FINAL DESIGN REPORT

Prototype Vehicles Laboratory Steering Apparatus

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STATEMENT OF DISCLAIMER

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EXECUTIVE SUMMARY

The Cal Poly PROVE Lab is designing a solar powered car to break the international land speed record. The space within the driver's cockpit that is allotted for the steering mechanism is too small for a conventional steering wheel. This report describes the design process that was followed to build a compact and lightweight steering apparatus for the driver. A lateral lever steering system was the final design selected for PROVE's solar car. This steering mechanism was designed to withstand the maximum expected loads applied by the driver during the three-minute run of the competition. The lateral lever steering apparatus is controlled by two adjustable handles. The rotation of the handles is limited to either a clockwise or counterclockwise direction relative to the longitudinal axis of the vehicle, thus turning the vehicle's wheels right or left, respectively. The final cost of the system was $250 including shipping and handling. As the PROVE car body was not completed during the scope of this project, our team was not able to complete our testing of the system. Although we were not able to test the apparatus, our team is confident that our system will successfully and safely steer PROVE's vehicle during their world record run in 2018.

1. INTRODUCTION

The Prototype Vehicles Laboratory (PROVE Lab) at California Polytechnic State University San Luis Obispo (Cal Poly) is developing a car to break the solar powered land speed record. Aerospace Engineer Lacey Davis is the driver of PROVE Lab's vehicle, one of the project stakeholders. Dr. Graham Doig, the second project stakeholder and PROVE Lab's advisor, has previous experience in alternative energy vehicle design. In 2008, he led the aerodynamic design of the Sunswift IVy solar car, which held the Guinness World Record for fastest solar-powered vehicle prior to 2014 (Fastest Solar Powered Car: Sunswift IVy Sets World Record, 2011). He was also instrumental in guiding the design and development of Sunswift eVe, a two-seater solar-electric hybrid sports car which is currently the FIA world record holder for fastest long-range (500km) electric vehicle (Crozier, 2014). Dr. Graham Doig approached the Mechanical Engineering Senior Design Project class with a unique problem. No existing steering wheel would be able to fit in PROVE Lab's vehicle design. A unique steering apparatus needed to be designed and built for use in the PROVE Lab solar car.

The PROVE team was composed of three Mechanical Engineers, Colby Genasci, Jorge Lopez, and Zachary Sharpell, who were chosen to take on the problem of creating a steering wheel that worked within the constraints of PROVE Lab's solar car.

The following report incorporates all relevant information from our critical design report including: the background, the project objectives, the design development, and the final design. The final design report introduces the following information: design realization, which describes our manufacturing process, and design verification, which describes our testing procedures. The report is concluded with our recommendations for moving forward with this product as well as comments on how to improve a similar type of project in the future.

2. BACKGROUND

Cal Poly's PROVE Lab aims to demonstrate the innovative engineering ability of college students by creating a solar powered vehicle built for one reason - to break a world record. To attain such a goal, lightweight and unique designs are required; one of those designs is the development of a steering apparatus that fits within the tight cockpit of the solar vehicle.

PRODUCT RESEARCH

To gain an understanding of the ideas that other vehicle teams have developed for steering apparatuses, we examined designs developed by universities, as well as designs developed by car manufacturers. The following section depicts designs that we considered to be innovative, and that could either be further developed or that could inspire a new design.

STANFORD UNIVERSITY SOLAR CAR

Stanford University's solar car team has created a variety of solar vehicles since its inception in 1989. Throughout their iterations of competition-ready vehicles, the steering wheels from 2009, 2011, and 2015 were constructed almost entirely of carbon fiber and included an array of buttons with various functions. Figures 2.1, 2.2 and 2.3 are images of the 2009, 2011, and 2015 Stanford University solar vehicle's steering wheels, respectively.

The 2009 steering wheel, shown in Figure 2.1, contained only four buttons on the wheel itself, with four more on the nearby dash. Two years later, a new iteration of their steering wheel contained seven buttons, and a wheel that was considerably smaller than its 2009 predecessor. Stanford's continued use of carbon fiber aligned with the focus of keeping the vehicle lightweight. The 2011 steering wheel, shown in Figure 2.2, had a thin profile in the middle, top and bottom of the wheel but a rounded profile along the right and left edges - where the driver would grab the steering wheel.

Continuing the use of carbon fiber and a multi-button interface, Stanford University's 2015 solar vehicle steering wheel, shown in Figure 2.3, introduced an LCD array. The LCD was used to provide information regarding speed, cruise control settings, battery pack current, motor temperature, and battery pack temperature to the driver (Morita, n.d.).

Figure 2.1 - Stanford University's 2009 solar car steering wheel (University, 2009 Stanford Solar Car, 2009).

Figure 2.2 - Stanford University's 2011 solar car steering wheel (University, 2011 Stanford Solar Car, 2011).

Figure 2.3 - Stanford University's 2015 solar car steering wheel (Morita, n.d.)

After finding images of the Stanford University solar car, we realized the restrictions we had for our steering wheel design would not have been satisfied by the Stanford design due to its large size.

Ford's Experimental "Wrist-Twist" Design

In 1965, Ford brought in Robert J. Rumpf, an aerospace engineer who had previously worked on missiles, to work on experimental auto designs. The original design that Rumpf created called for the removal of Mercury's original steering wheel and the implementation of two smaller wheels, allowing for 'wrist-twist' steering. Figures 2.4 and 2.5 are Ford's experimental driving prototypes (Eric, n.d.).

Figure 2.4 - Ford's 'Wrist-Twist' prototype steering system (Eric, n.d.).

Figure 2.5 - Ford's 'Wrist-Twist' prototype steering system with driver sitting in seat (Eric, n.d.).

There were some advantages to Ford's innovative design. Its first advantage was its size. Because it was smaller than a standard steering wheel, there was more room for visibility and driver adjustability. This design also allowed the driver to put his or her arms on an armrest for increased comfort while driving. Both the size and adjustability of the 'Wrist-Twist' steering system had the potential to be used to our advantage in our final design. We needed a steering apparatus that fits in a very small cockpit, but the driver also needed reliable and easy to use controls. One downside to this design was that it would have been hard to include any type of display or buttons to control the throttle of the PROVE Lab solar car.

HONDA EV-STER

A popular design in prototype showcase cars is the use of a joystick steering system. In 2012, Honda implemented their EV-Steer system in their Odyssey vehicle. This joystick steering wheel was "adopted for the thorough pursuit of the joy of driving." EV-Steer used twin levers for its steering system controls. Figure 2.6 shows Honda's unique take on reinventing the steering wheel (Thomas, 2014).

Figure 2.6 - Honda's 2012 EV-Steer joystick steering system (Thomas, 2014).

An advantage of this steering system was that it was aesthetically pleasing. This was an important consideration because one of the criterion for PROVE Lab's solar car, per Dr. Doig, was that the steering apparatus had to be attractive. For our PROVE Lab steering apparatus, we needed something more compact with a surface on which we could implement throttle buttons, brake levers, and a feedback display, if possible.

MERCEDES-BENZ JOYSTICK

Another car manufacturer that tried implementing a joystick as a steering mechanism was Mercedes-Benz. In 1993, the Saab Prometheus included a unique steering concept using a drive-by-wire joystick, as shown in Figure 2.7. This joystick was positioned at the center of the cabin, rather than in front of the driver, to increase the safety of the driver in case of an accident.

Figure 2.7 - Mercedes-Benz F200 center-mounted joystick (Davis).

The Mercedes-Benz design provided an advantage to the driver, even if the joystick was not visible as the driver directed the car. This advantage was that the space the joystick occupied was minimal – an ideal aspect for our PROVE car. However, a major issue that stemmed from using this type of steering mechanism was the level of complexity of wiring the joystick inside the cockpit. Additionally, the joystick was more sensitive compared to a steering wheel, especially when driving over rough surfaces or bumps, which might have caused the driver to lose control of the steering joystick.

Tiller - Karl Benz's Tricycle

Many early prototypes of the car did not have steering wheels at all. Figure 2.8 shows Karl Benz's 1886 tricycle, complete with a tiller as the steering component (Top 10 Weird Steering Wheels, n.d.). The tiller directed the front wheel of the vehicle just like a boat rudder. The tiller was made of wood, but a carbon version with built-in shift light was implemented in 1893 and is shown in Figure 2.9. Benz's redesigned Benz Velo became the world's first production car.

Figure 2.8 - Karl Benz's tricycle with wood tiller steering apparatus (Top 10 Weird Steering Wheels, n.d.).

Figure 2.9 - Benz Velo's carbon tiller steering apparatus (Top 10 Weird Steering Wheels, n.d.)

The biggest advantage to the tiller-style steering control was its size. Because it was smaller than a standard steering wheel, there was more room for visibility and it could easily fit inside a confined cockpit. One downside to this design was that it would have been difficult to implement any sort of display without implementing a dashboard.

3. OBJECTIVES

The Cal Poly PROVE Lab is designing a solar powered car to break the international land speed record. The space within the driver's cockpit that is allotted for the steering mechanism is too small for a conventional steering wheel. Therefore, the PROVE team has built a compact and lightweight apparatus to allow the driver to safely steer the vehicle.

To gain a better understanding of what PROVE Lab wanted to see in the finished steering apparatus, we spoke with Dr. Doig and received the following needs for the design:

1. Keep the scope small and create something attractive and well-made, not something put together last minute.
2. Utilize as little vertical space as possible.
3. Allow driver to control speed and braking from the steering wheel.
4. Keep the steering apparatus as light as possible.

CUSTOMER REQUIREMENTS

After further refinement of Dr. Doig's needs and multiple meetings with the PROVE Lab mechanical team, we generated the following customer requirements list:

1. The total cost of the interface system must be less than $200, PROVE supplies the funding.
2. The interface must be designed in such a way that it does not require changes to the current driver position plan.

3. The system must be designed in such a way that the driver can enter and exit the car with the system in place.
4. The presence of the system in the cockpit area must not inhibit the driver's ability to exit the vehicle within 15 seconds.
5. The system must interface with a ½" splined-shaft steering column center-mounted in the driver compartment.
6. The system must convert the driver's input into rotational motion of the column – the rotating aspect of the pinion and column are constraining parameters.
7. The system must exist within a 1.43 cubic foot volume on each side of the driver
    - The exception to this is the inclusion of members connecting the hand grips to the column – these may cross above the driver's body, provided that they do not present an impediment to motion or egress.

Engineering Specifications

From our background research on steering wheel design, as well as consideration of the customer's requirements, we developed engineering requirements which were used to verify our final design. In a Quality Function Deployment (QFD), also named the House of Quality, we listed and compared the customer requirements and the engineering requirements. The QFD can be found in Appendix A. Each of the customer requirements was weighted based on importance to the customer - the driver of the solar car. Each engineering requirement was given a relationship rating to each customer requirement (strong, moderate, or weak), and was compared to the other engineering requirements to verify positive or negative correlation. Strong correlation between two engineering requirements meant the two requirements of focus were redundancies, and one needed to be changed or deleted.

We rated how well the customer's expectations and the engineering requirements were met by our assumed final product as well as previous steering wheels that have been developed. Results of the QFD allowed us to gain an understanding of how well other steering wheel designs fulfilled the customer and engineering requirements, and provided us with engineering specifications, shown in Table 3.1.

Table 3.1 - Prototype Vehicles Laboratory Steering Wheel engineering specifications.

Spec. #	Parameter Description	Target (units)	Tolerance	Risk	Compliance
1	Cost	$200	Max	L	A
2	Contact with canopy	Yes/No	Binary	H	T
3	Time for driver exit	15 seconds	Max	M	T, S
4	Throttle Buttons	Yes/No	Binary	H	A, T, S
5	Brake handle support	Yes/No	Binary	H	A, T
6	Steering column interface	Yes/No	Binary	H	A, T

Risk: H = High Compliance: M = Medium L = Low

A = Analysis
T = Testing
I = Inspection
S = Similarity to Existing Design

For each specification shown in Table 3.1, we assigned a target, estimated tolerance, risk association, and compliance. The targets were provided to us through discussion with Dr. Doig as well as with the PROVE Lab team, and were the goals for our finished design. The tolerance was the range of deviation we could accept in the final design. Our tolerances were either maximums or binary (yes or no), being that the solar vehicle has yet to be built and that dimensions are currently unknown to the PROVE Lab team. The risk was an assessment indicating how vital the specification would be to the final product. A high-risk specification was crucial to the proper function of our steering wheel design, whereas a low risk specification was not vital to the solar car's success. Compliance was how we ensured that the engineering specification parameter targets were met.

Details comprising each parameter are as follows:

1. Cost was a low risk specification because a variation of a dollars is not vital to the proper function of a steering wheel. We were able to verify the cost of the steering system through preliminary budgeting (Analysis). Since our expenditures were $50 above our expected budget, our sponsor, Dr. Doig, allotted funding to cover the extra expenses.
2. Contact with canopy was a high-risk specification because if contact with the canopy is made, the steering wheel could inhibit the solar car from making its world record run. To ensure contact with the canopy is not made, physical testing must occur once the PROVE car has been built, since the digital CAD model is a "perfect world" render which may not be representative of the finished vehicle.
3. Time for driver exit was a moderate risk specification because the fulfillment of this requirement is the responsibility of both the driver and design of the steering system. Testing on the driver exit time will be performed once the car is built; however, based on the lead concept design, we could proceed with the expectation of very little driver interference and for the driver exit time to stay below the target.

4. Throttle buttons were a high-risk specification because they are how the driver will control the speed of the vehicle. Analysis during CAD design verified that room was made for the throttle buttons, and testing in the finished product will ensure that the buttons fit properly. Based on similar designs of other steering wheels, button incorporation into the steering wheel was not a difficult issue to overcome.
5. Brake handle support was a high-risk specification because the driver must be able to brake the vehicle from the steering wheel. PROVE Lab previously decided that handle style braking, as opposed to pedal style, would be utilized. Analysis during CAD design verified that room was made for the brake handles, and testing in the final steering wheel will ensure that the brake handles fit appropriately. There have not been handle activated brake setups on previous vehicles.
6. Steering column interface was a high-risk specification because the steering system must be able to connect to the designed steering column to allow the driver to safely drive the PROVE car down the runway. Analysis during CAD design verified that the steering system successfully connected to the steering column.

4. DESIGN DEVELOPMENT

The design development that we implemented to tackle this project followed a generic process. This process included defining the problem, identifying the specifications required for this project, carrying out extensive brainstorming, developing sketches, and modeling the most appealing concept ideas. After we completed our ideation process, we evaluated the generated concept ideas with decision matrices to narrow down our selection for a prototype. Even though the scope of our project changed often, we provided our best effort to create designs which could be easily modified if the customer's requirements changed unexpectedly.

All of the sketches and prototypes that we created in our ideation sessions were based off of PROVE Lab's initial scope and requirements for our project. These were:

1. Allocated space in cockpit (with driver inside):
    Height- 4", Length- 30", Width- 6"
2. 5° steering angle of PROVE car required
    Must turn 30-45° to maximize steering control
3. Quick disconnect required
4. Accommodate for throttle control
    Throttle control will be a button on steering apparatus
5. Must integrate with a braking system
    Mountain bike brakes
6. Must integrate with rack and pinion steering rack.
    Steering Rack is located at the feet of the driver
7. Steering apparatus may be moved to head room of cockpit if top design requires the space
8. Incorporate a display system (display system controlled by buttons)

After our ideation was completed, the PROVE team redefined their project requirements and the car's cockpit dimensions. This change had a large influence on which of the prototypes that we came up with during our ideation sessions would meet all of the new requirements. The new project requirements are listed under the *Idea Selection* section.

INITIAL IDEATION

We began ideation by breaking the steering mechanism into three categories: materials, connectors, and method of steering. Since the weight of steering apparatus was one of our defined requirements, we selected and evaluated different types of light-weight material with strong rigidity to construct the steering apparatus. Previously, a quick disconnect/release feature was a required scope for the steering apparatus, so we brainstormed possible connector types that would allow for a quick disconnection of the steering apparatus from the steering rack. This brainstorming is detailed further into our design process. The method of steering category of the steering mechanism refers to how steering is actuated. Typical steering systems utilize a steering wheel; however, we were not limited to developing a typical steering wheel. To document the ideas, we created three lists – one for each area of the steering mechanism. We each wrote down ideas for all three areas of the system on sticky notes and placed them in the appropriate category. This is shown in Figure 4.1.

Figure 4.1 - Image of the brainstorming session we used to develop three aspects of the steering apparatus.

Many of the ideas written down during our first ideation stage using the sticky notes were impractical, such as using Velcro as a connector. We refined our first attempt at ideation by conducting additional ideation sessions during which we created sketches of steering apparatuses.

Three sketches created during ideation are shown in Figures 4.2 through 4.4.

