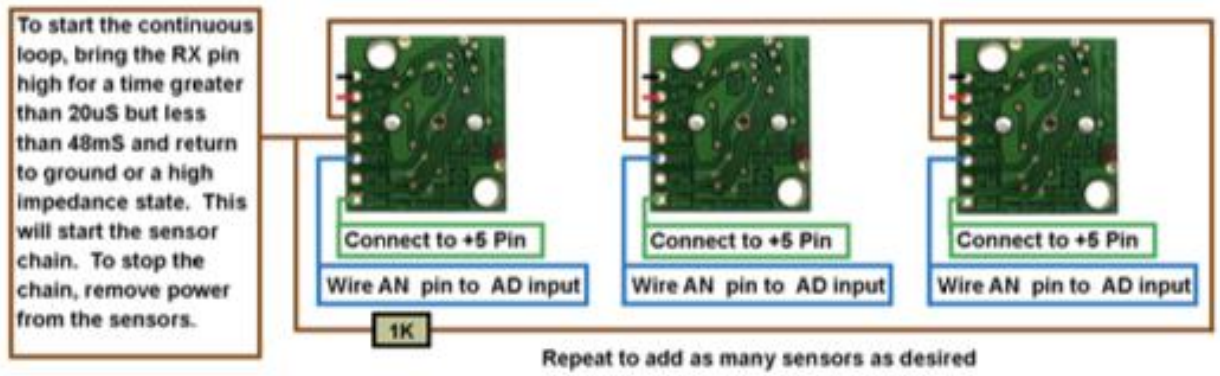


Figure 76: The manufacturer's suggested wiring of a continuous loop chain of ultrasonic sensors. In this configuration, once the first sensor is triggered to operate by the microcontroller unit, the sensor will range and trigger the next sensor in the loop to operate. This cycle will continue through the loop until power is disconnected from the sytem [9].

To achieve this the ground terminals, supply voltage terminals and analog output terminals of each sensor are connected in the same fashion as a single sensor would be. In addition, the BW, RX and TX terminals of the sensors are used [44]. The BW terminal for each sensor is connected to the 3.3V supply voltage terminal of the microcontroller unit. When the BW pin is held high the TX output sends a pulse, suitable for low noise chaining. The RX pin of the first sensor in the chain is connected to both a digital output terminal of the microcontroller unit and the TX pin of the last sensor in the chain. Additionally, a 1 kΩ resistor is placed in series with the path between

the RX pin of the first sensor and the TX pin of the last sensor. The RX pin of the first sensor will initially be triggered by the microcontroller unit to begin the continuous loop and from then on out will be triggered by the TX pin of the last sensor in the loop. The TX pin of every other sensor is similarly connected to the RX pin of the next sensor in the loop in order to continue the sequential triggering process.

