MER419 - Design Report

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Team 1

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- ❖ Editors: Kentaro, Andrew
- ❖ Create and add figures, after first draft (David, Jimmy)

1. INTRODUCTION

Project Introduction

Teams of students spent the term designing, building, and testing a robot to compete against a six-year-old girl at mini-golf. In the past, there have been two such competitions, with varying rules regarding the drive system of the vehicle, the way in which the robot strikes the ball, and the scope of the project with regards to which actions the robot must take to complete the hole. For this competition, the teams were required to build a robot capable of playing a hole through from start to finish: this means that in addition to being able to physically strike the ball, the machine also needed to move between shots and reposition itself, without being touched by team members above the ball in preparation for its next shot. During this competition, several new rules were enforced over previous competitions. The robot was required to use one of the putters available at the course to strike the ball, then move between shots to finish the hole, with a penalty for taking longer than the three minutes allowed to finish the hole.

Background

Because there have been two past occurances of this competition, the rules which control the robot design became stricter, in this case requiring the putter used to be one of the course available rental putters, rather than an unrestricted structure which did not restrict the method of hitting the ball. Further, due to past vehicles needing excessive time to position themselves and aim for their shot appropriately, a strict time limit was included in the rules this year, with an accompanying suggestion that the teams keep this in mind throughout the design process, specifically by decoupling the aiming of the putt from the steering of the robot. The time limit was set to 60 seconds per hole, and for holes which go over, a penalty is assessed to the offending team’s score. Early on, it was apparent that the surface of play would be a factor in both the results of the putting and driving of the vehicle, and rough terrain and narrow gaps in between vertical extrusions were identified as risk factors for completion of play.

Project Summary

This report presents the design of a mini-golf robot that competed in the Spring 2018 MER419 competition, “Robot vs. Girl”. The robot is capable of traveling around the mini-golf course and putting a golf ball towards the hole with a stock mini-golf putter. The functional decomposition of the design consists of three primary functional requirements: locomotion, aiming, and putting. The design consists of two subsystems: a driving subsystem, and a putting subsystem. The driving subsystem is capable of omnidirectional translation and rotation, allowing for the locomotion and aiming functionalities of the robot. The putting subsystem is capable of swinging the equipped putter to putt the ball, similar to how a golfer drives a putt.

Since the primary goal of this design is to maximize the probability of this robot winning the mini-golf competition, a competition strategy was formulated and referenced as the foundation of the design concept. Based on the guidelines of the competition and observations made at the course, calibrating a long first putt to bypass obstacles and making small precise putts once near the hole was determined to be the optimal strategy to minimize the number of strokes per hole. Therefore, accuracy of putting was chosen to be the highest design priority. Additionally, given the 10-week timeline of the project, simplicity of design was also prioritized to minimize the time-cost of development and the number of opportunities for design failures.

Members of the project team were organized into two groups, one of which focused on developing the driving subsystem, and the other focused on developing the putting subsystem. A team leader was assigned to lead the project, and a group leader was assigned within each group to lead the development of their respective subsystems.

2. DESIGN REQUIREMENTS

The requirements for this design were defined by the project description and subsequent design milestones, observations made from surveying the course at Pirate's Hideout, where the competition was held, and team decisions made through the design process. All relevant design requirements are listed in Table 1. The project description constraints on the functionality of the robot, the user interaction and control, and the labor and monetary costs are included. These constraints serve to hold all designs to an equal standard. The project description, along with select subsequent milestones, also serve to hold their performances to a certain level of quality. For example, while the requirement to decouple the steering and aiming functionalities does not necessarily serve the primary goal of minimizing strokes per hole, it does serve the secondary goal of minimizing the time required to complete each hole. Surveying the mini-golf course introduced practical design requirements meant to ensure the robot's ability to properly perform at each hole. Potential obstacles present throughout the course constrained the design to ensure that every hole could be traversed. Additional design requirements were assigned throughout the project due to restrictions inherent to the development process. Limited time and resources imposed constraints on the practicality of design ideas, and therefore requirements such as ease of manufacture and maximum cost were introduced to guide the development toward a realistically achievable design.

Table 1 - List of Design Requirements

Requirement Type	**Design Requirement**
Project Description/ Design Milestone	Robot must putt using one of the putters available at the miniature golf course
	The putter must be supported only at the grip and in such a way as to not damage it
	Each movement of the ball (or stroke) must be produced by moving the head of the putter so as to cause a single impact with the ball. Pushing the ball and double impacts are not allowed (penalty: on stroke penalty

	and repeat the stroke)
	Must be controlled wirelessly using no more than 6 RC channels
	The robots can be positioned by hand for the first stroke of each hole. After that, the robot cannot be handled again without penalty until the next hole. The one exception to this rule is the 5-min timeout described below.
	The entire device must form a single unit
	No components may be added or removed during the competition, except to make repairs or change batteries
	The golf balls at the miniature golf course must be used during the competition
	Everyone on the team must take a turn at operating the machine to ensure ease of operation
	Can't use duct tape in the construction of the device
	Total cost must be less than $500 (not including the cost of the radio)
	Each robot will be subject to the time constraint of 3 minutes to complete the hole. This time was based on the playing speed of the Professor's 6-year old daughter and adjusted based on difficulty of operating the robot. (Penalty: automatic maximum score of six strokes if over three minutes to complete hole)
	Each team is allotted one 5-minute timeout to make repairs. These timeouts can only be taken when the machine is between holes
	If the robot needs to be handled while the hole is still being played, the team will be assigned the maximum score for that hole
	Robot and operators must not damage the putter, golf balls or golf course
	Robot will not be allowed to compete until it passes the inspection of the course owners
	Noise from the machines must not disrupt other golfers
	Balls within 6 inches of the border may be moved (along the line perpendicular to the railing) so as to lie no more than 6 inches away from the border
	Local course rules will be enforced. In the event that they conflict with

	these official competition rules, the competition rules take precedence
	Any robot deemed unsafe to operators or spectators will not be allowed to participate in the matches
	Must look like something the Professor would want to buy
	Must decouple steering and aiming functionalities
Survey of Mini-Golf Course	Must weigh less than 16 lbs
	Must be able to maneuver around all necessary obstacles
	Must be able to hit ball away from wall with 6” spacing
	Must be able to putt ball past all obstacles with first putt for every hole
From Development Process	Must perform properly on course turf (given mecanum wheels design option)
	Minimize parts manufactured in machine shop

3. DETAILED DESIGN

3a. DESIGN OVERVIEW

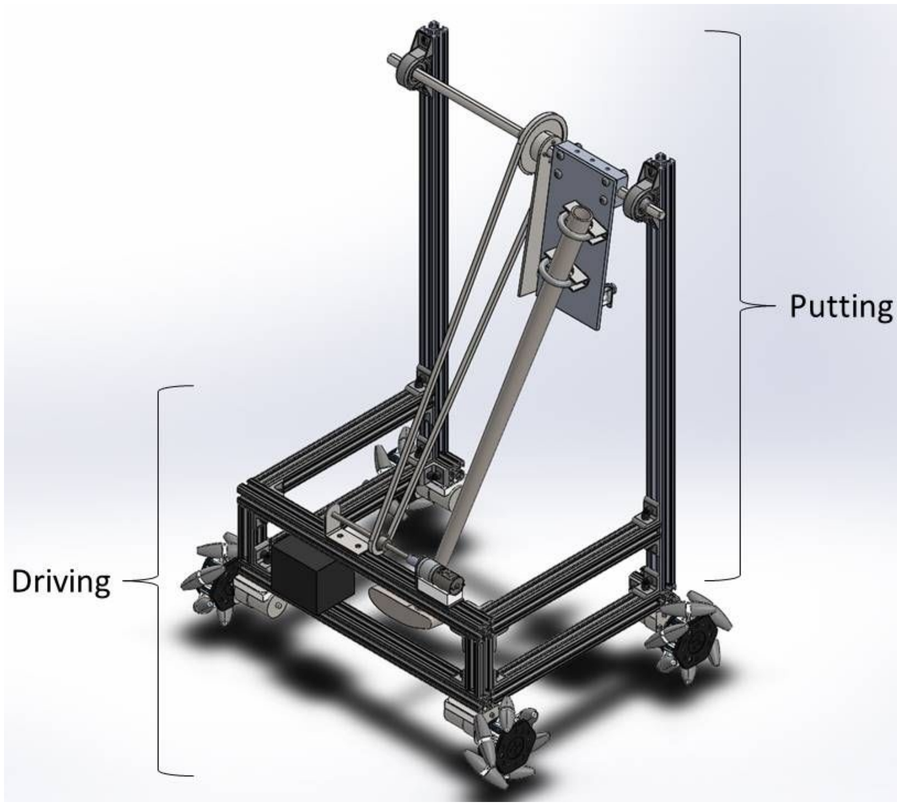


Fig. 1 - Full CAD assembly of design

The development of the mini-golf robot design was categorized into three sections, the driving subsystem, the putting subsystem, and the electronics and controls. The Putting system uses a pendulum design to swing the putter head to impact the ball. The stroke is loaded using a chain-and-sprocket drivetrain, and is released using an electromagnet. The mecanum wheels used in the driving system are capable of omnidirectional driving and allow for both locomotion and aiming capabilities. Both the putting pendulum and driving platform structures are constructed using T-slotted rail extrusions. The motor control circuit is implemented using Arduino boards and an onboard power source, and manual RC control is implemented using Arduino code.

3b. DRIVING SUBSYSTEM

Design Overview

The putting machine is driven by four different mecanum wheels with a four inch diameter. Each wheel is placed on the corners and is driven by its own brushed DC gearmotor. The wheels are connected to a motor driver, which is then connected to an Arduino board. This allows for omnidirectional movement. Using mecanum wheels cuts down on the time it takes to line up a shot compared to standard wheels because it is easier to drive up on the ball and either rotate about the ball or move side to side to line up the putter and ball with the hole.

Since the driving mechanism is pivotal to the success of the machine, the DC motors that were selected to power the device are more powerful than they need to be. In theory, one motor is powerful enough to move the entire vehicle. This was done to safeguard the putting machine from any unexpected weight and other unforeseen problems regarding contact of all four wheels and the ground. Through testing, it was found that the vehicle was able to traverse the golf course obstacles including a 30 degree incline, rocks, and rough turf.

The center of gravity is also an important aspect of the driving subsystem because mecanum wheels need each wheel to have the same contact with the ground and equal weight distribution for optimal performance. In order to ensure that the center of gravity is in the middle of the vehicle, it was placed on a thin object and balanced accordingly. It was observed that increased wheel contact improved stability and allowed the for the vehicle to move in all directions as expected.

The frame was also found to be a significant factor in the design. Since all four wheels must have equal contact with the ground, if the frame is not completely flat then the wheels will have uneven contact with the ground resulting in skewed sideways motion. To ensure the frame was stable, it was built on a flat table (in the machine shop) that has a tolerance of 0.005mm, unilaterally. After the frame was fully assembled it was placed on the table and was tested for flatness by attempting to rock the frame. Once the frame was determined to be flat, the wheels were put on and again tested on the table.

Mecanum wheels - How they work

Because the design chosen relied on the ability of the vehicle to move freely and position itself over the ball before rotating the entire vehicle to aim the putt, a large initial challenge was finding a method to position the vehicle in 2 dimensions without necessarily having to drive there using traditional steering methods. Additionally, once the vehicle was in position over the ball, the vehicle needed to be able to rotate in place to aim the putt without disturbing the placement of the putter with respect to the ball. Several options were initially considered, from treads to two driven wheels with two casters, to omnidirectional wheels of various designs. It was immediately brought to our attention that for robots of the approximate size that we were planning on building, treads were impractical due to their high friction, and the two driven wheels with 2 casters was identified as taking longer to position and aim due to the fact that the driven wheel designs were incapable of moving in all directions.

This left a decision between the different types of omnidirectional wheels. There were two major designs considered, the "omni" wheels which used rollers perpendicular to the wheel axis aligned lengthwise along the perimeter of the wheel, and the significantly more costly "mecanum" wheels, which feature rollers at a 45 degree angle from perpendicular. While both of these designs are capable of moving in all directions, the fact that the rollers on the mecanum wheels are not fully perpendicular to the direction of movement allows the wheels to behave almost the same as regular wheels when moving forward and backward, raising both the speed and the efficiency of the vehicle. This also allows the wheels to be mounted in the same matter as regular wheels, rather than on the angle required for mounting "omni" wheels.

Using the Mecanum wheels to drive the robot keeps many of its functions the same as with any other wheel: in order to drive forward and backward, all wheels turn simultaneously, such that they move similar to the wheels on a car. Turning is accomplished in a very simple manner: by turning the left wheels faster than the right wheels, for example, the vehicle turns right, and vice versa. By rotating the front and back wheels inward and outward, so that the speed of each is equal and opposite, the rollers in the wheels give, and the robot slides right and left. Finally, rotation of two diagonal wheels while keeping the other two still causes the rollers of the inactive wheels to slip right and left, as the motion of the two driving wheels pushes the vehicle forward as well into a diagonal movement. Using different combinations and levels of each of the above detailed movements allows the vehicle to move in all directions without turning, as well as turn to face a new direction, which allows for superior location and direction control over other locomotion systems considered.

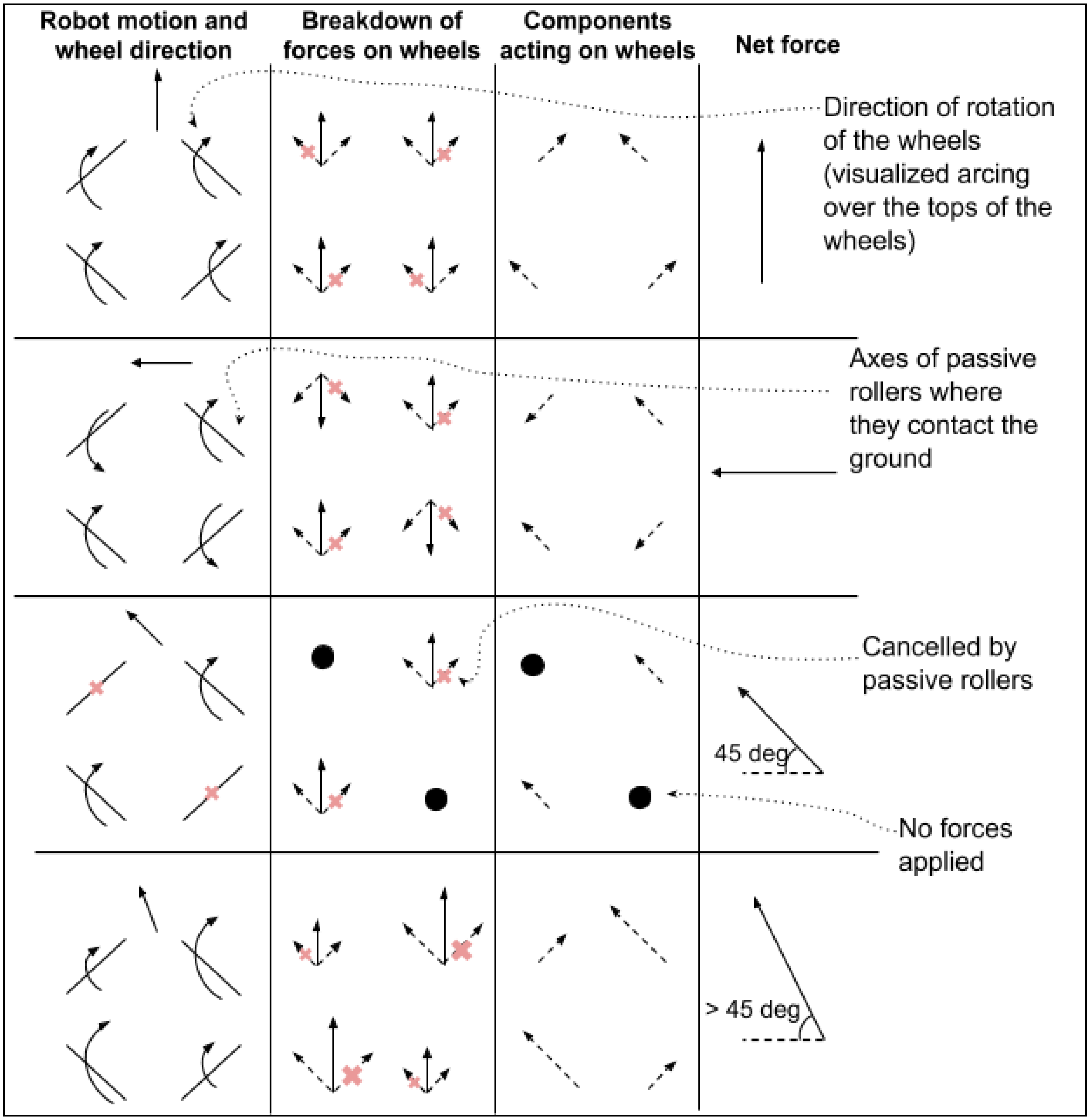


Figure 2: A breakdown of the forces acting on mecanum wheels to produce various movements.

Mecanum wheels - Research

The mecanum wheels were one of the biggest unknowns in the early design stages. Our primary concerns were as follows. Would they work on the golf course turf? What are the minimum requirements for successful implementation of the mecanum wheels? How do we size our motors which will power the wheels? And how do the wheels work? Several of the resources found and all of those mentioned here are listed under References.

Because time was short and the budget was tight, a large amount of energy was expended researching these questions. Our first question, "would they work on the turf?", was never directly answered; however, some forum pages indicated that the wheels would function in actual grass, which bolstered our hopes. We tried to make use of a thesis submitted by Nishant Sonawane [3] which discusses the calculation of kinetic friction on mecanum wheels, though it provided a more complicated explanation that we required.

We came across one set of instructions on Instructables [2] which outlined one possible implementation of mecanum wheels, and explained some of the minimum requirements. For example, the wheels must be assembled and attached such that when looking from above, the axles of the passive rollers point toward the center of the robot. Another article on the RoboteQ website [1] clearly demonstrated which combinations of wheel movements produce which movements from the robot and provides some insights on the electronics and programming implementation.

Tlale and de Villiers' article on the kinematics and dynamics of mecanum wheels [4] was helpful for understanding the forces involved in mecanum wheel motion, aiding in our comprehension of how various movements are completed. This article, however, was unclear regarding power losses, complicating the process of sizing our motors. Some articles indicated a loss of 50% of the power produced by the motors due to the passive rollers and still others indicated a loss of 75%. With this limited information, we found inexpensive gearmotors to use for the wheels, each of which are capable of moving the entire robot on their own, thereby mitigating the issue as completely as possible. Toward the end of the project, further research was done to address some performance issues, and a new source [5] was found that explained that approximately 70% of the applied torque translates to forward motion using mecanum wheels when configured in an optimal geometry, but this value can fall to as low as 45% in other non-optimal configurations.

Structure

The chassis was initially designed in order to accommodate both the mecanum wheels and the putting subsystem. The final chassis design is shown in the Modifications section. This original design was intended to be as light and simple as possible. It needed to be large and rigid enough to support the estimated weight, while being compact enough to allow for easy navigation around obstacles. The initial chassis design is shown in Figure 3.

Figure 3- Robot Chassis

At 18” wide, it is narrow enough to move around most obstacles at Pirate’s Hideout. It is also wide enough to allow the putter, which is angled, to have its head near the center of the robot, which is helpful for aiming purposes. The main vertical uprights are high enough to allow the head of the putter to be near the ground when fastened. Added to the bottom of the frame is the 2 inch radius of the mecanum wheels, which are attached to the motor mounts fastened on the bottom of the frame. The back side of the frame is open to allow the putter to have a full range of motion on its backswing. For the final design, foam was to the bottom of the frame to prevent damage to the putter when it hits the front of the frame on its follow through. To provide adequate stability to the wheel and putter system, the second level of supports was added, though this was removed for the final design.

The material selection for the frame was very important and allowed us to make several design decisions. We chose to use 1” 80-20 aluminum extrusion from McMaster-Carr. A key feature of the extrusion is that it acts as a rail, allowing for fasteners to be easily placed at any point along the rail, on any of the four sides. This allowed for easy assembly and disassembly, and made it easy to modify our design when needed. Another benefit was that the fasteners and corner brackets needed to secure the extrusion rails can be purchased through McMaster-Carr. Due to the cost the corner brackets, we purchased a length of 1” angle iron and cut pieces out to the same major dimensions as the purchased corner brackets. To add even more support and rigidity to the chassis, we used discarded sheet metal to act as corner plates fastened at three points on some outside faces (as opposed to interior corners, which could only be supported using the corner brackets). In some cases, spacers were used to ensure that the screws used with the fasteners wouldn’t hit the bottom of the extrusion rail slots.

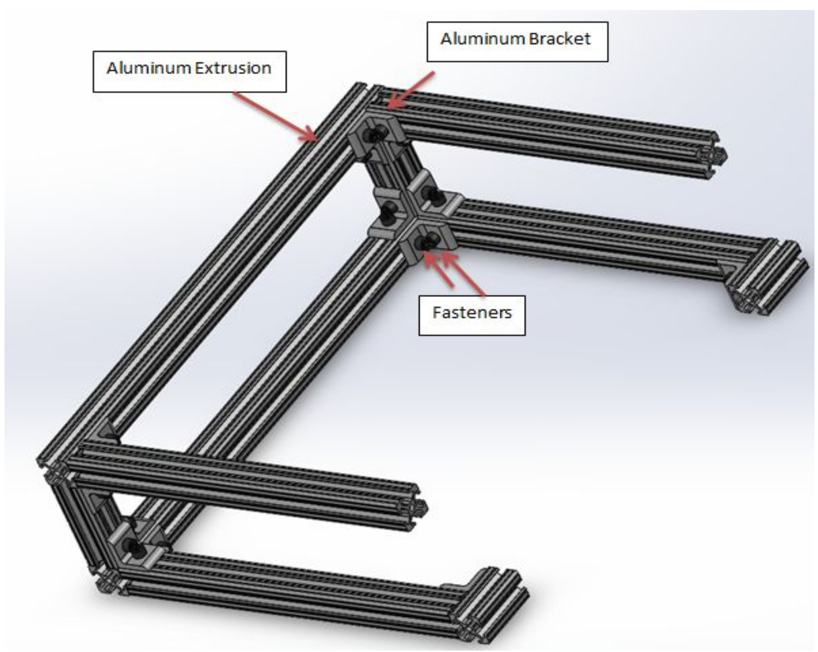


Figure 4: The chassis mount with fasteners and bracket attached to aluminum extrusion

The motor mounts were made from scrap steel and water jet cut. They were designed to accommodate the motors and fasten to the bottom of the chassis using the same standard fasteners, with spacers to ensure the proper screw depth. A 3D printed spacer matching the contour of the motor body helps mitigate a potential moment on the end of the motor, which is screwed to the motor near the axle at the outside of the chassis footprint. Hose clamps provide further support for the motor and 3D printed spacer. The total wheel motor configuration is shown in Figure 5.