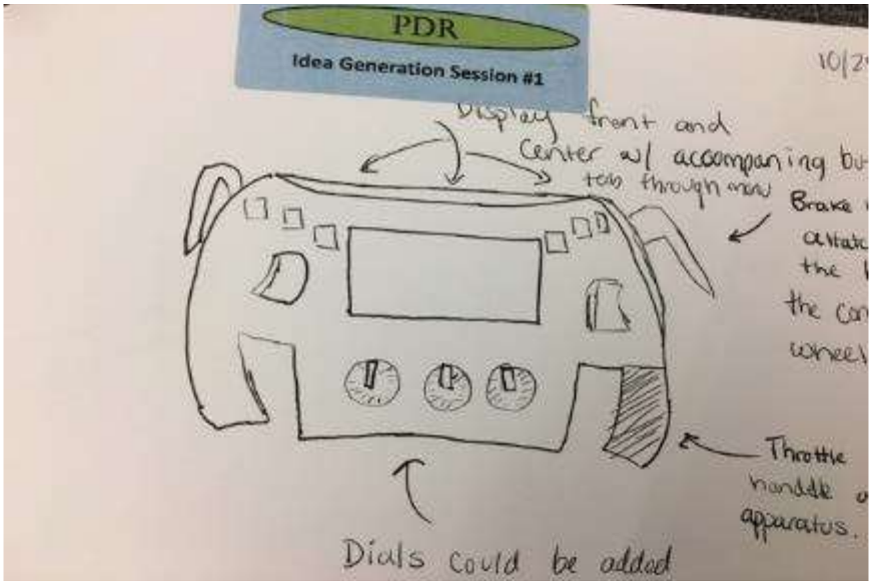

Figure 4.2 - Sketch of a racing wheel generated during the first idea generation session.

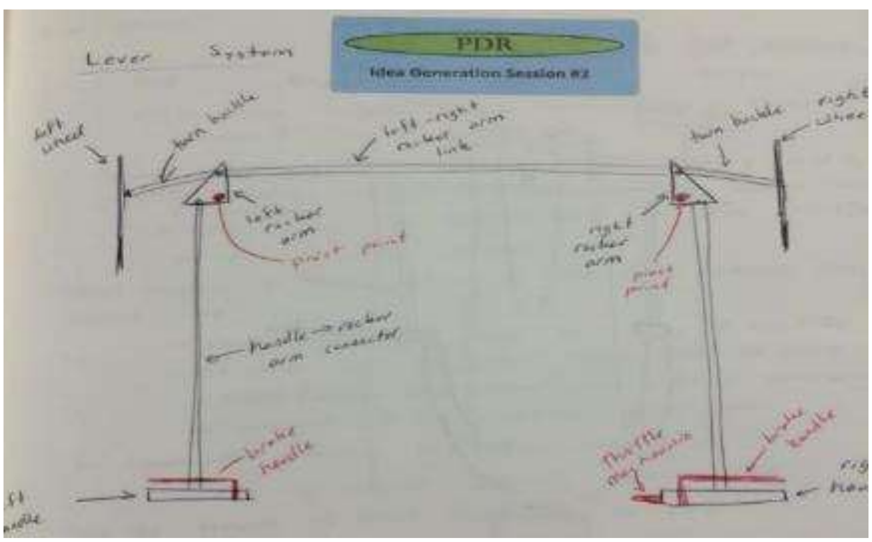

Figure 4.3 - Sketch of a rocker arm based steering apparatus obtained from the second idea generation session.

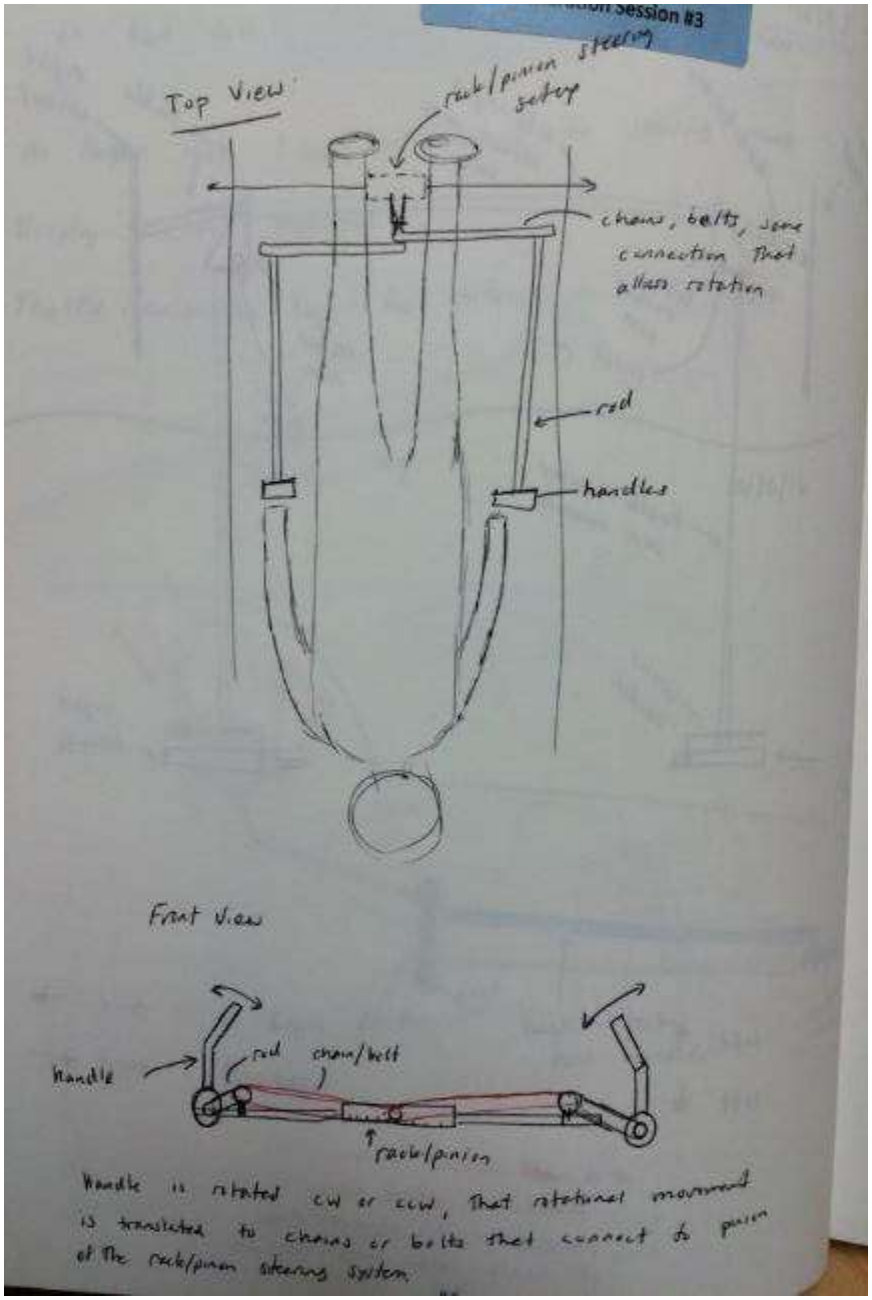

Figure 4.4 - Sketch of the lateral lever steering apparatus generated during the third ideation session.

With each of these concepts, we tried to satisfy all of the project requirements originally given to us by the PROVE team. After going through these brainstorm sketches, each one of our team members reviewed the drawings and gave feedback on the ideation drawing. These comments were then used to make additions or revisions to the drawings in order to create the top three choices, all of which were capable of satisfying the project requirements and safely steering the PROVE car down the runway during its potentially world record breaking run.

CONCEPT DESIGNS

From the sketches drawn in our ideation sessions, we created three physical prototypes. The three sketches that we chose to create mockups for are shown in Figures 4.5 through 4.7. These physical prototypes gave us an understanding of the scale of our product and a better understanding of how our final product could be manufactured.

Figure 4.5 - Physical prototype of the race wheel based off the Stanford solar vehicle.

The racing wheel design would have allowed the driver to interface with the vehicle in the manner that they would in everyday vehicles – rotating their hands in a circular fashion. The throttle buttons, brake handles, and an LCD would easily have fit on the steering wheel, and the driver would have been able to control the vehicle while being able to see the steering wheel. Since the racing wheel would have needed to be placed within the driver's canopy, there would have been a limited amount of space allotted for the wheel. Furthermore, the steering column shaft would have needed to be extended into the canopy to connect the racing wheel with the rack and pinion steering mechanism.

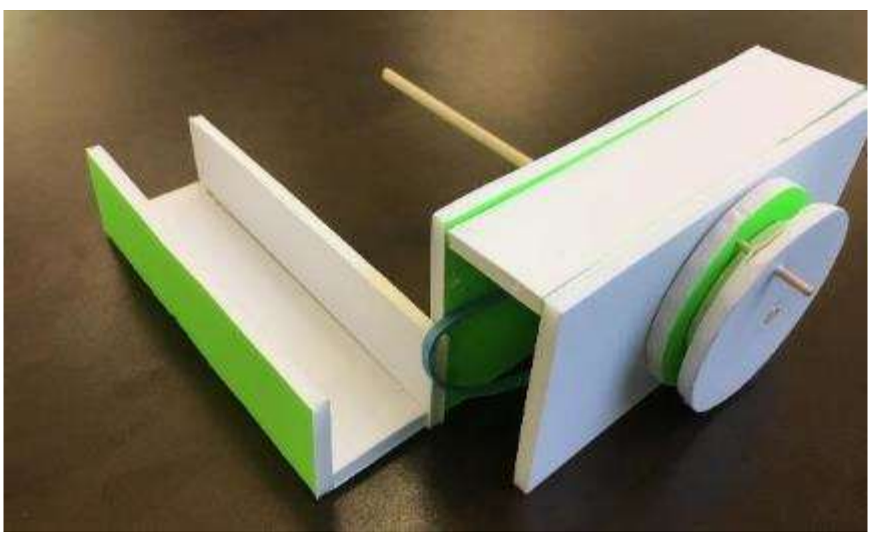

Figure 4.6 - Physical prototype of the tiller type steering system.

The tiller type steering system would have allowed the driver to steer the vehicle with one hand, and would not have required the driver to maintain a line of sight to the steering apparatus. Attaching throttle control buttons, brake handles, and an LCD to

this type of steering system would have been more difficult than with the race wheel. Subjectively, we believed that the driver would not have as much control of the vehicle as compared to the racing wheel. Since the driver would not have had control of the vehicle's steering angle with both hands like in a normal vehicle, there would have been a lack of "steering feel", or steering feedback associated with steering a vehicle (What is Exactly Steering Feedback, 2015).

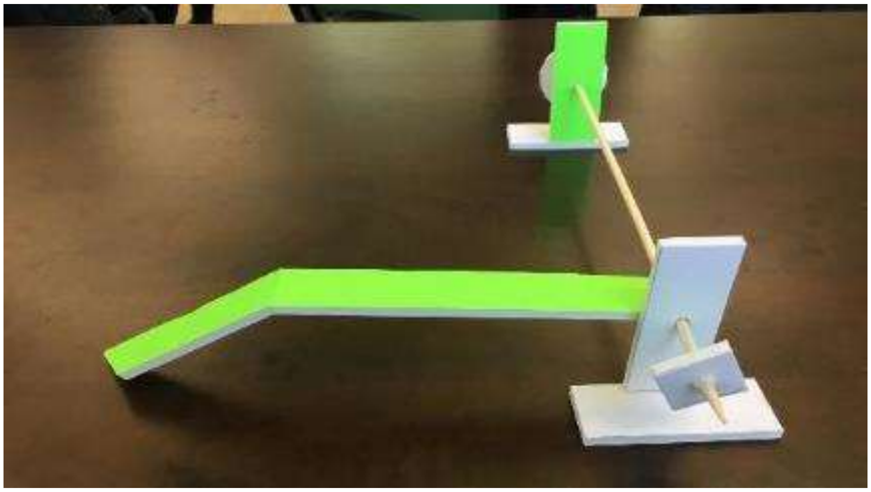

Figure 4.7 - Physical prototype of the lateral lever steering apparatus.

The lateral lever design would have provided the driver with two levers which rotated about the longitudinal (front to back) axis of the vehicle. Throttle control buttons and brake handles would have been mounted to the handles, but an LCD would not have been able to be incorporated into this design. Notably, this system would have allowed the driver to control the vehicle without requiring the driver to see the steering apparatus.

By building physical prototypes of each of our designs we could physically see the advantages and disadvantages presented by each of our designs. Although creating prototypes was helpful in guiding our decision on which design would be the best, we felt that we needed to utilize a method that was objective rather than subjective to show the most suitable concept for us to move forward with.

IDEA SELECTION

For our idea selection process, we compared each of our concepts in a Pugh Matrix, shown in Figure 4.8 and in Table 4.1. In our Pugh matrix, we used a standard steering wheel as our datum, or comparison point for our other designs. We chose a standard steering wheel as our basis of comparison because our original goal was to create a steering apparatus that could perform in the same way as the steering wheel of a typical car, but in the limited area of operation inside the PROVE cockpit.

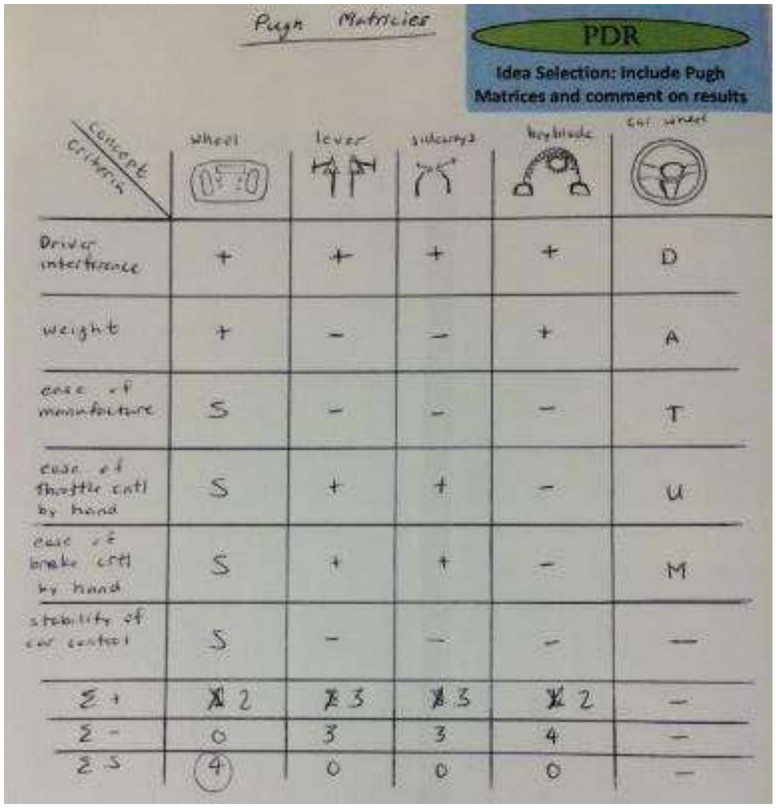

Figure 4.8 - The initial Pugh Matrix which compared 4 steering apparatus ideas to the datum of a car wheel.

Table 4.1 - Final decision matrix used to decide on the lead concept. It should be noted that the racing wheel was declared as our best concept; however, the PROVE team gave us new requirements after we had made the decision matrix that caused us to abandon the racing wheel in favor of the lateral lever concept.

Criteria	**Concept**			
	Lateral Lever	Rocker Arm	Race Wheel	Car Wheel (DATUM)
Driver Interference	9	9	5	5
Weight	3	3	7	5
Ease of Manufacture	3	3	9	5
Ease of Throttle Control	9	9	7	5
Ease of Brake Control	9	9	7	5
Stability of Car Control	3	3	5	5
Steering Rack Integration	3	1	5	5
SUM	39	37	45	35

As seen in Figure 4.8, all data points with an "S" indicate that the specific design concept performed as well as our datum, a standard steering wheel. Data points with a "+" indicate that the design concept performed better in that specific requirement. All data points with a "-" indicate that the design concept performed worse than the datum in that specific requirement. All criteria was chosen based on the original project requirements given to us by the PROVE team.

While our final Pugh Matrix, shown in Table 4.1, indicated that a racing wheel would best satisfy our original customer requirements, we ultimately did not utilize the racing wheel as our lead concept. The reason for this decision was an update of cockpit dimensions and requirements, provided by the PROVE Lab team, which made the racing wheel unusable as a steering apparatus. These were:

1. Allocated space in cockpit (with driver inside):
   Height – 7", Length – 40", Width – 8.5"
2. Steering apparatus must be retractable or not in driver's way during egress
3. Accommodate for throttle control
   Throttle control will be an ATV push throttle
4. Must integrate with a braking system (mountain bike brakes)
5. Incorporate display system (optional)
   One button will be placed on the steering apparatus
6. Must integrate with rack and pinion steering rack
   Steering rack will be placed at the most convenient location for the steering apparatus
7. Steering apparatus must be located by the legs of the driver

These revised specifications eliminated the racing wheel as an option because a lack of canopy space no longer allowed the steering apparatus to be placed inside of the canopy. At the time the PROVE Lab team informed us of this change, we did not have sufficient time to restart ideation and redo concept development. Utilizing the new requirements, we selected the option which best fit within the updated steering space and was second to the racing wheel – the lateral lever steering apparatus.

5. FINAL DESIGN

The lateral lever steering, shown in Figure 5.1, was the final design selected for PROVE Lab's solar car. This steering mechanism was designed to withstand the maximum expected loads applied by the driver during the three-minute run of the competition. After the concept stage of design, the dimensions for the PROVE car's canopy were changed, and our choice was therefore adjusted to meet the new requirement list. This design was initially second to the racing wheel mentioned previously.

