MEMO

To: Perry Wood

From: Team 9: Matt Gerlich, Alex Hawley, Phillip Kinsley, Heather Kutz, Kevin Montoya, and Erik Nelson

Date: May 1, 2014

Subject: Human Powered Vehicle Project Final Report

To address the need of a form of transportation that combines the benefits of bicycling commuting with the practicality of automobiles the team has designed, analyzed and fabricated a vehicle to compete in the American Society of Mechanical Engineers (ASME) Human Powered Vehicle Challenge (HPVC).

This project has the clients of the American Society of Mechanical Engineers and the Northern Arizona University student section advisor, Perry Wood. Each of these clients presented the team with objectives and constraints in which the vehicle is designed around. The most significant of these design objectives were for the vehicle to be capable of high speeds, have an improved coefficient of drag over traditional bicycles, and protect the rider from the outside environment.

Presented in this final report is the team's vehicle design that meets all of the given requirements. The vehicle's design is a three-wheeled, recumbent style vehicle enclosed by a full fairing. It will be powered using a standard bicycle drivetrain with an integrated reverse gear. The practicality of an automobile is addressed in the design with the ability to carry cargo, a weatherproof fairing, and a lighting system that includes brake lights, turn signals and a headlight. The design also accommodates a large range of riders through an adjustable seat position.

The team constructed the prototype vehicle, Pulaski, and competed in the ASME HPVC West competition on April 24th through 27th. The vehicle finished 2nd overall and received awards in five of the six categories. The design presented throughout this report cost approximately $6,000 to build and test. A detailed breakdown of the costs can be seen in this proposal.

The following report includes a detailed introduction to the project, the proposed design, details on the prototype fabrication, the vehicles testing, competition results, and a cost analysis of the vehicle.

With Regards,

Team 9: Matt Gerlich, Alex Hawley, Phillip Kinsley, Heather Kutz, Kevin Montoya, and Erik Nelson

Human Powered Vehicle Challenge

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Team 9

Final Report
Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design I – Spring 2014

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NOMENCLATURE

Symbol	Description	Units
A	Area	in^2
b	base	in
c	Distance from neutral axis to extreme fiber	in
C	Airfoil length	in
C_d	Coefficient of drag	
C_R	Coefficient of rolling resistance	
d	Diameter	in
E	Modulus of elasticity	ksi
F	Applied force	lbs
f	Frictional force	lbf
F_d	Drag force	N
g	Acceleration due to gravity	m/s^2
h	height	in
$\bar{h}_l$	Average convection coefficient	W/m^2K
I	Moment of inertia	in^4
k	Theoretical stress concentration factor	
k_{cd}	Thermal conductivity	W/mK
L	Length	in
l	length	M
M	Moment	lb-in
m	Mass	Kg
N	Normal force	lbf
$\overline{Nu_l}$	Average Nusselt number	
q	Notch sensitivity	
Re_l	Reynolds number at maximum length	
$Re_{l,c}$	Critical Reynolds number	
s	Slope of a hill	°
t	Thickness coefficient	
V	Velocity	m/s
V_w	Wind velocity	m/s
W	Power	Watts
x	X coordinate of airfoil	in
y_t	Y coordinate of air foil	in
η	Drive train efficiency	
μ_s	Coefficient of static friction	
ρ	Density	$slug/in^3$

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ABSTRACT

As the world population expands in both stature and volume, the demand on existing transportation systems is continually increasing. These loads pollute our environments and often times are extremely expensive. With this is mind, a team of undergraduate mechanical engineering students designed a vehicle functioning on human power that can act as a viable, healthy, alternative form of transportation. This alternative is capable of traveling at speeds in excess of 40mph, while still being able to safely navigate the obstacles of typical automobile environments. Similar vehicles have been developed previously, but none have adequately combined the benefits of bicycle commuting, while offering the practicality of automobiles.

The design of this human powered vehicle was broken into six key subsections: Frame, Fairing, Steering, Ergonomics, Drivetrain, and Innovation. An alloy frame of 6061-T6 aluminum supports the weight of the occupant and maintains appropriate spatial and geometry relationships of critical components. Steering components that allow for a turning radius as low as 12.3 feet are mounted to this internal frame along with the occupant's seating. The position of the rider was optimized for maximum power output using a stationary fixture to measure rider power output over a range of operating positions. A drive train constructed of traditional cycling components allows the vehicle to travel at speeds ranging from zero to 45 MPH for a typical occupant, with much higher speeds possible for physically fit drivers. To further increase the vehicle's maximum speeds a low drag shell encompasses the entire vehicle, giving it aerodynamic properties a fifth that of a typical commuting bicycle and rider. Innovative features not typically found on human power vehicles are included such as complete lighting systems and remote operated ventilation systems.

The designed assembly had its' performance as a traffic worthy vehicle evaluated and road tested at the Human Powered Vehicle Challenge (HPVC) hosted by the American Society of Mechanical Engineers (ASME). The vehicle successfully illustrated its superior design by placing 2nd overall in the international competition. Awards were presented to the design team for the vehicle's innovative reverse mechanism, its thorough overall design, and the vehicle performance in high speed and long distance tests.

The design of this vehicle occurred during a five month span and the fabrication of a fully functional prototype spanned another five months. While the cost of development was in excess of $5000 dollars it is projected that a production version of such a vehicle could also sell for a price significantly cheaper than an automobile.

1.0 INTRODUCTION

Team 9 was given the opportunity to build and compete in the HPVC sponsored by the ASME. The HPVC consists of creating a human powered vehicle that can be used as an alternative form of transportation in everyday life. During the competition, the team will be competing in multiple events that evaluate the design, innovation, endurance, and speed of the vehicle. In the design section, the team will be required to submit a report that describes the engineering analysis and work that went into the design of the overall vehicle.

In order to define the problem, the team worked with the client Perry Wood, to identify the project need, goal, as well as the project's objectives and constraints. For the team to begin the design process the operating conditions were evaluated as well as a state of the art review was conducted. After evaluating the problem and its' specific requirements the team generated concepts for important aspects of the design, as well as conducted analysis to select the final design seen in Figure 1.1 below. With the final design selected, the team performed a cost analysis for the single prototype as well as a production run of the vehicle.

(a) (b)

Figure 1.1- Final Design (a) Without Fairing and (b) With Fairing

1.1 CLIENT

The Human Powered Vehicle project has two major clients. These are the American Society of Mechanical Engineers, and the Northern Arizona University ASME Student Section Advisor Perry Wood. The Human Powered Vehicle Challenge is a worldwide competition through American Society of Mechanical Engineers. While ASME is a client for this project the main client is Perry Wood, a Mechanical Engineering lecturer at Northern Arizona University. Perry Wood has been the section advisor for eight years and this will be his fifth year being the client for a capstone human powered vehicle project.

1.2 PROBLEM DESCRIPTION

The client, Perry Wood, presented a problem to the team that current forms of transportation do not meet the needs of society. Specifically, he expressed the lack of a completely human powered form of transportation that can travel at high speeds, operate in an urban environment, and protect the rider from various weather conditions and hazards.

1.3 STATE OF THE ART RESEARCH

The team utilized a range of resources during the design of the human powered vehicle. These sources range from experts in specific fields, dedicated human powered vehicle literature, and text books.

Field experts were invaluable to the success of the team. Members consulted experts in the fields of composites manufacturing, rapid prototyping, human powered vehicle design, machining, and heat treatment processes. These experts provided information to team members through verbal and email communications. In most cases these experts were contacted by team members in an effort to find solutions to a specific problem. Often information contributed exceeded the original scope of contacting the person. The contributions of these individuals have impacted nearly every component of the vehicle. These experts were identified through either previous personal contact with a team member or at recommendation of the project's faculty advisor Perry Wood.

Team members also referenced the large amounts of human powered vehicle specific knowledge contained within literature dedicated to the relatively small field. The International Human Powered Vehicle Association (IHPVA) published a human powered vehicle specific, technical journal from 1977 to 2004. This journal was referenced extensively during the design of both the drivetrain and low aerodynamic drag components. *Bicycling Science* [6], a book published by the MIT press details the application of traditional mechanics and exercise science concepts to the pursuit of efficient, human powered vehicles. This source has provided a wide range of information to team members, including background information and technical calculation formulas.

As with most engineering tasks the application of techniques learned in classrooms and from textbooks is adequate. The team has utilized knowledge accumulated throughout their time as undergraduate students. For more complicated design scenarios classroom text books were referenced for both calculation formulas and technical explanations. Texts detailing the fields of statics, dynamics, fluid mechanics, heat transfer, thermodynamics, biomechanics, aerodynamics, machine design, manufacturing, computer aided design, and composites design, were all referenced during the design phase of this project.

2.0 PROBLEM FORMULATION

2.1 IDENTIFICATION OF NEED

After the HPVC was assigned, the group met with the client, Perry Wood, and discussed what outcome he would like to see from this project. After the meeting, the team thoroughly reviewed the HPVC rules set forth by ASME. Multiple topics were deemed important, from which, the following need statement was formed:

"There is no current form of transportation that provides the benefits of bicycle commuting, while offering the practicality of automobiles."

The need statement exposes a noticeable gap between the two categories of bicycle commuting and automobile transportation. For instance, bicycle commuting includes less financial expenditures and traffic, ease of access to parking, and health benefits. Automobiles offer multiple benefits including weather protection, aerodynamics, operator comfort, safety, and cargo space.