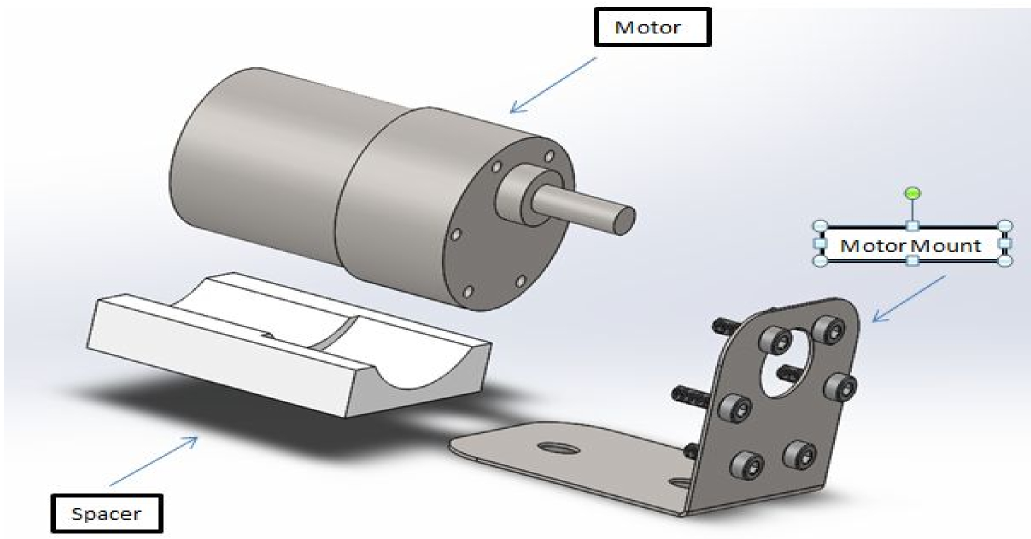


Figure 5- The wheel motor components

The last feature is the mounting system for the battery and electronics. This included a narrow wooden beam fastened to the T-slot frame, providing a makeshift shelf on the chassis in a position that doesn't interfere with the putter motion. One benefit of using the aluminum extrusion for the chassis is that the mounting, which was the last feature to be designed, was easy to integrate with the rest of the design.

3c. PUTTING SUBSYSTEM

Design overview

The putting subsystem was tasked with designing a means by which to project the ball towards the hole. It was decided early in the design process that we would focus on a simple yet robust design. Considering this goal, we developed a putting system that makes use of a load and release style system. The overall putting system is provided in figure 6. The overall design has been classified into three different subfunctions including, the putter holder/pendulum, the drivetrain and the trigger mechanism.

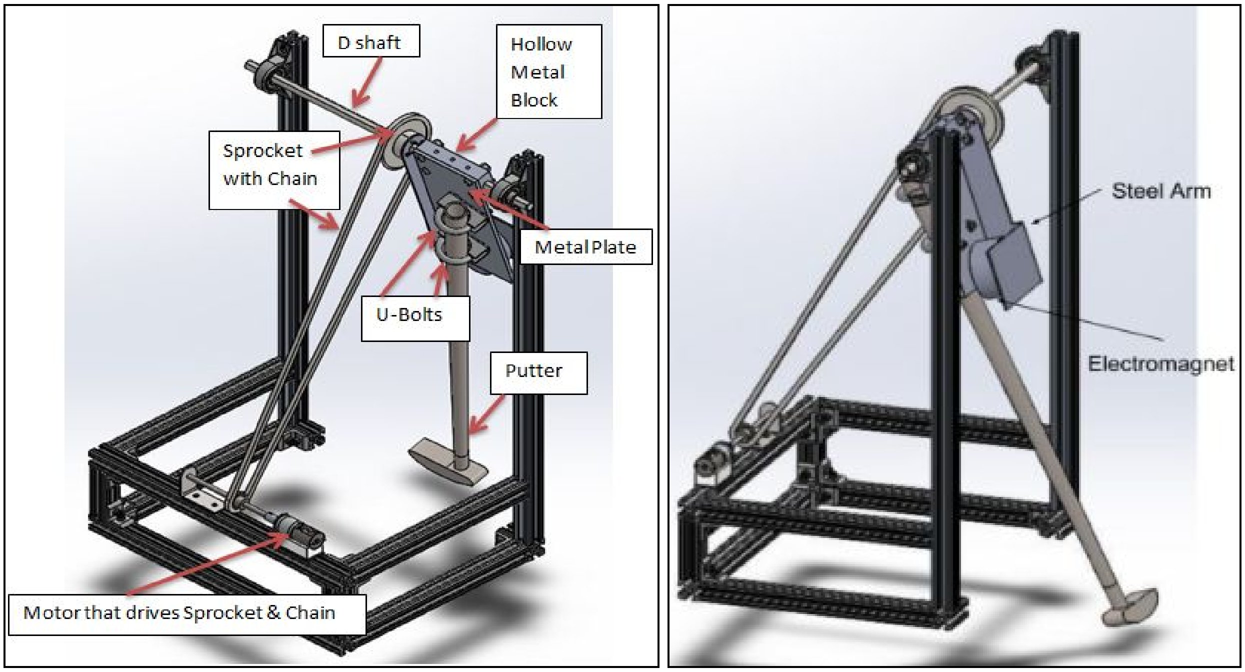


Figure 6: The pendulum design assembly

The design operates by securely attaching the putter to the frame with clamping U-bolts. The putter holder allows the putter to spin freely along the axis. A motor is connected to a sprocket and chain system which drives the putter up to the desired angle before releasing the putter. A steel arm is attached to the large sprocket on the top shaft. The arm provides the driving force to the putting system. To begin the putter energizing process, the electromagnet is engaged and comes into contact with the driving arm. Due to the force of the magnet, the arm is now attached to the putter holder and is able to load the putter to the desired position. Once the putter is ready to be released, the electromagnet is disengaged and allows the putter to swing through and hit the ball.

Throughout the design process the number of parts required as well as the number of parts requiring manufacturing was considered, with the goal of minimizing both of these values. This can be seen in the putter holder design. Although these parts required some manufacturing, the amount of work that was required to produce the parts was minimized, in most situations only requiring a few holes to be drilled in the pieces. In addition, several attempts were made to simplify the trigger mechanism. A rocker-slider mechanism is a strong option for the mechanism, however it requires the manufacturing of several precise pieces. Options such as a solenoid or an electromagnet can be bought off-the-shelf and do not have additional pieces which would require manufacturing.

Another aspect of our design that we wished to implement was adjustability. Although there was rationale behind each decision that was made in the design process, there were still a lot of unanswered questions throughout the process. This goal lead to the decision to use fasteners such as set screws and aluminum extrusions, rather than more permanent solutions. This allows for quick disassembly and rebuild of the mechanism.

A great deal of our design process included testing proof of concept for the different portions of our system. Although calculations were conducted to size each of the parts in consideration, the general consensus was that it would be beneficial to actually see each of these concepts operate. Therefore, tests were conducted to determine how far the ball would be able to travel from a pendulum design and to determine the potential effectiveness of each of the potential trigger mechanisms.

Pendulum

Playing any version of golf, the ideal motion for a golfer is to swing the club so that the ball will reach close to or in the hole. To create a golfing robot there are two options for the swinging motion that hits the golf ball. A drivetrain that is motorized so the putt head has enough force to hit and move the golf ball towards the hole or a pendulum that allows gravity to create a swinging motion that will enable the putter head to hit the ball towards the hole. In our putting subsystem, we have adopted the pendulum methodology. From our calculations, if the golf club is raise to 90 degrees in five seconds and released the impact force of the putter head on the golf ball allows the ball to displace as far as 50 ft on flat turf. Given that the farthest hole is only 40ft, the pendulum idea is sufficient for the golf robot. This was proven experimentally before beginning fabrication of the actual putter system using a testing apparatus designed to demonstrate the dynamics of the putter swinging motion (as further discussed in section 5a).

To accomplish the pendulum motion of the putter, we had to consider how we would load

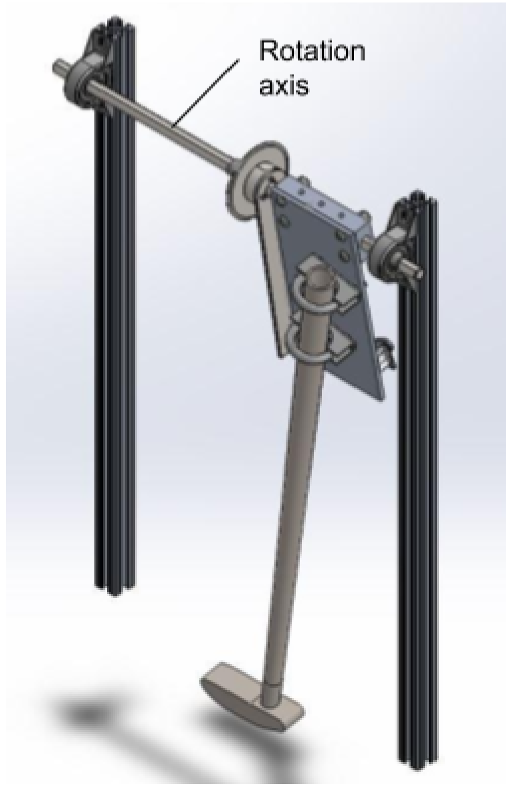


Figure 7: Putter pendulum system

the putter and how we would release the putter so that the putter head would hit the ball accurately. From a consensus design choice, the team decided to use a sprocket chain mechanism that is powered by a motor to load the putter in the 90 degree orientation, shown in Figure 7. The putter is held up by using two U-bolt grips that attach to a metal plate putter holder. This putter holder is attached to a hollow metal block that enables the putter to load from the sprocket and chain mechanism through the d-shaft axle. To keep the metal plate and block secure, screws are tightened so that the metal plate and metal block attachment is rigid. The axle has a steel plate attachment that when magnetized by the electromagnet will enable the putter to load from the sprocket chain mechanism. Further details of the sprocket chain mechanism, motor, metal plate, steel plate and electromagnet will be explained as this full pendulum motion of the putter will be split into two parts. First is the drivetrain portion, where the sprocket chain mechanism is loaded by a motor and the putter held onto by a metal arm. Then comes the trigger mechanism that uses the magnetic force of the electromagnetic to release the steel plate from the putter holder, enabling the putter to have the full pendulum motion to hit the golf ball.

Drivetrain

The drivetrain for the putting subsystem is composed of two main components: the gear motor and the chain and sprockets. A gearmotor was selected based on the power and torque calculations that can be seen in the appendices. A gearmotor was chosen because of the higher torques attainable from gearmotors. In this application we didn't want a high speed motor. The full specifications of the gearmotor can be seen in the appendices, but the key specifications are at 12V: ω_{NL} = 43 RPM, T_{Stall} = 250 oz-in. To attach the motor to the robot a motor mount was manufactured through the use of a water jet cutter. The same process was used to manufacture a support for the other side of the drive shaft.

To increase the torque from the motor, a chain and sprocket system was used to create a gear ratio of 2.97. The small sprocket was mounted on the drive shaft with a set screw and the large sprocket was mounted with an oil embedded bushing on the top shaft to allow the sprocket to spin freely on that shaft. Lateral movement of the large sprocket was prevented by placing a shaft collar on either side of the large sprocket. A magnet arm was rigidly attached to the large sprocket and drives the rotation of the putter when the magnet is activated. The magnet arm was also cut out of sheet steel using a water jet cutter. To attach the magnet arm to the large sprocket, the sprocket required machining to modify it to be suitable for use. A mock-up of the chain and sprocket system can be seen in figure 8.

Figure 8 - Chain and sprocket assembly

The idea of using a worm gear set to hold the putter in the loaded position was explored as well. The budget only allowed for a plastic worm gear, not metal, so we needed to determine the stress the worm gear teeth would face. A fairly standard value for the maximum allowable stress for plastic is 5000 psi and the number calculated for our system was upwards of 30,000 psi. That calculation can be found in the appendices. This meant that we were not able to use a plastic worm gear since a metal one would not fit within the budget. The worm gear set idea was abandoned and it was decided that we would order the gearmotor with a motor encoder. The encoder allows for a constant torque to be applied when the putter is loaded up. This counteracts the backdrive the motor experiences from the weight of the putter and putter holder, allowing the putter to be held at a constant position.

Trigger mechanism

The trigger mechanism has experienced significant change from the initial design process. The current design, figure 10, consists of a DC Electromagnet which is mounted to the back side of the putter holder. A single bolt is used to secure the electromagnet to the plate. The hook arm is secured to the driven sprocket with several bolts. The arm can be seen in figure 9. It is important that the arm be made out of steel so as to ensure that the arm will become

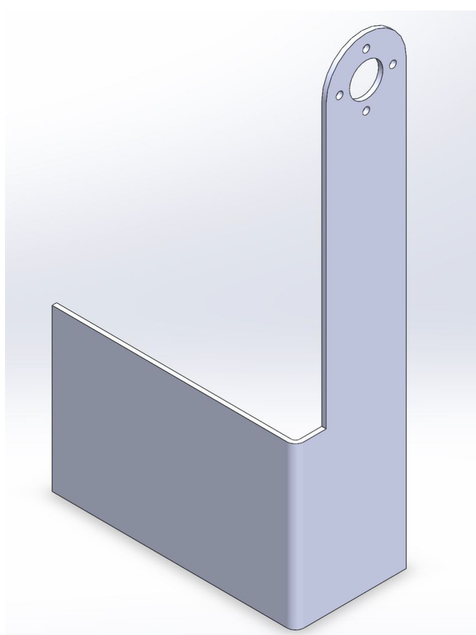


Figure 9: Putting system trigger mechanism magnetic arm

stick to the electromagnet. The arm extends the length of the putter holder and has a 90 degree bend at the bottom of the arm. The bent section of the arm serves the purpose of creating a plane that will be parallel to the plate. In order to engage the electromagnet, electricity is supplied to the device. The force caused by the magnet will secure the putter to the driven arm and allow the putter to be raised to the desired angle. Once the desired angle is achieved, the putter is allowed to swing freely by terminating the electrical supply being provided to the electromagnet.

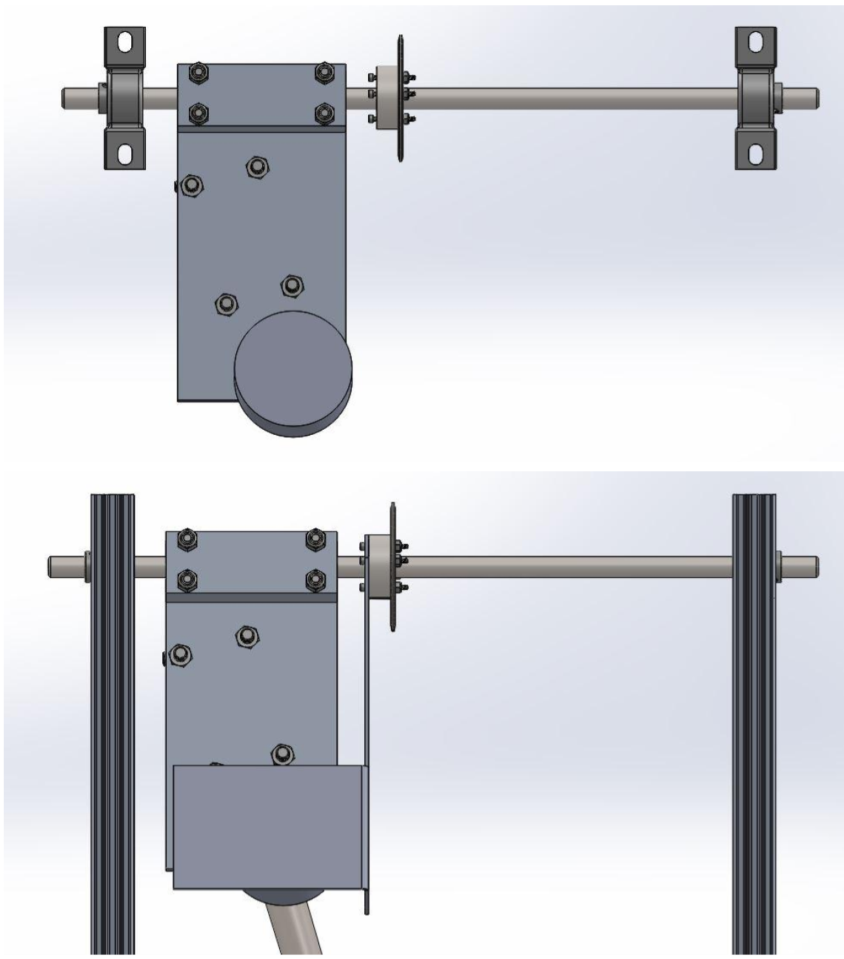


Figure 10: Trigger mechanism, top: electromagnet,
bottom: electromagnet with magnetic arm

Several previous designs were considered and tested to act as a trigger mechanism. Such designs include a rocker-slider mechanism as well as a DC pull-type solenoid. Both of these designs consisted of a pin extending from the side of the putter holder which would act as a contact point for a driven hook arm. When it was time to release the putter, the pin would be retracted allowing the putter to swing freely. Initial calculations determined that a solenoid should be able to provide enough force to retract the pin. However, during testing the solenoids were unable to provide enough force to complete the task.

3d. ELECTRONICS & CONTROLS

Design Overview

The putting machine is run using an Arduino that controls all electrical aspects of the vehicle. The system is powered by a 12 DCV battery. Roughly speaking, the system works by getting an input from the RC controller which is then processed by the Arduino which outputs a PWM (pulse width modulation) signal that is then amplified by one of the motor drivers. The amplified signal is then sent to either the wheel motors, the chain mechanism, or the release mechanism.

PWM is a technique used to regulate a DC voltage to power DC motors. It works by sending out a signal that is either on or off. Based off the duration of either on or off it is possible to create a range of different voltages. This allows the group to change the amount of power produced by one of the mechanisms in order to create precise movements depending on the situation. However, the Arduino only outputs a 5 DCV signal and the motors all require 12 DCV.

To step up the voltage, so that there is sufficient power going to each mechanism, a motor driver was used in conjunction with the Arduino. It is important to note that the motor driver does not amplify the power from the Arduino. Instead, the motor driver takes the 12 DCV input from the battery and just imitates the input signal from the Arduino. This output signal is then transferred to the designated mechanism. In total there are 3 different motor drivers that power 6 different motors.

Implementation

This functionality is relatively simple to implement. The radio controller pairs with its receiver. This receiver, powered with 5V from the Arduino board, has a separate output pin for each radio channel. These outputs are digital, meaning that they will be read by the board as having a value of 1 if it is high (meaning there is a voltage on that pin) or a 0 if it is low. These outputs pulse on and off at various frequencies depending on the state of the control. For example, channel 2 (as seen in figure 11 below), which controls rotation of the robot, will pulse least rapidly when the stick is pushed farthest left, and most rapidly when the stick is pushed farthest right. The Arduino reads these signals and calculates the time passed between pulses in microseconds. This ranges from approximately 1080 to approximately 1880 where, in the example of channel 2, 1080 microseconds are measured between pulses when the stick is in the far right position, and 1880 microseconds when the stick is in the far left position. The motor drivers accept inputs ranging from -255 (which generates a full 12V running the motor backward) to +255 (12V running the motor forward), so an equation was derived to scale the pulse readings to be within that range, where a pulse reading of 1080 will result in a value of -255 when passed through the equation and 1880 will produce +255.

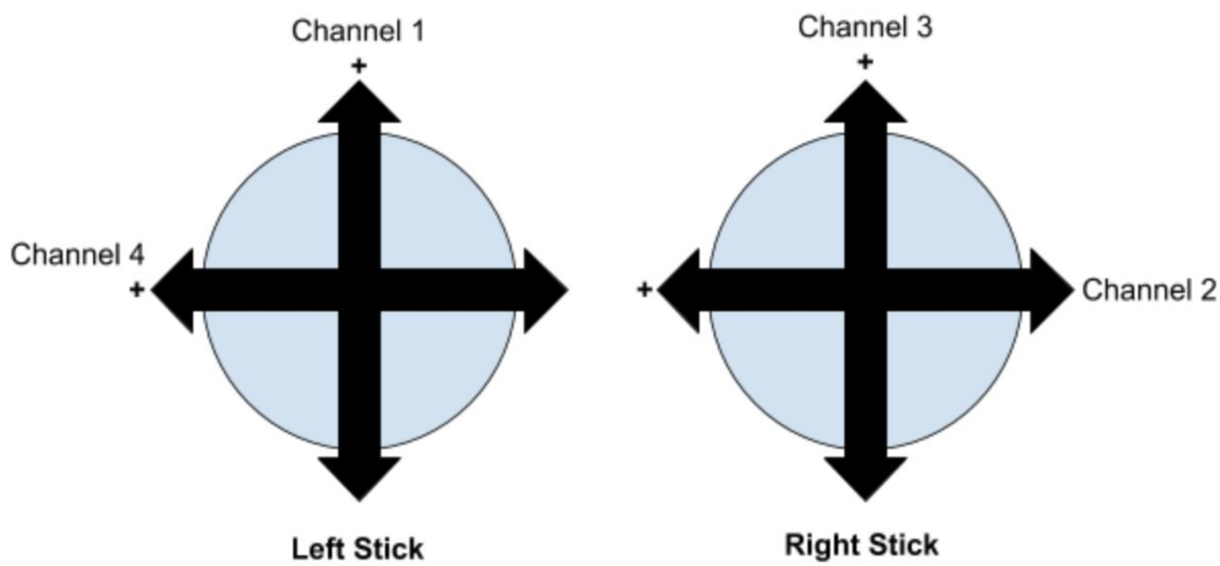


Figure 11: A diagram of the RC joystick controls and their corresponding channels. The "+" indicates the direction in which the pulse width from the receiver increases.

Currently, the driving controls are fully decoupled from one another, meaning only one can be used at a time. The robot can be moved forward or back OR left or right OR be rotated at a given time. We hoped to implement some code that would take inputs from all three controls and calculate the speeds at which the motors must rotate to produce the desired movement of the robot. This would allow us, for example, to drive forward while also commanding the robot to rotate, producing a curved path of motion.