Figure 5.1 - Concept rendering of the lateral lever steering system. Note that the steering rack is not included in this figure, but would be interfaced at the double sprocket (located near the bottom left of the figure).

The lateral lever steering apparatus is controlled by two adjustable handles. The rotation of the handles was limited to either a clockwise or counterclockwise direction relative to the longitudinal axis of the vehicle, thus turning the vehicle's wheels right or left, respectively. Each handle assembly was mechanically connected via a longitudinal tube attached to a sprocket, as shown in Figure 5.2. Each sprocket was connected to the steering rack with Number 25 ANSI roller chain (not pictured in Figure 5.1). A double sprocket attached to the steering rack allowed each handle to have a dedicated roller chain connection. This redundant system was designed to maintain the driver's control of the vehicle even if one of the two roller chain connections failed. An ATV-style, finger operated throttle and hand operated braking levers were attached to the handles to provide the driver with control over the solar car. Each longitudinal tube was supported in two places by ball bearings, which were in a housing connected to the floor of the driver's cockpit. In the following sections a detailed description is provided for each components of the steering lever mechanism.

Figure 5.2 – Close-up view of the handle assembly's adjustable connection to the longitudinal rod. The handle's collar is held in place with a clevis pin, which allows for a fore and aft adjustment of 2.5 inches at 0.5 inch increments.

The primary advantage of the lateral lever steering apparatus was its ability to provide a steering angle that was within the scope provided by PROVE Lab – at least 30 degrees both clockwise and counterclockwise. The handles also provided the space necessary to accommodate the throttle control and the braking system, so that the driver was able to control the vehicle using only their hands. Additionally, the handles did not interfere with the canopy due to their placement beside the driver's legs. Although our design supported all of the control systems for the vehicle, did not interfere with the canopy or the driver, and provided the required steering angle, there was one disadvantage present in this design. If PROVE Lab were to decide to implement a display system in the vehicle, the steering apparatus would not have room to support it. The display would need to be mounted elsewhere within the vehicle. Since the display was an optional requirement, we were willing to accept this shortcoming since all of the major requirements were successfully fulfilled. Because of our choice of the lateral steering apparatus as our final design, we believe that future cockpit dimension changes or body alterations will have little to no effect on the steering apparatus' operation.

LONGITUDINAL ROD

The longitudinal rod connected each handle to a sprocket. In our first design, the rod material was carbon fiber – 0.5 inches in diameter with a 0.125-inch wall thickness. This material choice was initially made because we expected the carbon fiber rod to provide the most resistance to deflection due to torque caused by the driver's input to the handle. We determined that the 22-inch carbon rod had an angular deflection of 8.9° for a 45 lb_f force applied on a 6-inch handle (see Appendix B for calculations). We did not know if this deflection was large relative to other materials, so we determined the angular deflection for two additional rod materials.

An aluminum, 6061-T6 rod with an outer diameter of 0.5 inches and wall thickness of 0.049 inches had an angular deflection of 2.8°, and an angular deflection of 0.9° from 4130 chromoly steel. Based upon our angular deflection calculations, we found that a carbon rod was expected to deflect the most, so we decided to employ aluminum for the longitudinal rod material. While the chromoly steel was found to deflect less than aluminum, we chose to use an aluminum tube for the longitudinal rod to save slightly less than 0.5 lbs in the overall weight of the system. Overall vehicle weight would affect the performance of the vehicle, and we wanted to save weight where possible to meet the under 5 lb requirement.

Interfacing with the adjustable handles required the longitudinal rod to have a linear array of 3/16-inch diameter through holes. Each hole was separated by 0.5 inches, and six holes in total allowed for a total of 2.5 inches in fore/aft handle adjustment. A clevis pin was placed in the selected adjustment hole to lock the adjusted handle placement. Holes in the longitudinal rod can be seen in Figure 5.3.

Handle Assembly

The driver must be able to control the vehicle from the steering apparatus, so we had to ensure our design was ergonomic and supportive of the vehicle's throttle and brakes. Initially, we intended to manufacture the handle assembly of the steering apparatus using a wet carbon fiber layup over foam core. While creating a manufacturing plan for the carbon-foam handle design, we realized forming an inner foam mold would require hours of sanding and an extensive understanding of shapes that are comfortable for the human hand. Furthermore, we did not know what the throttle and brake apparatuses required for proper mounting. In exchange for the carbon-foam handle design, we employed a simpler idea. A 7/8-inch outer diameter aluminum tube with a wall of 0.049 inches welded to a 5/8-inch outer diameter, 0.049-inch wall collar provided the same functionality as the carbon-foam design, but also introduced new possibilities for fulfilling our requirements.

Adjustability, throttle and brake support, and comfort were all requirements for our design, albeit at different levels of importance. Through the switch from the carbon-foam design to the all-aluminum design, we were able to fulfill all three requirements – keeping the carbon-foam design would not have given us that ability. We made the handle adjustable, with respect to the longitudinal axis of the vehicle, by incorporating a 7/32-inch hole in which a 3/16-inch clevis pin would fit (see Figure 5.3 for a visual description). The difference in hole diameter to clevis pin diameter ensured a clearance fit such that manufacturing imperfections in the pin and drilled hole would not prevent adjustment of the handle position. The clevis pin restricted fore and aft movement as well as rotation of the handle about the longitudinal rod. Rotation of the handle about the longitudinal rod was considered a critical failure because it meant that the driver would be rotating the handle in an attempt to steer the vehicle, but the longitudinal rod (connected to the sprocket and steering rack) would not be receiving this rotational input.

Figure 5.3 - Interface of the handle assembly to the longitudinal rod using the clevis/cotter pins as the mechanism to lock fore and aft handle adjustment.

Inclusion of the throttle and the brake were achieved through our choice of 7/8-inch outer diameter tubing for the handle. Since we assumed the throttle and brake chosen by the PROVE Lab team were similar to those used on recreational vehicles (ATVs and motorcycles) and bicycles, we made our handle diameter the same as the handle diameters of recreational vehicles and bicycles. Furthermore, the use of 7/8-inch outer diameter tubing allowed us to utilize a bike handle cover (typically foam or rubber) to give our handle a comfortable feel for the driver. To improve the ergonomics of the handle design, we found that the handle needed to be inclined 15° from vertical to relieve stress on the driver (Moderator, 2017).

BASE-MOUNTED BALL BEARING

The longitudinal rod which transfers the driver's rotational input to the steering rack needed to be held above the floor of the driver's cockpit. To accomplish this, we utilized ball bearings mounted within a housing that was secured to the floor. Two base-mounted ball bearings supported each longitudinal rod – one ball bearing was located toward the sprocket attached to the longitudinal rod, and the second was located at the other end of the rod where the handle was attached. By using two ball bearings – one at each end – the moments induced into the longitudinal rod by the tension within the chain became negligible. Additionally, utilizing ball bearings created a low friction medium for the rotation of the longitudinal rod. Hence, no apparent damping was added to the steering apparatus from the driver's point of view. Fatigue life calculations were not required for the ball bearings because full rotations of the handle were not physically possible – the steering system was designed to experience a maximum of 30 degrees clockwise and counterclockwise. Our design allowed for 35 degrees of rotation in both clockwise and counterclockwise directions (interference with the roll cage of the cockpit occurred at angles greater than 35 degrees), which limited the steering apparatus from experiencing greater than 70 degrees of total rotation. Furthermore, with low loading expected by the driver, we were confident that fatigue would not serve as a point of failure for the bearings.

Roller Chain and Sprockets

Connecting the driver's rotational input to the steering rack required the use of either chains, belts, or gears. We ruled out a gear transfer case because the cost for the gears would have been too high, and multiple gears would have been required to span the 14-inch distance between each longitudinal rod and the sprockets at the steering rack input shaft. When comparing belts and chains, we based our final decision on safety. Belts, unless highly tensioned, could slip. In this case, if a belt were to slip, then the "center" of our steering system, where both steering handles point perpendicular to the flat cockpit floor, would be altered. Slippage of the belts during vehicle operation would mean that the driver could no longer control the direction of the vehicle. While the vehicle was expected to remain in a straight line during operation, we wanted our design to support unexpected behavior. In this case, unexpected behavior was defined as steering the vehicle during a straight-pathed run. Chains were recognized as the preferred choice because the "center" of our steering system would be maintained, to a certain extent, even if tension in the chain was lost.

After deciding on chain as our medium of connection, we sized the chain needed for application. We expected a maximum tension of 43.2 lb_f in the chain, so we selected ANSI Number 25 roller chain. With a rated working load of 88 lb_f, we were assured that the Number 25 chain was sufficiently strong for our system.

With our roller chain selected, we found the smallest sprocket available on McMaster Carr. Our reasons for this were: (1) a smaller sprocket meant the physical size of the steering system would be decreased, so more room would be available in the cockpit, and (2) McMaster Carr had a wide range of sprockets and was the source of many other parts within our system, so we could reduce shipping costs by purchasing multiple parts from the same supplier. Strength of the sprockets, specifically at the teeth, in torsion was not a concern because we calculated 4.5 lb-ft of torque in the worst loading condition (45 lb_f applied at a 6-inch radius from the longitudinal rod's axis of rotation).

The smallest sprocket size we found was 1.25 inches in outer diameter. We planned to use this sprocket for placement on the longitudinal rod and steering rack; however, the PROVE Lab team requested a change in sprocket size on the longitudinal rod to provide the correct steering ratio for their steering rack (which was established after we determined our initial sprocket size). The final sprocket sizes for our steering apparatus were 1.25 inches in outer diameter at the steering rack shaft, and 1.57 inches in outer diameter at the longitudinal rods. Each sprocket was connected to its respective shaft via set screws. This gave us the ability to alter sprocket placement on the shaft as needed. Final sprocket locations are shown in Figure 5.4.

Figure 5.4 - Side view of the sprockets showing their offset position. The offset allows one chain to connect each lever to the steering rack.

Tensioner Assembly

We decided to implement a tensioner into our steering apparatus because it gave us the ability to alter the tension within the connecting roller chain without shifting the support-base ball bearing mounts. We were not able to utilize a typical bike tensioner due to its large size, so we searched for chain tensioners that were smaller than those found on bicycles. On McMaster Carr, we found a base-mounted, non-spring-loaded chain tensioner, shown in Figure 5.5. The tension in the chain loop was adjusted by changing the angle of the tensioner arm holding the idler sprocket, also shown in Figure 5.5.

The idler sprocket utilized in the tensioner assembly included a ball bearing on which it freely rotated. This sprocket was the largest of all three within our steering apparatus system, at 1.73 inches in outer diameter; however, it was the smallest idler sprocket available for ANSI Number 25 chain. There was no listed tension rating for the idler sprocket, but we assumed it was comparable with our longitudinal rod and steering rack sprockets. Hence, we were confident that the idler sprocket would be able to support the minimal tension our system needed. A 3/8”-16 shoulder bolt was the last piece of our tensioner assembly. Its sole purpose was to hold the idler shaft in place. Expected loading on the bolt was so low, due to minimal tension in our chain, that it was not necessary to determine the stress experience by the bolt.

Figure 5.5 - Close-up of the tensioner assembly. In the full steering apparatus assembly, there is one tensioner assembly for each steering handle.

MANUFACTURING PLAN

Beginning with the longitudinal rods, a horizontal band saw was required to cut the stock to length. A manual vertical mill and 1/2-inch endmill were then used to face the cut edges for smoothing, and a buffing wheel was used to take the top oxidized layer off of the rods to give the rods a clean appearance. The 6 adjusting holes were made with a manual mill and drill collet using a 3/16-inch drill bit.

The handle collars were cut to length from stock using a horizontal band saw, and a manual vertical mill with 1/2-inch endmill was used to face the newly cut edges. The manual mill was then used to drill the 3/16-inch hole through which the cotter pin fits.

The handles were first cut to nominal length using a horizontal band saw, and a manual vertical mill with 1/2-inch endmill was used to face the newly cut edges. A manual mill using 15° parallels and a 5/8-inch endmill were used to create the angled slots where the handle collar and handle meet. An all-around TIG weld then joined the handle collar and handle. Final sanding and deburring were required to ensure that the handle assembly slides along the longitudinal rod easily.

All manufacturing processes – the milling for the handle, collar, and longitudinal rod as well as the TIG welding to mate the collar and handle – were possible to complete at the Cal Poly machine shops. Appendix C shows the drawings for all parts of the steering system, and provides a clear view of which features required manufacturing.

COST ANALYSIS

The cost of the steering apparatus was primarily due to the stock pieces ordered from McMaster-Carr. Aluminum stock material was ordered from Online Metals for the fabrication of the custom parts. A layout of all the stock parts and material ordered can be seen in the Bill of Materials within Appendix D. The total budget for the steering apparatus is projected at $430, which will be funded by the overall PROVE car budget. A brief overview of the cost for each subsystem can be seen in Table 5.1.

Table 5.1 - System level overview of the cost for each subsystem for the steering apparatus.

Subsystem	Cost [$]
Handle Assembly	17.44
Support Assembly (long. rod, bearings, etc.)	103.82
Tensioner Assembly	256.72
Chain	41.12

The most expensive aspect of the steering apparatus was the tensioner system, due in part to the near $100 price of each tensioner body. One of our requirements was to remain within a budget that was below $200, so we found other tensioning systems based on a floating tensioning design. This decreased the total tensioner assembly cost by about $160 – shipping and tax were not taken into account. PROVE Lab has not decided on a final tensioning system, so we proceeded with the more robust, floor-mounted tensioning system.

SAFETY CONSIDERATIONS

A safety hazards checklist can be seen in Appendix E. Due to the simplicity of our steering apparatus, there is not much of a cause for concern regarding any major safety issues. We created our design to account for any potential failures to the system that could cause the apparatus to fail or cause the PROVE driver to lose control of the car. Our team has located three potentially hazardous scenarios that may cause accidents, and we have taken precautions to avoid this. These possible situations are stepping on the mechanism, handle position slip, and driver interference with chain and steering rack interfaces.

We analyzed the worst case scenario of damage caused by stepping on the apparatus. This could potentially occur when the PROVE driver is entering or exiting the cockpit of the car. Assuming that a 150-lb driver placed their entire weight at the center of the longitudinal rod, our analysis shows that the aluminum rod will only deflect by 0.32 inches. This deflection is well within the bounds of safety, as the longitudinal rod has been designed with the strength to withstand forces much greater than 150 lbs before yielding.

In the case of handle position adjustment and slip, there is a clearance of 0.029 inches between the handle collar and the longitudinal rod to allow for up to 2.5 inches of driver handle adjustment. To prevent the handle from slipping up or down the longitudinal rod while the car is in motion, our PROVE team has implemented a clevis pin that will lock the collar to the desired placement on the longitudinal rod. This clevis pin will not yield in the case of a force of 45 lb_f being applied as a moment on the top of the handle, ensuring that the driver will not have any worry of losing steering control

while inside the cockpit. If it is determined that there is too much play between the collar and the longitudinal rod after the clevis pin has been locked into place, our team will extend the collar of the handle to allow for a second clevis pin, eliminating any play. This ensures that the driver will have the utmost confidence regarding her safety while steering the PROVE car down the runway.

In the case of possible driver interference with the chain or steering rack interface, the PROVE Lab team has agreed to construct safety guards that will be installed over these two subsystems. This ensures that the driver will not be able to have her clothing accidentally caught by either of these subsystems while she is operating the steering apparatus.

PROVE Lab has listed several safety considerations in their scope given to our team. Design verification of these requirements will be covered in Section 7 - Testing.

MAINTENANCE AND REPAIR CONSIDERATIONS

The steering apparatus has been designed with the knowledge that it will only be used a handful of times. Thus, there is little concern regarding maintenance or repair. Once again, the simplicity of our design gives us confidence that there will not be failure in any of our subcomponents before the attempted world record run by the PROVE car. The only maintenance procedures that our team will suggest to the PROVE Lab team will come after test runs are performed. If it is found that small adjustments to the placement of the handles or the tension in the chain are necessary, these adjustments can be easily and intuitively made as requested by the PROVE driver and PROVE Lab team.

6. PRODUCT REALIZATION

The manufacturing process of the steering system began in the fourth week of the Spring quarter, after the majority of the materials arrived from the vendor. All parts were manufactured in-house, with the exception of the sprockets, the chain tensioners, and the support bearings. Manufacturing of the steering levers was completed at the Aero Hangar Shop and the Advanced Manufacturing Lab, both of which are located on campus.

MANUFACTURING PROCESSES

Construction of the steering apparatus began with the longitudinal rods. We did not utilize the horizontal band saw to cut the stock down; rather, we left the rods at 24 inches – the extra two inches of stock was negligible for operation. We did not need to face the cut edges, as there were none, but we deburred after each drilling operation to clear chips and sharp edges using the Burr King 1000 deburring machine. We used a milling machine to drill the six 3/8-inches holes on the longitudinal rod as depicted in Figure 6.1. In order to cut aluminum, the required spindle speed was 1500 rpm. To prevent the rod from moving, we used a “vee block” that was placed in a vise to secure it firmly. Since the outer diameter of the longitudinal rods was the same as the inner diameter of the support bearings, we had to use an abrasive wheel to take off between 0.01 and 0.015 inches from the outer diameter of each longitudinal rod. This allowed the rods to slide through the support bearings. The estimated time spent working on the longitudinal rods was 2 hours.