2.2 PROJECT GOAL

From the need statement above, Team 9 created the following project goal:

"Design a human powered vehicle that can function as an alternative form of transportation."

With this project goal the team will have the ability to venture into territories that previous NAU teams have not in the past.

2.3 OBJECTIVES

The design objectives for this project are based on the customer needs, as well as the desire for a successful performance at the ASME Human Powered Vehicle Challenge. The design objectives can be seen in Table 2.1.

Table 2.1-Objectives

Objective	**Measurement Bias**	**Units**
Vehicle can reach high speeds	Top speed on a flat surface	mph
Light weight	Total weight of vehicle	lbs
Highly maneuverable	Turning radius	ft
Contains cargo space	Volume of storage space	ft^3
Support cargo weight	Load storage space can hold	lbs
Large field of view	Total horizontal plane rider can see	degrees
Protects rider from roll over	Force roll bar can sustain	lbs
Aerodynamic	Drag force on vehicle	lbs
Production run manufacturability	Unit manufacturing cost for production run of 360	dollars
Fits diverse range of operators	Amount of seat adjustability	ft

2.4 OPERATING ENVIRONMENT

In order for the team's human powered vehicle to meet the stated objectives, the vehicle must be tested within various operating environments. These environments include computer software, laboratories, field tests, and other miscellaneous environments.

In order to test the vehicle for the highest speed it is capable of reaching, the team members will each ride the vehicle down a long straight road as fast as they can. A GPS will be used to measure the max speed. Maneuverability will be tested by setting up cones in a parking lot at the desired radius and turning the vehicle within these cones.

The team will create a second roll bar identical to the roll bar that will be used on the vehicle to protect the rider and test it in a laboratory. A load will be applied to the roll bar using a Load Cell to determine the load required for failure. A laboratory will also be used when testing a 3-D printed model of the fairing in a wind tunnel. This test will tell the team if the goal of a low coefficient of drag can be achieved with the designed fairing. SolidWorks will also be useful for the same type of test on the computer generated fairing model.

Many tests can be conducted in various environments using a common tool, trial and error, or just the bike and team members. These tests will most likely occur in a machine shop where the bike is stored. A common tool such as a scale will be used to weigh the vehicle as well as the cargo that the vehicle will carry. The cargo space must be able to hold the given weight and fit a particular size of cargo, which can simply be placed in that space to ensure a perfect fit. Several tests can be conducted while a rider is sitting in the stationary vehicle. One of these tests, a visual test, includes the rider's field of view. One team member can hold an object and can pick various locations around the sides and front of the vehicle and ask the rider sitting inside the vehicle if he or she can see that object at each location. By doing this test, the team will know where there are blind spots and can make adjustments as necessary. Another test is the adjustability of the seat. Riders of various heights will adjust the seat as needed and verify that their required seat placement is available.

2.5 CONSTRAINTS

Design constraints were established from the above objectives; these are displayed in Table 2.2. Additional constraints were taken from the HPVC rulebook [8], to make the vehicle suitable for competition.

Table 2.2-Constraints

Costumer Constraints	**ASME Competition Constraints**
Capable of exceeding 40 M/h (64.4 km/h)	Turning radius of ≤ 26.25 ft (8 m)
Vehicle weight of ≤ 80 lbf (36.3 kg)	Capable of completing 6.21 miles (10 km) in under 2.5 hours
Coefficient of drag less than that of a traditional cyclist	Roll protection system must handle 600lbf (2670N) at an angle of 12 degrees from vertical with less than 2 in (5.1 cm) deflection and 300 lbf (1330 N) side load with less than 1.5 in (3.8 cm) deflection
Development budget of $6500.00	Must have a seat belt
	Field of view must equal or exceed 180°
	Vehicle must be capable of traversing a 5% uphill or 7% downhill
	Carry a parcel of 15 X 13 X 7.9 in (38 X 33 X 20 cm) with a mass of 12.1lbf (5.5 kg)
	Come to a stop at a speed of 15.5 M/h (25 km/h) in a distance ≤ 19.7ft (6 m)
	Head lights, tail lights, side view mirrors, reflectors, and a horn

2.6 QFD

In order for the team to measure the vehicle's features with engineering standards, a Quality Function Deployment (QFD) was created. The QFD will guide the team in making difficult design decisions with consideration to competitive products. As seen in Figure 2.1, the relationship between engineering requirements, customer requirements, and bench marks from past vehicles will be used to make design decisions. The customer requirements listed are those deemed most important by the client.

		Engineering Requirements									**Bench Marks**	
		Yield Strength	**Deformation**	**Cost**	**Velocity**	**Coefficient of Drag, Cd·A**	**Volume**	**Degree**	**Distance**	**Weight**	**The AXE (2012-2013)**	**Rose Hulman**
Customer Requirements	Reach high speeds				x						x	x
	Light weight			x						x		x
	Maneuverable								x	x	x	
	Carry cargo						x			x	x	x
	Large field of view							x				
	Protect rider	x	x									x
	Aerodynamic				x	x					x	x
	Manufacturability			x								x
	Range of rider sizes						x			x	x	
	Units	psi (kpa)	in (m)	$	ft/s (m/s)	in^2 (m^2)	in^3 (m^3)	°	ft (m)	lbf (kg)		
		Engineering Targets										

Figure 2.1-Quality Function Deployment

3.0 PROPOSED DESIGN

3.1 FRAME DESIGN

The frame is made up of 6061 Aluminum, heat treated to T6. This material selection was made because of its high strength to weight ratio and machinability. The main center tube and outriggers feature 1.5 inch square tubing. This was chosen because a square cross section has excellent resistance to bending due to its high moment of inertia. In addition, a square is much easier to mount a seat to than most other cross sections. Several gusset plates are located in areas that experience high stress and deflection to achieve a very stiff and strong structure. The final frame design is shown in Figure 3.1.

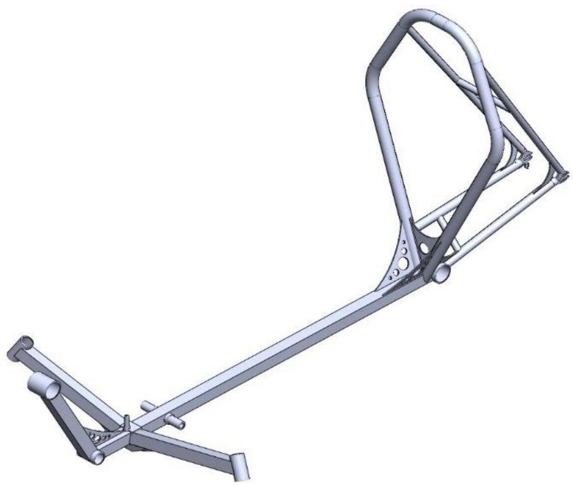

Figure 3.1- Frame Design

3.2 FAIRING DESIGN

A fairing is a specifically designed shell that can either encompass a portion or the entire vehicle. Its purpose is to decrease the aerodynamic drag of the vehicle and therefore, increase the efficiency. It can be made from a large range of materials: plastic, sheet metal, carbon fiber, or other types of composites. The final design for Pulaski can be seen in Figure 3.2. The final dimensions for the fairing are a length of 114 inches, a width of 24 inches, and a height of 38 inches.

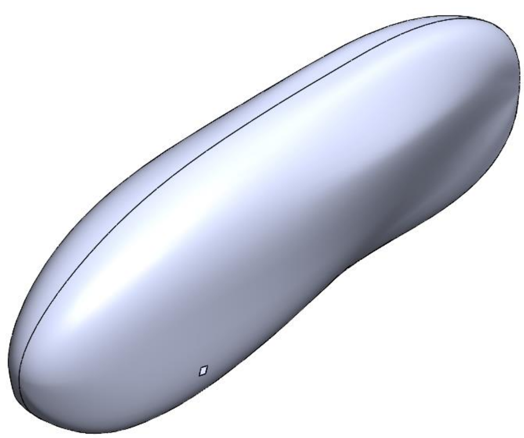

Figure 3.2- Final Fairing Design

$$y_t = \frac{tC}{0.2}\left[.2969\left(\sqrt{\frac{x}{C}}\right) - .1260\left(\frac{x}{C}\right) - .3516\left(\frac{x}{C}\right)^2 + .2843\left(\frac{x}{C}\right)^3 - .1015\left(\frac{x}{C}\right)^4\right] \quad (1)$$

Where:

y_t = Y coordinate of air foil [in]
t = thickness coefficient
x = X coordinate of airfoil [in]
C = airfoil length [in]

The design was derived from a NACA air foil equation, 2415, which can be seen in Equation 1 [2]. The final shell is made of 3K, 2x2 twill, carbon fiber. Two layers were used throughout the entire body, while some areas have three layers to increase stiffness. Testing was conducted in the NAU composites lab to determine the modulus of elasticity of carbon fiber. ASTM standard D790 was used to conduct the tests. The results showed that two layers of carbon fiber orientated at 90˚ x 90˚ deflected 0.4 inches at five pounds. Three layers of carbon fiber at 90˚x90˚x90˚ had the same deflection at twenty pounds. The decision to use two layers was made to decrease the weight of the fairing. To address the deflections, certain portions have foam stiffeners to increase the rigidity. To allow ease of access to essential components, the nose, tail, upper tail, and door, are all removable and have lips to ensure a proper fit. To achieve a smooth surface finish, the fairing was laid up in a two piece negative mold created from a positive foam plug. Due to the fully enclosed fairing, the rider will be protected from the outside environment with a water replant surface finish and cover from direct sunlight. This will increase the comfort of piloting Pulaski.