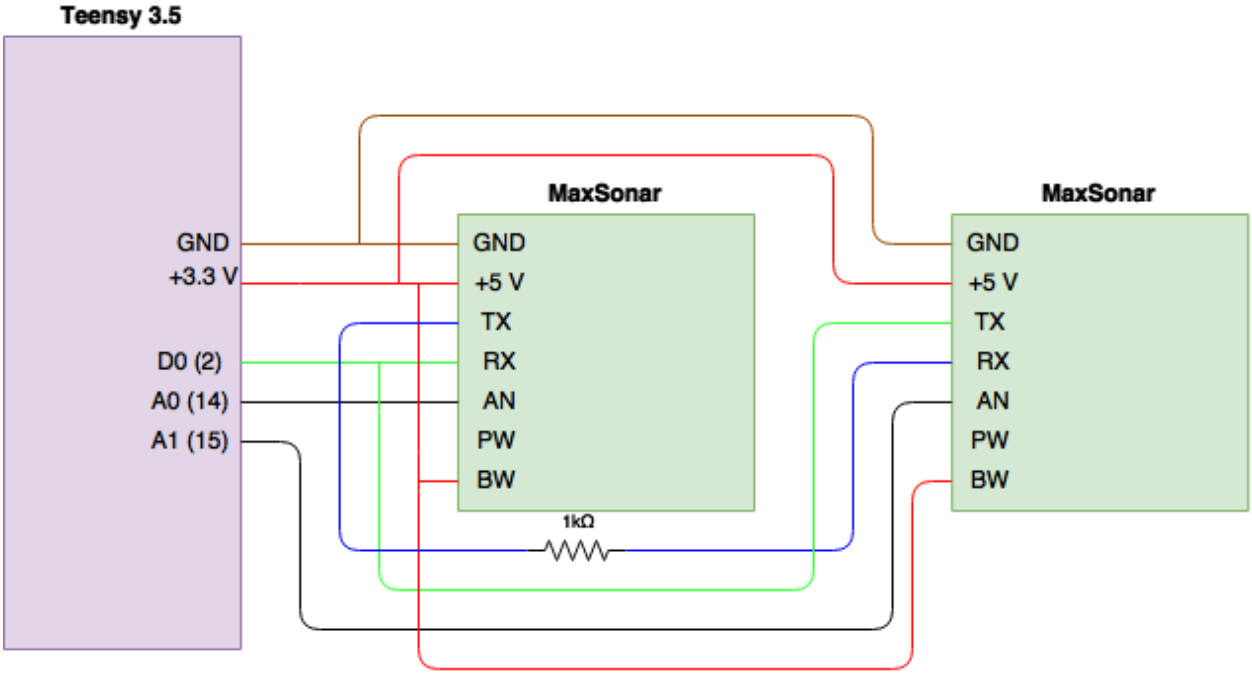


Figure 77: The circuit diagram of the ultrasonic system designed to be installed on the WPI Goat Cart. This system is designed to incorporate two ultrasonic sensors in a continuous loop chain.

In theory, after each complete cycle of the sensor array, multiple readings will be available for analysis on the processing side of the system. The first program was designed around utilizing these readings to make an informed decision on whether the cart should stop or not.

After being assembled, a series of program versions were designed, tested, troubleshot and improved until the program met all accuracy requirements and suffered zero errors. The final result is a program that will report the distance of an object and a corresponding warning to the serial monitor when an object is within 20 inches of either sensor. This operation is dependent on the speed of the cart and should only be used when the cart is operating at speeds used for applications such as parking (0 – 5 mph). In order to achieve this level of accuracy, two ultrasonic sensor modules were used in a continuously looped chain controlled by the specialized program. The system status and corresponding program variable status can be easily tracked using (Figure 78).

The final program is designed to first run the setup() function. The setup() function is used to initialize variables, print status messages to the serial monitor and configure the microcontroller pins and serial data transmission. A helper function, called sonarInit(int controlPin), is used to handle all the timing restrictions of the sensors during power up and configure the microcontroller pin associated with initially triggering the sensors for ranging. All the values used for timing restrictions and delays are based off of values reported by the manufacturer in the datasheet for the sensor [43]. The delays used are essential for operation of the system.