Figure 6.1 – Drilling 3/8'' holes on the Aluminum 6061-T6 rod with the mill drill at the Cal Poly Aero Hangar Shop.

The next step was cutting two pieces, each at a length of 1.50 inches, from a 5/8-inch outer diameter aluminum tube to create handle collars using the cold saw from the Composites Lab. These collars were deburred using the belt sander to remove the sharp edges. A 3/16-inch drill bit was used to create the clevis pin holes, and a 7/32-inch drill bit was used to enlarge the holes since there was not enough clearance to line up the longitudinal rod and handle collar holes. Both handle collars were polished with a buffing wheel to prepare the surface for TIG welding.

Once the handle collars were completed, we cut two pieces from a 7/8-inch outer diameter aluminum tube to a length of 8 inches each using the cold saw. These pieces were used as the handles. In order to create the angled slots where the handle collar and handle meet, we used a manual mill with 15° parallels to hold the aluminum rods at the desired position while drilling the angled slots. These slots were made using a 5/8-inch drill bit. Since a smooth surface was required for our handles to weld together with the collars, we deburred the handle tubes using the belt sander to remove any sharp edges. We used a deburring tool on any location where the belt sander could not reach. Prior to welding the pieces together, we aligned the pieces as depicted in Figure 6.2 to make sure that the collars fitted without interference in the slots of the handles. An all-around TIG weld was made to join the handle collar and handle. Final buffing was used to clean the TIG welds and to allow the foam handles to fit on easily.

Figure 6.2 – Verification of the alignment between the 5/8'' diameter collar with the 7/8'' diameter handle prior to the welding process.

DIFFERENCES FROM PLANNED DESIGN

The overall system was slightly different from the final planned design. Figure 6.3 shows the final product and Figure 6.4 shows the final planned design proposed at the Critical Design Review stage. Our final product differed from the final concept primarily with the tensioning system. Being that we were $230 over the goal budget of $200 for the project, we sourced a different tensioning system. Rather than a bolt mount tensioner, which would have required a cast iron body, locking bolt, and additional sprocket, we chose a floating chain tensioner. The benefits of utilizing this tensioning system were decreased weight, lower cost, and smaller encasement.

Figure 6.3 – Final product of the lateral lever steering system. Note that the steering rack, double center sprocket, and tensioners are not included in this figure, because they require a completed cockpit for setup.

Figure 6.4 – Final concept rendering of the lateral lever steering system from the Critical Design Review.

Additional differences can be seen between Figures 6.3 and 6.4; however, the absence of the dual center sprocket was due to the fact that the actual vehicle cockpit has not been completed. The dual center sprocket attaches to the steering rack, which is still being built. The black foam handles in Figure 6.3 were part of the original design, but were not incorporated into the final design rendering.

The final difference that is apparent between the two images is the acrylic backing used to hold the finished steering apparatus. This acrylic base was neither part of the final design nor was it part of the final product. Rather, it was incorporated in the final product purely for display purposes.

7. DESIGN VERIFICATION

To ensure our apparatus met the design requirements given to us by the PROVE Lab team, we created a design verification plan (DVP), as seen in Appendix F. All tests had pass/fail acceptance criteria, but were unable to be carried out according the timeline specified in our project Gantt Chart, shown in Appendix G. The tests will be performed after PROVE Lab finishes constructing the full vehicle – an expected date of completion was not available at the time of the writing of this report. Tests will be completed and, if necessary, the needed design changes will be made at least two weeks before PROVE Lab's world record attempt.

TESTING

There are three main areas for testing our steering apparatus. These tests include:

1) Interference Tests - These tests will cover item numbers 1 and 6 in the DVP.
   Item 1 specifies that the steering apparatus cannot make contact or interfere with the canopy of the PROVE vehicle. Item 6 specifies that the steering apparatus must rotate a minimum of 30 degrees before making contact with the roll cage inside the cockpit of the PROVE vehicle.

   In order to test these specifications, the PROVE Lab team will follow a simple testing protocol of loading the PROVE driver into the car and closing the canopy. The driver will then rotate the handles 30 degrees to the left and to the right of vertical. The PROVE Lab team will then record whether the specifications are met with a pass mark, meaning that the steering apparatus is free to rotate 30 degrees from vertical before making contact.

2) Driver Safety Test – This test will cover item number 2 in the DVP.
   Item 2 specifies that the steering apparatus must not inhibit the driver from exiting the vehicle in less than 15 seconds.

   In order to test this specification, the PROVE Lab team will follow a simple testing protocol of loading the PROVE driver into the car and closing the canopy. The PROVE Lab team will then start a stopwatch to time how long it takes the driver to fully exit the vehicle. The PROVE Lab team will repeat this process a minimum of three times to ensure that the steering apparatus does not interfere with a rapid exit from the vehicle.

3) System Interface Tests – These tests will cover item numbers 3, 4, and 5 in the DVP.
   Item 3 specifies that the PROVE throttle actuation buttons must fit on the steering apparatus. Item 4 specifies that the PROVE brake handles must fit on the steering apparatus. Item 5 specifies that the PROVE steering column must interface with the steering apparatus.

To test these specifications, the PROVE Lab team will follow a simple testing protocol of installing the throttle, brakes and steering column to the steering apparatus. The PROVE Lab team will then record whether the specifications are met with a pass mark, meaning all systems interface with the steering apparatus.

RESULTS

Since PROVE Lab has not yet constructed the full vehicle, full scale testing will be put on hold until the steering apparatus can be installed. Once PROVE Lab constructs the vehicle, or an updated full-scale model, we will place the steering apparatus into the cockpit and complete the testing plan. To ensure our steering apparatus is tested correctly, a detailed testing protocol has been delivered to the PROVE Lab team. Our team is confident that the steering apparatus will meet all specifications, allowing the PROVE Lab team to safely and quickly get the PROVE vehicle onto the track to attempt to break the world record. Throughout the process of designing the apparatus, all given specifications were followed as closely as possible. The design allows for simple installation with no cockpit interference, easy system integration, and effortless exit from the vehicle.

8. CONCLUSIONS AND RECOMMENDATIONS

This report provided an overview of the background, objectives, preliminary design, final design and design realization of our steering apparatus created for the Cal Poly Prototype Vehicles Laboratory. During our preliminary design stage, the PROVE Lab team altered the requirements and constraints that we had been given for the steering apparatus. This change led us to select the lateral lever steering system during ideation, rather than the racing wheel. We chose the second-best concept because the first-place concept no longer met PROVE Lab's requirements. During our critical design phase, we redesigned the handles and longitudinal rods, added a tensioning system, and varied the sprocket size on the longitudinal rods. By implementing these changes, we created a durable and safe steering apparatus which gave the PROVE car's driver complete control of steering, throttle, and braking. Following approval by the PROVE team, we ordered the parts required for our design and constructed the steering apparatus. Testing our steering apparatus was unfortunately impossible as the PROVE car body was not completed within the time frame of this senior project. In June 2018, our steering apparatus design will be used in PROVE Lab's record-attempt runs.

Building upon this project, there are a few things that could improve the product and the experience. One recommendation that our team has is to make sure that the scope of the project is more defined before moving into the critical design stage. Not having agreed upon specifications for the project at this stage limited what our team could accomplish with the final product. For example, if the PROVE Lab team had known what brake handles and throttle mechanisms were going to be used during the preliminary design stage, our team could have come up with an intuitive way to implement those parts into our design. While we are extremely confident in our design and we had almost no complications during manufacturing, we were not able to verify our theoretical calculations to ensure that all safety specifications were accomplished. This was out of our team's hands, but we suggest that future teams make sure to make testing their product a priority.

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APPENDIX A

Quality Functional Deployment Diagram

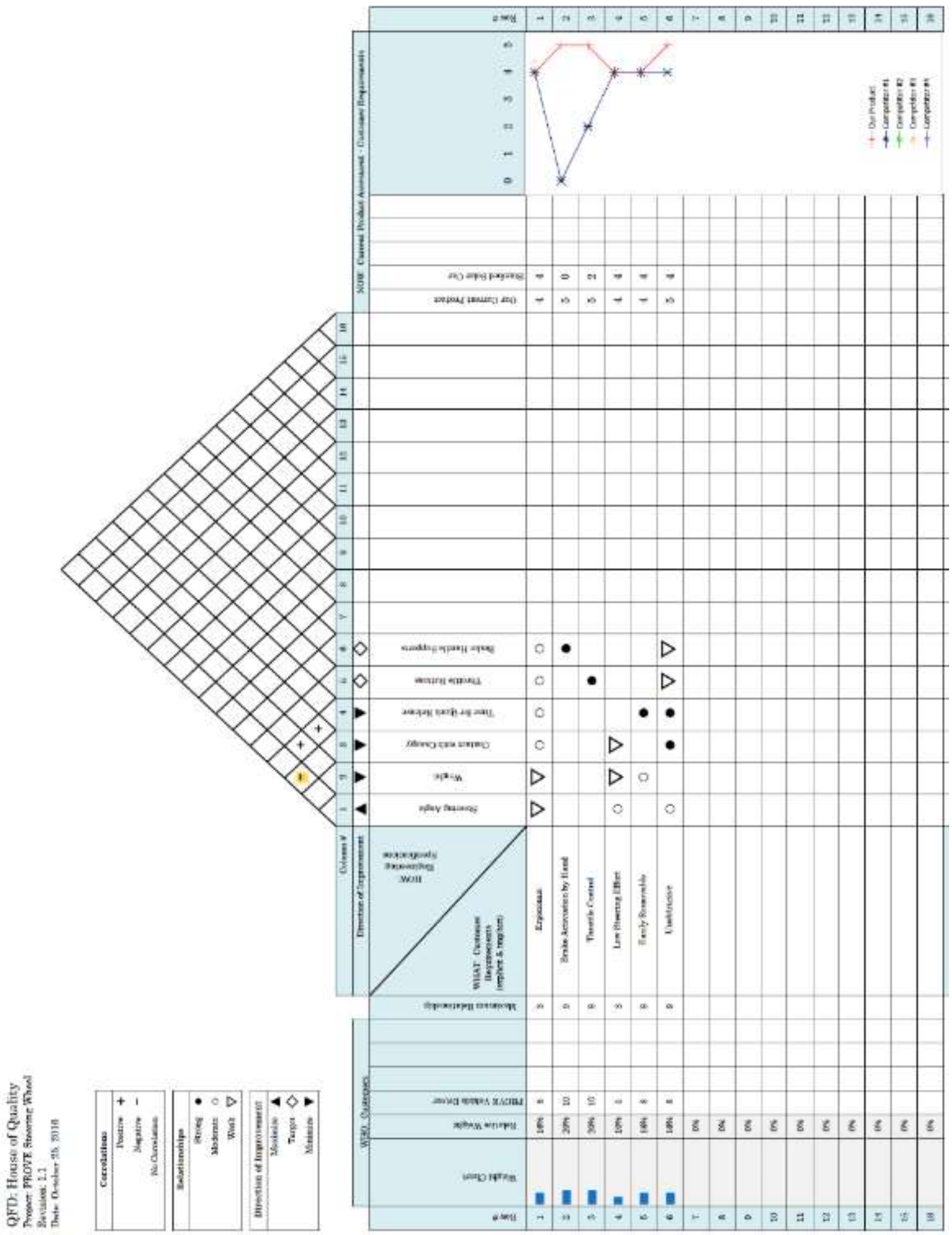


Figure A.1 – QFD chart top portion analyzing the PROVE non-steering wheel

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target	± 30 degree	≤ 5 pounds	Yes/No	10 second	Yes/No	Yes/No										
Max Relationship	3	3	9	9	9	9										
Technical Importance Rating	85.92	75.61	206.1	342.9	249	249										
Relative Weight	8%	6%	17%	28%	20%	20%										
Weight Chart																
Our Product	5	5	5	4	4	5										
Standford Solar Car	5	5	4	4	4	0										

Current Product Assessment - Engineering Specifications

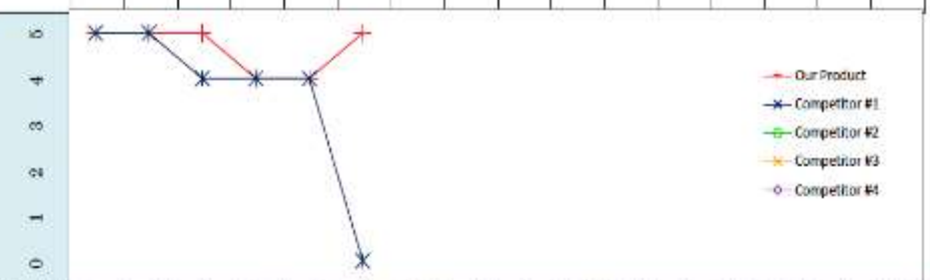


Figure A.2 – QFD chart bottom portion analyzing the PROVE non-steering wheel

APPENDIX B

Calculations and Analysis

Variables:

$F_h = Force\ at\ the\ handle$
$T_r = Torque\ applied\ on\ longitudinal\ rod\ due\ to\ F_h$
$r = length\ of\ handle$
$\theta = Angular\ deflection\ of\ longitudinal\ rod$
$l = Length\ of\ longitudinal\ rod$
$G = Shear\ Modulus\ of\ Elasticity$
$J = Polar\ Moment\ of\ Inertia$
$T_c = Torque\ at\ longituinal\ rod\ sprockets$
$F_{tension} = Tension\ in\ chain\ attached\ to\ longitudinal\ rod\ sprocket$
$r_{sprocket} = Radius\ of\ longitudinal\ rod\ sprocket$

TORQUE IN THE STEERING SYSTEM

To determine the torque within the longitudinal rod, we utilized Equation 1,

$$T_r = F_h r \qquad \text{Eq. 1}$$

Using the maximum expected force, F_h, of 45 lb_f and handle radius, r, of 8 inches,

$$T_r = 360 \text{ ft-lb} = 30.5 \text{ Nm} \qquad \text{Eq. 2}$$

Next, we wanted to find the angular deflection of the longitudinal rod due to T_r. We used Equation 3 as follows,

$$\theta = \frac{T_r l}{GJ} \qquad \text{Eq. 3}$$

Where,

$T_r = 30.5$ Nm
$l = 22$ inches $= 0.56$ m
$G = 26$ GPa
$J = 1.49E - 09\ m^4$

By solving Equation 3, we determined that the 6061-T6 Aluminum longitudinal rod would experience and angular deflection of,

$$\theta = 2.8° \qquad \text{Eq. 4}$$

TENSION IN THE ANSI NUMBER 25 CHAIN

To determine the tension in the steering system's chain, we first had to determine the torque applied at the outer diameter of the sprocket attached to the longitudinal rods. To determine T_c we used Equation 5,

$$T_c = F_h r = T_r \quad \text{Eq. 5}$$

Where,

$T_r = 30.5$ Nm

By solving Equation 5, we found that $T_c = 30.5$ Nm. Using Equation 6, we were able to determine the tension within the ANSI Number 25 Chain.

$$F_{tension} = \frac{T_c}{r_{sprocket}} \quad \text{Eq. 6}$$

Where,

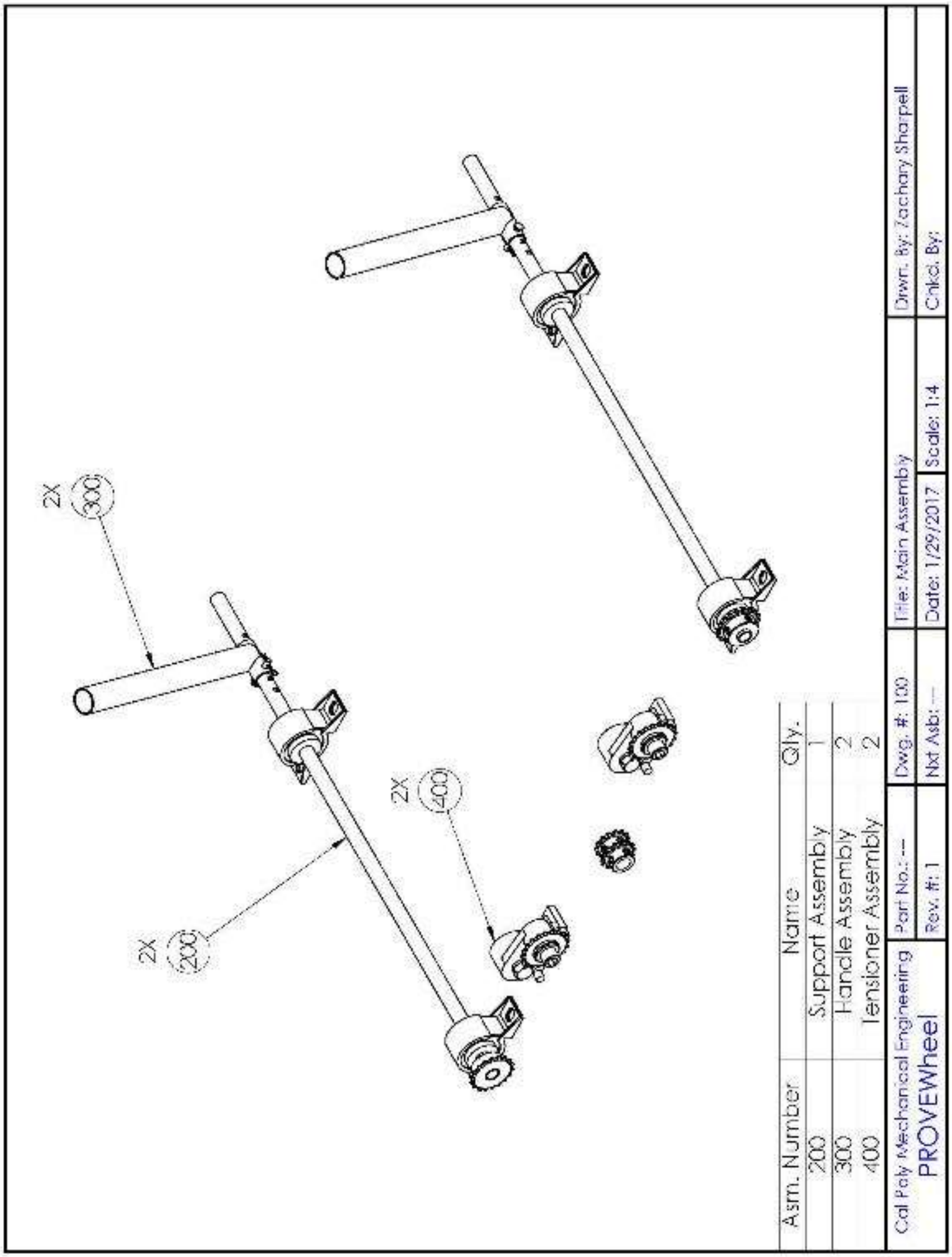
$T_c = 30.5$ Nm
$r_{sprocket} = 1.25$ inches $= 0.032$ m