3.3 STEERING DESIGN

The steering for Pulaski is a crucial component that will determine how well the vehicle will maneuver. To ensure a high degree of maneuverability Pulaski was designed to meet the objective of a turning radius less than 26.5 ft.

To select the final design for the final steering configuration, three different types of steering systems were considered for the vehicle. The first of which is a rack and pinion setup similar to that used in most cars. The next type is a Pittman arm, which is used in most solid front axle vehicle applications, such as trucks and jeeps. The final design considered was a bell crank with a push-pull interface, similar to that found in a zero turn lawn mower.

After comparing the three options, the bell crank push-pull system was selected. This design can be seen in Figure 3.3. The operator has two handles to interface with, where the user pulls right to turn right and pulls left to turn left. This system uses a set of adjustable linkages from the steering arms to turn a central bell crank. The bell crank is fixed to the frame, but is allowed to rotate freely about a vertical axis. The purpose of this is to transfer the horizontal rotation motion of the steering arms to a vertical axis. The tie rods are then connected between the bell crank and the steering knuckles. The benefits of this system include easy adjustability, with interchangeable bell cranks, as well as large amounts of leverage for easy maneuvering.

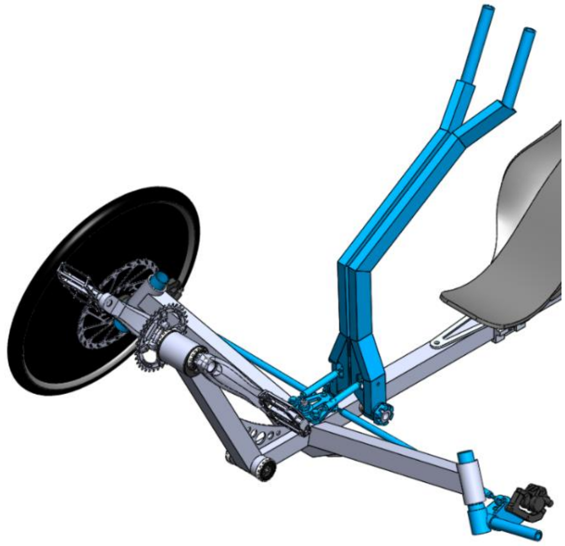

Figure 3.3- Bell Crank Push Pull

3.4 ERGONOMICS DESIGN

Ergonomics for Pulaski were designed to allow the rider to get maximum efficiency while maintaining comfort. A key design aspect established by the team is seat adjustability. The team members vary in height from 5’4” to 6’3” and it was imperative that every team member be able to operate the vehicle with comfort and efficient power transfer. With this in mind, the seat design must include a way to adjust the seat quickly to fit the appropriate operator. Through brainstorming, the team concluded that the easiest way to secure the seat in position would be with a quick-release pin. For easy pin access, the hole is through the bottom bracket and through the top surface of the square center tubing. It is placed directly in front of the edge of the seat, between the rider’s legs. Delrin plastic, known for its low coefficient of friction, is glued to the inside of the bracket and along the center tube so the seat will slide forward and backward easily. The assembly of the pin system, bottom bracket, and back support bracket can be seen in Figure 3.4.

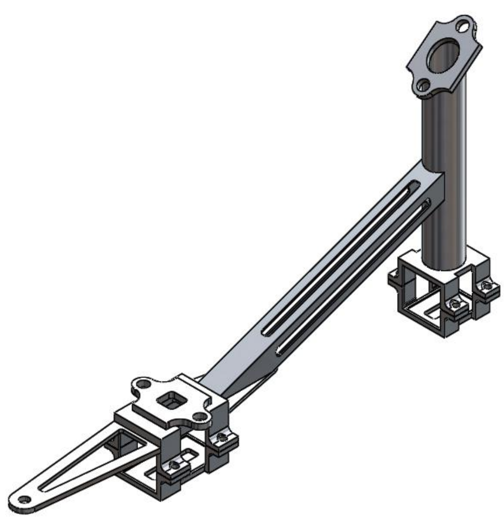

Figure 3.4- Seat Bracket

The team chose an angle of 122° for the final rider position. This angle is between the rider's hip to the cranks and the rider's hip to his/her shoulder. The angle was chosen based on a power output test using a stationary recumbent bicycle (please refer to the Development Testing section for more information). By choosing this angle, the rider has a clear view of the road, a comfortable sitting position, and efficient power when operating the vehicle.

To ensure the rider is safe and secure during operation, a 3-point retractable seat belt is implemented into the design. The three points are attached to the frame and are directed through small brackets on the sides of the seat for easy accessibility. The over-the-shoulder design was selected for extra security to lock the rider's upper body in place in case of a collision.

3.5 DRIVETRAIN DESIGN

Pulaski's drivetrain design focused on three main objectives: light weight, high efficiency and increased functionality. These were selected to address the objectives of a lightweight design, capable of reaching high speeds and be highly maneuverable. When selecting the drivetrain design for Pulaski, three configurations were evaluated: an internally geared hub, a standard cassette, and a standard cassette with an integrated reverse gear. The internally geared hub was quickly eliminated due to both its high weight and decrease in efficiency, 90.8% compared to 93.1% of a standard rear cassette [1]. The drivetrain configuration selected uses a standard 10 speed cassette with an integrated reverse gear, allowing Pulaski to reach high speeds with the added functionality of traveling in reverse when needed. This configuration can be seen in Figure 3.5 below, with the reverse gear located at the base of the roll bar. Pulaski's reverse gear is engaged through the use of a cable, located on the steering arm, locking the shaft in place and allowing direct drive of the rear wheel. The reverse mechanism design can be seen in the Innovation section.

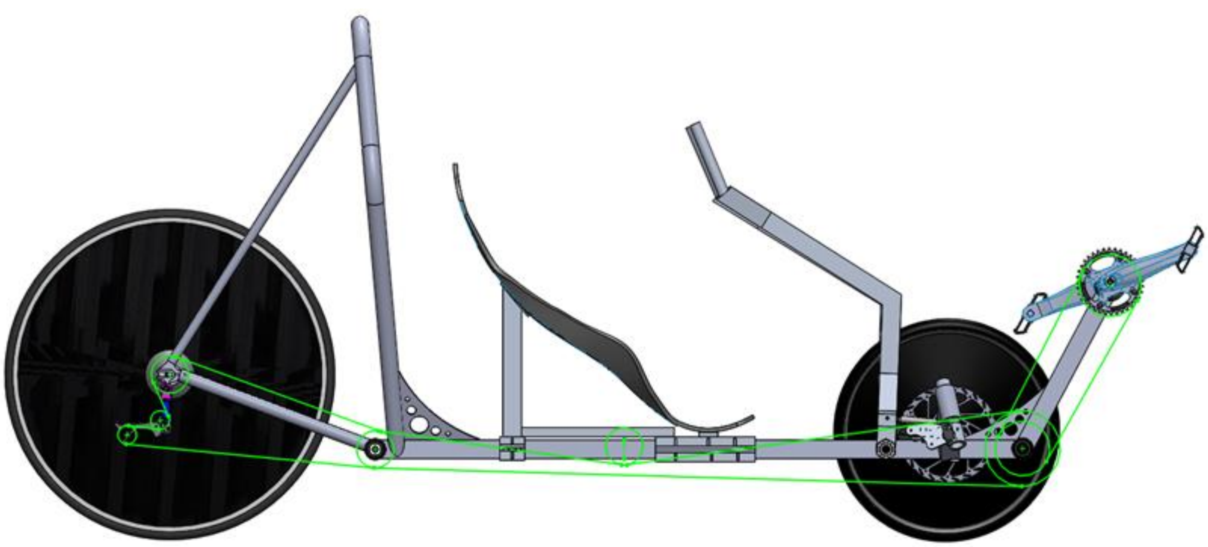

Figure 3.5- Drivetrain Location on Vehicle

3.6 INNOVATION DESIGN

The team incorporated several innovative ideas to enhance the functionality and safety of the vehicle. These innovations include a ventilation duct, an integrated lighting system and a reverse mechanism.

Pulaski was designed to operate in a large range of weather conditions without the rider overheating or freezing. This was through the implementation of a closable, low drag ventilation duct. During the operation of a human powered vehicle, riders generate considerable heat which limits operation time. Pulaski’s closeable duct was developed to allow the vehicle operator to be comfortable in a much larger range of climates while also allowing for a decrease in drag if desired. The duct is remotely closable by the operator through the use of electrical servo, microcontroller, and steering mounted input button. A Stratasys brand Fused Deposition Modeling (FDM) machine was used to fabricate the final two ducts, one on each side, which will be bonded into Pulaski’s outer fairing. Figure 3.6 shows a detail view of the duct shape and operating mechanism.