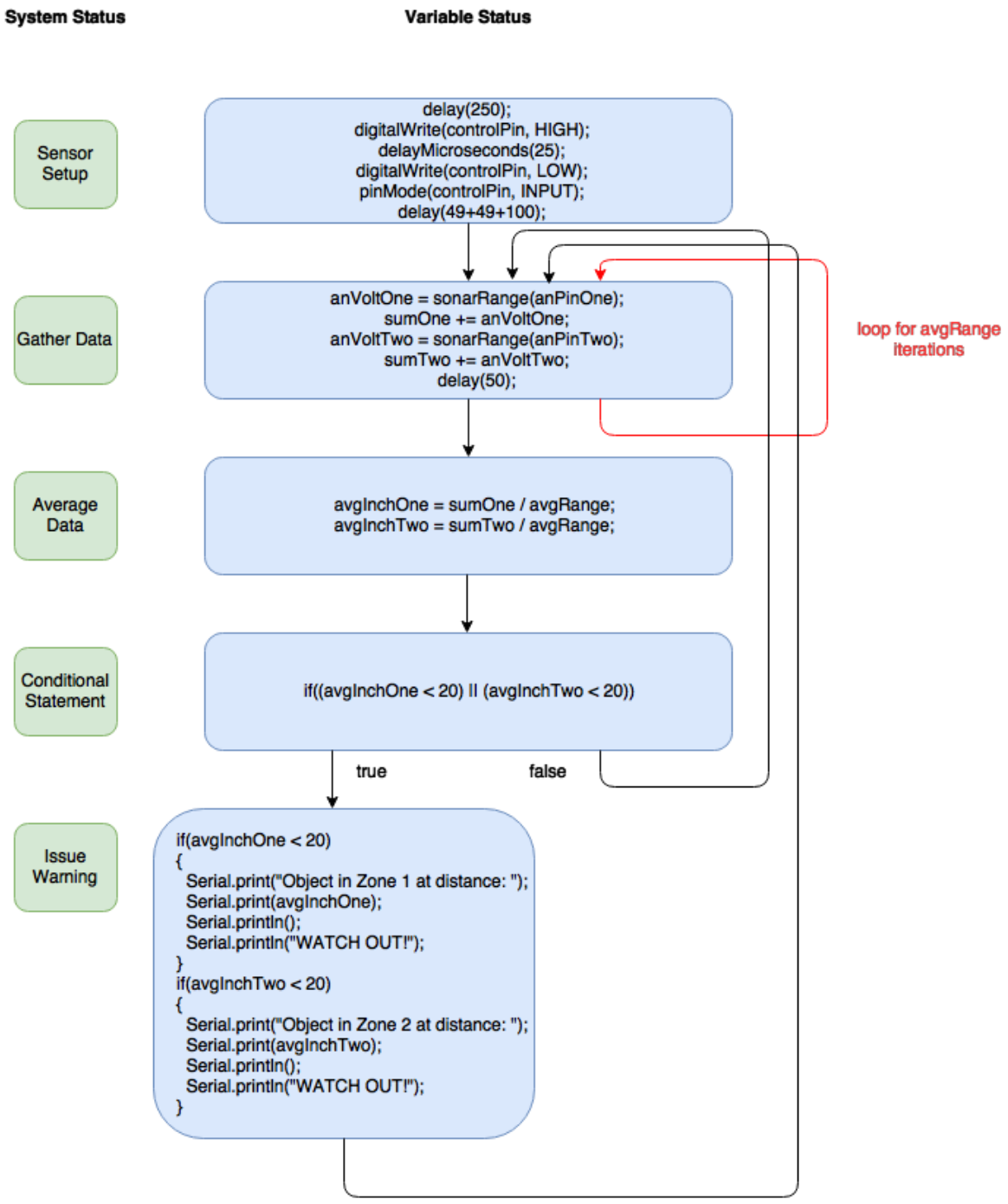


Figure 78: A flow chart documenting the changes in the status of the ultrasonic system and the corresponding status of the changes in the variables of the associated specialized program. The code that this flow chart represents can be found in the appendices of this paper.

```
void sonarInit(int controlPin)
{
  // wait for boot
  delay(250);
  // trigger ranging
  digitalWrite(controlPin, HIGH);
  delayMicroseconds(25);
  digitalWrite(controlPin, LOW);
  // Make high-impedance input to signal round-robin
ranging.
  pinMode(controlPin, INPUT);
  // wait for calibration+initial ranging times.
  delay(49+49+100);
  // sonars should alternate automatically now
}
```

After configuration is complete, the program enters the continuous loop() function. In the loop() function, the range data is gathered from each sensor. This is accomplished using the helper function sonarRange(int sonarPin). This helper function makes use of the analogRead() function of the Arduino library which reads the value from the specified analog pin [45]. Using analogRead(), the input of voltages between 0 and 3.3V is mapped into integer values between 0 and 1023. This yields a resolution of 3.3V per 1024 units, or 0.003V per unit. The analog output of each sensor is (3.3V/512) per inch [43]. Using all of this information, the conversation rate for

the analogRead() function output value to the desired value of inches is found to be 0.5. The helper function in this case does just that; returns the desired value of distance in inches.

```
int sonarRange(int sonarPin)
{
  // At 3.3V, inches =
((analogRead()/1024)*Vcc)/(Vcc/512) = 0.5
  return analogRead(sonarPin) * 0.5;
}
```

In each iteration of the loop() function, a set of forty values from each sensor are gathered over a period of approximately two seconds and averaged out. These values represent the average of the distance of the closest object to the sensor over a period of two seconds. The two second period is a result of the number of iterations of the loop (controlled by the variable avgRange) and the time it takes, with delays, for the loop to run through a single interation. The benefit of averaging the recorded values over a period of time is to eliminate any anomalies to the system.

```
for(int i = 0; i < avgRange; i++){
  anVoltOne = sonarRange(anPinOne);
  sumOne += anVoltOne;
  anVoltTwo = sonarRange(anPinTwo);
  sumTwo += anVoltTwo;
  delay(50);
}
avgInchOne = sumOne / avgRange;
avgInchTwo = sumTwo / avgRange;
```