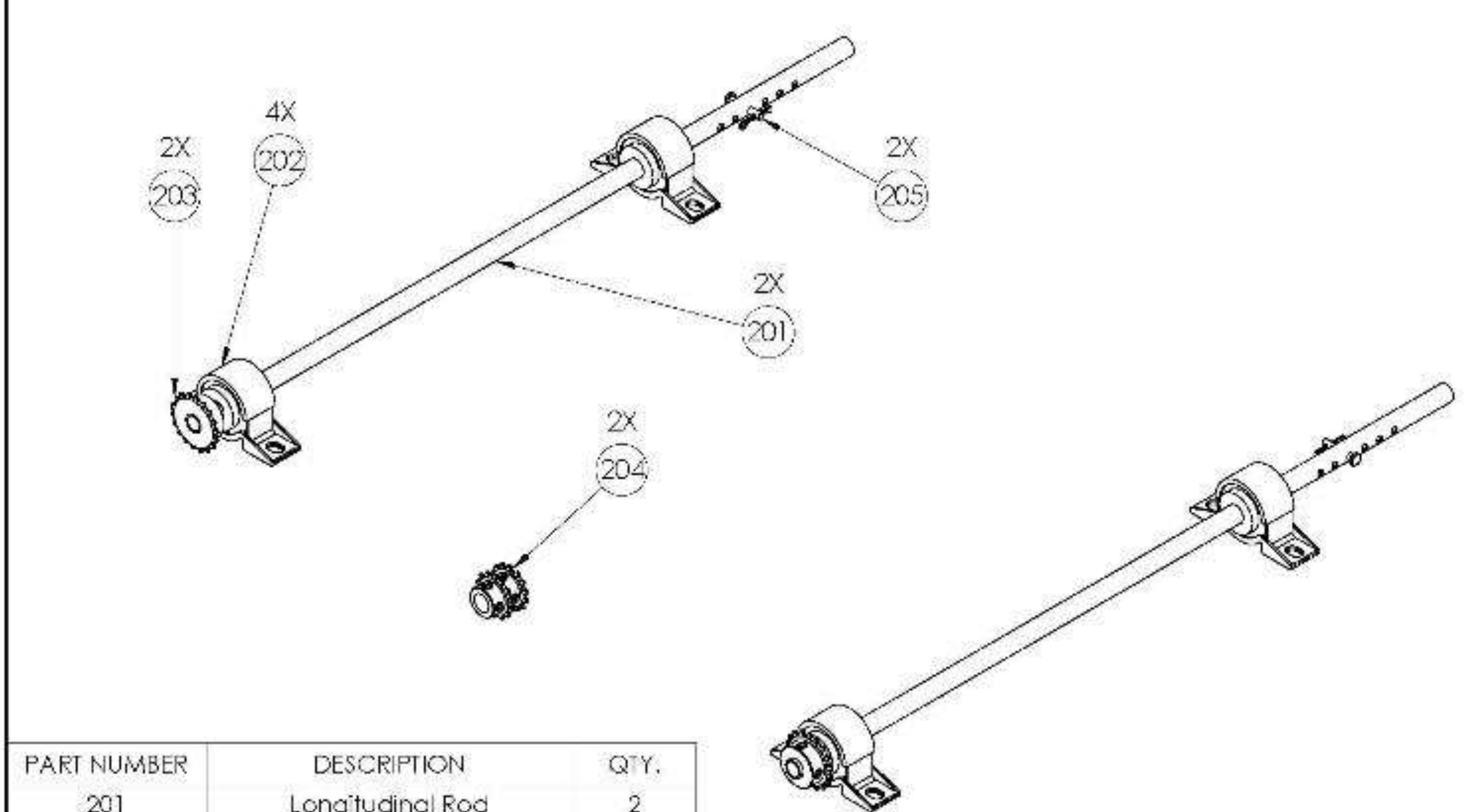
Which gave us

$$F_{tension} = 960.63 \text{ N} = 215.96 \text{ lb}_f \quad \text{Eq. 7}$$

Since our chain had a max tensile strength of 875 lb_f, we were confident ANSI Number 25 Chain would support our maximum expected loading

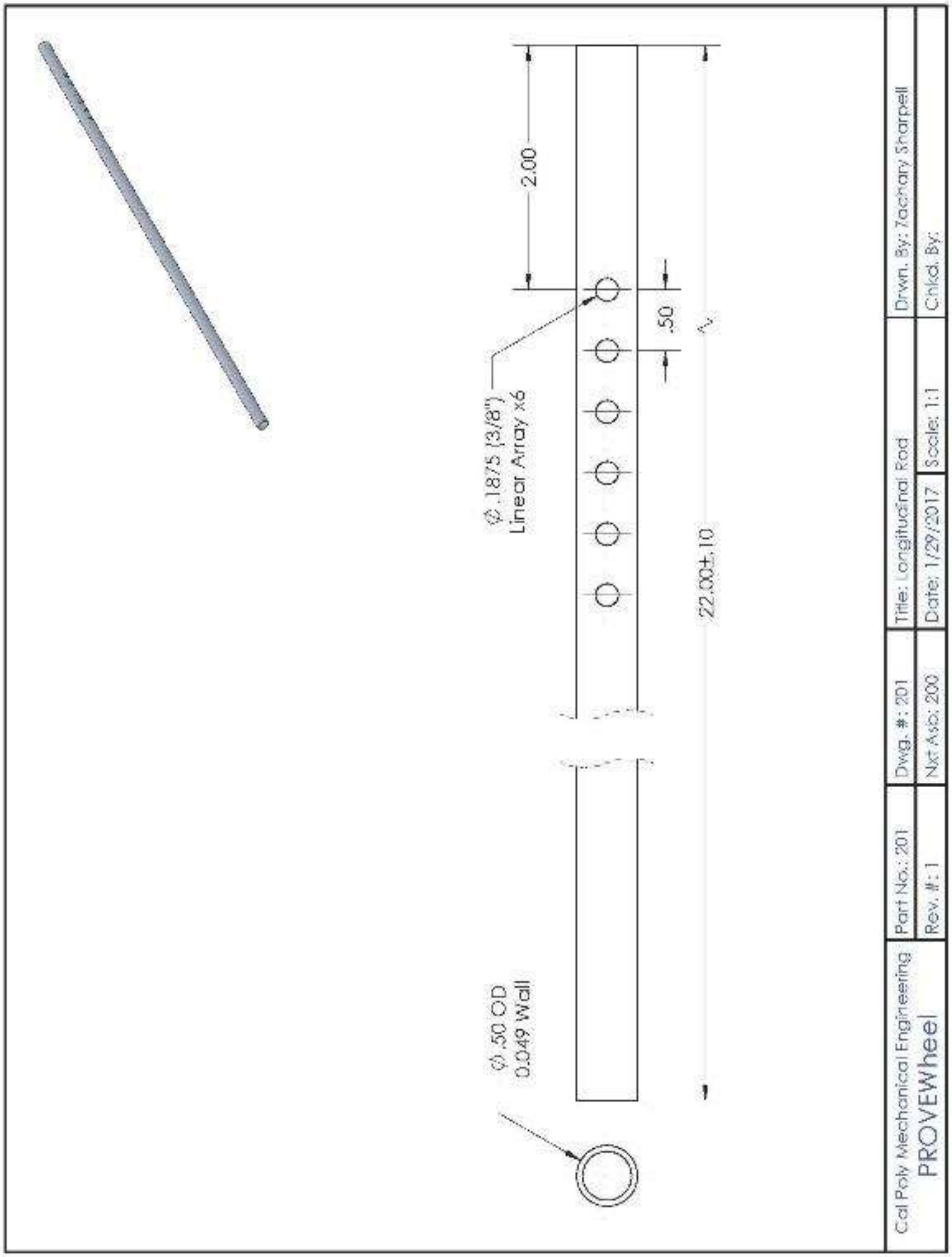
APPENDIX C
Engineering Drawings

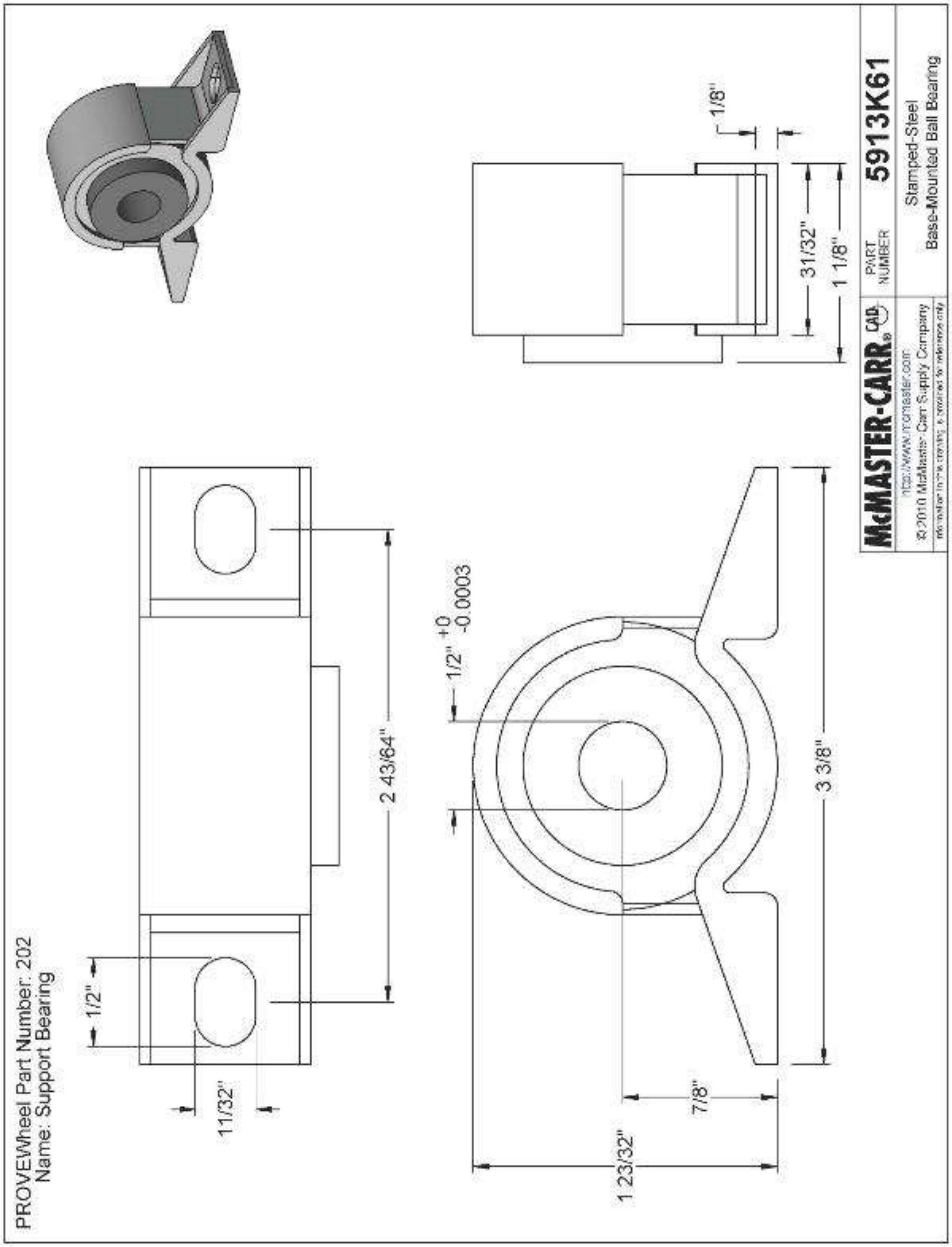


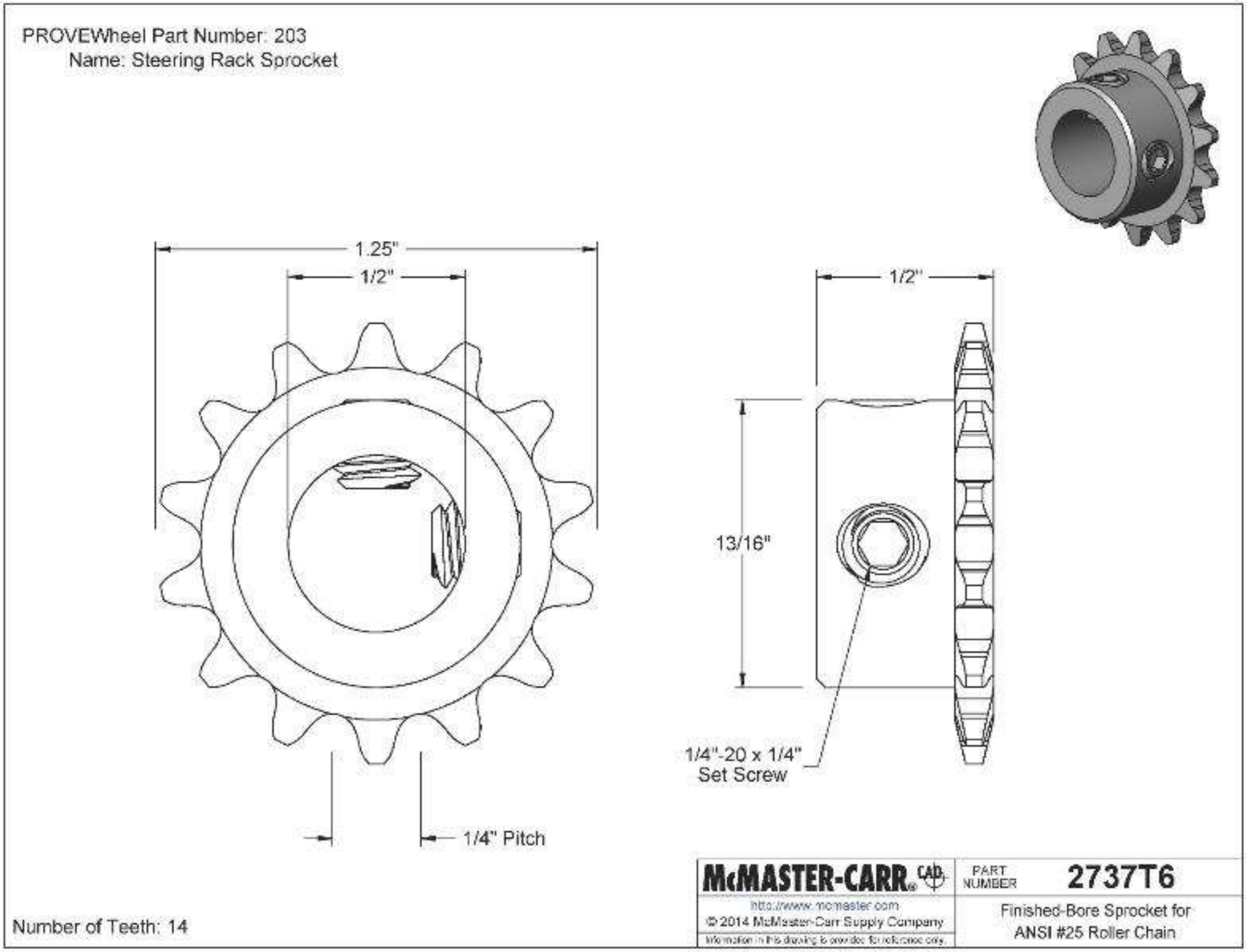


PART NUMBER	DESCRIPTION	QTY.
201	Longitudinal Rod	2
202	Support Bearing	4
203	Rod Sprocket	2
204	Steering Rack Sprocket	2
205	Clevis Pin	2