The putting controls are similar, with channel 3 controlling the rise and fall of the putter to power the swing; however, there are two distinct differences. First is the trigger mechanism. This will depend on an electromagnet controlled with channel 5 (not shown), which is linked to switches S1 and S3 on the radio controller. This magnet expects a 12V input, which can be controlled most easily using a motor driver. When the switches are both in the up position (producing a pulse width of approximately 1880 microseconds), a PWM input of 255 will be supplied to the motor driver, which should trigger an output of 12V to the magnet. This will enable the magnet. As soon as one of the two switches is flipped (producing a new pulse width of approximately 1490 microseconds), an input of zero will be supplied to the motor driver, the magnet will be disabled and the putter will be allowed to swing freely.

The second distinct difference in the implementation of the putter system is the way in which the position of the putter is maintained in preparation of a swing. The gearmotor selected does not lock up, so backdriving is a considerable concern when the putter is in its raised position. To mitigate this issue, a gearmotor was selected with a rotary encoder attached. Though our encoder relies on electronic sensors, rotary encoders can be understood as containing a disk with slots cut out of it (crudely demonstrated in figure 12 below). This imagined disk has a light shone on a point on it in line with a light sensor. When the sensor sees the light it knows the disk has rotated such that a slot has aligned with the light. It can count the number of times the light sensor has been triggered to determine how far the wheel has rotated from a starting position. Our encoder can be imagined as having two such disks, approximately 90 degrees out of phase from one another. Depending on the pattern with which the sensor is triggered (ie. which disk triggers the sensor first), the direction of rotation can be determined, as visualized in Figure 13. This encoder can be relied on to maintain the position of the putter. The radio controller is used to bring the putter to the desired angle and then the Arduino watches the encoder to determine whether the putter has moved. If the encoder indicates that the putter has lowered, the Arduino will send power to the motor to raise the putter back to the desired position. This is currently implemented using proportional control, meaning that the power supplied to the motor is directly proportional to the encoder position's distance from the desired position. Though this does have the downside that there will always be some amount of “sag” in the putter (ie. it will always sink some amount), this ensures that the an equilibrium will be found where the motor provides exactly the torque required to counter the torque applied to the shaft by the putter.

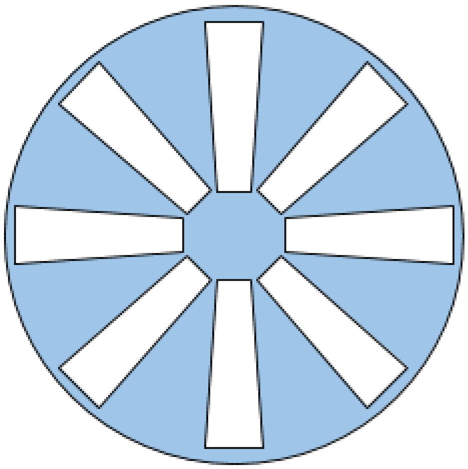


Figure 12: A sketch of a rotary encoder.

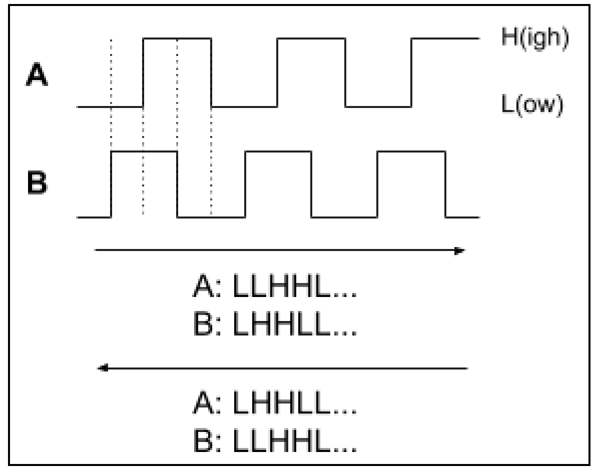


Figure 13: A visualization of the states of the rotary encoder disks over time, and how the sequence of their change can help determine the direction of rotation.

4. FINAL DESIGN

4a. FINAL PRODUCT: PHOTO GALLERY

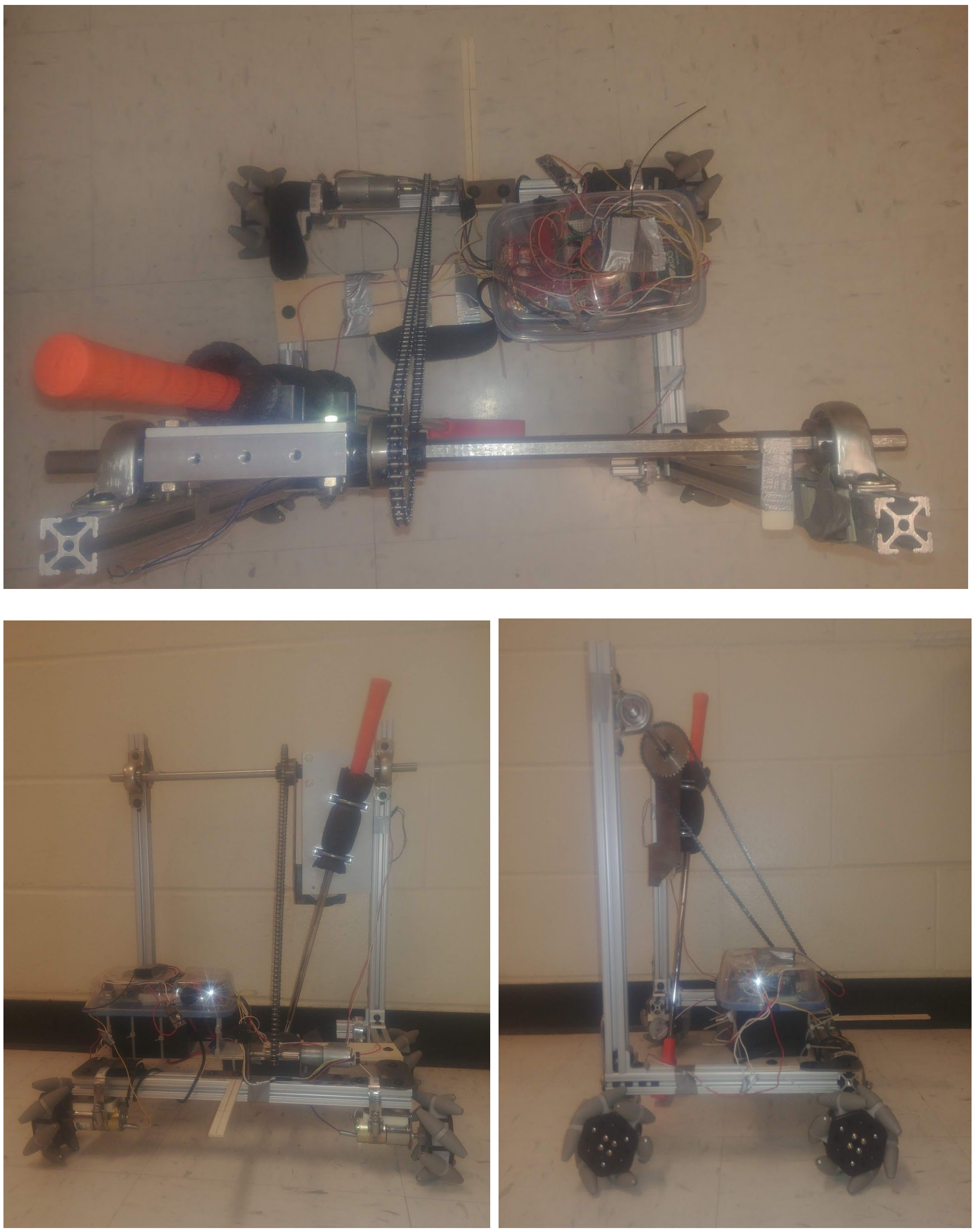


Fig. 14: Top, front, and right-side views of FIONA.

Fig. 15: Isometric View of FIONA

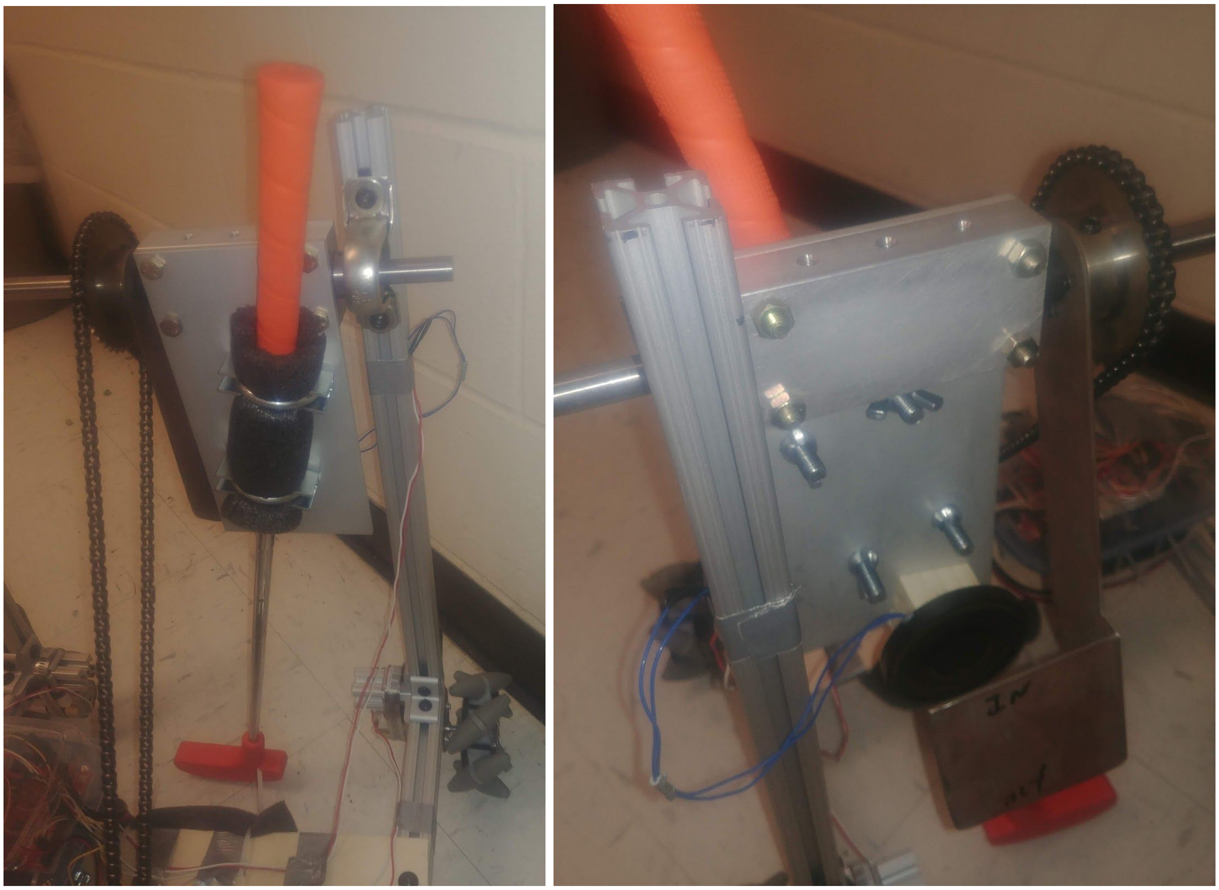


Fig. 16: Detail view of front (left) and back (right) side views of putter load and release mechanism, featuring non-marring putter clamp (front) and electromagnet coupled with steel plate for putter release (back)

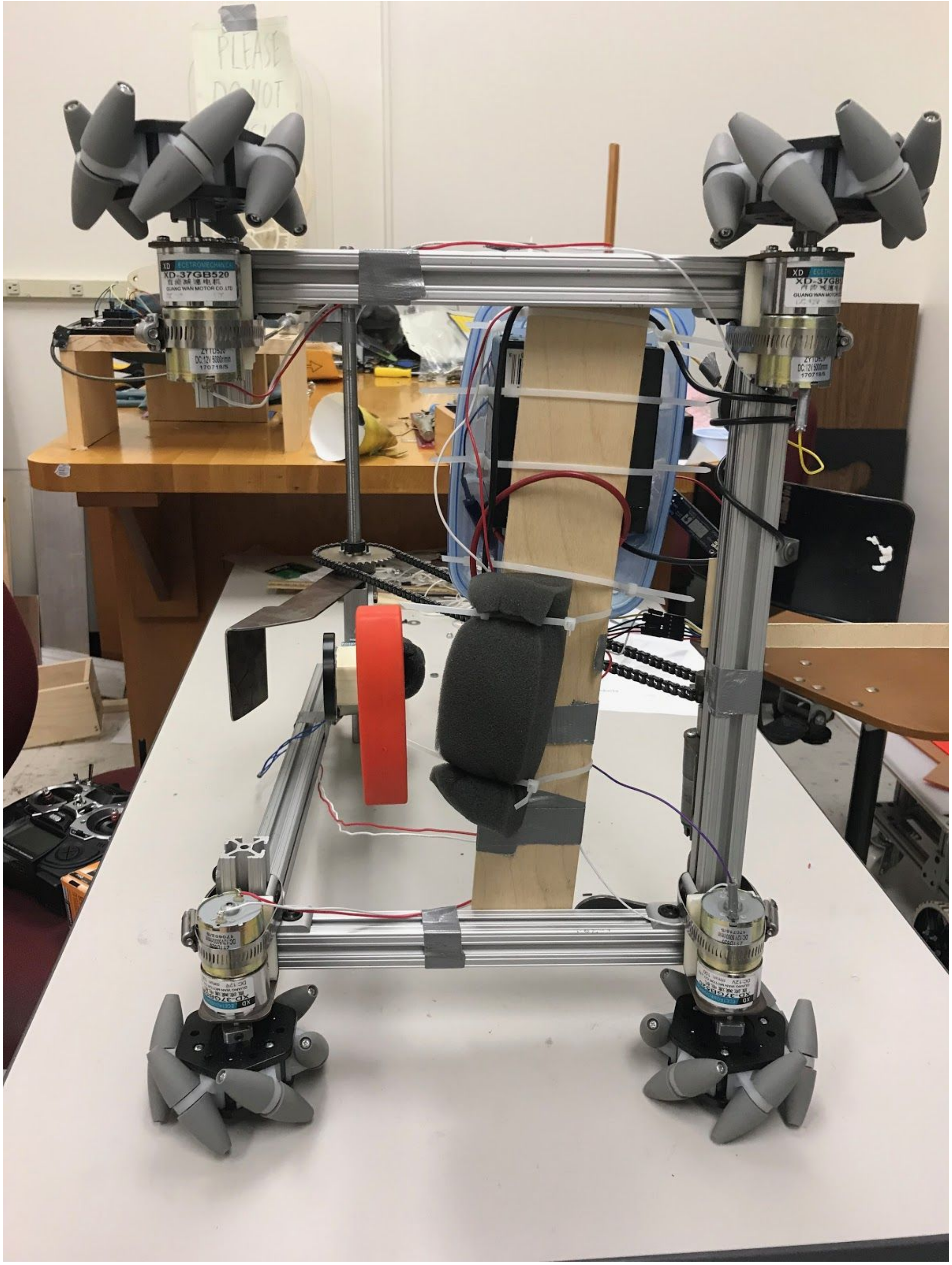


Fig 17: bottom view of FIONA. Note that the axles of the rollers of the mecanums from this angle form an approximate ring, or O shape. This orientation allows the mecanum wheels maximum maneuverability for both forward/back, turning, and side-to-side strafe.

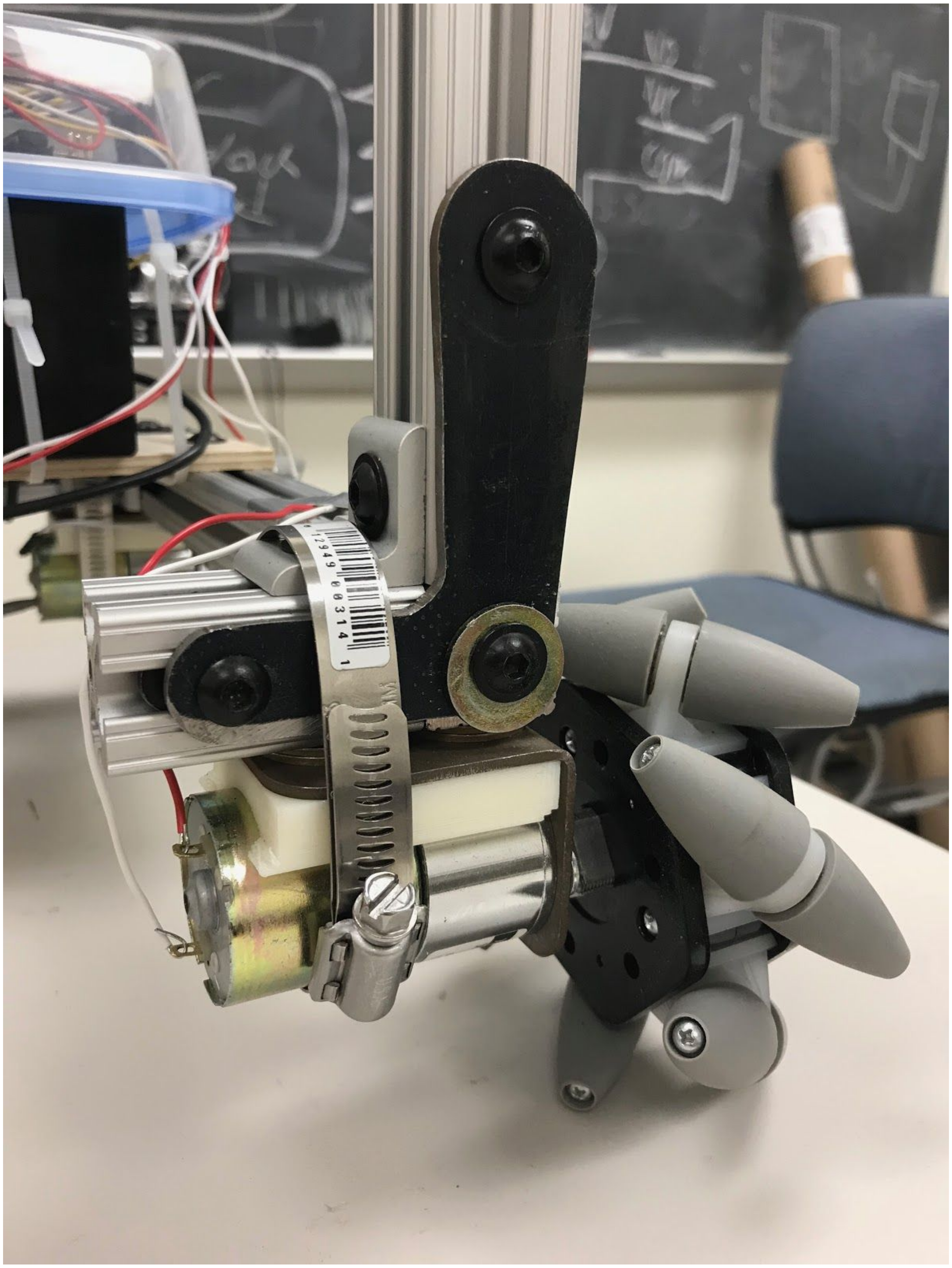
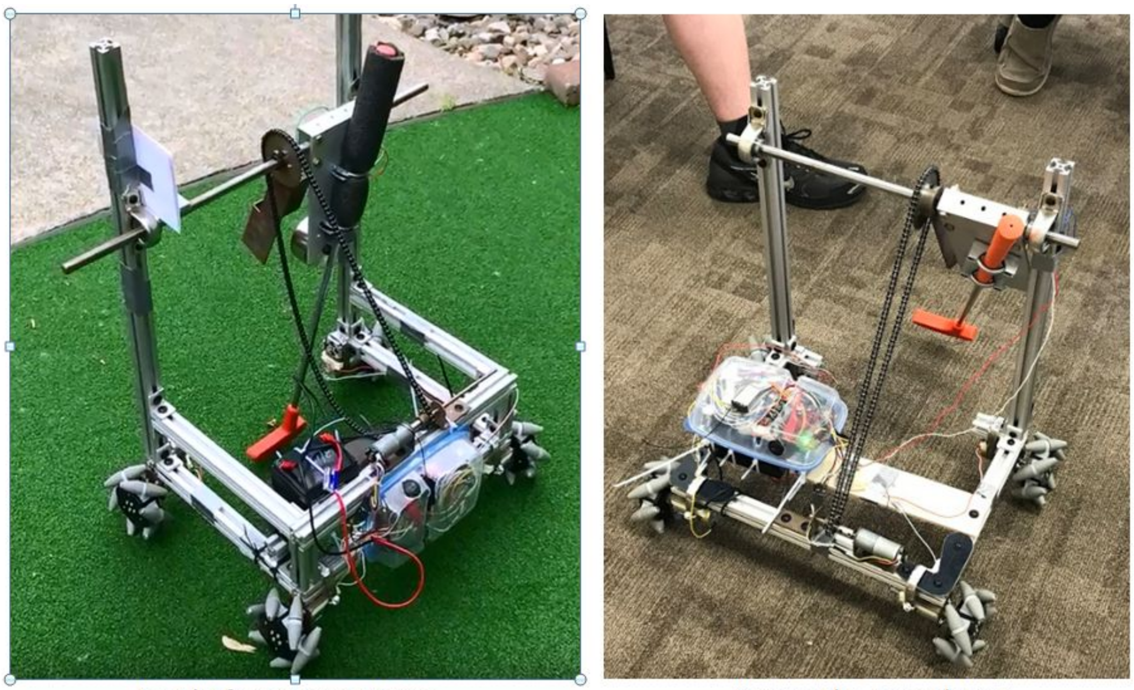


Fig. 18: Detail of wheel mount and frame construction. Steel L-bracket used on corner to stiffen and reinforce aluminum T-slot structure. Mecanum wheel (left) directly connected to gear motor output. Each motor is mounted on a bracket to the aluminum T-slot rail, then supported with a 3d printed cradle and hose clamped to frame for stability.

4b. SUMMARY OF IMPORTANT MODIFICATIONS

Driving System

The two primary issues we encountered stemmed from a lack of power from the motors. After the full assembly was completed, the robot was completely unable to strafe left or right on the turf (one of the primary benefits of the mecanum wheels). This was undoubtedly contributed to by the unexpectedly high weight of the robot (approximately 25 lb, when the original power calculations were done using 16 lb). We took the most logical course of action: reducing the weight. The base dimensions were left untouched, but we decided to experiment with removing the upper layer of the chassis, which was primary there for support. With added support from surface plates, we found that the robot was nearly as rigid as the original design. This was the only significant portion of the wheel and chassis subsystem that could be removed to reduce weight without compromising the structure. For a detailed adjustment see Figure 19. However, this modification, in addition to the decreased weight in the putter system, reduced the total weight of the robot to 19 lb. At this weight, strafing movement became possible on the course turf, although it was still slow and unreliable enough to be impractical for normal use.