If either of these averages is less than twenty inches, a warning with the name of the corresponding sensor and the average distance is printed to the serial monitor.

```
if((avgInchOne < 20) || (avgInchTwo < 20))
{
  if(avgInchOne < 20)
  {
    Serial.print("Object in Zone 1 at distance: ");
    Serial.print(avgInchOne);
    Serial.println();
    Serial.println("WATCH OUT!");
  }
  if(avgInchOne < 20)
  {
    Serial.print("Object in Zone 2 at distance: ");
    Serial.print(avgInchTwo);
    Serial.println();
    Serial.println("WATCH OUT!");
  }
}
```

Using this program, the team was successfully able to detect the presence of any object in close proximity to the cart and issue a warning when the object became within a user defined minimum range of twenty inches.

The final steps in the process of engineering a solution were to install the ultrasonic sensor system onto the cart and prepare future teams for successful operation. As of the end of C-Term 2018, the ultrasonic sensors have not been temporarily integrated in a way that is ideal for future testing (Figure 79).

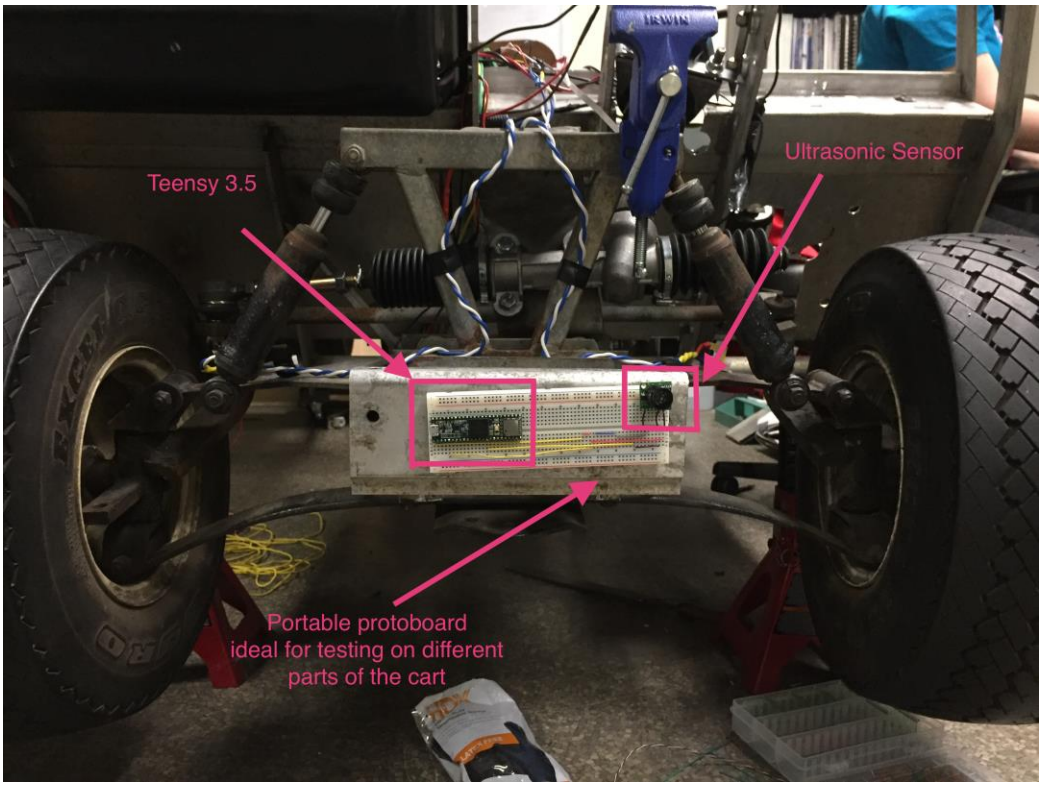


Figure 79. A single ultrasonic sensor wired to a Teensy 3.5 on a portable proto-board. This configuration was implemented because it is best suited for testing. When the cart is in a state where it can be used for testing outside, the attachable and detachable proto-board can be moved to different points on the cart. This will help to determine where on the cart that ultrasonic sensors are most necessary.