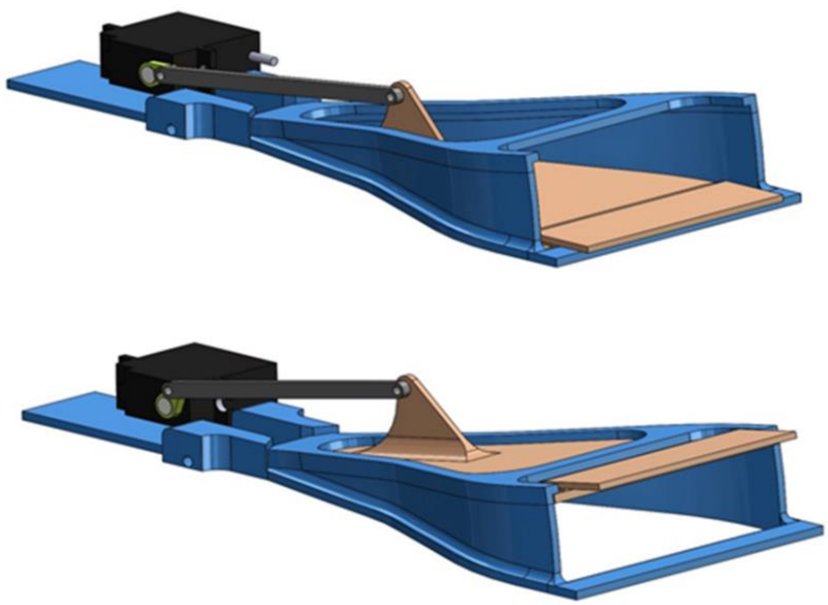

Figure 3.6- Duct Design

To improve the safety of Pulaski, a complete electrical lighting system was incorporated into the design. This includes brake lights, a headlight, internal lighting, and running lights. Team members of previous projects experienced difficulty communicating their intentions to automobile drivers when operating a fully faired vehicle on city streets. Subsequently, fully functional turn signals were also incorporated. Pulaski’s front wheel covers house these turn signals, which are viewable from a full 360 degrees. Figure 3.7 shows the vehicle lighting arrangement.

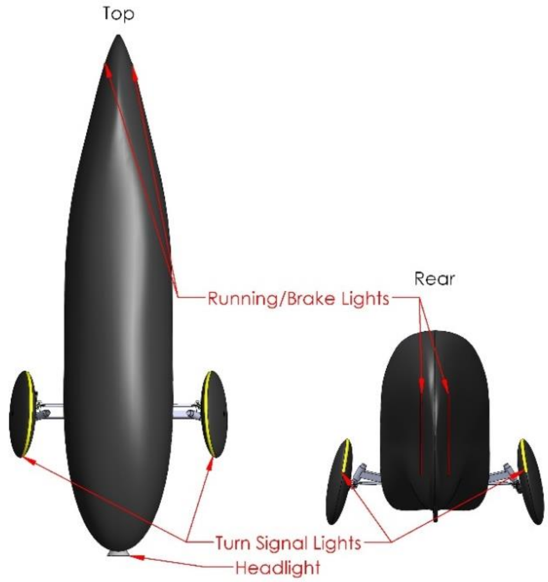

Figure 3.7- Light Configuration

One of the innovative features incorporated into Pulaski to improve the vehicles functionality and safety is an integrated reverse mechanism. This system, in conjunction with the vehicle's drivetrain, allows for Pulaski to travel in both the forward and reverse direction as needed. When activated through a lever on the steering arms the reverse mechanism engages two shafts, giving the rider direct drive of the wheel. Thus when the lever is pulled and the rider pedals backwards, Pulaski will travel in reverse. This reverse gear design is shown in Figure 3.8.

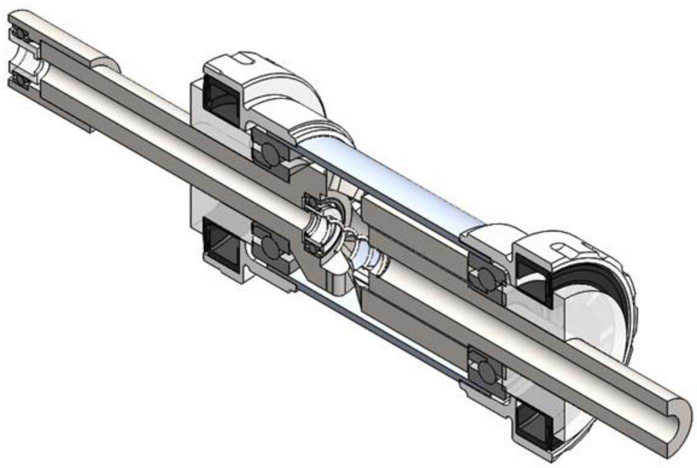

Figure 3.8- Reverse Mechanism Section View

The added functionality of the reverse mechanism improves the vehicles usefulness in an urban environment. During normal operation, there are instances when a driver must correct for an over turn, move away from an obstacle, or exit a parking spot. With the reverse mechanism integrated into the system, the rider can safely stay within the vehicle while conducting any of the previously mentioned maneuvers, rather than having to exit the vehicle and manually move it.

Pulaski's incorporation of a dedicated reverse gear on the vehicle is particularly innovative when combined with the standard drivetrain. While a standard bicycle with a fixed gear orientation could travel in reverse, it does not offer the high speeds achievable with a 10-speed cassette. Through the integration of the reverse mechanism, Pulaski can reach high speeds during standard operation while having the added benefits of the safety and functionality of reverse.

4.0 ANALYSIS

4.1 ROLL PROTECTION SYSTEM ANALYSIS

The roll protection system (RPS) of the vehicle was analyzed to ensure that it met the ASME rollover constraints. The analysis was done using finite element analysis (FEA) software. A summary of the performed analysis can be seen in Table 4.1.

Table 4.1- RPS Analysis

Objective	Method	Result
Numerically verify that the roll protection system meets ASME constraints	Finite element analysis using SolidWorks Simulation	Maximum top load deflection of 0.602 inches and maximum side load deflection of 0.593 inches

The model was treated as a solid body composed of 6061 T-6 aluminum. The yield strength was assumed to be 40,000 psi with a modulus of elasticity of 10,000 ksi [3]. The center tube, where the seat is attached, was set as a fixed boundary condition. A 600 lbf (2670 N) static force was applied 12° from vertical, and a 300 lbf (1330 N) static force was applied at shoulder height to the roll bar. The two loading cases and their FEA results can be seen in Figure 4.1.

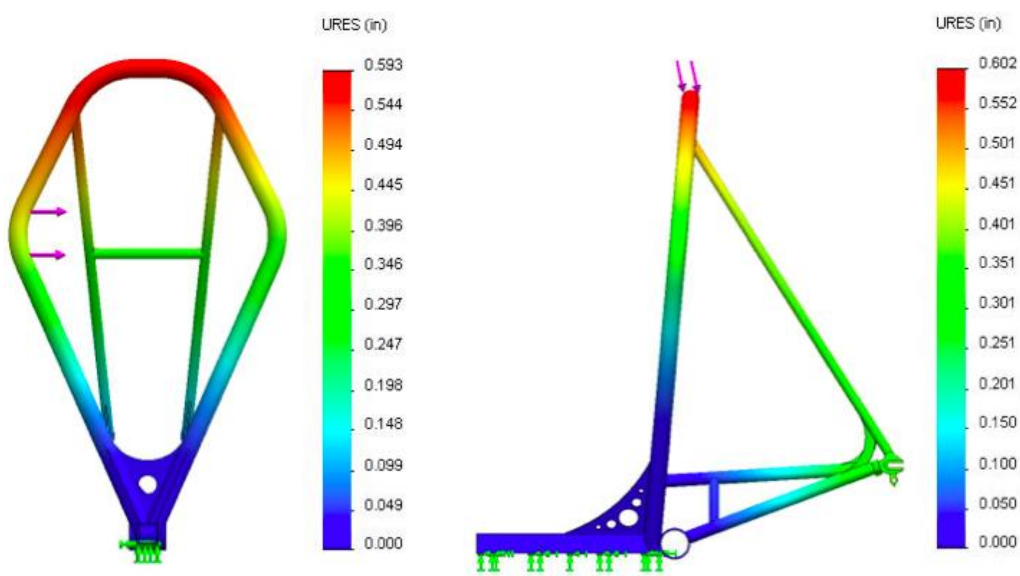

Figure 4.1- FEA Deflection Analysis of RPS

The top load analysis resulted in a maximum deflection of 0.548 inches, while the maximum allowable in this case is 2 inches. The side loading condition must deflect less than 1.5 inches, and the analysis showed a maximum deflection of 0.590 inches. Both analyses resulted in deflections that were significantly less than the required limits, therefore the roll protection system meets the ASME constraints numerically.

4.2 OUTRIGGER ANALYSIS

One of the other critical structural components, in addition to the roll protection system, is the outrigger arms supporting the front wheels. These elements have a large moment acting on them, thus analysis was conducted to minimize deflection, and reduce the risk of failure. FEA was performed, and hand calculations were done to check the validity of the results. A summary of the analysis can be seen in Table 4.2.

Table 4.2- Outrigger Analysis

Objective	Method	Result
Numerically and analytically verify that the outrigger arms have minimal deflection	Finite element analysis using SolidWorks Simulation and hand calculations	Factor of safety of 2.4 and max deflection of 0.185 inches

The model was treated as a solid body, and the material was assumed to have the exact same properties as in Section 2.1. The applied load was determined by attaching an accelerometer to one of the outriggers of The Axe. The vehicle was then driven over 1” x 6” boards at 25 mph, with a 160 lbf rider to simulate a worst-case loading condition. The highest value recorded from the accelerometer during this was 275 lbf. The FEA results for stress can be seen in Figure 4.2.