Just before Competition　　　　During the Completion

Figure 19: The adjustment made to reduce the weight for the competition

The other main issue we encountered was due to a fault of the battery. We were finding that, while the robot performed as intended with a freshly charged battery, it rapidly became sluggish, and soon after, unresponsive. We discovered that as long as at least 12V were provided by the battery, the robot could function as intended; however, as the batteries discharged, their voltage outputs were quickly reduced. To mitigate this issue we have added a step-up voltage regulator, which keeps the battery voltage output steady even as it discharges, and which we hope will allow us to use a given battery for much longer before having to switch it out. The voltage regulator used could adjust its output via a potentiometer, so the output voltage was set to 13.7V because the maximum voltage the battery would reach was approximately 13.3V.

Putting System

The putting system has experienced several small modifications since the initial draft of the report. Nearly all of the modifications were made with the goal of decreasing the weight of the putting system. The aluminum extrusion supports have been cut down to 18 inches with the putter now being choked up as high as possible. By choking up on the putter, it can now be loaded past 90 degrees. In addition, unneeded lengths of the two shafts were cut off and any excess material on the magnetic arm was also cut off. Finally, the original electromagnet was replaced with a new electromagnet with a similar diameter, but has half the weight. In order to have the electromagnet be flat with the magnetic arm, a wood spacer was produced and placed between the putter holder and the electromagnet. By performing these small modifications we were able to decrease the weight of the putting system. The overall process by which the putting system works remained the same.

5. RESULTS OF TESTING

5a. PRELIMINARY TESTING

Putting

Figure 20 - Putting test rig

Preliminary testing was conducted for the putting subsystem. We wanted to determine whether or not a putter pulled back to 90° and released as a pendulum had enough power to hit a golf ball the required distance and up the hills that will be faced at the course. To accomplish this two simple wooden supports were made and a ¼” steel shaft was run between them inside oil embedded bushings. A simple holder was made to attach the putter to the test rig with zip ties. The holder was based off the design for the final putter holder used for the robot and recreated with wood. The test rig can be seen in figure 20.

The test rig was brought to the course and tested on a few of the holes. Pulled back to 90°, the test rig was able to putt the golf ball more than 30 ft (flat ground) on the longest hole at the course. A hole with a short steep hill (roughly 30°-40°) was tested and the rig, again loaded to 90°, was able to hit the ball to the top. It was found that the most difficult hole for the pendulum power was a hole that had a long 20°-30° incline (more than 25 ft). When the rig was loaded to 90° the ball was only hit about ⅔ of the way up the incline. However, this distance was enough to allow the ball to go around an obstacle and off of the incline. The rig was then loaded to roughly 120° on the same hole and the ball was hit all the way up the incline. This preliminary testing was a proof of concept for the pendulum powered swing.

Driving

Figure 21 - Mecanum wheel testing apparatus

Preliminary testing was also conducted for the driving system due to the lack of information on mecanum wheels performance on uneven turf. All available literature on mecanum wheels describes their performance on flat smooth surfaces, so to confirm that the design concept would in fact work for the mini-golf course terrain, driving experimentation was conducted. The minimum effort necessary to prepare a driving testing apparatus was given in order to test as early as possible urgency of testing over all other aspects of the development was crucial because if the mecanum wheels could not work on the course, a redesign would have been necessary to ensure proper performance for the competition. The testing apparatus design was also kept minimal to avoid spending too much of the budget in case the purchased parts would not be usable after a redesign. Before fabricating the entire driving platform, a simple platform with a basic mecanum wheel setup was constructed for testing, as seen in Figure 21. Hard-coded commands were implemented into the Arduino code because implementing interactive control using an RC controller would take additional time to develop.

Testing the mecanum wheels on the course proved that they could be used to properly navigate the terrain and aim the target line. Performance in the forward/backward and rotation directions performed without any flaws, and strafing motion was achieved in most circumstances after the tolerances of the structure and location of the center of gravity were adjusted.

5b. EVALUATION OF METRICS

Table 2: Completed Metrics Table

Metric #	Req. #	Metric	Units	Importance (1-5)	Target value	Measured value
1	1	Average time to complete a hole	s	4	50	134
2	2,7	weight	lbs	2	16	19.7
3	2	Static tipping angle	deg	4	30	45
4	5	# RC channels used	#	5	<6	5
5	6	Total cost	$	4	500	512.49
6	8	Total # of parts	#	1	<100	54
7	8	Total # of parts manufactured by machine shop	#	4	<10	7
8	8	Total # of waterjet parts	#	3	<25	4
9	9	Difference in time between fastest driver and slowest driver on same hole	s	3	10	12
10	9	Intuitiveness scale 1-10	#	2	10	8
11	11	Time to load putter to max position	s	3	5	2.05
12	12	Min. distance between ball and wall at which putter can hit ball (min 6”)	in	4	6	4
13	13	Standard deviation of ball distance traveled given a consistent loading angle (40°)	in	4	12	9.237
14	13	Standard deviation of ball trajectory alignment with target line given a consistent putter position	deg	5	1	0.577
15	14	# of obstacles unable to maneuver around	#	4	0	0
16	15	Smallest angle adjustment possible for putter aiming	deg	5	1	1

17	15	Smallest angle adjustment possible for putter loading	deg	4	1	1-5

Metric descriptions:

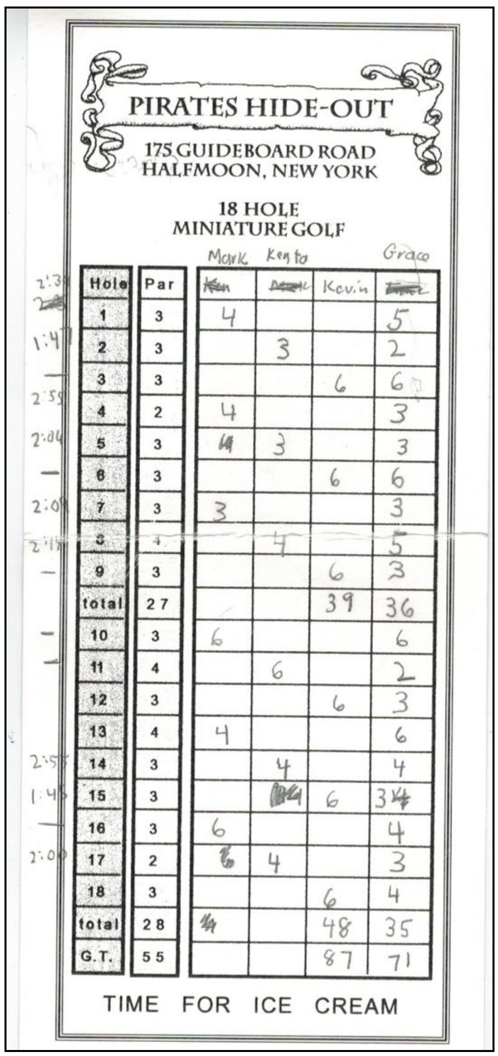
1. While the average time to complete each hole went over the metric, it was well under the time limit for the competition. The average time during competition is not a fully accurate representation of the speed of the robot because the drivers were not controlling the robot to perform as fact as it can. Since the robot had proven to be able to complete certain holes in under 50 seconds, the drivers were not concerned with the three minute time limit and therefore did not aim for a fast time. It was discovered during testing that the wheels were too small to travel the course quickly given the power output of the battery. However, the small diameter of the wheels allowed the team to make up time in fine adjustments.
2. The test completed vehicle weighed more than expected. This was due to a number of modifications and unforeseen consequences from small amounts that added up. For instance, in the original calculations washers, connectors, and the electromagnet were not considered. To lower the weight the group took off the stabilization apparatus above the wheels.
3. The vehicle did not tip over on the course. However, through some testing it was seen that it was possible to tip the vehicle on the course. To counteract this problem the vehicle was driven away from dangerous inclines and the putter was raised or lowered.
4. The number of RC channels was 5 as more were not needed.
5. The total cost was slightly higher than the target value, but this was also the case for all competing teams.
6. The total number of parts was kept under 100 so the vehicle would not be complicated.
7. The manufactured parts were kept at a minimum to ensure the vehicle did not have many parts.
8. The number of waterjet parts was kept to a minimum to ensure the vehicle did not have many parts.
9. The time difference between the slowest and fastest player was determined from the

times each team member achieved during a practice session. On a practice hole (fabricated indoors) that took approximately one minute to complete, the maximum time difference between players was approximately 12 seconds.

10. The vehicle was easy for people to pick up and use right away. This is because the controls were relatively simple to use. The addition of the aiming mechanism allowed different members to constantly aim towards their target. It was observed that the biggest difficulty for each member was learning how to keep the time down for each hole. Once the individual remembered to move the putter in position while moving towards the ball, the time was significantly reduced.
11. The time to load the putter to the maximum power was kept below the design metric. This was in part due to the electromagnet, which reduced the loading time.
12. The putter was able to hit a ball away from the course wall when it was 4” away, given the consistent height of the bricks that constructed the wall.
13. The ball distance traveled given a consistent putter loading angle was sufficiently consistent for the competition. Since a ball will sink into a hole even is it still has some speed when it reaches the hole, the allowable deviation was considered greater than the diameter of the hole. The deviation increased as the distance show increased
14. The angle of the ball trajectory given a repeatable putt was highly consistent. This test was done on flat turf at the course. However, the ball was hit so that it only traveled between 1 and 2 feet. If the ball were hit at further distances, the deviation could increase due to more encounters with imperfections in the terrain.
15. There was no obstacle the vehicle could not move around during the competition.
16. The angle was easy to change and was able to handle small adjustments.
17. The mecanum wheels allowed for the vehicle to rotate almost perfectly and the smaller diameter wheels allowed for great control of rotation. The minimum angle achievable is set to a range since there is approximately a $\pm 2°$ uncertainty due to the underdamped oscillation of the putter drivetrain motor when at lower torques.

5c. RESULTS OF COMPETITION

For the competition the rules were changed to account for problems faced by the teams. The first rule change was that the robots only played six holes total, instead of a full 18. The teams rotated and only played every third hole. The time limit for the robots to play a hole was increased from 60 seconds to three minutes. However, if the three minute time limit was exceeded then a maximum score of six would be awarded automatically. The girl, Gracie, always putted first and there was a one minute time limit for the robot to get off the first shot after she finishes the hole. Finally, if the robot was unable to to drive to the ball it could take up to three putts from tee, assuming a one penalty stroke to return the ball to the tee.


PIRATES HIDE-OUT
175 GUIDEBOARD ROAD
HALFMOON, NEW YORK
18 HOLE
MINIATURE GOLF

Hole	Par	Mark	Kento	Kevin	Grace
1	3	4			5
2	3		3		2
3	3			6	6
4	2	4			3
5	3	[illegible]	3		3
6	3			6	6
7	3	3			3
8	4		4		5
9	3			6	3
total	27			39	36
10	3	6			6
11	4		6		2
12	3			6	3
13	4	4			6
14	3		4		4
15	3		[illegible]	6	3 ~~4~~
16	3	6			4
17	2	[illegible]	4		3
18	3			6	4
total	28	[illegible]		48	35
G.T.	55			87	71

TIME FOR ICE CREAM

Figure 22 - Final scorecard for the competition at Pirates Hideout

The scores for our team can be seen in Figure 22 in the the center column marked as Kentaro. For the second hole, our robot played at par, which was three strokes. For the fifth hole, our robot also played at par of three strokes. For the eighth hole, our robot played again played at par, this time four strokes. At the eleventh hole, our robot played two strokes over par because of misalignment with the hole. At the fourteenth hole, our robot played one stroke over par due to hitting the first shot into a rock hazard. At the seventeenth hole, our robot played two strokes over par because of misalignment of the put.

Overall, the robot performed well during the match. Of all the robots, it played the lowest score relative to par for the holes it played. One function of the mecanum wheels used in the driving system, strafing, did not work well on the turf at the course and it was believed that this would be a large detriment to performance. However, when playing it was found that with just rotation and forward/reverse the robot could be very competitive, especially given the extended time limit. The rotation provided by the mecanum wheels allowed for very small adjustments of the robot position in relation to the hole. This allowed for the robot to be very accurate when aligning the put with the hole. The putting mechanism allowed for fine adjustment in the amount of power behind each put, however it was difficult to judge just how much the putter needed to be loaded for each put. The battery on the robot had been draining quickly in previous tests, only lasting about three holes. We also saw a consistent drop off in the power sent to the motors. This problem was solved by adding a voltage regulator into the circuit, that allowed us to send a constant voltage to the motors. After this solution was implemented, the robot lasted all six holes during the competition without a need to change the battery.

At the end of the competition for the six holes our robot played, it was five strokes over par. Many of the extra strokes over par on holes were due to loading the putter too high. This caused the ball to skip over the hole and add strokes to the score. This showed that more practice driving the robot would have been incredibly useful and would have almost certainly improved our score.

6. CONCLUSIONS

The robot developed throughout this project is a mini-golfing robot that can traverse golf course terrain to aim and putt a ball into the hole. The design is ultimately the combination of two subsystem designs: the driving subsystem and the putting subsystem. The driving subsystem uses the omnidirectional locomotion capabilities of mecanum wheels to quickly navigate the course and aim the putter to the correct alignment. The multiple degrees of freedom provided by the mecanum wheels eliminated the need for a separate aiming subsystem. The structure of the driving platform was constructed using T-slotted aluminum extrusions with multiple fasteners and brackets at each connection to ensure the structure was rigid enough to remain sufficiently flat while being used. The putting subsystem utilized a pendulum design in which the putter was fastened onto a rotating axle that raised the putter to a desired height and then released it to impact the ball. The loading mechanism consisted of a chain-and-sprocket drivetrain that rotated a steel arm that engaged and raised the putter using an electromagnet. The putter was released by disengaging the electromagnet. Due to the added mass of the putter fastening system and the electromagnet, the rotating part of the putter assembly had an increased moment of inertia that contributed to the total energy that the putter system was capable of transferring to the ball. The entire robot was controlled using two Arduino boards, and the power supplied by the battery was kept at the desired level for competition using a voltage regulator.

All but one of the functionalities included in the final design worked sufficiently in the final product used at competition. The only insufficiently performing function was the strafing motion of the mecanum wheels. While strafing was still possible, the trajectory and speed of its movement was too inconsistent to be reliably used during the competition. However, given the extended time limit for each hole and since the strafing functionality served to shorten the time necessary to aim the putter trajectory, the robot was still able to perform to the standards of the competition. The robot could traverse the entire course at sufficient speeds, aim a sufficiently accurate shot, and hit the ball over a sufficiently far distance. The difficulties confronted during competition resulted mainly from the performance of the people controlling the robot and not the robot itself.

Many lessons about engineering design were learned throughout this project. The most important lessons are listed below in order of importance and relevance to the final product:

1. Continuous testing of design parameters throughout fabrication is key to ensuring that the resulting final product will be developed as planned. This lesson was particularly relevant to the fact that the weight of the final product was significantly above the value used for design calculations and limited the strafing abilities of the mecanum wheels. If the weight had been tested earlier in the fabrication process, this issue could have been addressed before the work and time was put in to complete the structure.
2. Conservative assumptions must be made when necessary for streamlined progression of the project. When designing a product without all the necessary information to ensure optimal performance and optimal cost, the assumptions must be made that will maximize the probability that the product will work even if unforeseen issues are found during fabrication. Once a prototype has been developed based on these assumptions, the design can be modified toward optimal performance and cost given the new information collected through testing. Since the performance of mecanum wheels on the golf turf was unknown during the initial design phase, the wheel-driving motors were sized conservatively to ensure that even if the researched understanding of the wheels were misguided, the motors would still be sufficient in driving the robot. The motors were still underpowered in driving strafing motion, but this was due to the underestimation of the weight, not not the sizing of the motors. If the weight had been assumed to be greater than the estimated value by a factor of safety, this issue may not have occurred.
3. Simplicity is key to the robustness of a design. The more parts there are on a product, the more possible points of failure there are, and therefore the more likely it will fail in application. The robot design required many active control systems to ensure intuitive user control, and therefore the electronics design needed to be relatively complicated. This lead to the robot failing to operate multiple times due to unexpected electronics malfunctions during both of the allotted full testing session at the course.
4. It is important to balance the benefit of minimizing manufacturing effort with the cost effectiveness of manufacturing custom parts. Minimizing the number of machine manufactured parts is important for streamlining the development process, but given the

limited availability of certain parts on the market, manufacturing custom parts can also significantly alleviate the cost of production. Fourteen corner brackets needed to be purchased for the T-slotted extrusions that constructed the robot, which cost over $50. After this purchase additional brackets needed to be ordered for the rest of the structure, but instead of ordering the same store-bought brackets, custom brackets were manufactured from an aluminum 90° angle iron that cost $5. Despite the fact that this increased the manufacturing effort, this allowed for the purchase of other crucial parts later in the project. If the brackets were manufactured from the start, the $50 spent on the bought brackets could have been saved.

7. REFERENCES

[1] "Driving Mecanum Wheels Omnidirectional Robots." *DC Motor Controllers*, 27 Oct. 2015, www.roboteq.com/index.php/component/easyblog/entry/driving-mecanum-wheels-omnidirectional-robots?Itemid=1208.

[2] Instructables. "Mecanum Wheel Robot - Bluetooth Controlled." *Instructables.com*, Instructables, 5 Mar. 2018, www.instructables.com/id/Mecanum-wheel-robot-bluetooth-controlled/.

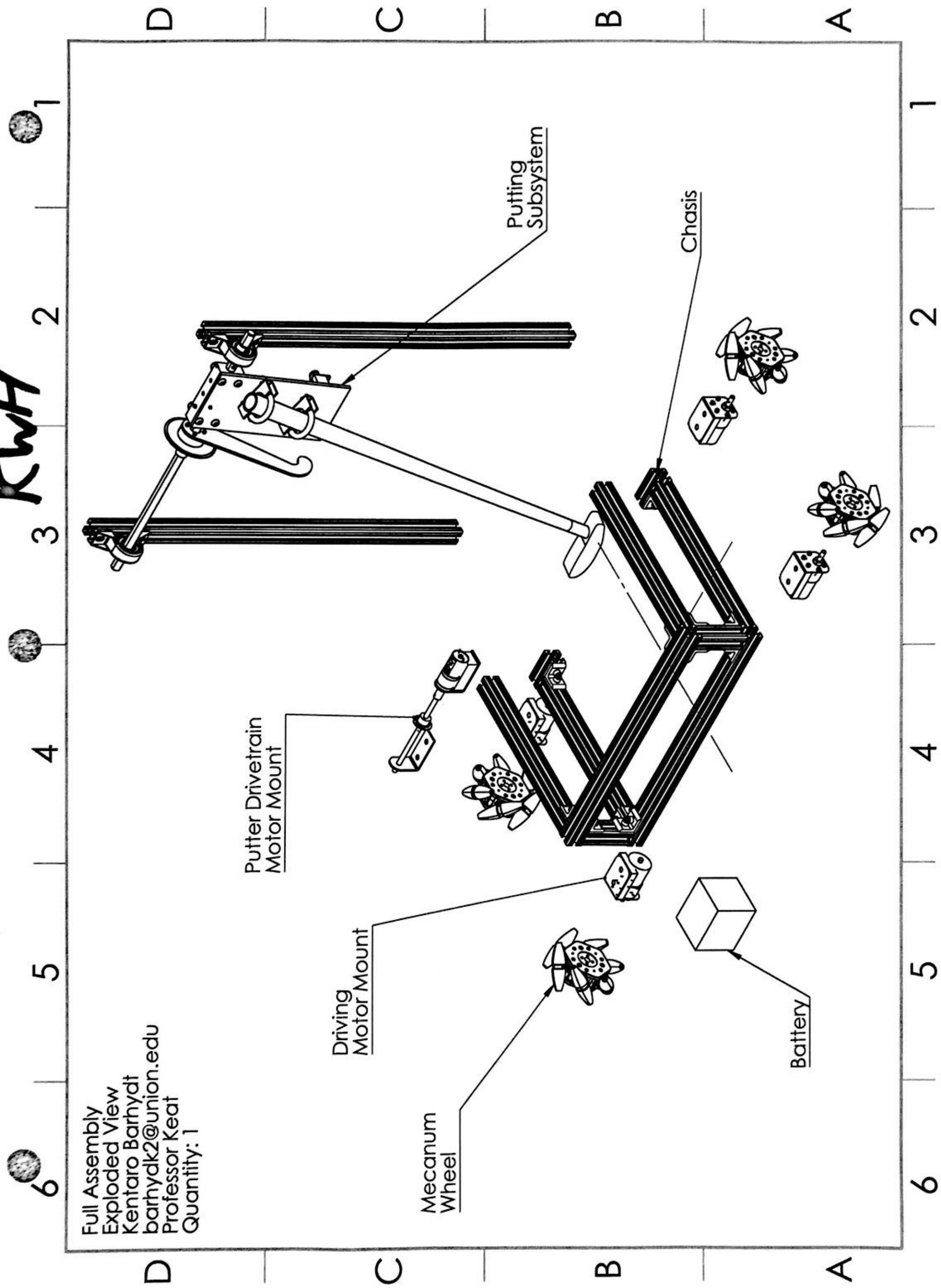
[3] Sonawane, Nishant. "An Experimental Method to Calculate Coefficient of Friction in Mecanum Wheel Rollers and Cost Analysis Using DFMA Techniques." *Embry-Riddle Aeronautical University*, 2015, commons.erau.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1249&context=edt.