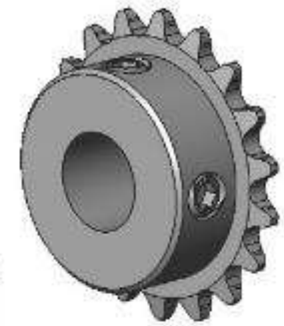
Cal Poly Mechanical Engineering PROVEWheel	Part No.: --	Dwg. #: 200	Title: Support System Assembly		Drwn. By: Zachary Sharpell
	Rev. #: 1	Nxt Asb: --	Date: 1/29/2017	Scale: 2:7	Chkd. By:

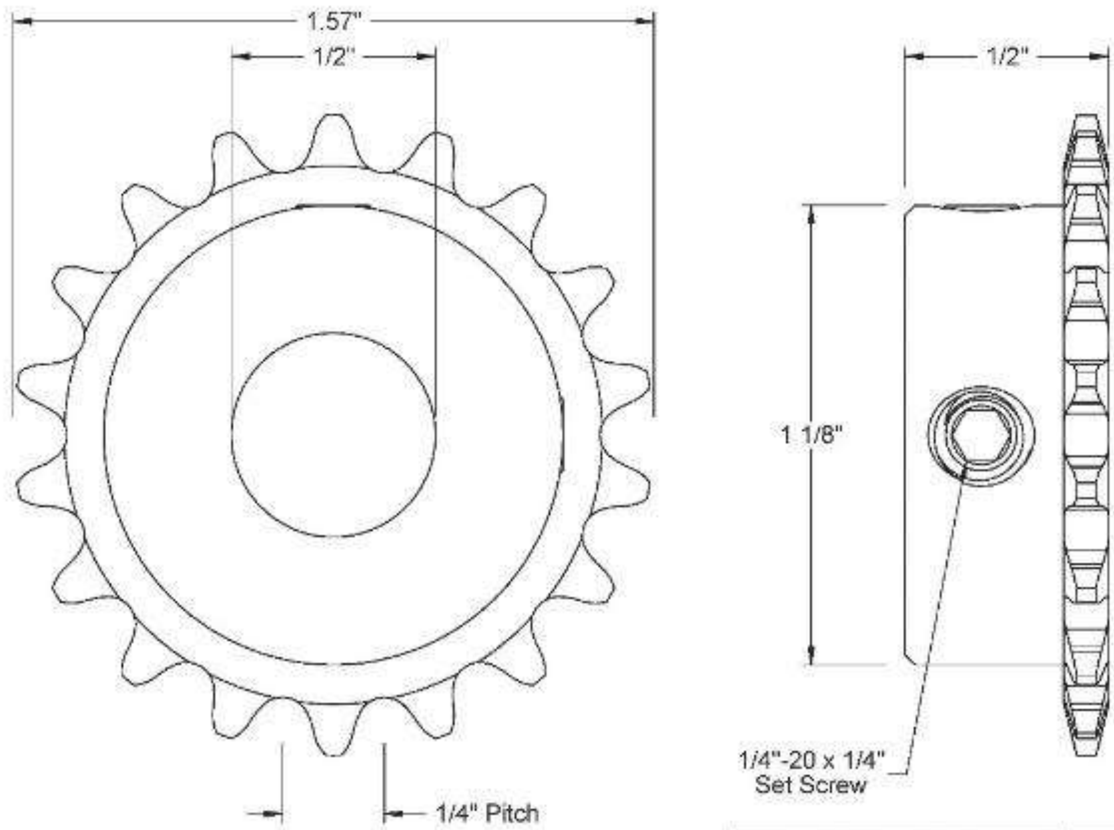

Ø.50 OD
0.049 Wall
Ø.1875 (3/8")
Linear Array x6
2.00
.50
22.00±.10
Cal Poly Mechanical Engineering
PROVEWheel
Part No.: 201
Rev. #: 1
Dwg. #: 201
Nxt Asb: 200
Title: Longitudinal Rod
Date: 1/29/2017
Scale: 1:1
Drwn. By: Zachary Sharpell
Chkd. By:


PROVEWheel Part Number: 202
Name: Support Bearing
1/2"
11/32"
2 43/64"
1/2" +0 -0.0003
3 3/8"
7/8"
1 23/32"
1/8"
31/32"
1 1/8"
McMASTER-CARR
http://www.mcmaster.com
©2010 McMaster-Carr Supply Company
PART NUMBER
5913K61
Stamped-Steel
Base-Mounted Ball Bearing


PROVEWheel Part Number: 203
Name: Steering Rack Sprocket
1.25"
1/2"
1/4" Pitch
1/2"
13/16"
1/4"-20 x 1/4"
Set Screw
Number of Teeth: 14
McMASTER-CARR
PART NUMBER
2737T6
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Finished-Bore Sprocket for
ANSI #25 Roller Chain

PROVEWheel Part Number: 204
Name: Rod Sprocket





Number of Teeth: 18

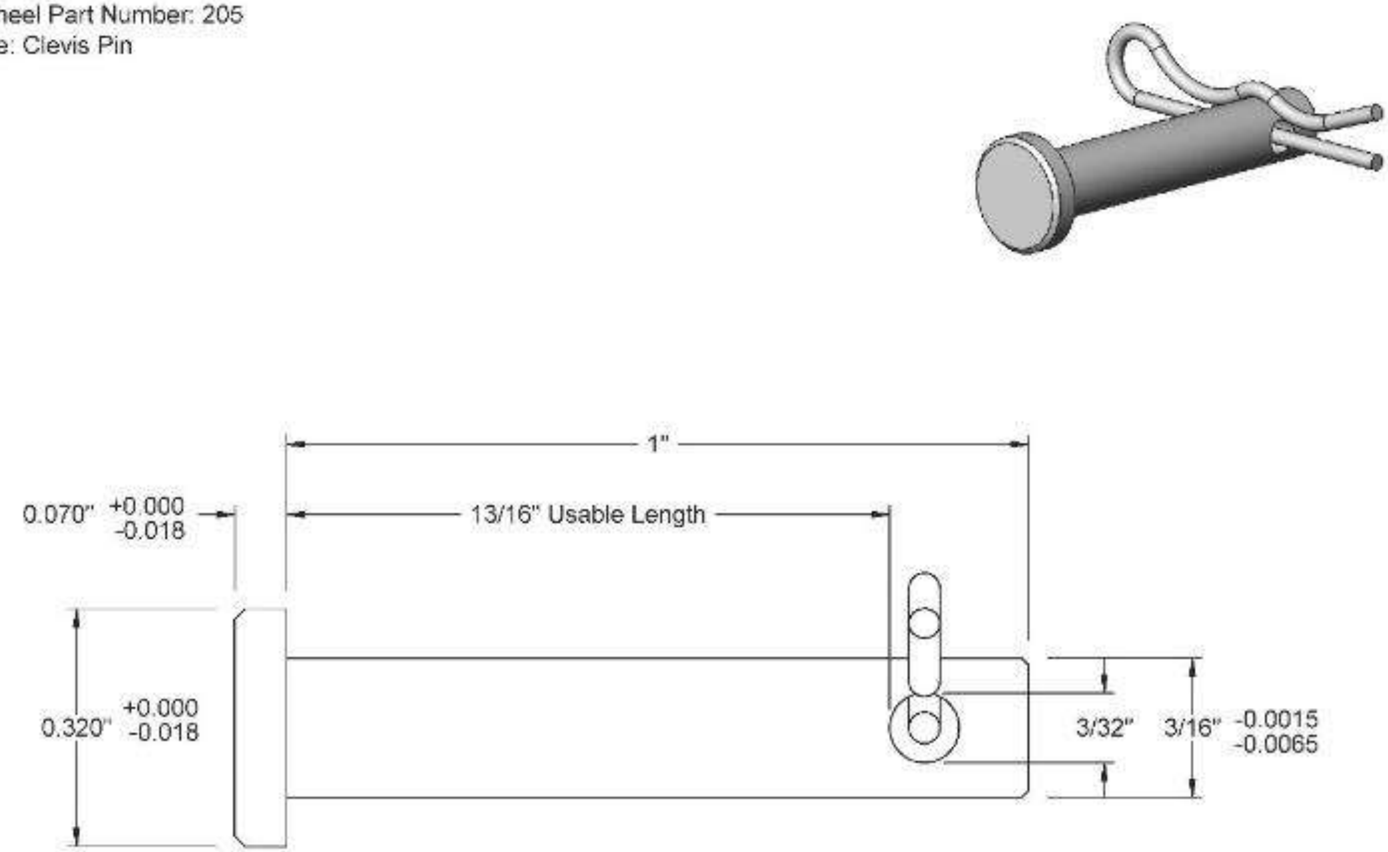
McMASTER-CARR® CAD

http://www.mcmaster.com

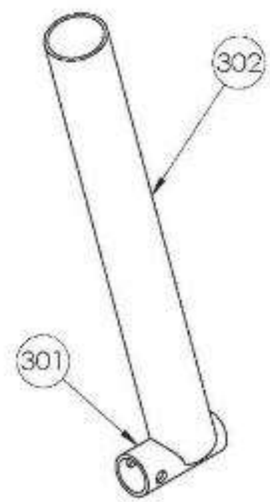
PART NUMBER 2737T11

Finished-Bore Sprocket for ANSI #25 Roller Chain

PROVEWheel Part Number: 205
Name: Clevis Pin

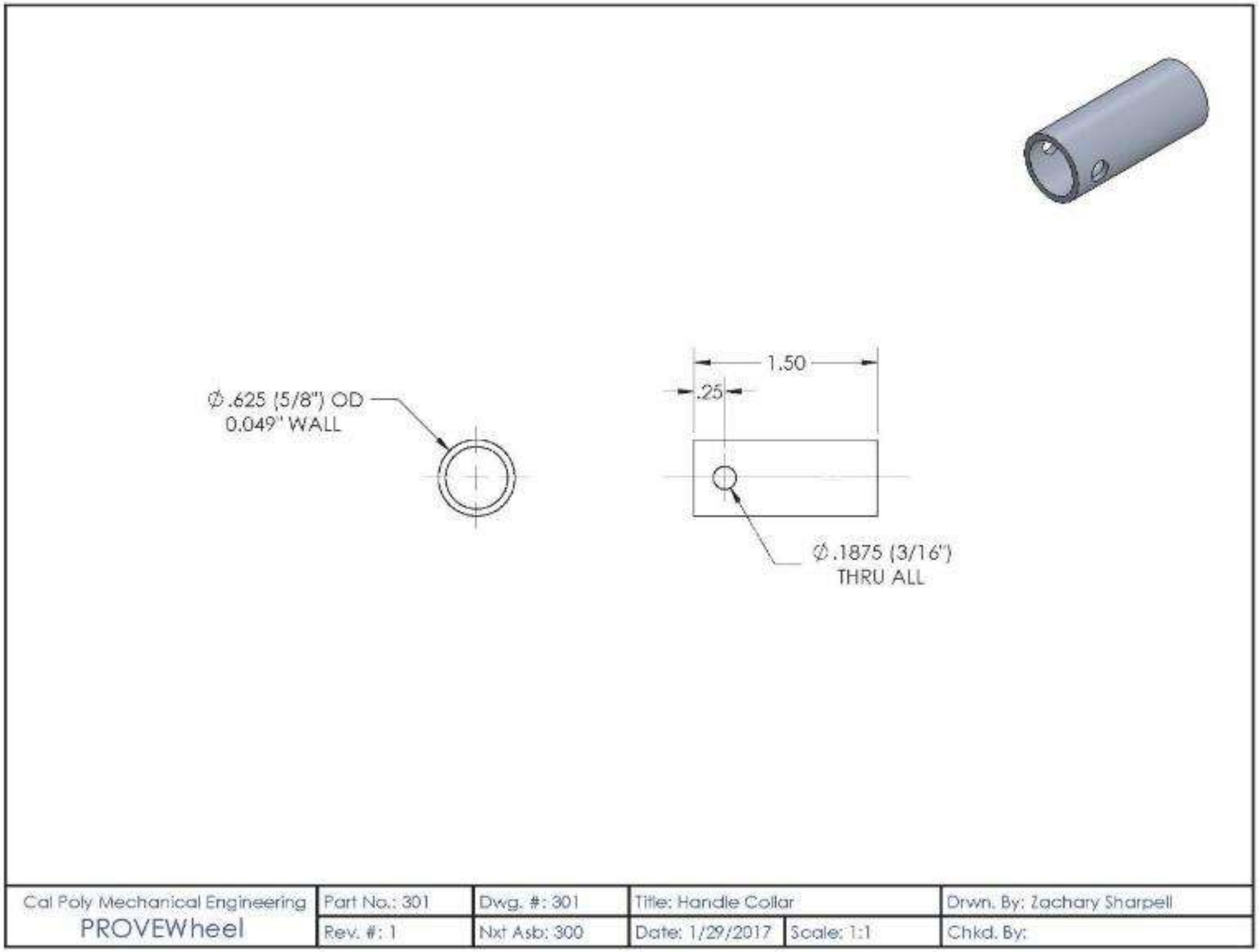


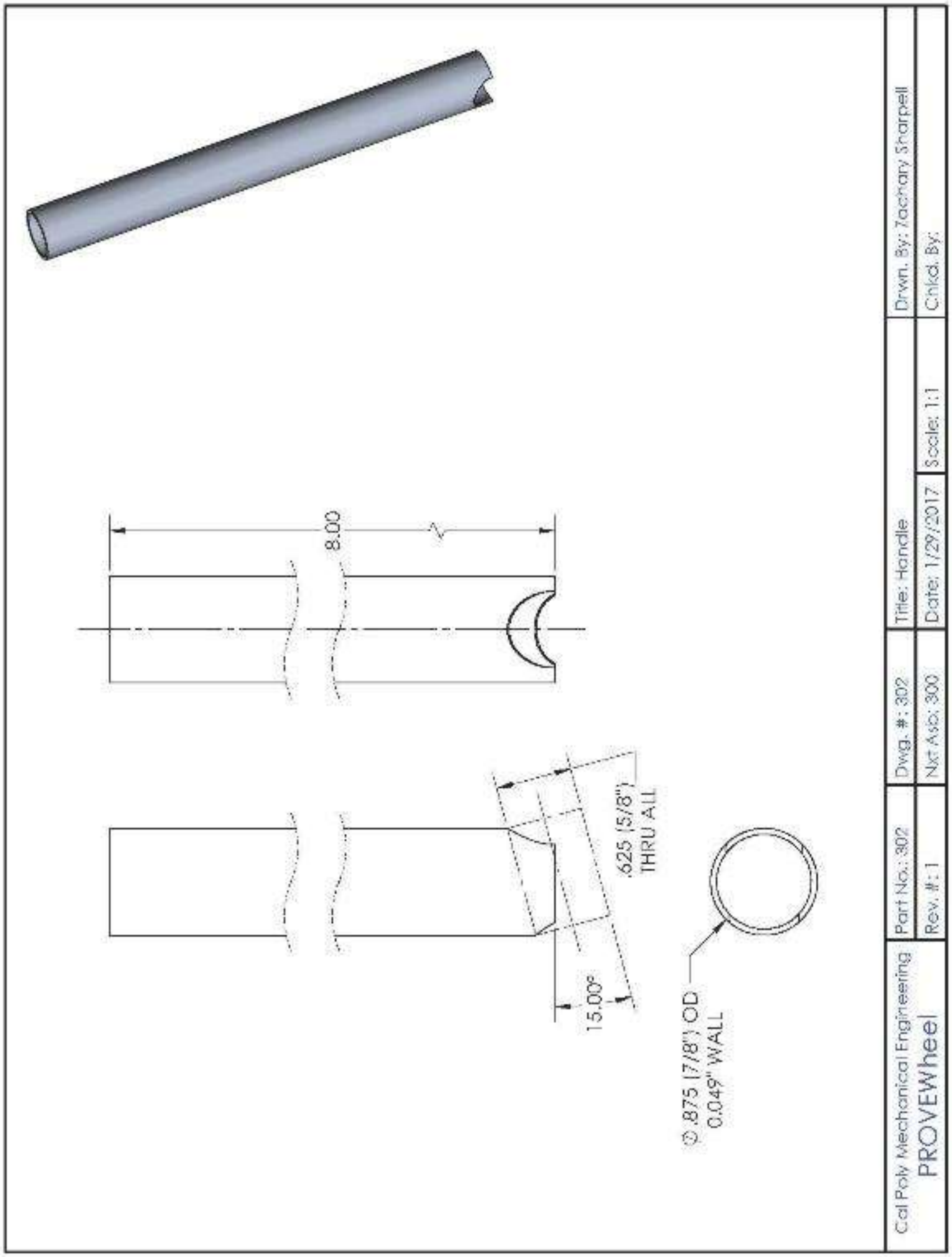
McMASTER-CARR® CAD	PART NUMBER	92401A576
http://www.mcmaster.com © 2012 McMaster-Carr Supply Company Information in this drawing is provided for reference only.		Clevis Pin with Reusable Cotter Pin