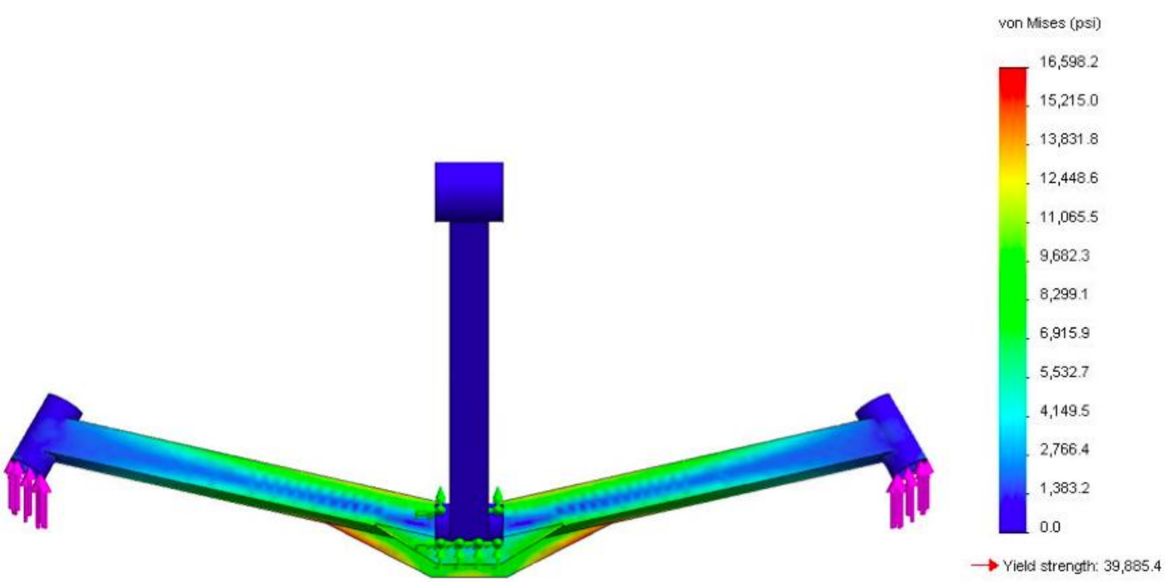

Figure 4.2- Outrigger Stress FEA Results

In the hand calculations, the outriggers were assumed to be 2D and the angle off of the z-axis was not factored in. A comparison between the FEA results and the hand calculation results can be seen below.

Table 4.3- Outrigger Analysis Results

Type of analysis	**Max Deflection [in]**	**Max Stress [psi]**
FEA	0.185	16,598
By Hand	0.159	14,593

Due to the complex angles that were accounted for in the FEA, but not in the hand calculations, slight differences between the two results appeared. However, due to the magnitude of the deflections and the stresses, these results appear to be accurate. With the assumed yield strength of 40,000 psi for aluminum, the outriggers have a factor of safety of 2.4.

4.3 STEERING KNUCKLE ANALYSIS

The outer dimensions of the steering knuckles were fixed by the commercial products they interface with, and FEA was used to determine the appropriate wall thicknesses to minimize weight. Analysis was completed for different configurations of aluminum and steel knuckles. Two fixture points were used as the boundary conditions, located at the top and bottom of the knuckle, to simulate the two bearings in the headset. A distributed force of 353 lbf was then applied to the axle to simulate the force that would be on the axle from the wheel; this can be seen in Figure 4.3 below. This force was determined using accelerometer data, as shown in Appendix A.

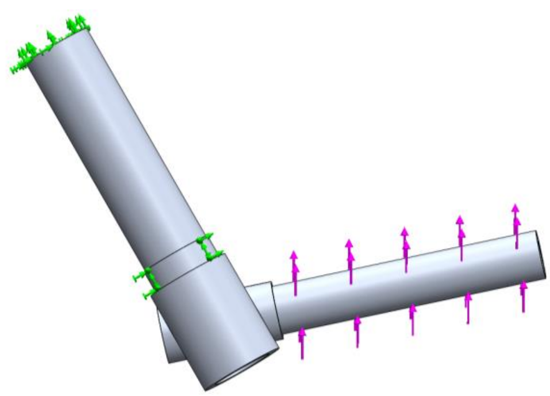

Figure 4.3- FEA Setup

The first configuration is 4130 chromoly, where both the steer tube and axle are hollow and optimized to make the tubes as thin as possible while minimizing stresses. The yield strength of the chromoly is assumed at 67,000 psi and a max stress calculated at 34,000 psi, giving a factor of safety of about 2 before yield. The weight of the chromoly knuckle is 0.73 lbf. The next configuration tested was 6061 T6 heat treated aluminum. The force, fixtures, and outside diameters were the same as the previous configuration. Only the inside diameters were changed to reduce material and weight. The yield strength of the aluminum was assumed at 40,000 psi and a max stress of 20,000 psi was obtained from the analysis, which can be seen in Figure 4.4. This resulted in a factor of safety of 2. The weight of this configuration is 0.43 lbf which is significantly lighter than the chromoly option, making the aluminum knuckles the favorable choice.

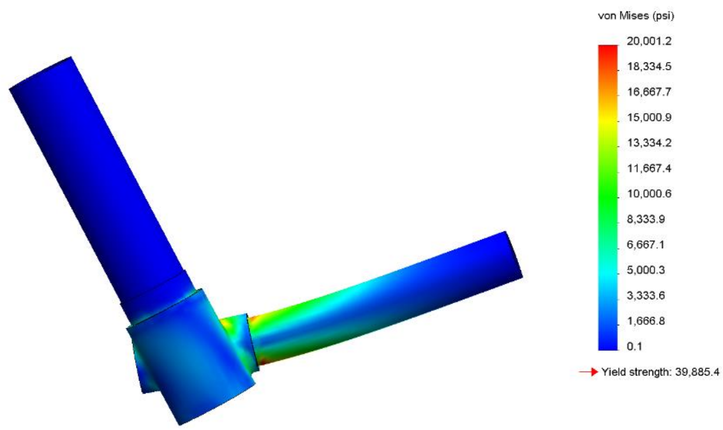

Figure 4.4- Aluminum Knuckle FEA

4.4 AERODYNAMIC ANALYSIS

The purpose behind Pulaski's fairing is to have a lower C_dA than that of a normal cyclist, 491 in^2 [4]. C_dA is the coefficient of drag, C_d, multiplied by the front cross sectional area, A, of the object. The C_dA of the vehicle and cyclist are compared to show the relation with regard to their aerodynamic drag. Over a dozen models were created and tested using SolidWorks FlowWorks Computational Fluid Dynamics (CFD). The designs ranged from partial fairings on the front or rear of the vehicle, as well as full fairing designs. Once it was decided that a full fairing would be used, over 40 different designs were created to show the effects of length, width, and height on a fairing of this nature. The assumptions made in the flow analysis includes: air as the fluid, incompressible, laminar flow, wind speed of 40 miles per hour, no humidity, gravity, no roughness, temperature of 68.09˚ F, and a pressure of 14.7 psi. Figure 4.5 shows Pulaski in the flow analysis.

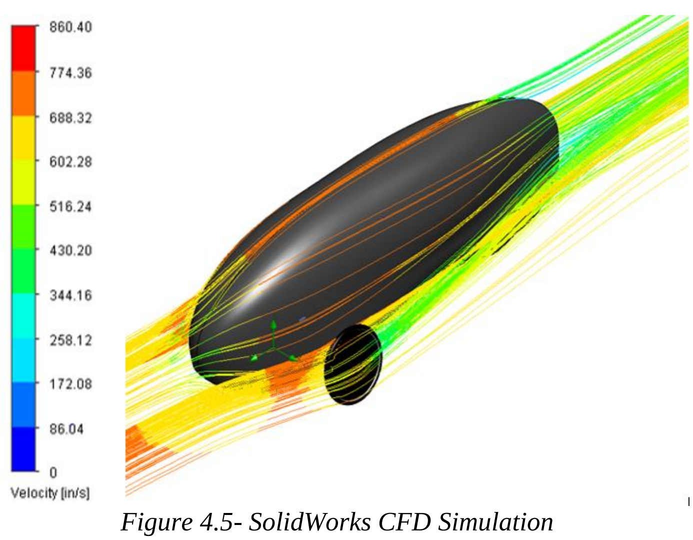

Figure 4.5- SolidWorks CFD Simulation

The CFD analysis showed a force of 2.09 lbf at a speed of 40 miles per hour. With those numbers, the C_dA of Pulaski is 90.2 in^2. Comparing the C_dA of the fairing covered vehicle to that of the cyclist, the fairing has twenty percent the C_dA. With this information, it is shown that the fairing covered vehicle has a more efficient design, and will help utilize the rider energy to reach high speeds and travel further distances.

4.5 DRIVETRAIN ANALYSIS

To select the optimal gear ratio for Pulaski, a MATLAB code was used to achieve a maximum velocity with minimal rider effort. Pulaski was designed around NAU's design requirement of reaching 40 mph and the ASME requirement of navigating a course at high and low speeds. A rider position study was used to determine the team's average and maximum cadence. This rider position study found the instantaneous maximum and average cadence over the course of a one-minute and a three-minute test. These results are displayed in Table 4.4.