[4] Tlale, N. S., and de Villiers, M., 2008, "Kinematics and Dynamics Modelling of a Mecanum Wheeled Mobile Platform," "*15th International Conference on Mechatronics and Machine Vision in Practice, M2VIP'08*", Auckland, New Zealand, pp. 657–662. https://pdfs.semanticscholar.org/f971/36b372f36a588373142e17e8b68f6994227e.pdf

[5] N. Tlale and M. de Villiers, "Kinematics and Dynamics Modelling of a Mecanum Wheeled Mobile Platform," *2008 15th International Conference on Mechatronics and Machine Vision in Practice*, Jan. 2009. https://ieeexplore.ieee.org/document/4749608/

8. APPENDICES

Appendix A - Assembly Drawings



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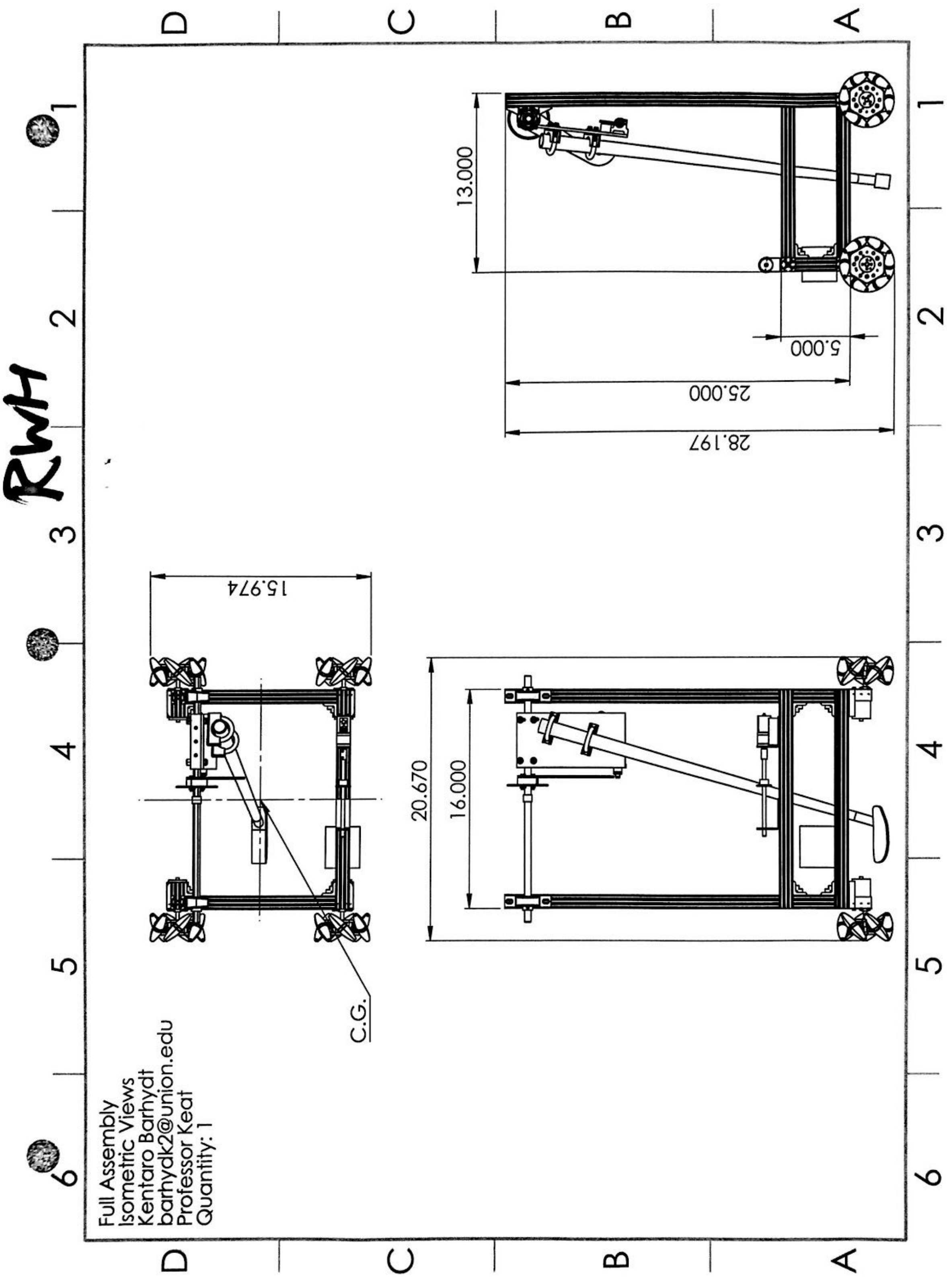

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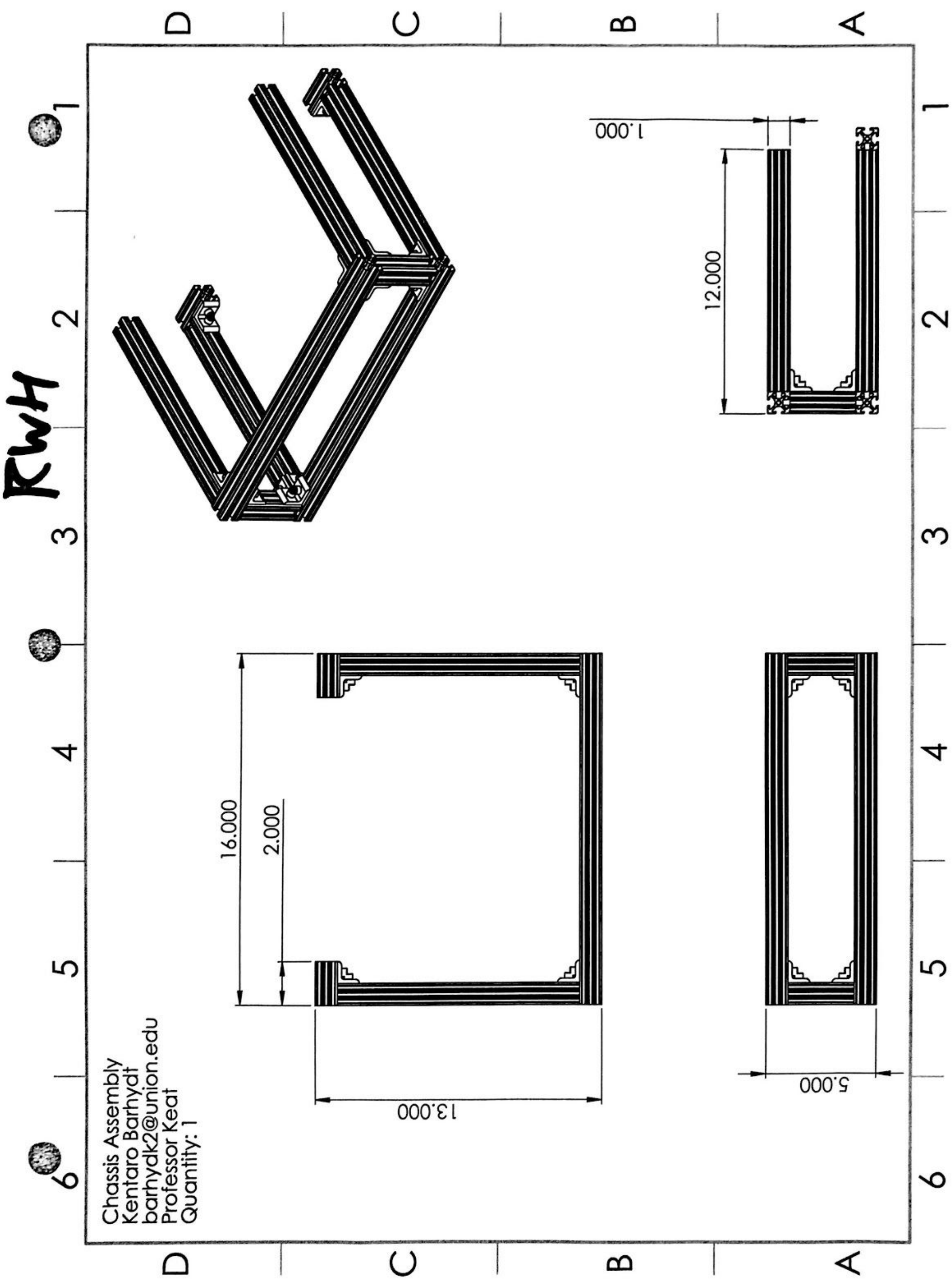

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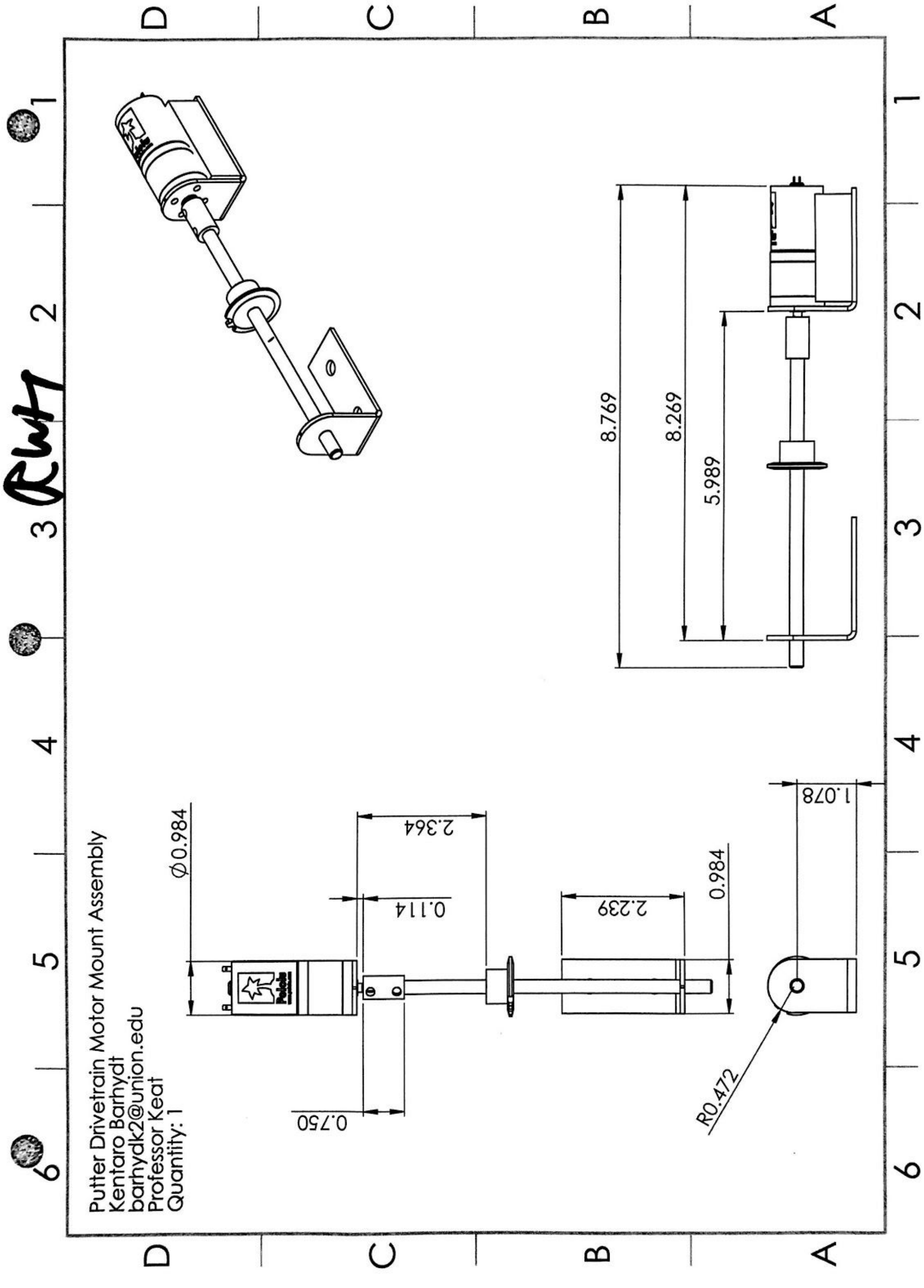

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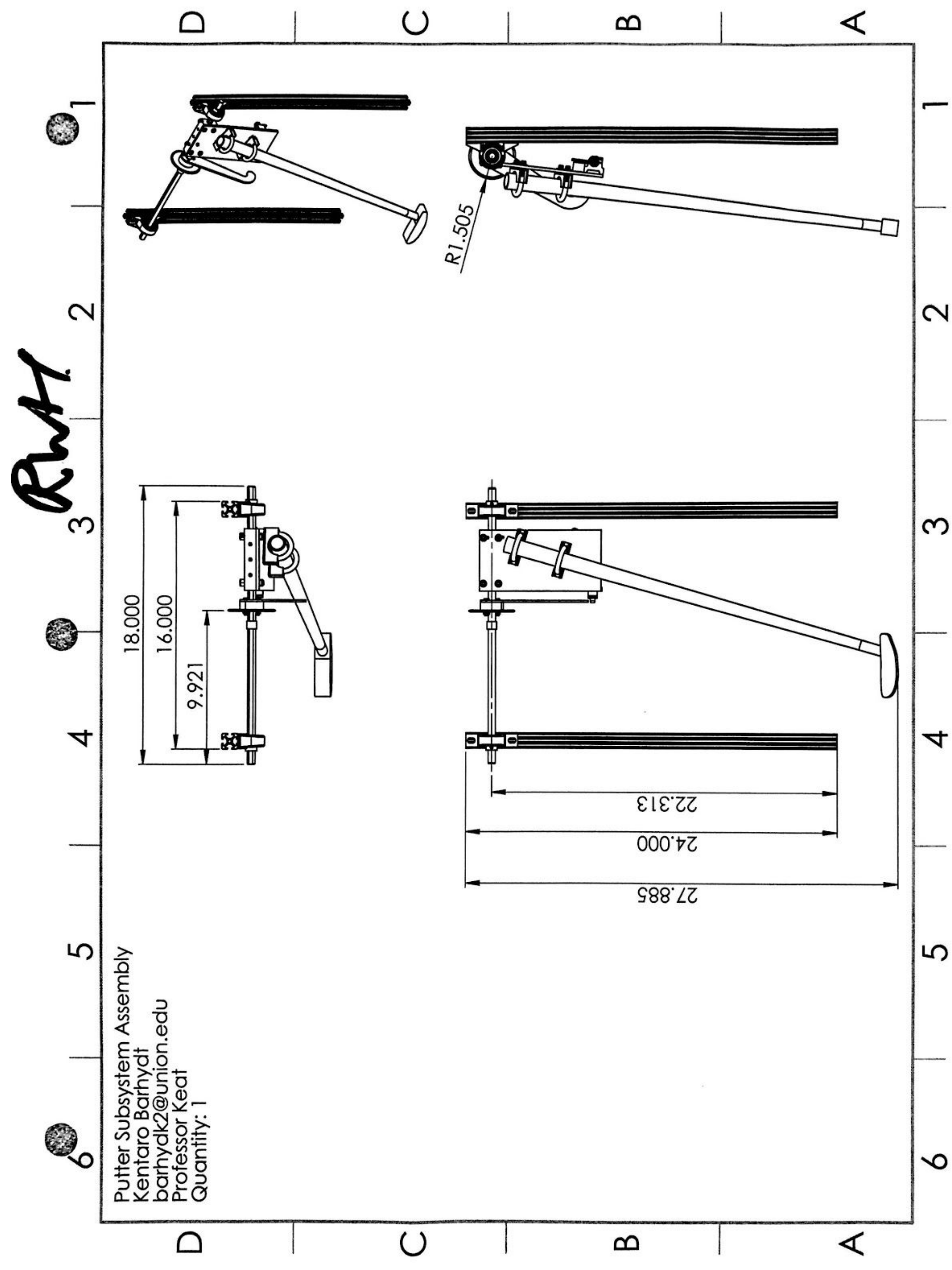
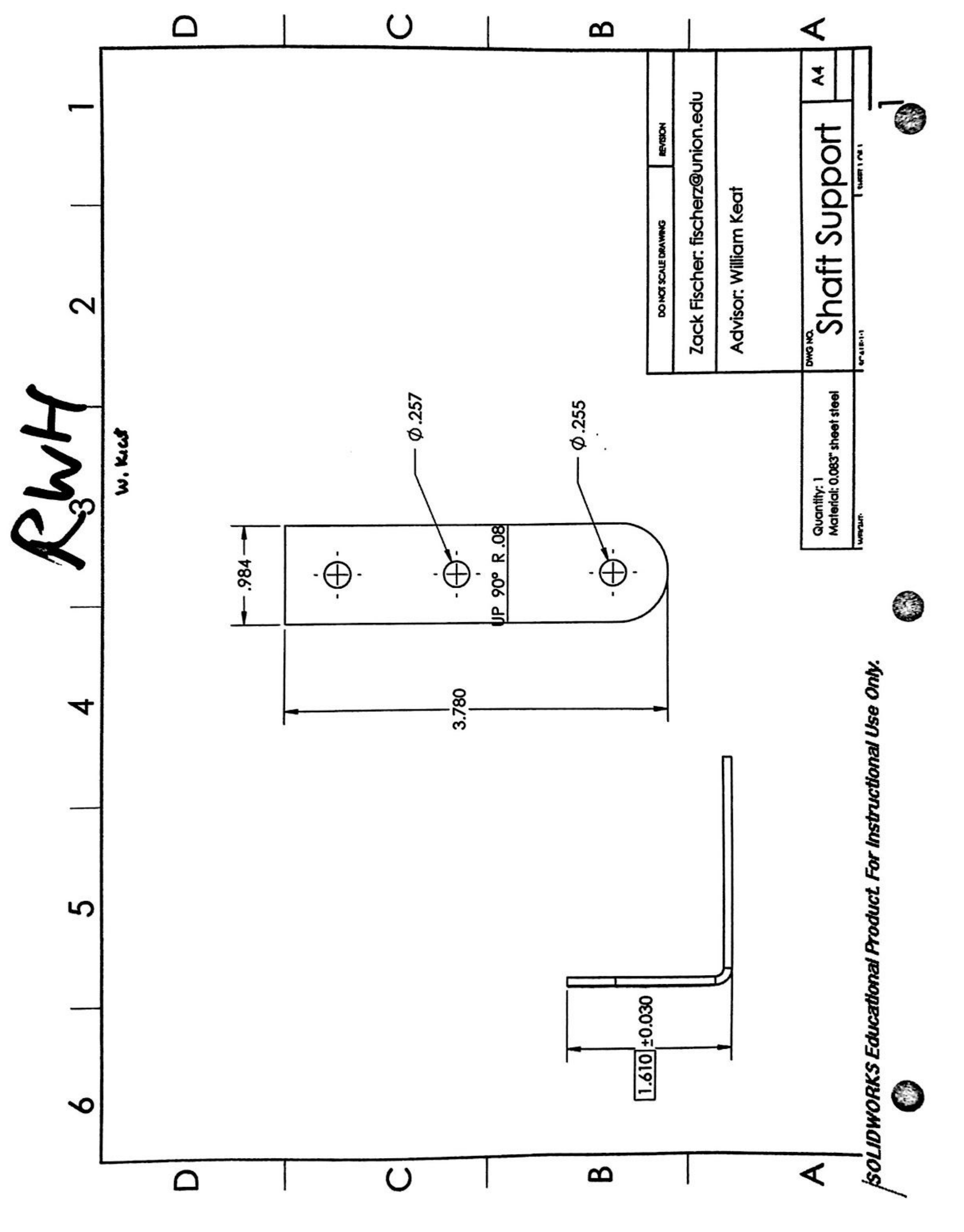
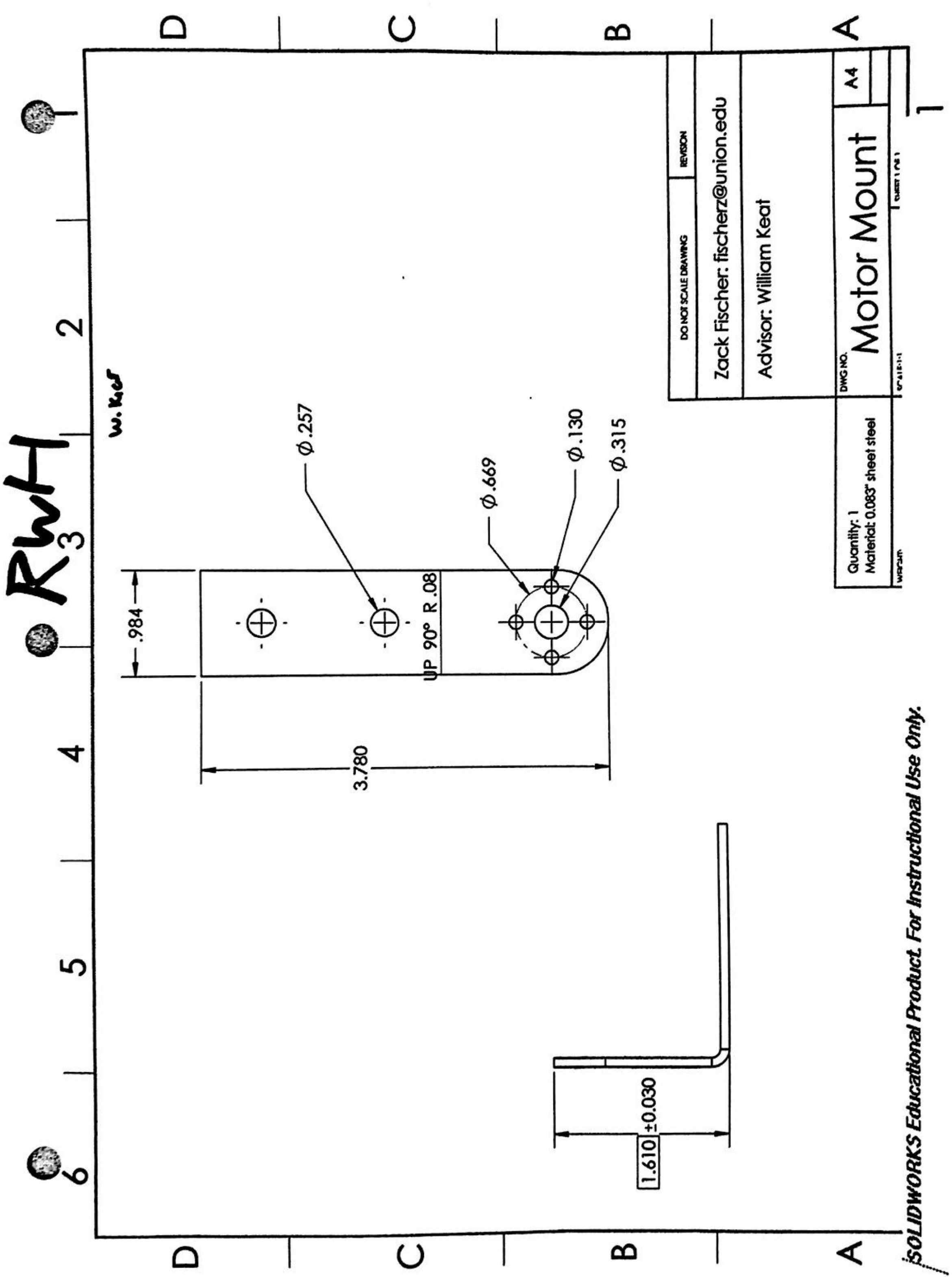