Future teams should approach this system from two points of view: hardware and software. From the hardware perspective, consider a more permanent solution to mounting the sensors onto the cart. It was envisioned by this year's team that the sensors could be fitted into the plastic body of the cart. Permanent locations for the cart should be carefully considered for optimal use. To ensure the functionality of ultrasonic sensors, testing should be conducted outdoors when the cart in a driving state to determine where on the cart the sensors will be most useful to the overall system. However, please have it be noted, that if a future team decides to add more than two

ultrasonic sensors to the same array that timing restrictions must be taken into consideration. Adding another sensor to array means that more time will be necessary for the loop to run through in its entirety. Therefore, data is attained at a slower rate. Additionally, future teams should consider making improvements to how the components are secured onto the cart in order to increase durability and longevity. From the software perspective, this data should be able to transmit over CAN and correspondingly induce actions with the braking and throttle systems. At this moment in time, the program for this system simply prints a warning message to the serial monitor. Ideally, a similar warning message would be sent over CAN to the server. The server could then as a result generate a message to be sent over CAN for the braking system to apply a full stop when an object is detected within close proximity.

8.4 Sensors Summary

The 2017-2018 project team designed, tested and established plans for integration of two essential low-level sensor systems for the WPI Goat Cart. The first of the sensor systems is the speedometer/odometer. This sensor system can measure speeds up to approximately 30 mph, measure distance in intervals of approximately 13 inches, and transmit values of speed and distance to the cart's main server using CAN communication. The system hardware is completely integrated to the cart but operates only as a standalone feature. The second of the sensor systems is ultrasonics. This sensor system can report the distance of an object and a corresponding warning to the serial monitor when an object is within 20 inches of either sensor. The system hardware has yet to be integrated with the cart. Further software development is

required for both sensor systems in order to completely integrate them with the other components of the cart such as CAN, throttle, braking, or others as seen necessary. Future teams should continue to improve and adapt the software aspects of these systems as the other components of the cart evolve (i.e. as CAN improves and becomes more reliable). This year's team believes that the next step for sensors in this project would be to add imaging sensors and computer vision. These future systems are essential for the cart to be fully autonomous.

Chapter 9. Conclusion

Considering the state that the 2017-18 MQP team received the Goat Cart, they were able to improve upon it substantially. Although only one subsystem was initially in working order, the team was able to add four additional subsystems. Every part of the cart was worked on and improved. The power system almost exploded this year because the system did not use float chargers, but three batteries were replaced, and to prevent such an event from repeating itself, float chargers were installed for the batteries on the cart. The team completely redid the steering system, from getting a new rack and pinion, to redesigning the software so it could be controlled by the CAN bus. The braking system was moved in line with the physical break so it had enough torque to move the pedal. The throttle's motor controller was replaced. Its software was combined with the braking's software because the state of one system directly affects the state of the other one. Instead of working on vision, the team decided that adding sensors to collect data about the cart was a good base for future years to build off. All the data from each subsystem goes through the CAN bus, which gets data either from the subsystem, or sends commands to actuators. The team designed the CAN hardware and the message structure to be optimal for the Goat Cart. Additionally, sensors were added so that the cart has knowledge of itself and its surroundings. This year, the team added both odometery in order to track how far the cart has traveled, and ultrasonics that can identify if there is something on the ground over six feet away. Overall, the Goat Cart had to be completely transformed this year, so that future MQP teams have a solid base in which to build an autonomous cart.

9.1 Lessons Learned

What made this year's iteration of the Goat Cart successful was a strong vision of what needed to be done. Since the cart was in poor condition, it was easy decide this year's goal: to get the cart to go around the track. In other words, the goal was to build a roadworthy cart. Based on this goal, the team was able to figure out what needed to be improved upon or added to the Goat Cart.

In order to have successful results in such a big group, it was necessary to assign someone as the team leader. This person would keep track of everyone's work, and ensure that everyone was getting concrete results. Additionally, this team leader organized and kept track of the budget, planned meetings, and facilitated other logistical necessities. This year's team leader, Jade, was respected and well liked enough that everyone would listen to her and generally do what she said.

With each team member was responsible for a specific part of the project, communication was vital. During meetings, everyone gave a status update of what they were working on, and if there were problems, others either gave advice or arranged to help with the work. Using Slack, an online messaging system, allowed everyone to stay in contact outside of meetings. This compensated for only having two full team meetings a week and one additional meeting with Professor Wyglinski.