Table 4.4- Rider Cadence

	Average Cadence (RPM)	Max Cadence (RPM)
Rider 1	70	149
Rider 2	101	133
Rider 3	91	149
Rider 4	93	141
Rider 5	91	135
Rider 6	90	143
Average	89.33	141.67
Rounded Average	90	140

From these results, the team selected an average cadence of 90 rpm for extended periods of time and a maximum cadence of 110 rpm when a top speed is desired. The value of 110 rpm was selected by viewing the maximum instantaneous cadence of 140 rpm and reducing that cadence by 20%. This cadence was perceived as an achievable maximum. Table 4.5 displays the gear ratio and speed at each of the positions on the rear cassette.

Table 4.5-Gear Ratios and Speeds

Gear Ratio	Speed at 90 RPM (MPH)	Speed at 110 RPM (MPH)
1.63	11.44	13.99
1.83	12.87	15.73
2.09	14.71	17.98
2.44	17.16	20.98
2.79	19.62	23.98
3.25	22.89	27.97
3.66	25.75	31.47
4.18	29.42	35.96
4.88	34.33	41.96
5.32	37.45	45.77

As seen in the table above, the vehicle is capable of reaching 45.77 mph, while having a gear ratio of 1.63 in the lowest possible gear. By selecting a configuration with a low gear ratio, the vehicle will be capable of the start and stop motion on the course as well as reaching a max speed.

4.6 STEERING GEOMETRIES

There are several key steering geometries for this style of vehicle, which are very similar to those in a traditional automobile or other 4-wheeled vehicles. These include: a caster, camber, kingpin, and axle offset.

The first steering geometry analyzed was the caster angle. Caster is the degree of the pivot angle tilted forward, as shown in Figure 4.6. The caster angle is critical because it causes the wheels to automatically return to a straight position after turning. Most automobiles use a 4-5° caster angle, while go-carts and racing vehicles generally use a more aggressive angle around 12° [5]. The team selected to use a 13° caster angle since Pulaski will be used as a race vehicle.

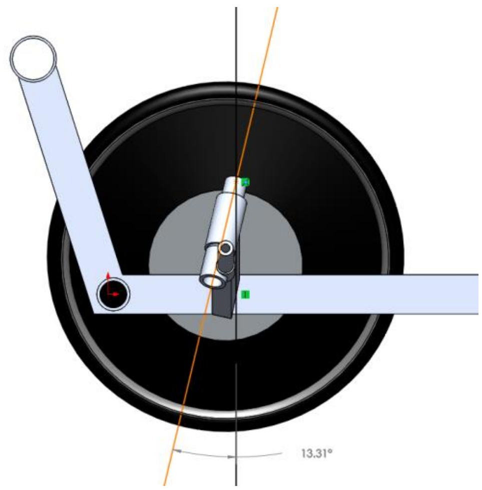

Figure 4.6- Caster Angle

The next important steering angle is the camber. This is the angle from the wheels to vertical, as seen in Figure 4.7. If the distance between the top of the wheels is smaller than the bottom of the wheels, the vehicle is said to have a negative camber, while the reverse is a positive camber. Most vehicles have a negative or neutral camber [5]. The team decided to go with a 12 degree negative camber for several reasons. These reasons include: improved stability and loading on the wheels. Bicycle wheels are designed to be loaded radially because the loading stays vertical in relation to the wheel. This application, however, will have very high side loading on the wheels. Therefore, having a drastic negative camber helps keep more of the force in the vertical axis of the wheel.

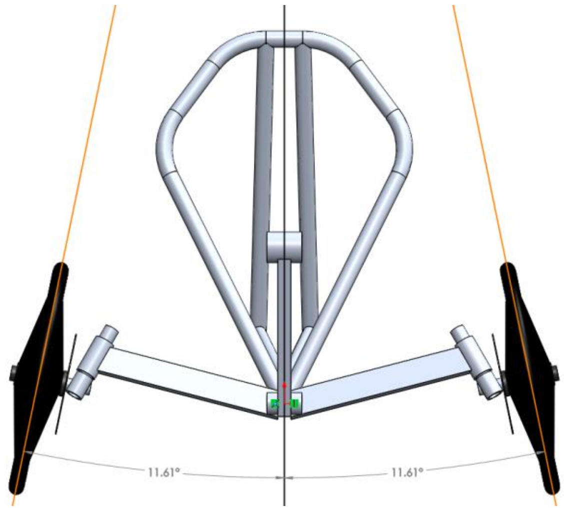

Figure 4.7- Camber Angle

The next geometry is the kingpin angle. This is the angle of the pivot axis from vertical, as viewed from the front of the vehicle, as seen in Figure 4.8. Some vehicles implement center point steering, where the tire pivots about the tire patch, which is where the tire contacts the ground. Center point steering allows the steering to be more precise and efficient [5]. The efficiency results from the reduction of tire scrub, which is unnecessary friction when the tires turn. With the geometry given, the kingpin angle becomes 30 degrees to achieve center point turning.

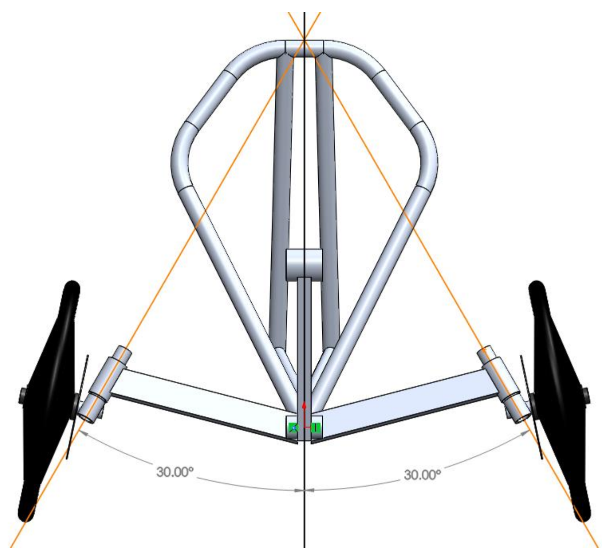

Figure 4.8- Kingpin Angle

The final geometry is the axle offset. This offset helps drastically with steering stability. If the axle of the wheel is in front of, or in line with, the pivot axis, the caster angle is negated. This can also cause undesirable steering motions. The most stable position is for the axle to be behind the pivot axis [5]. The team has chosen to put the axle 0.5 inches behind the pivot axis, shown in Figure 4.9, because of research and past experience with prior NAU HPVC vehicles.

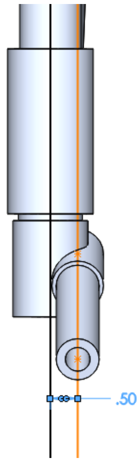

Figure 4.9- Axle Offset

4.7 TIPPING ANALYSIS

To ensure that the vehicle would resist roll-over during aggressive driving, a tipping analysis was completed. The goal of this analysis was to select a vehicle width that caused the tires to lose traction before the vehicle initiated a tip.

Pulaski's center of gravity, with rider on board, was assumed at the mid plane of the vehicle, 50% of the way between the front and back wheels, and 14 inches above the ground. A free body diagram was created including: the lateral inertial force, F, frictional force, f, weight of vehicle plus rider, W, and the normal force of the ground, N. Figure 4.10 below shows the diagram of the force relationship.

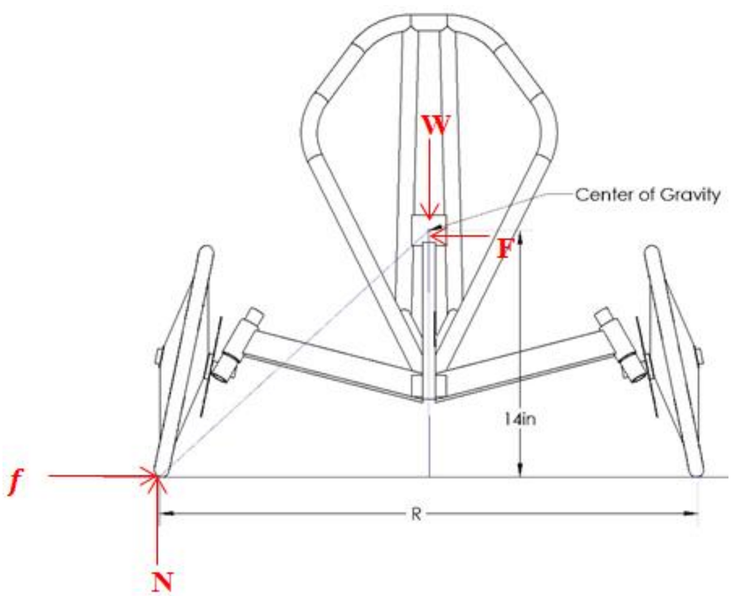

Figure 4.10- Tipping Analysis Free Body Diagram

The minimum critical width was determined to be 23 inches to avoid tipping during aggressive turning. However, bicycle lanes are usually a minimum of 48 inches in width [6]. Subsequently, the width of the vehicle's front wheels was chosen to be 46 inches, which will allow for a stable vehicle on all types of terrain. With this width, Pulaski will also be capable of traveling within bicycle specific lanes with space on either side.