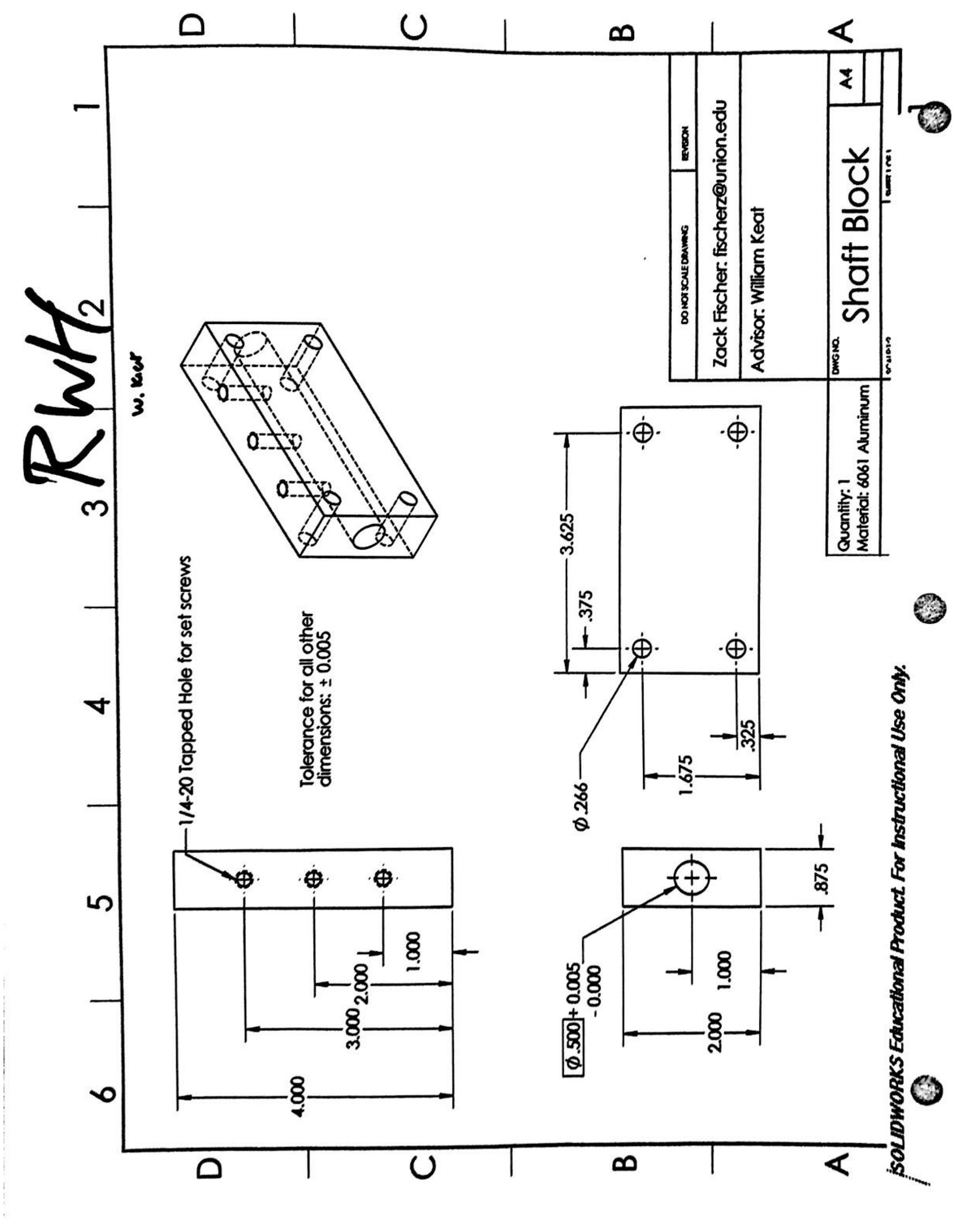
Appendix B - Parts Drawings



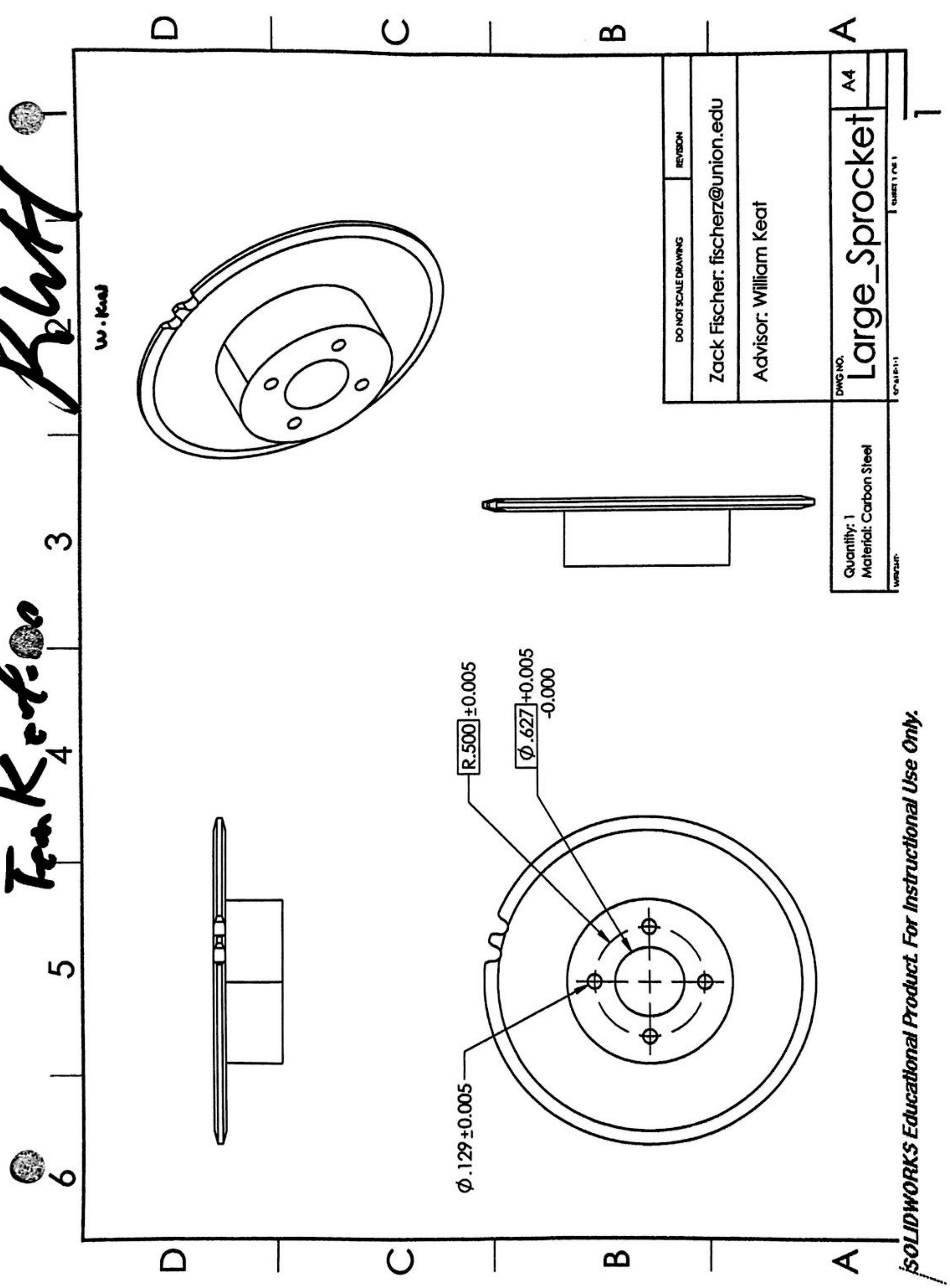
Appendix B - Parts Drawings



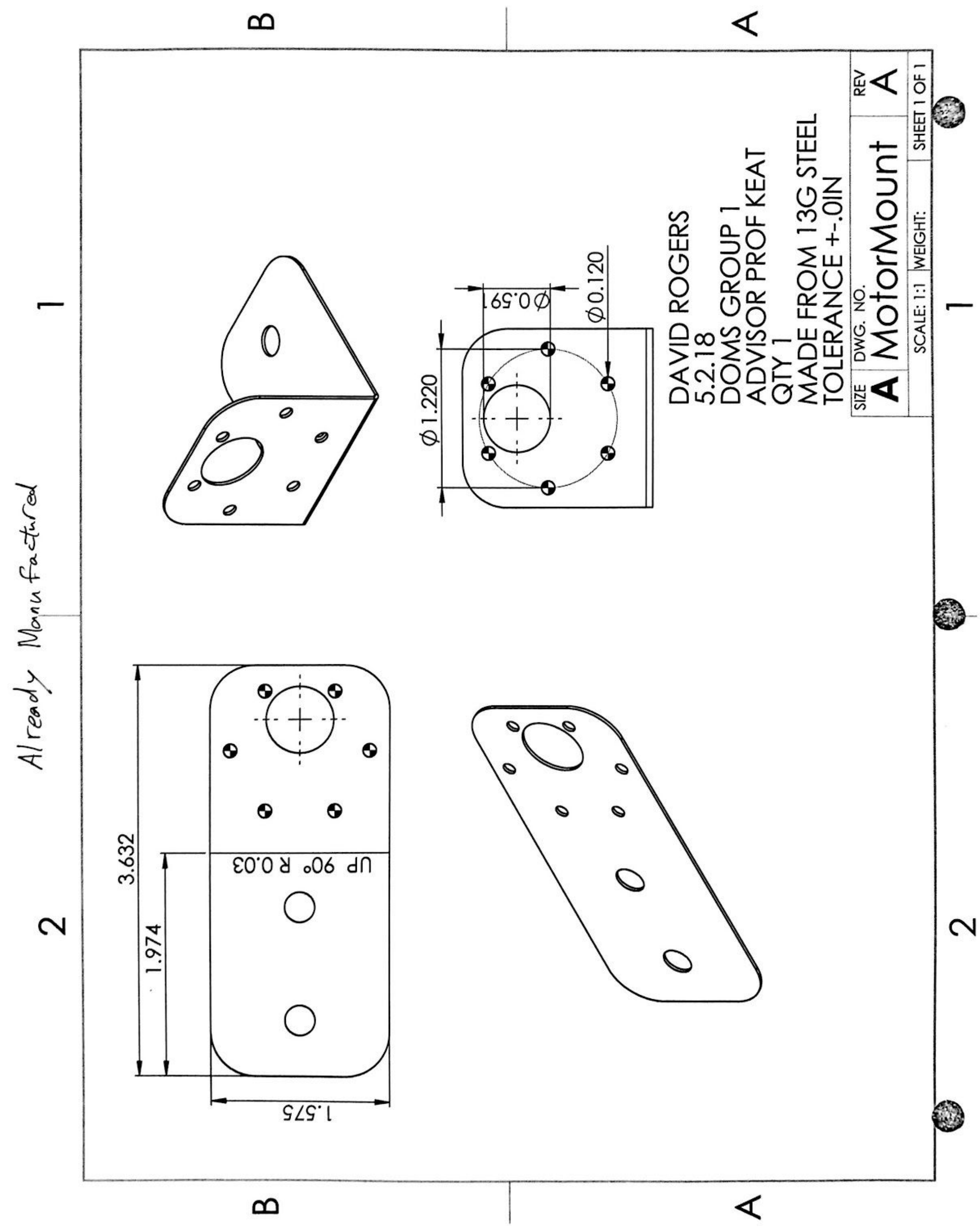
Appendix B - Parts Drawings



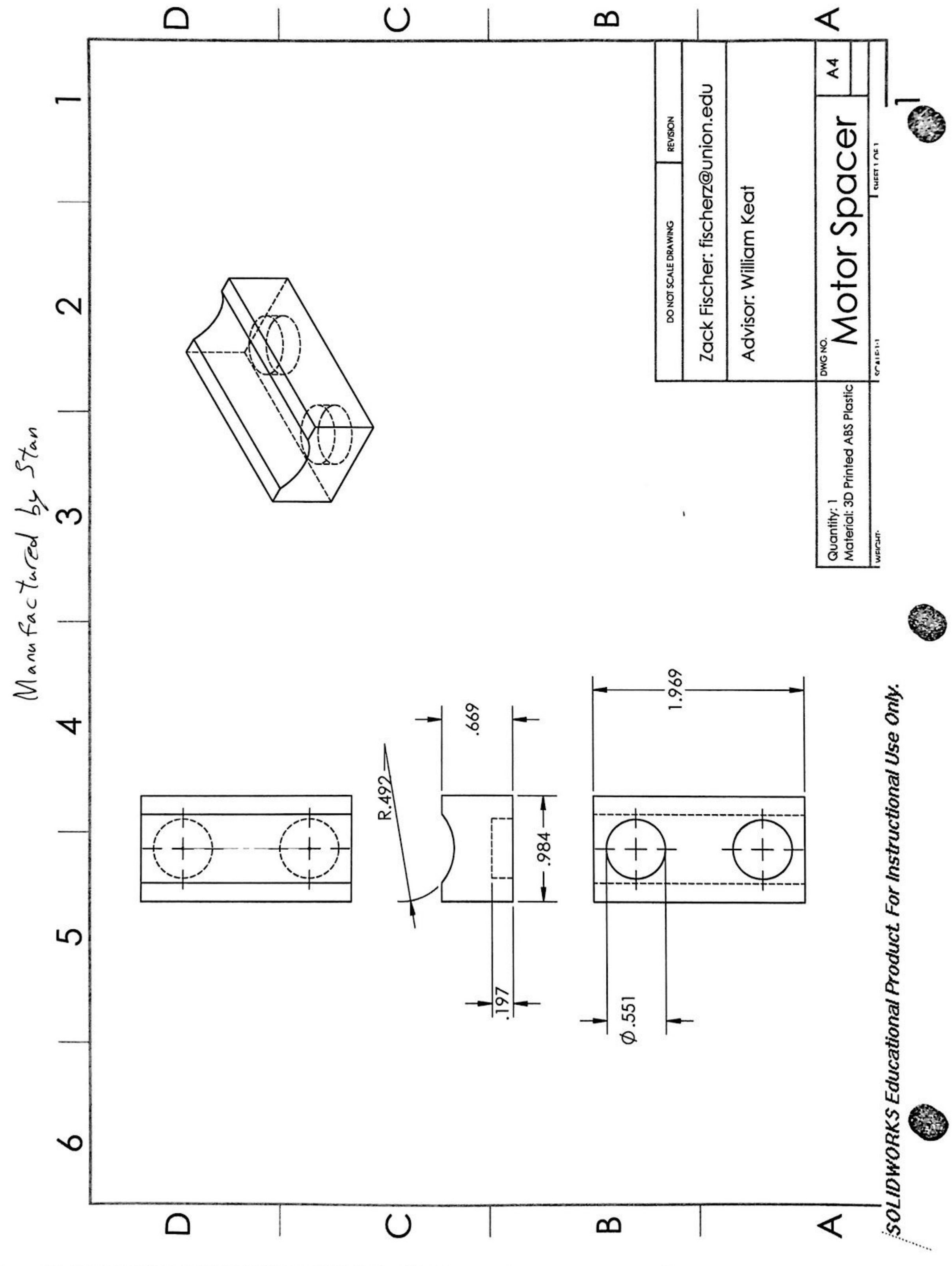
Appendix B - Parts Drawings



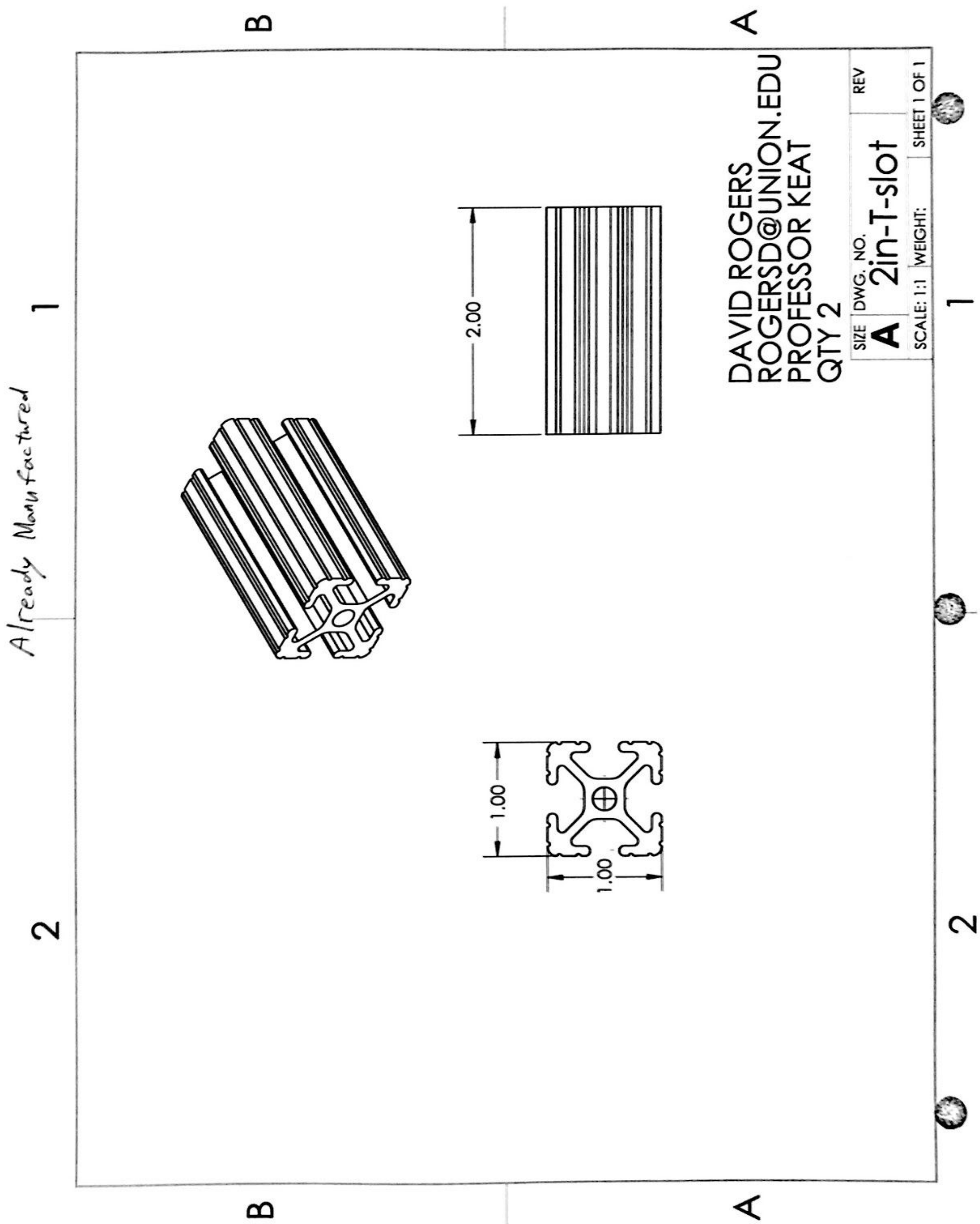
Appendix B - Parts Drawings



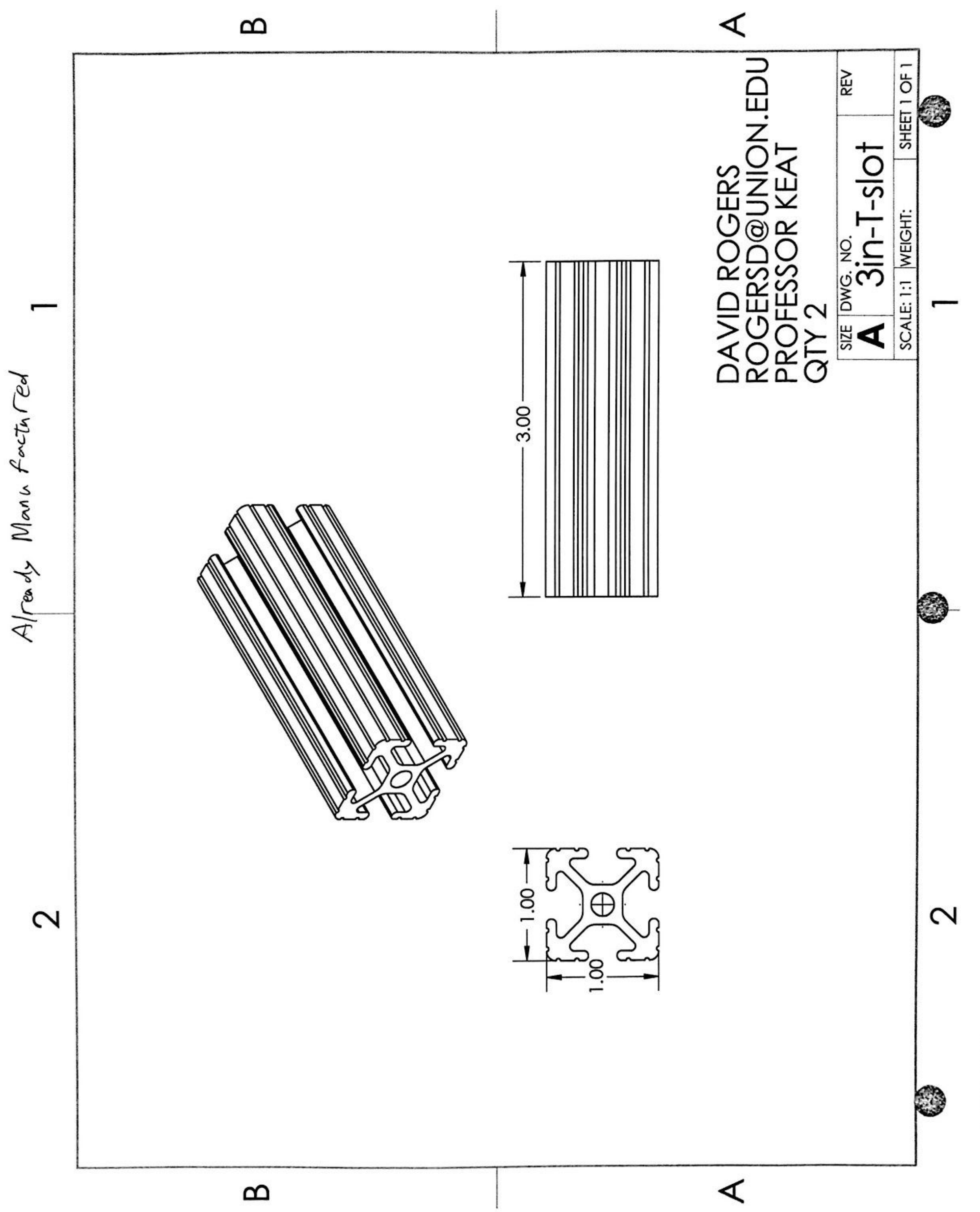
Appendix B - Parts Drawings



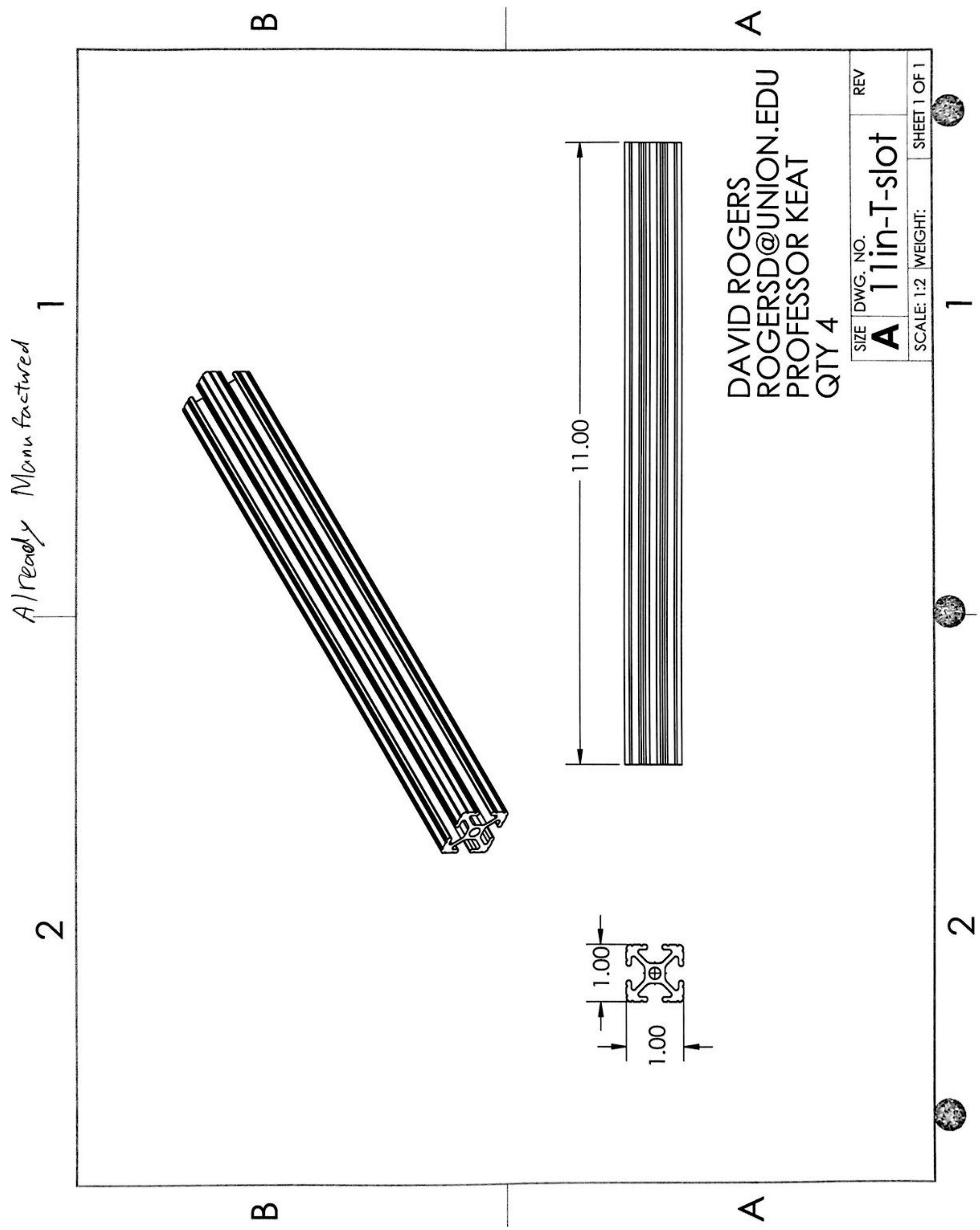
Appendix B - Parts Drawings



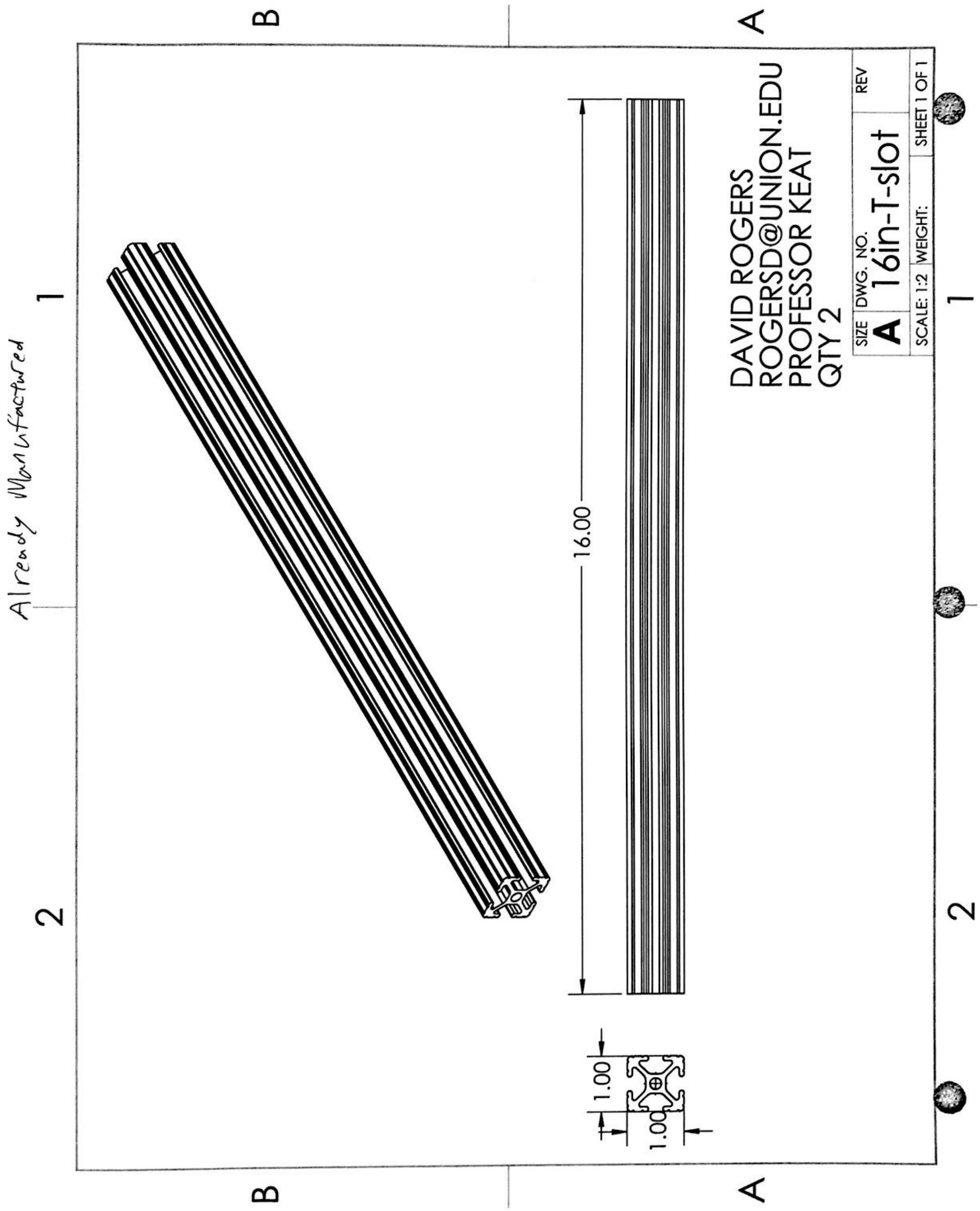
Appendix B - Parts Drawings



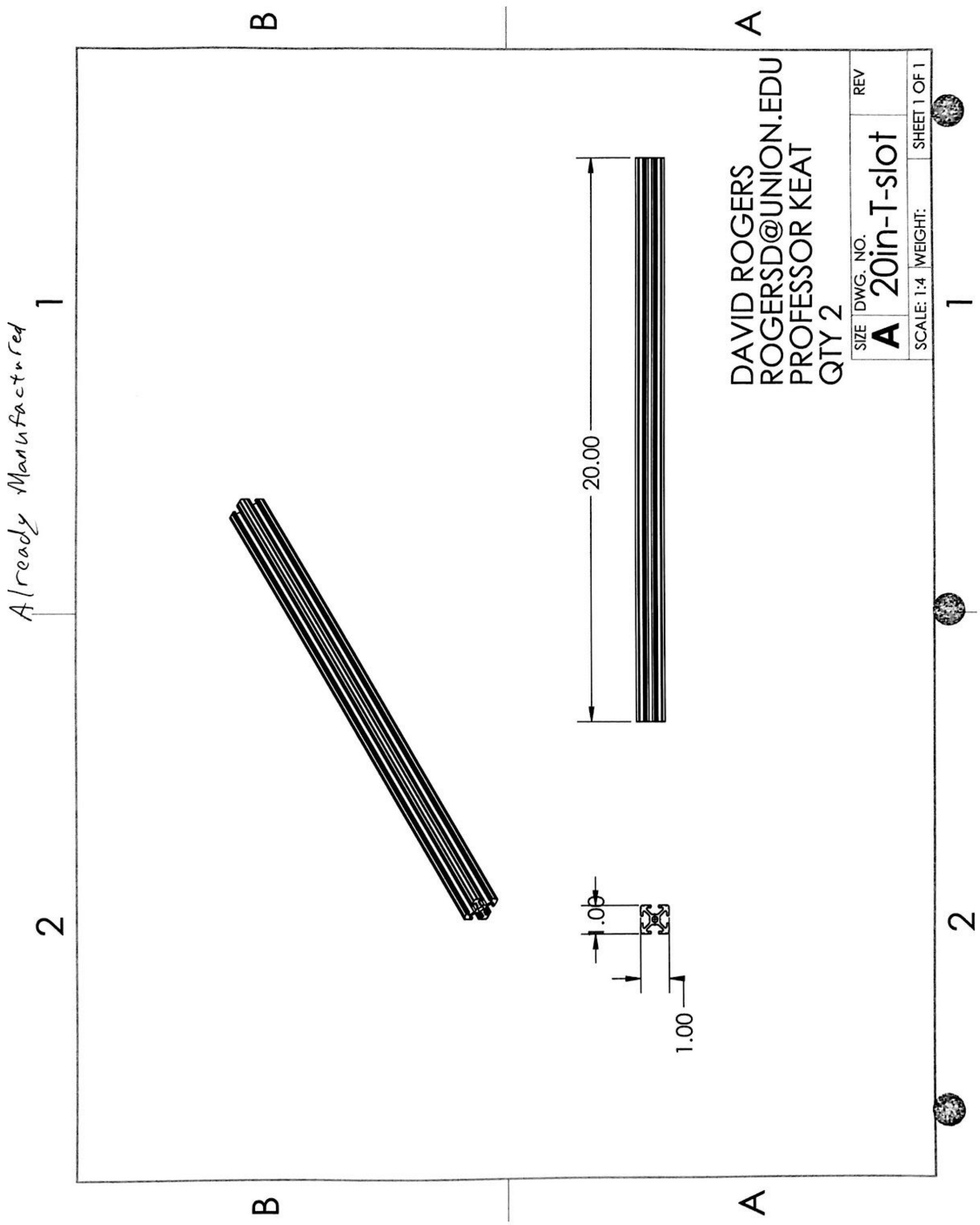
Appendix B - Parts Drawings



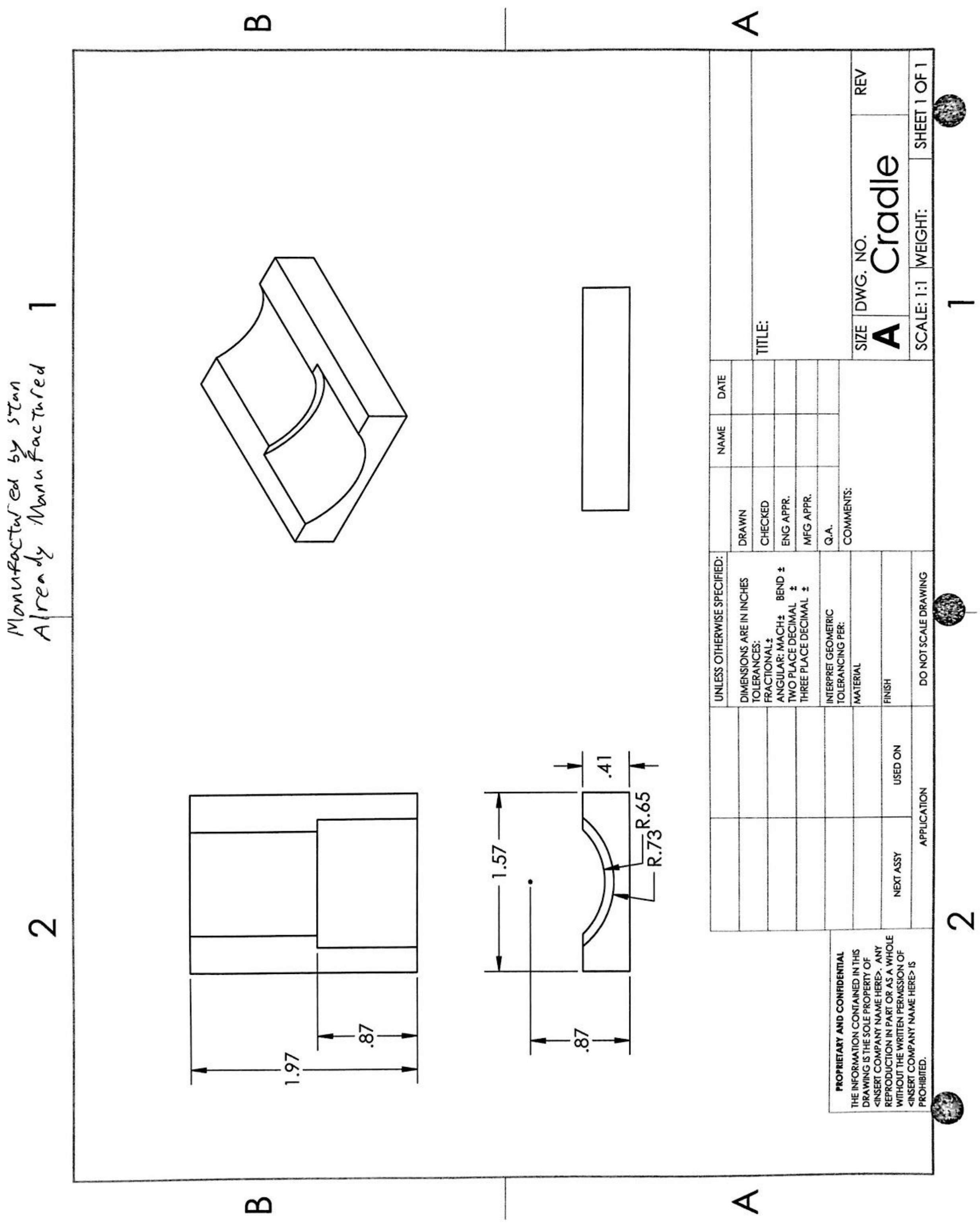
Appendix B - Parts Drawings



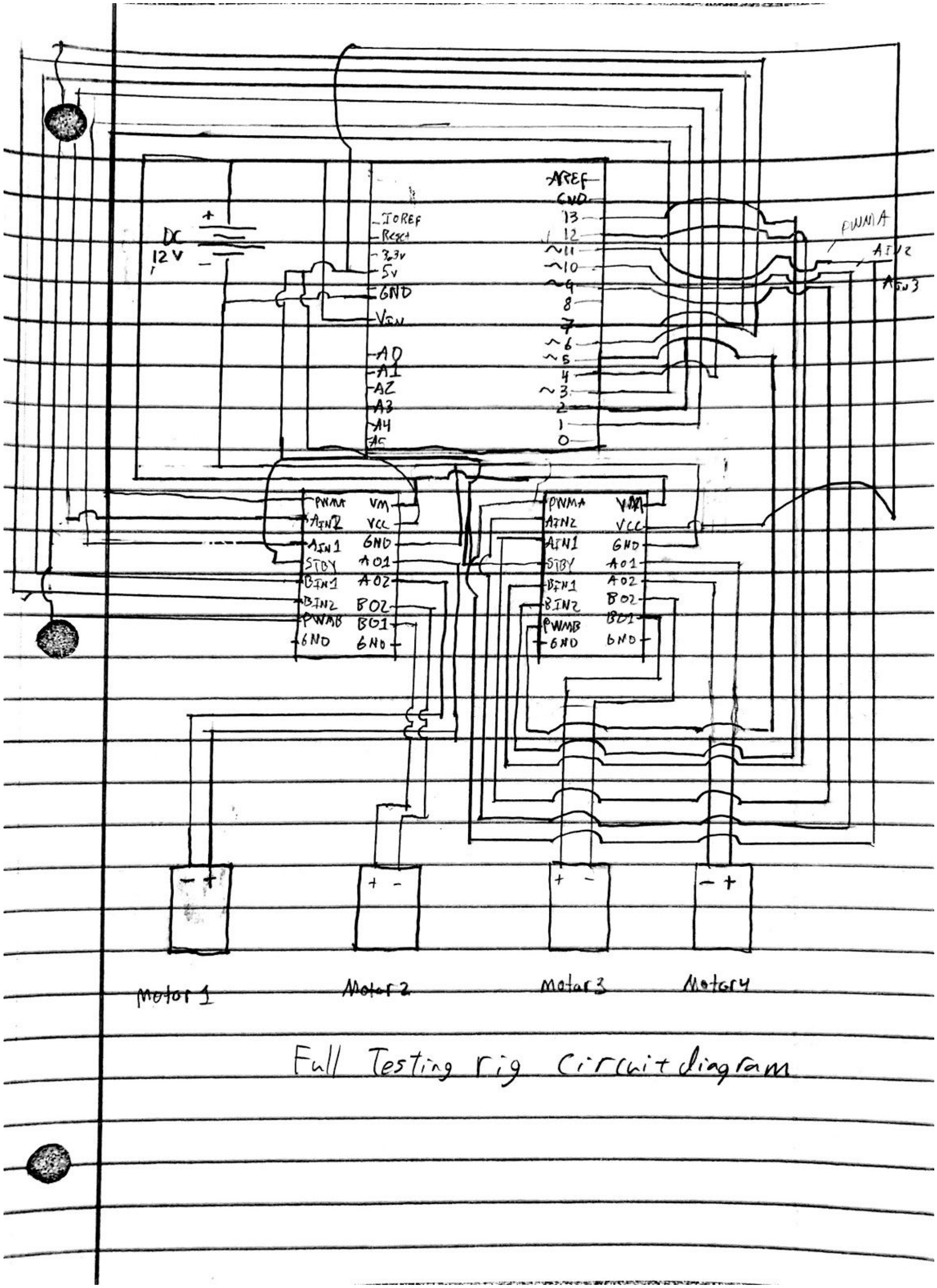
Appendix B - Parts Drawings



Appendix B - Parts Drawings



Appendix C - Electronics Design



Appendix D - Itemized Budget

Putting Group					**Driving Group**				
Item/Material	Source	Price	Quant.	Total Price	Item/Material	Source	Price	Quant.	Total Price
Motor: 172:1 Metal Gearmotor 25Dx56L mm MP 12V	https://www.pololu.com/product/3244	34.95	1	$34.95	T-Slotted Framing, Compact End-Feed Fastener, for 1" High Single Rail	https://www.mcmaster.com/#47065t139/=1cuft8u	$1.85	6	$11.10
Motor Coupler: 4mm to 1/4"	https://www.servocity.com/set-screw-shaft-couplers	$4.99	1	$4.99	T-Slotted Framing,End-Feed Fastener, for 1" High Single Rail	https://www.mcmaster.com/#47065t142/=1cvvbr3	$2.30	5	$11.50
Steel Shaft:D-Profile Rotary Steel Shaft 6" (1/4")	https://www.mcmaster.com/#8632t132/=1cmonzt	$6.64	1	$6.64	Wheel Motor Drivers	https://www.sparkfun.com/products/14450	$5.45	3	$16.35
Steel Shaft:D profile Rotary Steel Shaft 24" (1/2")	https://www.mcmaster.com/#8632t8/=1cmonoh	$16.88	1	$16.88	Angle iron for Corner Brackets (3' length)	https://www.lowes.com/pd/Steelworks-3-ft-x-1-in-Aluminum-Solid-Angle/3056837	$5.05	1	$5.05
0.25 (#25) Pitch, 12 Teeth, 0.25" Bore, Metal roller chain sprocket	http://shop.sdp-si.com/catalog/product/?id=A_6C_7-25B12	$11.01	1	$11.01	I/O pin extender	https://www.digikey.com/product-detail/en/microchip-technology/MCP23017-E-SP/MCP23017-E-SP-ND/894272	$1.24	2	$2.48
0.25 (#25) Pitch, 36 Teeth, 0.375" Bore, Metal roller chain sprocket	http://shop.sdp-si.com/catalog/product/?id=A_6C_7-25B36	$21.32	1	$21.32	T-slot rails (1x1 silver) (8' length)	https://www.mcmaster.com/#47065t101/=1cufsgd	$23.57	2	$47.14