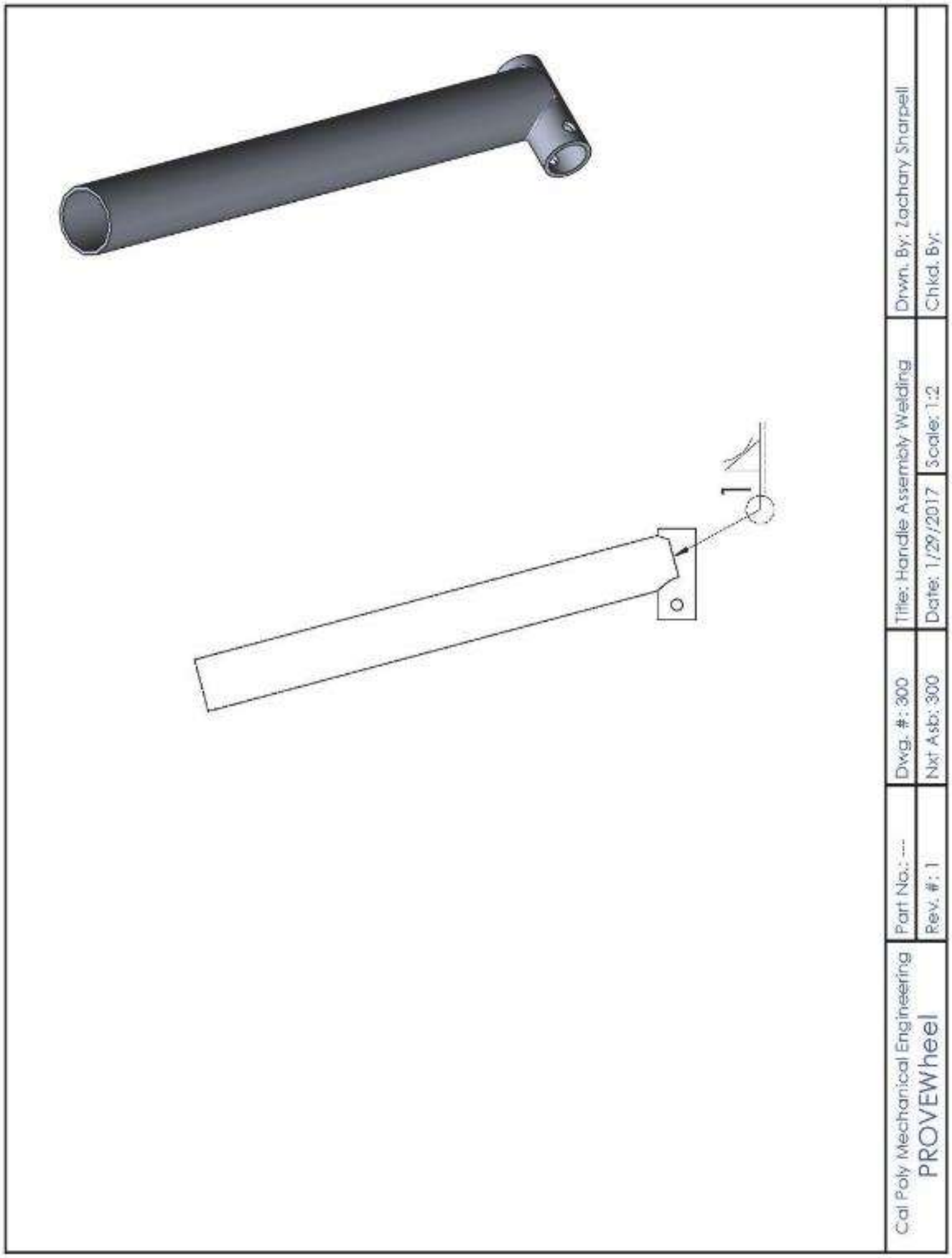
PART NUMBER	DESCRIPTION	QTY.
301	Handle Collar	1
302	Handle	1

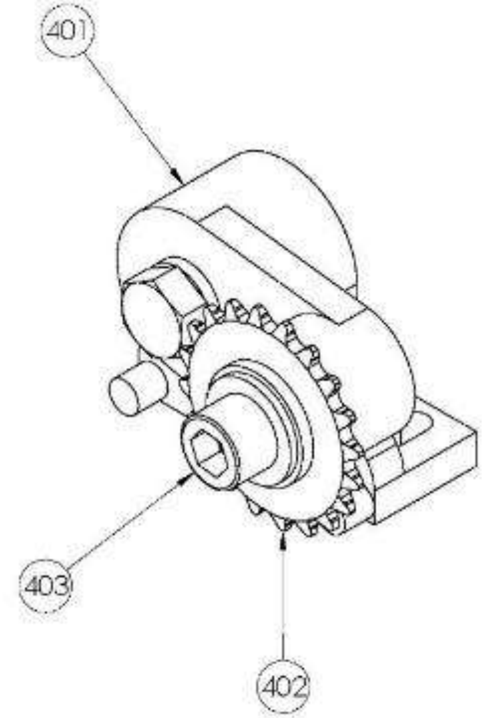
Cal Poly Mechanical Engineering	Part No.: ---	Dwg. #: 300	Title: Handle Assembly		Drwn. By: Zachary Sharpell
PROVEWheel	Rev. #: 1	Nxt Asb: ---	Date: 1/29/2017	Scale: 1:2	Chkd. By:


Ø.625 (5/8") OD
0.049" WALL
1.50
.25
Ø.1875 (3/16")
THRU ALL
Cal Poly Mechanical Engineering
PROVEWheel
Part No.: 301
Rev. #: 1
Dwg. #: 301
Nxt Asb: 300
Title: Handle Collar
Date: 1/29/2017
Scale: 1:1
Drwn. By: Zachary Sharpell
Chkd. By:



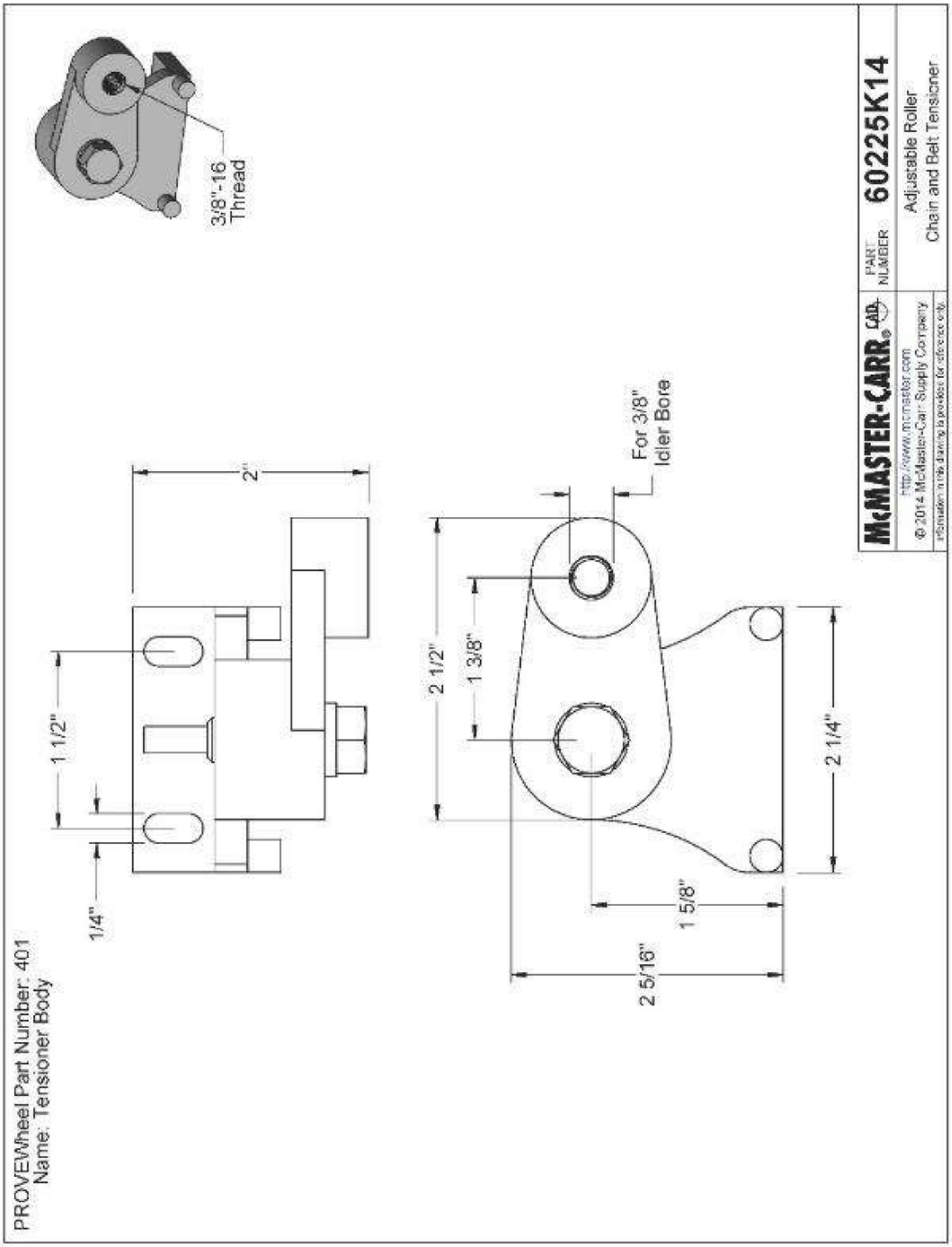
8.00
.625 (5/8")
THRU ALL
15.00°
⌀.875 (7/8") OD
0.049" WALL
Cal Poly Mechanical Engineering
PROVEWheel
Part No.: 302
Rev. #: 1
Dwg. #: 302
Nxt Asb: 300
Title: Handle
Date: 1/29/2017
Scale: 1:1
Drwn. By: Zachary Sharpell
Chkd. By:


Cal Poly Mechanical Engineering
PROVEWheel
Part No.: ---
Rev. #: 1
Dwg. #: 300
Nxt Asb: 300
Title: Handle Assembly Welding
Date: 1/29/2017
Scale: 1:2
Drwn. By: Zachary Sharpell
Chkd. By:
1

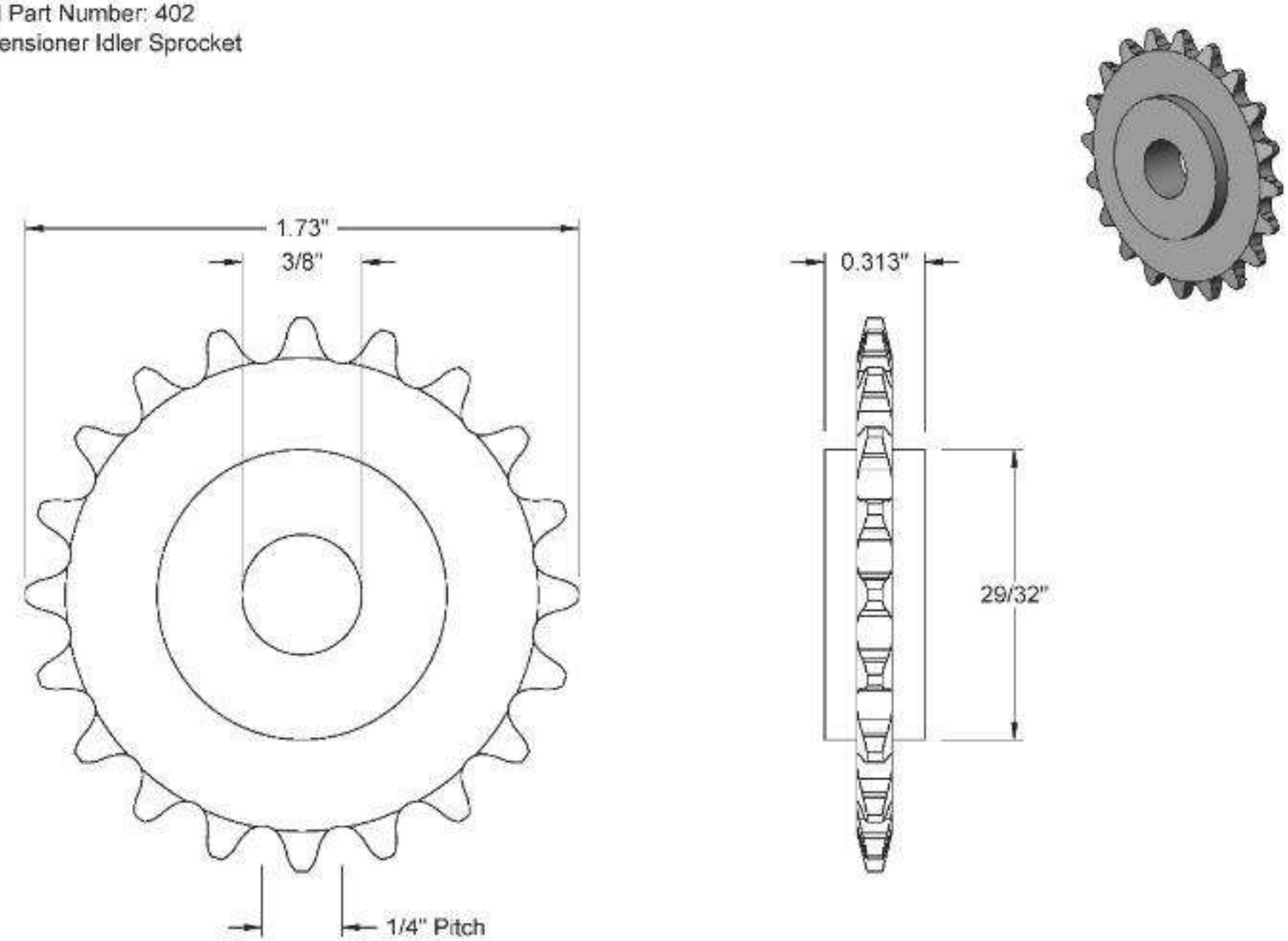


PART NUMBER	DESCRIPTION	QTY.
401	Tensioner Body	1
402	Tensioner Idler Sprocket	1
403	Retaining Shoulder Bolt	1

Cal Poly Mechanical Engineering PROVEWheel	Part No.: ---	Dwg. #: 400	Title: Tensioner Assembly		Drwn. By: Zachary Sharpell
	Rev. #: 1	Nxt Asb: ---	Date: 1/29/2017	Scale: 1:1	Chkd. By:


PROVEWheel Part Number: 401
Name: Tensioner Body
1/4"
1 1/2"
2"
2 1/2"
1 3/8"
For 3/8"
Idler Bore
2 5/16"
1 5/8"
2 1/4"
3/8"-16
Thread
McMASTER-CARR
CAD
PART NUMBER
60225K14
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Adjustable Roller
Chain and Belt Tensioner

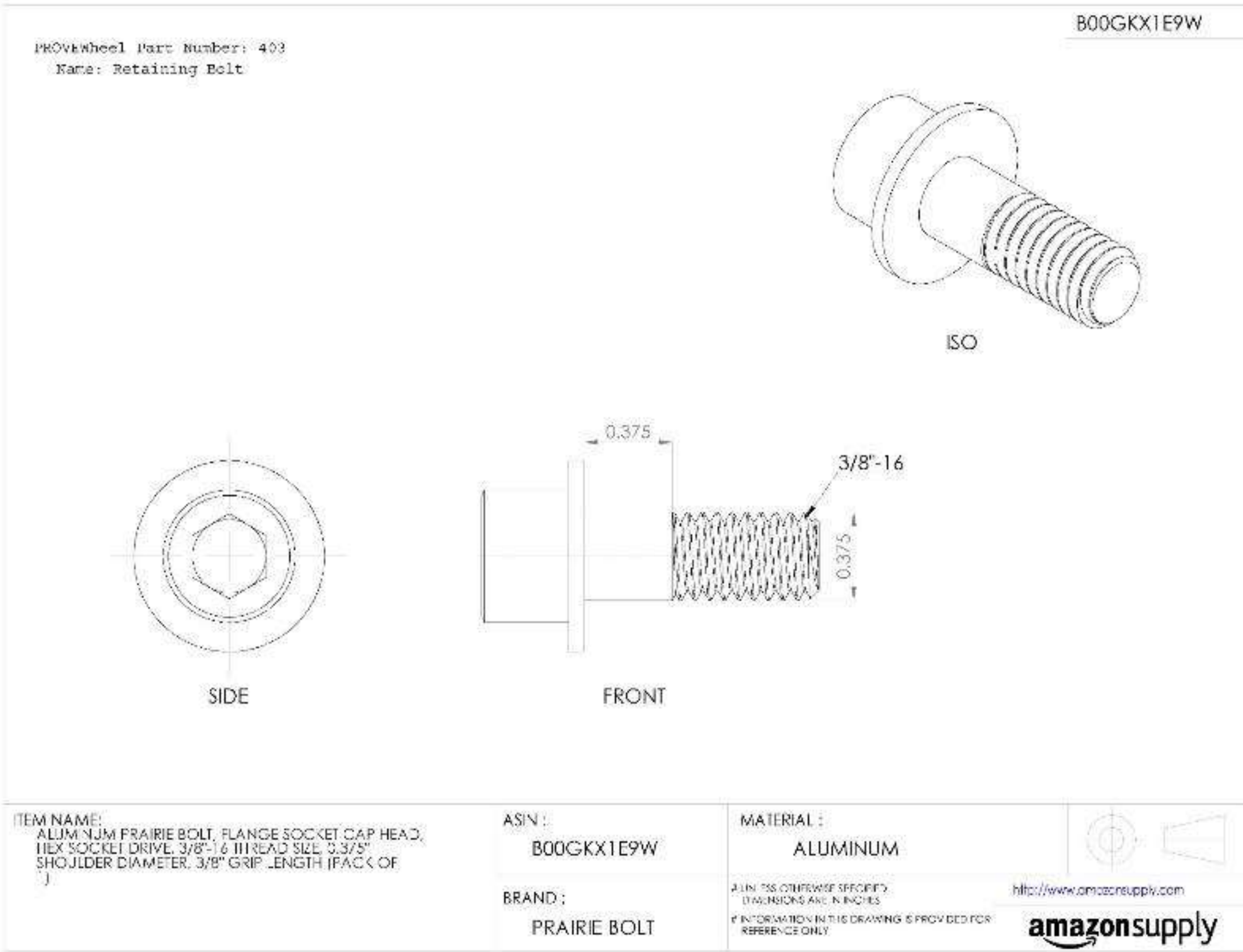
PROVEWheel Part Number: 402
Name: Tensioner Idler Sprocket