5.0 PROTOTYPE FABRICATION

5.1 COMPONENT MANUFACTURING

The team constructed the Pulaski prototype in the university's engineering projects lab. This facility is equipped with multiple computer numerical control (CNC) machines that aided in the precision and quality of component fabrication. Components of the steering, frame, fairing, drivetrain, and ergonomics sections all utilized the CNC lathe and mill machines that are stationed in this lab space. Figure 5.1-Figure 5.4 show detail views of parts fabricated through this process.

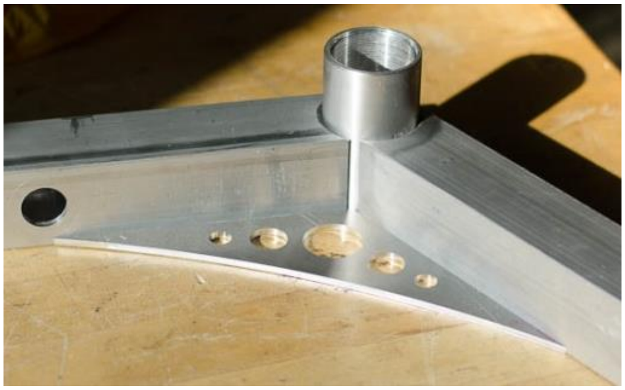

Figure 5.1- Gussets

Figure 5.2- Bell Crank

Figure 5.3- Seat Bracket Parts

Figure 5.4- Steering Knuckles

A precision alignment fixture was also developed by team 9 to hold critical components in the appropriate spatial relationships as they were fitted, and ultimately welded into place. Figure 5.5 shows this alignment fixture. While this fixture was developed around the fabrication of this human powered vehicle it will be available for future use by other vehicle based projects.

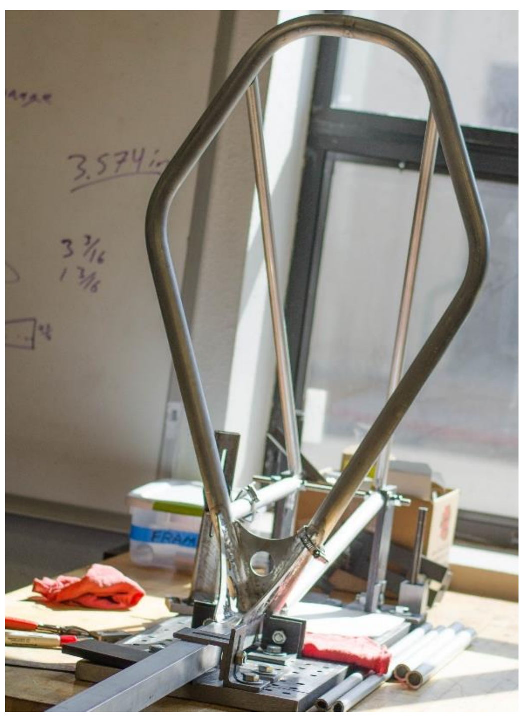

Figure 5.5- Frame Fixture

FDM 3D printers were used to validate designs as well as create final parts. Pulaski's reverse mechanism was initially designed using CAD software, however in the next design stage tolerances and functionality were validated with a 3D printed version of the mechanism. This early model of the reverse mechanism can be seen in Figure 5.6.

Figure 5.6- Reverse Mechanism Demo

Parts from the same FDM printer were used as functional components on the final prototype; cable stops and the ventilation ducts were fabricated from ABS in the same FDM process. Figure 5.7 illustrates the functional vent parts used on the prototype.

Figure 5.7- 3D Printed Vents

5.2 FAIRING MOLDS

For the fairing to be created, the team decided to create negative molds to create a fairing with a smooth outside finish. A foam male plug was cut and shaped to the design of the fairing. From there the foam was wrapped in fiberglass to achieve a hard shell. It was then sanded and formed with 40 girt sand paper and Bondo. Once the holes and divots were filled, it was painted with filler based paint and then a final coat of automotive paint. The male plug with the final coat of paint can be seen in Figure 5.8.

Figure 5.8- Male Plug

The surface finish that was shown would be equivalent to that on the final product. From there, a damn was built around the spine of the fairing to create the halved portions of the fairing. The two sides were laid up separate of one another and were then pulled off of the male plug. One of the halves can be seen in Figure 5.9.

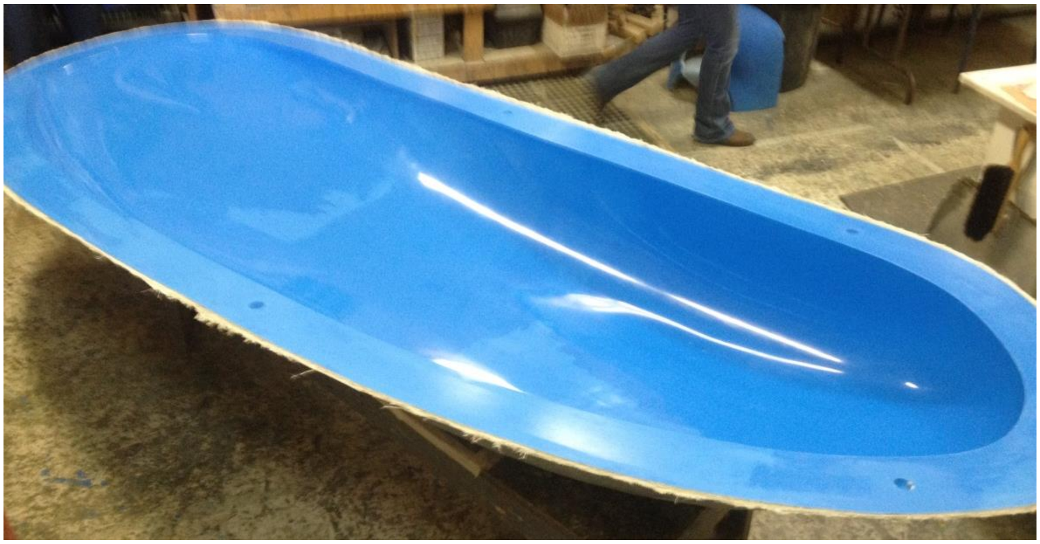

Figure 5.9- Half of Female Mold

At this point carbon fiber layup began. This was done in multiple steps to achieve removable maintenance doors and an entry door. When all of the parts were finished, the fairing was then bonded to the bike at the outriggers and around the roll bar. The seams were bonded with a two inch strip of carbon fiber. The bike layup process can be seen in Figure 5.10.

Figure 5.10- Fairing Layup with Completed Frame

5.3 HEAT TREATMENT

After the frame was welded it needed to be heat treated to regain full strength. This process involves a solution treatment in an oil bath, then a curing stage in an oven. Due to the high temperatures reached in the solution treatment the frame experienced warping, causing misalignment issues. In order to keep the frame from curing while realignment it was set on dry ice and wrapped in blankets for insulation as seen in Figure 5.11.

Figure 5.11- Frame Set On Dry Ice

The team fabricated a fixture with a cantilevered arm to twist the frame back into alignment seen in Figure 5.12. Alignment was verified with a level. After alignment issues were solved the frame went back into the oven for the final curing process to get to T6.

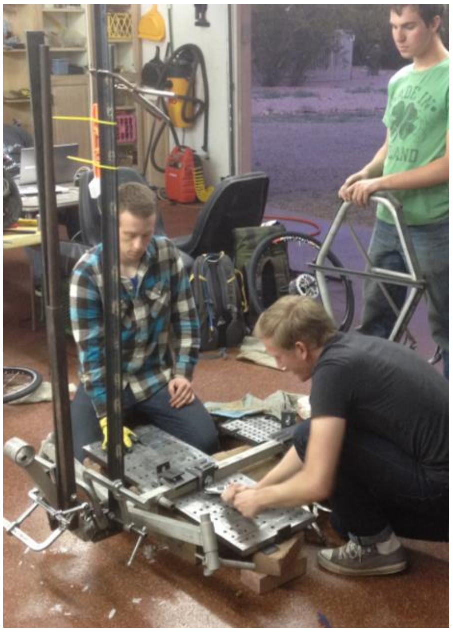

Figure 5.12- Frame Realignment Set Up

5.4 FINAL PROTOTYPE

The final vehicle design incorporated each element of the design in a clean, professional prototype design. Pulaski in its final state can be seen in Figure 5.13 below.

Figure 5.13- Final Vehicle Prototype

Pulaski featured a fully enclosed carbon fiber fairing with large side and front windows for a large range of visibility. The frame was comprised of polished 6061 T6 aluminum providing a rigid central frame and roll protection system for the vehicle. The vehicles drivetrain provided Pulaski the ability to reach high and low speeds while also having the functionality of traveling in reverse. An adjustable seat and steering system allowed a large range of riders to operate the vehicle under a varied of conditions. Additionally, a fully functioning light and vent system allowed the vehicle to operate in urban environments under a wide range of operating environment. An internal view of the vehicle and associated components can be seen in Figure 5.14 below.

Figure 5.14- Internal View of the Vehicle

6.0 TESTING AND RESULTS

6.1 RPS TESTING

To verify the analytical RPS results, physical testing was performed. An identical roll bar and rear end was constructed solely for these tests. The system was held at a 12° angle and a 2700 N force was applied to the top with a steel testing frame through the use of a hydraulic cylinder. Force was measured with a load cell and deflection was measured with a string potentiometer. The system was also loaded on the side at shoulder height with a 1339 N load. The results from this test can be seen in Table 6.1.