When working on the cart, the team discovered that, while ideas and plans came easily to the table, putting them into action was both the most challenging and the most important part.

However, understanding the initial state of the cart, and analyzing the best approaches to achieve the goal were still necessary. For this reason, during A term, the team decided to diagnose the state of the Goat Cart, do research, and plan the best approach to reach the goals and objectives proposed. The team also learned how to work under pressure and get the results demanded by their advisor on time, working to meet the Spark Party presentation deadline. They were able to get steering, braking, throttle, power and odometery in working condition for the second week of B term 2017. It was found that some parts, like braking, required less research, and probably could have been started towards the end of A term. The steering either needed much more research or advice from a Robotics Professor. The programing needed for the subsystems for Spark Party 2017 was not thoroughly debugged, and the team just had to pray for the best. Future teams should attempt to find a balance between research and intuition.

9.2 Future Work

9.2.1 CAN Future Improvements:

The CAN interface board ware went through two design stages and intense debugging to ensure a stable and reliable design. Hopefully, no problems will be found in the future with the CAN interface board. Nonetheless, it is expected that additions of CAN nodes with new sensors will occur in a future and it will require building more boards, currently the team built 10 boards and is using only four of them. When new boards do need to be made, the diagrams of the board design can be found in the GitHub documentation.

On the other hand, the software development of the CAN network in its infancy. The team created the basic CAN structure which will serve as the skeleton of the whole communication system of the cart. When more messages are added to the system, the upcoming teams will need to begin worrying about timing and prioritization, reliability and error checking, among other complex features.

9.2.2 Steering System Proposed Work

D**o not touch the steering system again!** Unless it breaks. The one exception to that is that a future team may desire to increase the steering gear ratio to facilitate more precise steering and reduce the likelihood of speed related damage. If this process is undertaken, a forty to one VersaPlanetary Gearbox should be purchased from VEXpro. The whole gearbox doesn't need to be ordered, only the new gear kit and a 0-2 stage screw kit need to be purchased. The replacement gearbox will be a dual stage gearbox as opposed to the single stage gearbox that is currently being used. This will occupy more space between the CIM motor and the steering rack, neither of which should be relocated! The solution to create room and accommodate a second gearbox stage is to cut the hexagonal output shaft of the gearbox shorter by the length of the additional gearbox stage. Below in Figure 77 is a photo highlighting the shaft that should be cut to accommodate the additional gearbox stage.

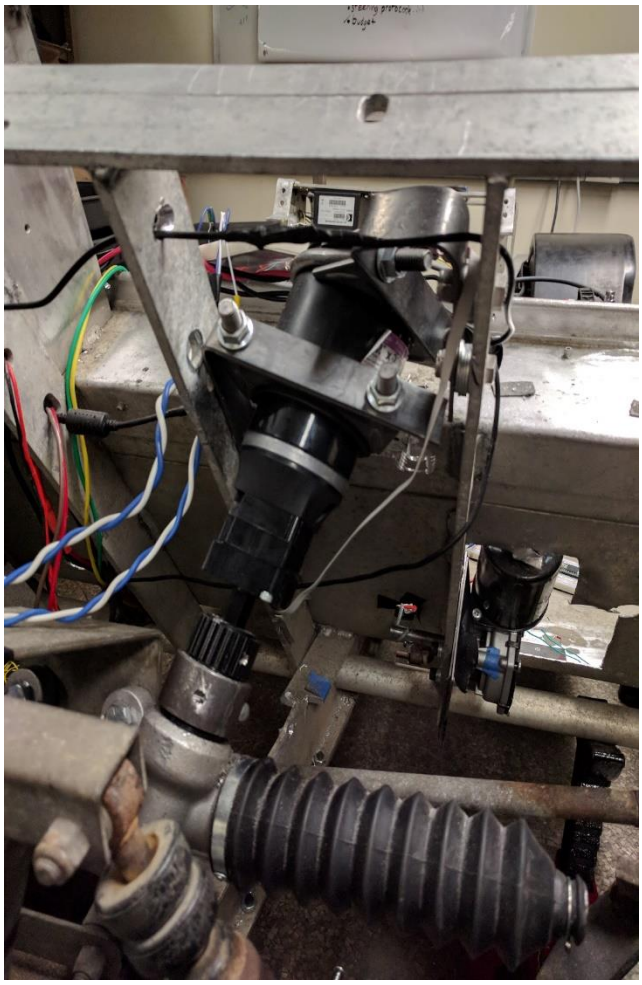


Figure 80: Shaft that Should be Cut to Accommodate a Two Stage Gearbox

There should not be any further modifications made to the steering system, however the suspension system of the cart is likely to need work in the near future. The bushings on the front and rear suspension as well as the shock absorbers are severely worn and past the end of their serviceable life. These parts should all be readily available from Buggies Unlimited.