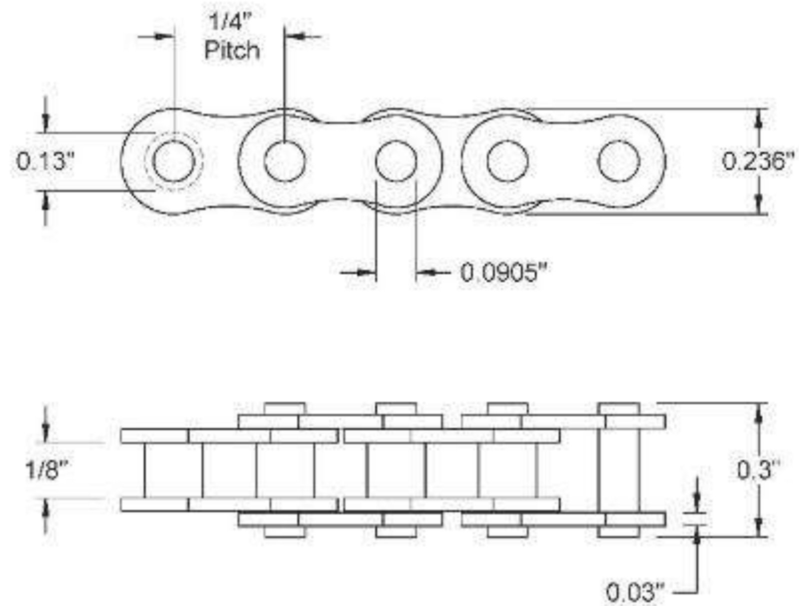
Number of Teeth: 20

McMASTER-CARR® CAD
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.

PART NUMBER 6663K11
Idler Sprocket for
ANSI #25 Roller Chain


B00GKX1E9W
PROVeWheel Part Number: 403
Name: Retaining Bolt
ISO
0.375
3/8"-16
0.375
SIDE
FRONT
ITEM NAME:
ALUMINUM PRAIRIE BOLT, FLANGE SOCKET CAP HEAD, HEX SOCKET DRIVE, 3/8"-16 THREAD SIZE, 0.375" SHOULDER DIAMETER, 3/8" GRIP LENGTH (PACK OF 1)
ASIN :
B00GKX1E9W
BRAND :
PRAIRIE BOLT
MATERIAL :
ALUMINUM
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
INFORMATION IN THIS DRAWING IS PROVIDED FOR REFERENCE ONLY
http://www.amazonsupply.com
amazonsupply

PROVEWheel Part Number: 500
Name: Steering Interface Chain



4 ft. Length

McMASTER-CARR® CAD

http://www.mcmaster.com

Information in this drawing is provided for reference only.

PART NUMBER **6261K284**

ANSI No. 25
Roller Chain

Appendix D
Bill of Materials

Asm. #	PN	Item	Description	Qty.	Supplier	Unit Cost	Ext. Cost
		Assembly Name					Asm. Cost
100		Main Assembly				**Total Cost**	**$ 427.22**
200		Support Structure					*$ 113.48*
	201	Drawn Aluminum Tube 6061 T6	1/2" OD, .049" Wall, 2' Length	2	Online Metals	$ 8.90	$ 17.80
	202	Low-Profile Mounted Ball Bearing	Self-Aligning 52100 Steel, for 1/2" Shaft Diameter	4	McMaster Carr	$ 10.95	$ 43.80
	203	Finished-Bore Sprocket for ANSI Roller Chain	#25 Chain, 1/4" Pitch, 14 Teeth	2	McMaster Carr	$ 10.07	$ 20.14
	204	Finished-Bore Sprocket for ANSI Roller Chain	#25 Chain, 1/4" Pitch, 18 Teeth	2	McMaster Carr	$ 11.04	$ 22.08
	205	316 Stainless Steel Clevis Pin with Cotter Pin	3/16" Diameter, 1" Long, 13/16" Usable Length	2	McMaster Carr	$ 4.83	$ 9.66
300		Handle Assembly					*$ 15.90*
	301	Drawn Aluminum Bare Tube 6061 T6	5/8" OD, .509" ID, .049" Wall, 1' Length	1	Online Metals	$ 4.74	$ 4.74
	302	Drawn Aluminum Tube 6061 T6	7/8" OD, .049" Wall, 2' Length	1	Online Metals	$ 11.16	$ 11.16
400		Tensioner Assembly					*$ 256.72*
	401	Roller Chain/Belt Tensioner	Horizontal Mount, for 3/8" Idler Bore	2	McMaster Carr	$ 97.16	$ 194.32
	402	Steel Idler Sprocket for ANSI Roller Chain	Low-Profile Hub, for #25 Chain, 1/4" Pitch, 3/8" Bore	2	McMaster Carr	$ 24.73	$ 49.46
	403	3/8" Shoulder Bolt with 3/8"-16 Thread	Aluminum Prairie Bolt, Flange Socket Cap Head, Hex Socket Drive	2	Amazon	$ 6.47	$ 12.94
500		Roller Chain					*$ 41.12*
	501	ANSI #25 Roller Chain	Roller Chain, ANSI Number 25, 1/4" Pitch, 4' Lengths	2	McMaster Carr	$ 20.56	$ 41.12

Table D.1 - Updated Bill of Materials with the new tensioning system.

Asm. #	PN	Item	Description	Qty.	Supplier	Unit Cost	Ext. Cost
		Assembly Name					Asm. Cost
100		Main Assembly				**Total Cost**	**$ 250.48**
200		Support Structure					*$ 113.48*
	201	Drawn Aluminum Tube 6061 T6	1/2" OD, .049" Wall, 2' Length	2	Online Metals	$ 8.90	$ 17.80
	202	Low-Profile Mounted Ball Bearing	Self-Aligning 52100 Steel, for 1/2" Shaft Diameter	4	McMaster Carr	$ 10.95	$ 43.80
	203	Finished-Bore Sprocket for ANSI Roller Chain	#25 Chain, 1/4" Pitch, 14 Teeth	2	McMaster Carr	$ 10.07	$ 20.14
	204	Finished-Bore Sprocket for ANSI Roller Chain	#25 Chain, 1/4" Pitch, 18 Teeth	2	McMaster Carr	$ 11.04	$ 22.08
	205	316 Stainless Steel Clevis Pin with Cotter Pin	3/16" Diameter, 1" Long, 13/16" Usable Length	2	McMaster Carr	$ 4.83	$ 9.66
300		Handle Assembly					*$ 15.90*
	301	Drawn Aluminum Bare Tube 6061 T6	5/8" OD, .509" ID, .049" Wall, 1' Length	1	Online Metals	$ 4.74	$ 4.74
	302	Drawn Aluminum Tube 6061 T6	7/8" OD, .049" Wall, 2' Length	1	Online Metals	$ 11.16	$ 11.16
400		Tensioner Assembly					*$ 79.98*
	401	**Floating Chain Tensioner**	**ANSI #25 Chain**	**2**	**USA Roller Chain**	**$ 39.99**	**$ 79.98**
500		Roller Chain					*$ 41.12*
	501	ANSI #25 Roller Chain	Roller Chain, ANSI Number 25, 1/4" Pitch, 4' Lengths	2	McMaster Carr	$ 20.56	$ 41.12

APPENDIX E
Design Hazard Checklist

DESIGN HAZARD CHECKLISK

Team: PROVE Wheel Advisor: Harding

Y	N	
☐	☒	1. Will any part of the design create a hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☒	2. Can any part of the design undergo high acceleration/decelerations?
☐	☒	3. Will the system have any large moving masses or large forces?
☐	☒	4. Will the system produce a projectile?
☐	☒	5. Would it be possible for the system to fall under gravity creating injury?
☐	☒	6. Will a user be exposed to overhanging weights as part of the design?
☐	☒	7. Will the system have any sharp edges?
☐	☒	8. Will any part of the electrical systems not be grounded?
☐	☒	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☐	☒	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☒	11. Will there be any explosive or flammable liquids, gases, or dust fuel as a part of the system?
☐	☒	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☒	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☒	14. Can the system generate high levels of noise?
☐	☒	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☐	☒	16. Is it possible for the system to be used in an unsafe manner?
☐	☒	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
All pinch points have been covered	No corrective action needed		

Appendix F

Design Verification Plan and Report (DVP&R)

DVP&R									
Report Date: June 2, 2017		Sponsor: Graham Doig			Component/Assembly: Lever Steering				REPORTING ENGINEER: PROVEWheel Team

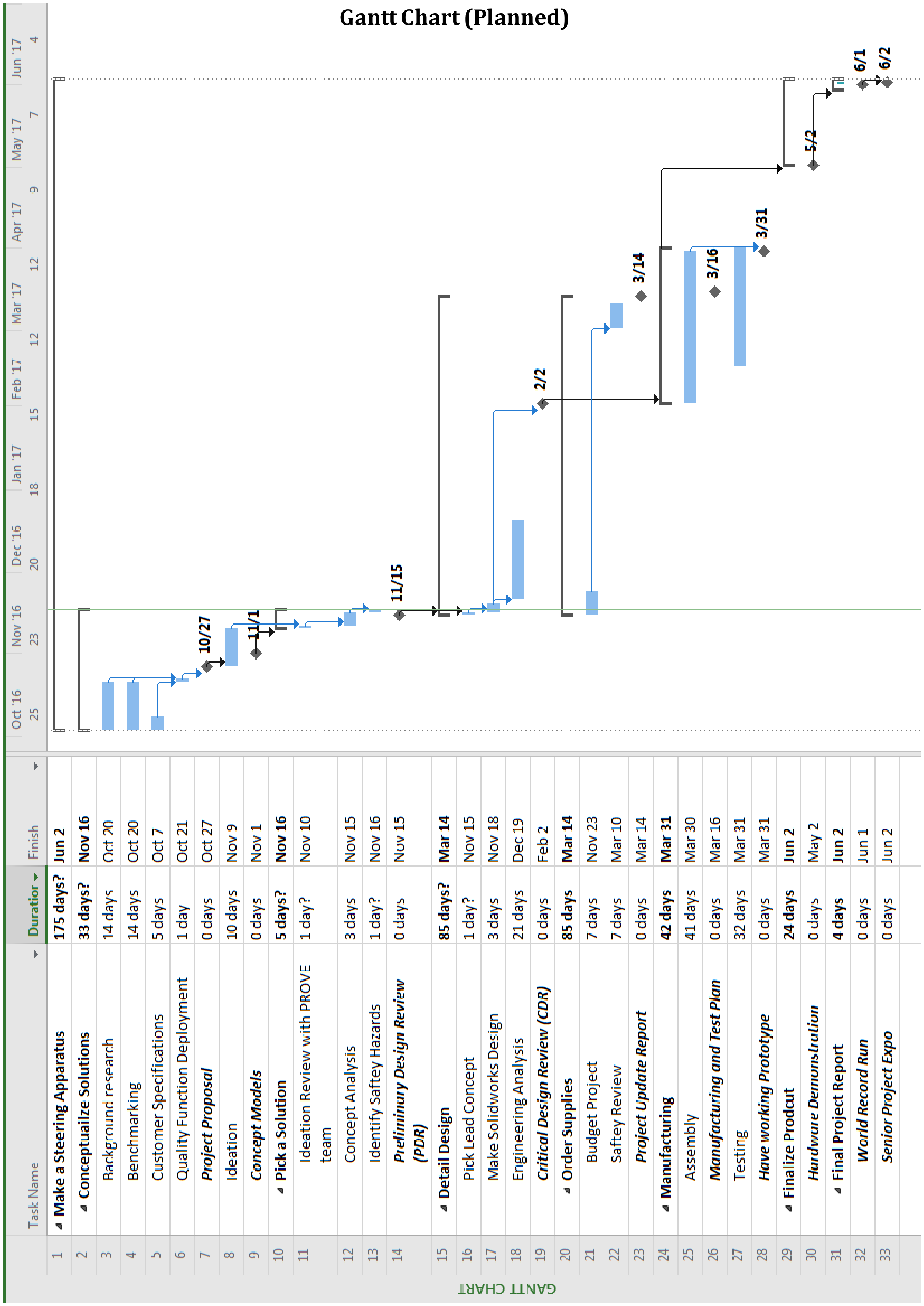
TEST PLAN

Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING	
						Quantity	Type	Start date	Finish date
1	Contact with canopy	Ensure that steering mechanism does not make contact or interfere with the canopy of the vehicle.	Contact (Fail) / No Contact (Pass)	All	CV	2	B,C	N/A	6/30/2017
2	Time for driver exit	Determine if steering system inhibits driver from egressing the vehicle in less than 15 seconds.	Overtime (Fail) / Else (Pass)	All	PV	1	C	N/A	6/30/2017
3	Throttle buttons	Test if the throttle actuation buttons fit within the steering mechanism design.	No fit (Fail) / Fit (Pass)	All	PV	1	B	N/A	6/30/2017
4	Brake handle support	Test if the brake handles fit on the steering mechanism design.	No fit (Fail) / Fit (Pass)	All	PV	1	B	N/A	6/30/2017
5	Steering column interface	Validate if the steering mechanism is able to connect to the steering column (if applicable).	Incompatible (Fail) / Else (Pass)	All	DV	1	B	N/A	6/30/2017
6	Roll cage interference	Ensure handles rotate a minimum for 30deg before making contact with roll cage	Interference (Fail) / Else (Pass)	All	DV	1	B	N/A	6/30/2017

It should be noted that the reason there is no start date listed is because at the time this report was completed, the PROVE vehicle has not fully been constructed. Once the vehicle is constructed and the steering apparatus has been installed, all item numbers will be tested.

APPENDIX G

Gantt Chart (Planned)



Gantt Chart (Actual)

	Task Name	Duration	Finish
2	**Conceptuailze Solutions**	**33 days**	**Wed 11/16/16**
3	Background research	14 days	Thu 10/20/16
4	Benchmarking	14 days	Thu 10/20/16
5	Customer Specifications	5 days	Fri 10/7/16
6	Quality Function Deployment	1 day	Fri 10/21/16
7	***Project Proposal***	0 days	Thu 10/27/16
8	Ideation	10 days	Wed 11/9/16
9	***Concept Models***	0 days	Tue 11/1/16
10	**Pick a Solution**	**5 days**	**Wed 11/16/16**
11	Ideation Review with PROVE team	1 day	Thu 11/10/16
12	Concept Analysis	3 days	Tue 11/15/16
13	Identify Saftey Hazards	1 day	Wed 11/16/16
14	***Preliminary Design Review (PDR)***	0 days	Tue 11/15/16
15	**Detail Design**	**124 days**	**Fri 5/5/17**
16	Pick Lead Concept	1 day	Tue 11/15/16
17	Make SolidWorks Design	3 days	Fri 11/18/16
18	Review Design with PROVE	7 days	Tue 11/29/16
19	Update SolidWorks design	3 days	Fri 12/2/16
20	Develop FMEA	3 days	Wed 12/7/16
21	Iterate FMEA	2 days	Fri 12/9/16
22	Develop DVP&R, Analysis Plan	5 days	Fri 12/16/16
23	Engineering Analysis	19 days	Fri 1/13/17
24	Construct Mockup Assembly	5 days	Fri 1/20/17
25	Iterate Design	5 days	Fri 1/27/17
26	Finalize BOM	2 days	Tue 1/31/17
27	***Critical Design Review (CDR)***	0 days	Thu 2/2/17
28	**Order Supplies**	**26 days**	**Fri 5/5/17**
29	Allow for Shipping Time	6 days	Mon 3/20/17
30	Double Check Received Items	1 day	Tue 3/21/17
31	***Manufacturing and Test Plan***	0 days	Thu 3/16/17
32	**Manufacturing/Testing**	**45 days**	**Fri 6/2/17**
33	Assembly	10 days	Fri 4/14/17
34	Testing	1 day	Fri 6/2/17
35	***Have Final Product for Use***	0 days	Wed 4/19/17
36	Senior Project Expo	0 days	Fri 6/2/17