Ultra-Low-Friction Oil-Embedded Sleeve Bearings	https://www.mcmaster.com/#1688k16/=1cr5ldl	$1.53	1	$1.53	T-slot corner brackets	https://www.grainger.com/product/80-20-Inside-Corner-Bracket-2RCW6	$3.40	14	$47.60
Bearings (1/2")	https://www.mcmaster.com/#5913k61/=1cmoo7y	$10.95	2	$21.90	Gear Motors	https://www.robotshop.com/en/12v-100rpm-583-oz-in-brushed-dc-motor.html	$12.99	4	$51.96
Chain: #25 Single Strand-Riveted Roller Chain, 10' (am-0370)	https://www.andymark.com/Roller-Chain-25-Series-p/am-0370.htm	$10.20	1	$10.20	4" Mecanum Wheels (4 pc)	http://www.andymark.com/4-inch-plastic-mecanum-wheels-p/am-2626.htm	$89.00	1	$89.00
Shaft Block (7/8"x2"x6") (Will also be Machined)	https://www.mcmaster.com/#8975k941/=1cr5v14	$11.20	1	$11.20	Andymark Nubs	http://www.andymark.com/AndyMark-Nub-p/am-nub.htm	$5.50	4	$22.00
Black-Oxide Alloy Steel Socket Head Screw-4-40 Thread Size, 1-1/8" Long-pack 10	https://www.mcmaster.com/#91864a029/=1cn5vr4	$6.47	1	$6.47	Hillman 3-ft x 1-in Aluminum Solid Angle	https://www.lowes.com/pd/Hillman-3-ft-x-1-in-Aluminum-Solid-Angle/3057235	9.64	1	$9.64
Clamping U-Bolt Zinc-Plated Steel, 5/16"-18 Thread Size, 1-5/16" ID	https://www.mcmaster.com/#3042t81/=1cvv4nv	$1.61	2	$3.22	Hillman 1/4-in to 20 Allen-Drive Alloy Cap Screws (2-Count)	https://www.lowes.com/pd/Hillman-1-4-in-to-20-Allen-Drive-Alloy-Cap-Screws-2-Count/3012523	$0.90	2	$1.80
Putter Board Holder Plate (6061 Aluminum 3/16" Thick x 4" Wide)	https://www.mcmaster.com/#8975k421/=1crsxof	*$12.72*	*1*	*$12.72*	Hillman 2-Count 5/16-in Zinc-Plated Standard (SAE) Regular Wing Nuts	https://www.lowes.com/pd/Hillman-2-Count-5-16-in-Zinc-Plated-Standard-SAE-Regular-Wing-Nuts/3012060	$1.27	2	$2.54
uxcell 12VDC 200N Electric Lifting Magnet Electromagnet Solenoid Lift Holding	https://www.amazon.com/uxcell-Electric-Lifting-Electromagnet-Solenoid/dp/B01N3386ZF/ref=sr_1_5?ie=UTF8&qid=1528783741&sr=8-5&keywords=electromagnet+uxcell&dpID=41EWip2EFHL&preST=_SY300_QL70_&dpSrc=srch	$14.35	1	*$14.35*	Pololu Adjustable 9-30V Step-Up Voltage Regulator U3V50AHV	https://www.pololu.com/product/2571	$16.95	1	$16.95
			Total:	**$177.38**				**Total:**	**$335.11**
Total (overall):	**$512.49**								