The current state of the steering software is a very good start. It has the basic functionality that is needed along with some more complex functions that are needed for autonomous driving such as calibration, receiving commands from CAN, and turning to the specific location. From this point, much can be done to improve the software.

The most important thing that the current software is missing is accuracy. For turning to specific degrees, the cart turns to the location but there is some allowed tolerance. Eventually the tolerances will add up and cause possible issues if there is a series of commands. The solution to this is to add in feedback. By adding a feedback loop the steering can notice how far off the goal it is and then continually correct itself. This could be done using a Proportional- Integral-Derivative (PID) control loop. PID loops are wonderful because they are a mathematically way of creating a feedback loop. An issue with using a PID loop is that it requires time to go to a position and then adjust.

A possible problem is that was not addressed is the steering only receives an input from the CAN bus, it does not send messages back saying that it has completed turning. It is likely that this is not an issue, because in most cars it is preferable to turn the wheels while driving because it reduces friction. However, it still would be good for the Goat Cart to keep track of what state the different subsystems are in.

9.2.3 Braking Future Plans

The team hopes that the braking mechanism that the team implemented is one that can last and be part of the base for the autonomous golf cart project moving forward and as such,

there are only a few plans for the brakes of the golf cart. One possible future improvement is that the team reached out to the brake motor manufacturer and they have agreed to send their newest version of the motor once they finish developing it. The new version of the motor has built in encoding on the motor shaft. This functionality would allow for different levels of breaking, such as slowing the golf cart instead of bringing it to a complete halt. In addition, this functionality would add safety into the system as it would no longer have to rely solely on the endstops for feedback on the position of the brakes. Secondly, the next team should trim the metal sheets that help mount the motor to prevent heavy loads from bending the plates and causing them to interact with the wheels. The section on the sheet in need of removal has been clearly marked. Lastly, the wiring of the brake system needs to be properly cable managed. Currently, there are wires going everywhere. These should be proper labeled and contained under or in the golf cart so that they do not get damaged or accidentally cut or unplugged.

9.2.4 Throttle Future Improvements

The main point of improvement the throttle system still needs is the control bridge between the Teensy and the motor controller currently being filled by the digital potentiometer. The programmer kit will allow the throttle input to be changed to a new range of acceptable input types as seen in Table 10. Unfortunately, its delay leaves this decision up to the next years MQP team.

Table 11: List of throttle control schemes possible upon arrival of programmer

Ten throttle types can be used with these controllers:

Type 0	2-wire potentiometer, 0–5kΩ
Type 1	2-wire potentiometer, 5kΩ–0
Type 2	single-ended 0–5V input
Type 3	2-wire potentiometer, 4.6kΩ–0
Type 4	2-wire potentiometer, 5.5kΩ–0
Type 5	2-wire potentiometer, 1kΩ–0
Type 6	ITS input
Type 7	single-ended 6.3–10.6 V input
Type 8	single-ended 6–12 V input
Type 9	single-ended 3-wire potentiometer, 0–5kΩ

If the motor controller and potentiometer are left in their current configuration, the cart will be unable to to travel at higher speeds without considerable risk of burning out the potentiometer again. If this deemed an acceptable tradeoff, the motor controller would need to be set to Type 1 from Type 0. This is needed to put the active slow speeds in the 5kΩ range instead of the 0Ω range and allow safe operation of the digital potentiometer. Most of the other potentiometer input Types offer no other major advantage or disadvantage over Type 1 and need not be considered. However, several other options available for the next team to consider. Given that analog potentiometers can handle significantly more current than their digital counterparts, an analog potentiometer input could be used along with a servo as a system to allow the speed to be set to specific levels. Alternatively, Type 2 could be used by using an analog output pin from the Teensy. The Teensy's maximum voltage limit of 3.3 V would still naturally limit the top speed but would eliminate the intermediary of the potentiometer. This could also be controlled by a digital output pin using pulse width modulation.

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