Appendix E - Calculations

Stress Analysis: Wheel Shafts

Bending $\sigma = \frac{Mc}{I}$ $M_{A\text{-cantilever}} = PL = 6.3365$ in·lb

$c = D_{shaft}/2 = 6mm/2 = 3mm \approx 0.125in$

Assume: - circular shaft $I = \frac{\pi}{4} r^4 = \frac{\pi}{4}(.125in)^4 = 1.917 \cdot 10^{-4} in^4$

- weight on 2 wheels (up hill/rough terrain) $P = \frac{1}{2} W_{vehicle} = \frac{1}{2}(23lbs) = 11.5 lbs$

- weight = 23 lbs L = shaft Length = 14mm = 0.551in

$$\sigma = \frac{Mc}{I} = \frac{6.3365\,in \cdot lb(0.125in)}{1.917 \cdot 10^{-4}\,in^4} \boxed{= 4{,}131\ psi}$$

Torsion: $\tau = \frac{Tr}{J}$ $r = D_{shaft}/2 = 6mm/2 = 3mm \approx 0.125in$

$J = \frac{\pi}{2} r^4 = \frac{\pi}{2}(0.125)^4 = 3.835 \cdot 10^{-4}$

Assume: - circular shaft $T =$

- 1.5m/s up 30° hill $P = T\omega \rightarrow P/\omega = T$

- weight on 2 wheels $P = Fv = W \sin 30° (1.5) = 17.25\ \frac{ft \cdot lb}{s}$

$P_{wheel} = P/2 = 8.675\ ft\cdot lb/s$

$\omega = \frac{v}{r} = \frac{1.5in}{s} \cdot \frac{1}{2in} = \frac{9\ rad}{s} \cdot \frac{60s}{1min} \cdot \frac{1rev}{2\pi\ rad} = 85.94$ RPM

$$T = P/\omega = \frac{8.675\ \frac{ft \cdot lb}{s}}{9\ \frac{rad}{s}} = 0.96\ ft \cdot lb$$

$$\boxed{\tau = \frac{0.96\,(0.125)}{3.835 \cdot 10^{-4}} = 3770\ psi}$$

Appendix E - Calculations

Zack Fischer

Worm Gear Set

$(F_e)_G = 0.188\ in$

$y = 0.1$

$r_G = \frac{0.625}{2} = 0.3125\ in$

$\lambda = 4.08°$ $n_d = 1.5$

$e = 56.8°$ $K_a = 1.25$

should be less than one (e.g. 0.80)

$L = \pi d \tan\lambda = \pi(0.625)\tan(4.08) = 0.14\ in/rev$

$P_x = \frac{L}{N_w} = \frac{0.14}{1} = 0.14\ in$

$P_n = P_x \cos\lambda = 0.14\cos(4.08) = 0.14\ in$

rad/min ?

$\omega_G = \frac{\omega_m}{GR} = \frac{(\frac{1}{2} \cdot 270.177)}{20} = 6.75\ \frac{rad}{min} \rightarrow V_G = \omega_G r_G = (6.75)(0.3125 \cdot \frac{1}{12}) = \underbrace{0.176}_{\text{very slow}}\ ft/min$

$P_m = \cancel{1.19}\ 0.25\ (\underbrace{15.625})(270.177) = \cancel{5023.67}\ 1055\ in\text{-}lb \cdot \frac{rad}{min} \cdot \frac{1 ft}{12 in} = \cancel{418.6}\ 87.9\ \frac{ft\text{-}lb}{min}$

$H_o = \cancel{0.0127}\ hp$

$.00266$

$W_G^t = \frac{33000\, n_d H_o K_a}{V_G e} = \frac{33000(1.5)(\cancel{0.0127}\ .00266)(1.25)}{0.176(\underbrace{0.568})} = \underbrace{\cancel{7861\ lb}}_{\text{too large?}}\ 1646\ lb$

this is certainly less than one

$\sigma_a = \frac{W_G^t}{P_n (F_e)_G Y} = \frac{\cancel{7861}\ 1646}{0.14(0.188)(0.1)} = \cancel{2.99 \times 10^6}\ 625,000\ psi$

@ 12V GR = 172:1

$T_{stall} = 250\ oz\text{-}in \cdot \frac{lb}{16\ oz} = 15.625$

Check of units:

$W_G^t = \frac{P_{out}}{V_{out}}\ \frac{ft\text{-}lb}{s}\ hp\ (550\ \frac{ft\text{-}lb}{s})\ 60$

$\frac{ft}{min}$

$W_G^t = \frac{P_{out}}{V_{out}} \cdot \frac{\overbrace{550\ \frac{ft\text{-}lb}{s}\ \ \frac{60 s}{min}}^{33000}}{hp}$

hp

$\frac{ft}{min}$

Appendix E - Calculations

Putter : $T_{putter} = 318$ oz-in

Pitch Diameter: 2.471 in, 0.966 in

$\therefore$ Torque on output side of worm gear set is:

$$GR_{sprocket} = \frac{2.471}{0.966} = 2.56$$

$$T_{out} = \frac{318}{2.56} = \boxed{124 \text{ oz-in}}$$

$\therefore$ Torque on input side of worm gear is (ignoring inefficiency)

$$T_{in} = \frac{124}{20} = \boxed{6.2 \text{ oz-in}}$$ torque on motor shaft

Interpolate corresponding ω_m from motor curve

$$T_{stall} = 15.6 \text{ in-lb}$$
$$\omega_{NL} = 270 \frac{rad}{min}$$

$$T_m = \frac{-T_{stall}}{\omega_{NL}} \omega_m + T_{stall}$$

$$0.388 = \frac{-15.6}{270} \omega_m + 15.6$$

$$\therefore \omega_m = 263 \frac{rad}{min}$$

And the angular velocity of the worm gear is

$$\omega_G = \frac{263}{20} = 13.2 \frac{rad}{min}$$
$$V_G = \omega_G r_G = 13.2 \left(\frac{0.3125}{12}\right) = \boxed{0.344 \frac{ft}{min}}$$

Calculate power:

$$P_{in} = H_o = T_{in}\omega_m = (0.388 \text{ lb-in})\left(263 \frac{rad}{min}\right) = 102 \frac{\text{lb-in}}{min}$$

Convert to Hp:

$$H_o = 102 \frac{\text{lb-in}}{min} \frac{min}{60 s} \frac{ft}{12 in} \frac{hp}{550 \frac{ft\text{-}lb}{s}} = \boxed{2.58 \times 10^{-4} hp}$$

Calculate W_G^+:

$$W_G^+ = \frac{33000\, n_d H_o K_G}{V_G e} = \frac{33000(1.5)(2.58\times10^{-4})(1.25)}{(0.344)(0.568)} = \boxed{81.71}$$

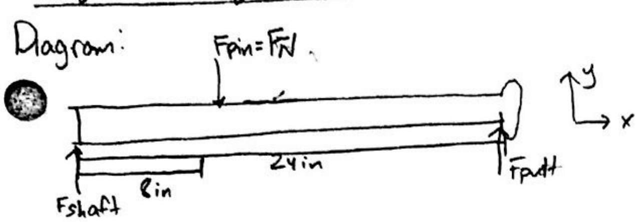
Sub into Lewis Equation:

$$\sigma_G = \frac{W_G^+}{P_n (F_e)_G y} = \frac{81.7}{(0.14)(0.188)(0.1)} = \boxed{31041 \text{ psi}}$$

Appendix E - Calculations

Required Torque Needed to Pull pin

Diagram:



Given:

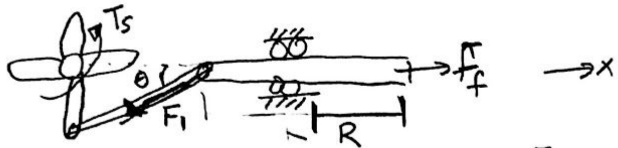
$F_{pull} = 2lb$

$\mu_{\substack{steel\,on\\ steel}} = 0.8$

$R = 0.5in$ (Distance pin needs to move)

$\Sigma F_y = F_{shaft} + F_{pull} - F_{pin} = 0$

$\Sigma M_0 = F_{pin}(8in) - F_{pull}(24in) = 0 \quad F_{pin} = 6lb$



$\Sigma F_x = 0 = -F_1\cos\theta + F_f \Rightarrow F_1 = \frac{F_f}{\cos\theta}$

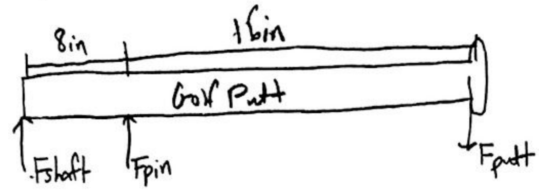
$T_s = F_1\cos\theta\, r \Rightarrow F_f\, r = 4.8lb * 0.5in = \boxed{2.4lb\,in = 38.4oz\,in}$

$F_f = F_{pin} * \mu_{\substack{steel\,on\\ steel}} = 6lb * 0.8 = 4.8lb$

- Requires a servo that has a minimum torque of 38.4ozin.

Appendix E - Calculations

Pin stress Analysis



Assume

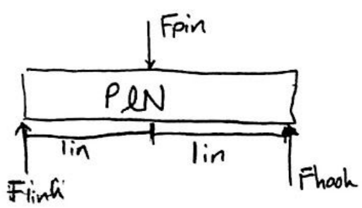
- Conservative C.G at the end of putt
- $F_{putt} = 2lb$
- Solid cylinder pin
- No torsion Force

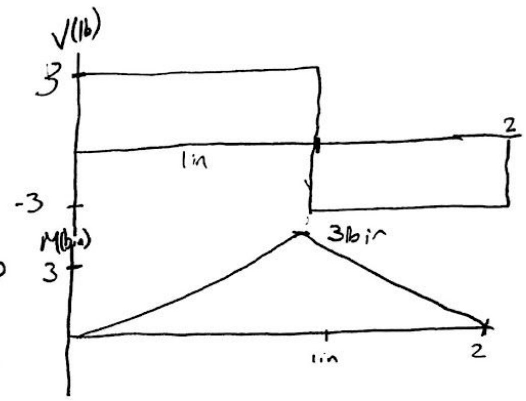
$$\Sigma F_y = 0 = F_{shaft} + F_{pin} - F_{putt}$$

$$F_{putt} = F_{shaft} + F_{pin}$$

$$\Sigma M = 0 = F_{pin} \cdot 8in - F_{putt} * 24in$$

$$F_{pin} = 6\,lb$$





$$\Sigma F_y = F_{link} + F_{pin} + F_{hook}$$

$$\Sigma M = F_{pin}(1in) - F_{hook}(2in)$$

$F_{hook} = 3lb$

$F_{pin} = 6lb$

$F_{link} = 3lb$

$$\sigma_{max} = \frac{Mc}{I} = \frac{3lb\,in * 0.15748\,inch}{4.833e\text{-}4\ in^4} = \boxed{977.55\ psi}$$

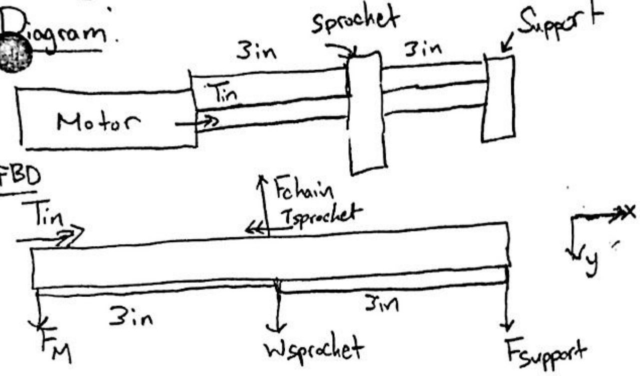
$C = 0.15748$ inch

$$I = \frac{\pi D^4}{64} = \frac{\pi(0315)^4}{64} = 4.833\ e\text{-}4\ in^4$$

Appendix E - Calculations

Driving Shaft on Stress Analysis

Diagram:



Assume
- Weight of sprocket negligible
- equations based off solid cylinder
-

$$\Sigma F_y = 0 = F_m + F_{support} - F_{chain}$$

$$\Sigma M = 0 = F_{chain} \cdot 3'' - F_{support} \cdot 6''$$

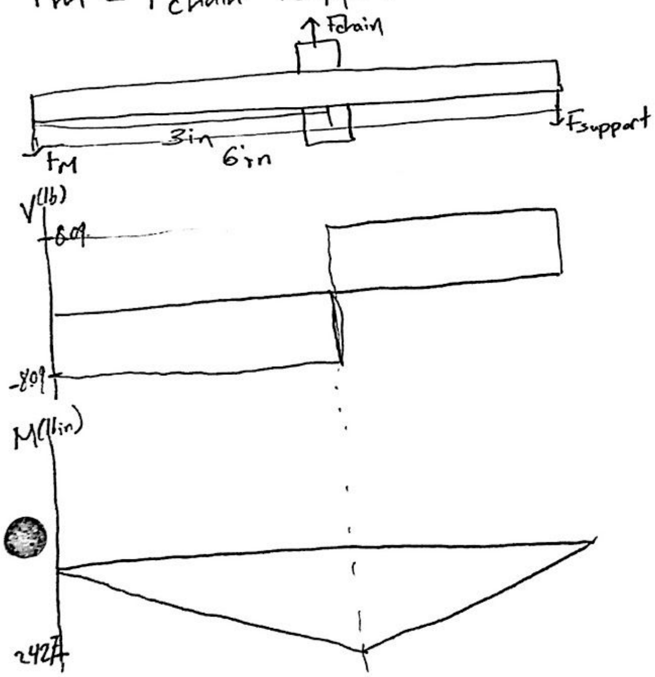
$$\Sigma T = 0 = T_{in} - T_{sprocket}$$

$$T_{in} = T_{sprocket}$$

$$F_{chain} = \frac{T_{in}}{r_{sprocket}} = \frac{7.815\,\text{lb-in}}{0.483\,\text{in}} = 16.18\ \text{lbf}$$

$$F_{support} = \frac{F_{chain} \cdot 3''}{6''} = 8.09\ \text{lbf}$$

$$F_m = F_{chain} - F_{support} = 8.09\ \text{lbf}$$



Appendix E - Calculations

$$\sigma_{max} = \frac{M_{max} C}{I} = \frac{24.27\ \text{lbin} * 0.125\ \text{in}}{1.917e\text{-}4\ \text{in}^4} = \boxed{15{,}825.5\ \text{psi}}$$

$$I = \frac{\pi D^4}{64} = \frac{\pi (0.25)^4}{64} = 1.917e\text{-}4\ \text{in}^4$$

$$T_{stall} = 15.63\ \text{lb-in} \Rightarrow \underbrace{7.815\ \text{lbin}}_{\text{Operates at } \frac{1}{2} T_{stall}}$$

$$J = \frac{\pi (d)^4}{32} = \frac{\pi (0.25)^4}{32} = 0.000383\ \text{in}^4$$

$$\tau_{max} = \frac{Tr}{J} = \frac{7.815\ \text{lbin} * 0.125\ \text{in}}{0.000383\ \text{in}^4} = \boxed{2550.6\ \text{psi}}$$

$$d_{min} = \left\{ \frac{n}{S_y} \left[\left(\frac{M_r(32)}{\pi} \right)^2 + 3\left(\frac{T(16)}{\pi} \right)^2 \right]^{1/2} \right\}^{1/3}$$

$n = 3$

$S_y = 60{,}000\ \text{psi}$

$$\left\{ \frac{3}{60000} \left[\left(\frac{24.27(32)}{\pi} \right)^2 + 3\left(\frac{7.815(16)}{\pi} \right)^2 \right]^{1/2} \right\}^{1/3}$$

$$\left\{ \frac{3}{60000} \left[61113.87 + 4752.47 \right]^{1/2} \right\}^{1/3} = \boxed{\underbrace{0.234\ \text{in}}_{\text{minimum diameter } n=3} < \underbrace{0.25\ \text{in}}_{\text{shaft diameter}}}$$

$$\delta_{max} = \frac{F_{chain} * L_{shaft}^3}{48 E I} = \frac{16.18\ \text{lbf} * (6\ \text{in})^3}{48 * 29e6\ \text{psi} * 1.917e\text{-}4\ \text{in}^4} = \boxed{0.0131\ \text{inch}}$$

$E = 29{,}000{,}000\ \text{psi}$

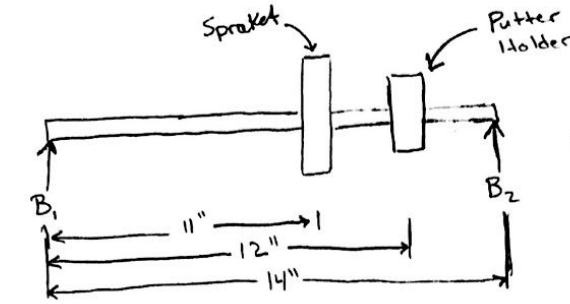
$I = \frac{\pi D^4}{64} = \frac{\pi (0.25)^4}{64} = 1.917e\text{-}4\ \text{in}^4$

$F_{chain} = 16.18\ \text{lbf}$

$L_{shaft} = 6''$

Appendix E - Calculations

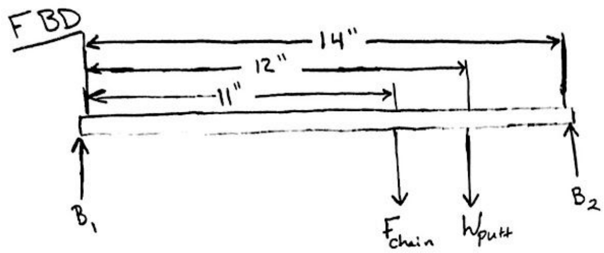
Passive Shaft Stress Analysis 5/10/18 Pg 1



Sprocket is not rigidly attached to shaft, therefore no torsion in the shaft.

Assume $W_{putt} \approx 2\,lb$

FBD



$$GR = \frac{2.869}{0.966} = 2.97$$

$$GR = \frac{T_{out}}{T_{in}}$$

$$T_{out} = GR \cdot T_{in} = 2.97 \cdot 7.815\,lb\text{-}in$$

$$\boxed{T_{out} = 23.21\,lb\text{-}in}$$

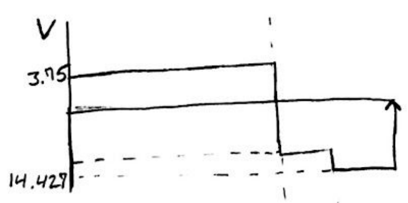
$$\Sigma F = 0 = B_1 + B_2 - F_{chain} - W_{putt} \rightarrow B_1 + B_2 = F_{chain} + W_{putt}$$

$$\Sigma M = 0 = B_2 \cdot 14" - W_{putt} \cdot 12" - F_{chain} \cdot 11" \rightarrow B_2 = \frac{W_{putt} \cdot 12" + F_{chain} \cdot 11"}{14"}$$

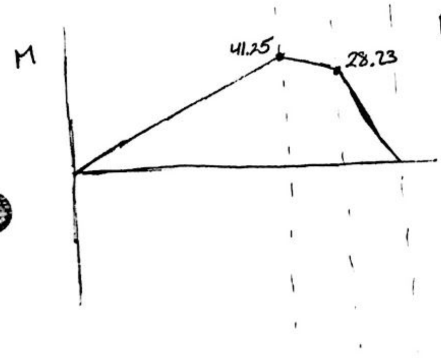
$$F_{chain} = \frac{T_{out}}{r_{sprocket}} = \frac{23.21\,lb\text{-}in}{1.4345\,in} \boxed{= 16.180\,lb}$$

$$B_2 = \frac{2\,lb \cdot 12" + 16.180\,lb \cdot 11"}{14"} \boxed{= 14.427\,lb}$$

$$B_1 = 16.180\,lb + 2\,lb - 14.427\,lb \boxed{= 3.75\,lb}$$

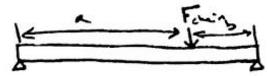


$M = 41.25\,lb\text{-}in$



Appendix E - Calculations

Passive Shaft Stress Analysis   5/10/18   Pg 2



$$\delta_{max} = \frac{Pb\,(l^2 - b^2)^{3/2}}{9\sqrt{3}\, l\, E\, I}$$

$$= \frac{16.180\,lb \cdot 3''\,(14''^2 - 3''^2)^{3/2}}{9\sqrt{3} \cdot 14'' \cdot 29000e3\,psi \cdot 0.00307\,in^4}$$

$$= \frac{124125.83}{19429764.91} \boxed{= 0.006388\,in}$$

$E = 29000e3$ psi

$I = \frac{\pi D^4}{64} = \frac{\pi (0.5)^4}{64} = 0.00307\,in^4$

$$\sigma_{max} = \frac{M_{max}\, C}{I} = \frac{41.25\,lb\cdot in \cdot 0.25\,in}{0.00307\,in^4}$$

$$\boxed{= 3359.12\,psi}$$

Assume FOS of 2

$S_y = 60{,}000 \rightarrow$ For that shaft

$$d = \left\{ \frac{n}{S_y} \left[\left(\frac{M_r\,(32)}{\pi} \right)^2 + 3\left(\frac{\cancel{T}^{\,0}\,(16)}{\pi} \right)^2 \right]^{1/2} \right\}^{1/3}$$

$$= \left\{ \frac{2}{60{,}000} \cdot \frac{41.25 \cdot 32}{\pi} \right\}^{1/3}$$

$$\boxed{= 0.241\,in}\ \checkmark$$