Table 6.1- RPS Testing Results and Comparison

Load	FEA Max Deflection	Physical Max Deflection	Maximum Allowable Deflection
Top 607 lbf (2700 N)	0.602 in (1.53 cm)	0.378 in (0.96 cm)	2 in (5.1 cm)
Side 301 lbf (1339 N)	0.593 in (1.51 cm)	1.382 in (3.51 cm)	1.5 in (3.8 cm)

The observed deflections were both below the ASME constraints. Additionally, a rider was strapped into Pulaski and rolled over. During this test, none of the rider's extremities came in contact with the ground. Based on these results the roll protection system for this vehicle is suitable and meets all requirements.

6.2 DEVELOPMENT TESTING

In order to optimize Pulaski's design, several tests were conducted during the design phase. These tests included finding the forces experienced when riding over obstacles and determining the position at which the rider will sit.

Table 6.2- Development Testing Summary

	Objective	Method	Results
Forces During Operation	Determine max forces at key locations on the vehicle	Attached accelerometer to key locations and simulate worst case scenarios	Experienced a max load of 222.5 lbf on the rear axle and a max load of 271.8 lbf on the front axle
Rider Position	Determine the angle of the seat for maximum power output and comfort	Measure power output for simulated sprint and endurance race at different angles using a test rig	Angle of 122˚ was chosen due to power during endurance test and increase in visibility

Pulaski design team chose to conduct accelerometer tests on NAU's 2013 entry, The Axe. This allowed the design and analysis phases to utilize real world loading. Wheel reaction forces were determined with the vehicle and operator placed on three scales, one for each wheel. While recording 15 data points per second, the acceleration recording unit was placed at each axle of the vehicle while the rider navigated a course of obstacles seen in current and past HPVC events. This specifically includes a small version of the rumble strip outlined in the 2014 rules. The recorded accelerations were translated into reaction forces through the use of Newton's second law of motion and plotted verse time.

Through inspection it was determined that all peak accelerations occurred at times of significant impact, thus all peak data points were considered realistic values. The maximum force experienced at each measurement location during the experiment was used as the design load during Pulaski's development.

Another aspect important to the development of Pulaski was the rider position. The maximum power output from the operator depends on the rider position, as various muscles are used at different angles. The angle between the rider's back and center tube of the frame was determined first, which relates to the rider's visibility. The team concluded that rider's eye level should be slightly higher than the top of the rider's foot on the pedals.

In order to determine the position of the rider in the vehicle, the team conducted several tests using a stationary recumbent bicycle. Over the course of three days, each team member was positioned at a different angle. This angle is between the hip to the center of the cranks and the hip to the shoulder, shown in green in Figure 6.1. The three angles tested were 115°, 122°, and 130°. Each rider had to complete a ten-minute warm-up, followed by a one-minute sprint, and a three-minute endurance test. The tests allowed the team to measure max and average power, max and average cadence, average heart rate, and energy expended.

Figure 6.1-Rider Position Angle

Figure 6.2 shows the max power of each team member's three tests for the one-minute sprint. The results show that an angle of 130° frequently had the highest max power among the team members. Since the riders vary significantly in weight, the power to weight ratio was calculated. The 130° angle had the highest average max power to weight ratio.

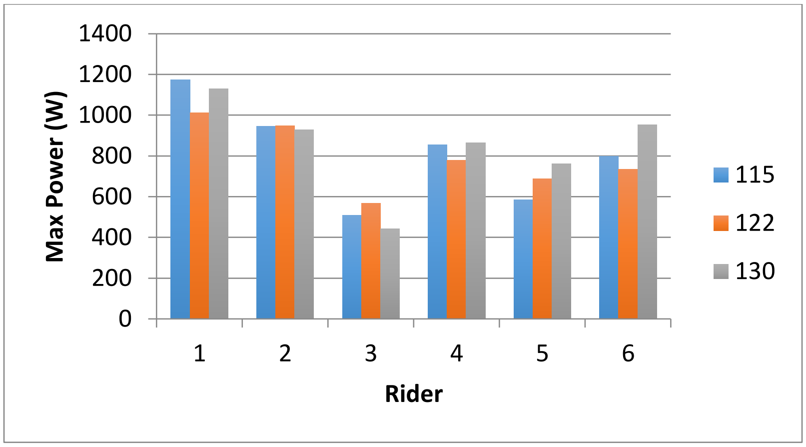

Figure 6.2- Max Power at Various Angles

Figure 6.3 shows the average power of each team member's tests for the three-minute endurance. These results show that an angle of 122° frequently had the highest average power among the team members. An angle of 122° also had the highest average for the power to weight ratio.

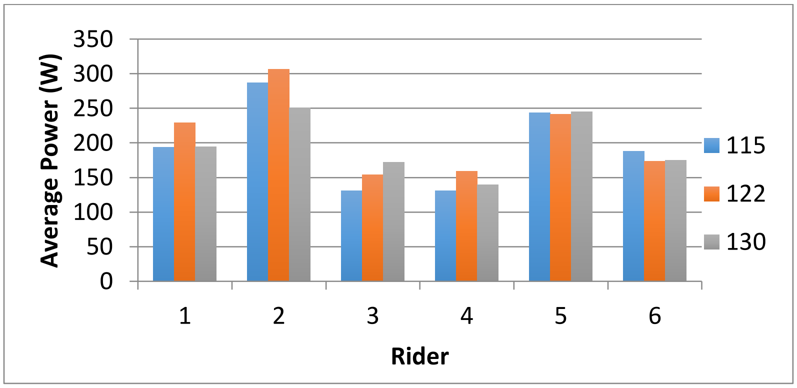

Figure 6.3- Average Power at Various Angles

After discussion, the team chose an angle of 122° for the final rider position. It was decided that the endurance test was deemed more important, for the vehicle is designed to be used in urban environments, which includes farther distances than a typical sprint. Visibility is also an important factor. By choosing a less steep angle, the rider will be able to see over the pedals and therefore, operate the vehicle safely.

6.3 PERFORMANCE TESTING

To verify Pulaski's performance, a series of physical tests was conducted. These tests evaluated the vehicle's turn radius, braking distance, top speed, and visibility. The objective, method, and results for the vehicle's performance are shown in Table 6.3.

Table 6.3- Performance Testing

	Objective	**Method**	**Results**
Turn Radius	Verify that Pulaski turning radius is within competition constraints.	Pulaski will complete a 180 degree turn. The distance between the outside wheel at the starting and ending point of the turn is the diameter.	Pulaski's turning radius was 8.4 feet, well within the competition constraint.
Braking Distance	Verify that the braking distance of the vehicle at 15.5 mph (25 km/hr) is under 19.7 feet (6 m).	Pulaski will enter a zone at 15.5 mph and immediately apply the brakes. The distance till a complete stop will be measured.	A complete stop from 15.5 mph was achieved in 12 feet.
Top Speed Test	Verify that the theoretical top speed of the vehicle reaches the constraint of 40 mph.	The speed of Pulaski will be measured with a 600 meter run up and 200 meter speed trap.	A speed of 44.8 mph was reached during testing.

Pulaski successfully passed each of the performance tests completed for turning radius, braking distance and top speed. The turning radius of the vehicle was far lower than the competition requirement, allowing Pulaski to be highly maneuverable throughout the events. Pulaski came to a complete stop in 12 ft, giving the team confidence in the vehicles safety. Lastly, Pulaski was able to reach 42 mph in a top speed test, surpassing NAU's objective of reaching 40 mph.

Another performance test conducted with Pulaski was a visibility test. To test the range of rider visibility each rider sat in the vehicle and reported their line of sight in each direction. The average visibility for the riders was found and is displayed in Figure 6.4. The shaded area represents the area visible while in the vehicle.

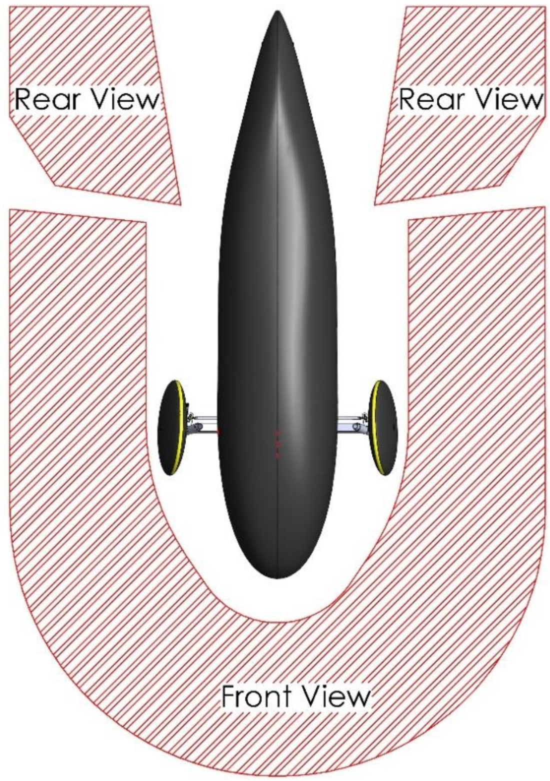

Figure 6.4- Field of Vision

6.4 COMPETITION RESULTS

The team competed in the Human Powered Vehicle Challenge (HPVC) sponsored by the American Society of Mechanical Engineers (ASME) in San Jose, California on April 24th to 27th. The competition included multiple categories such as overall placement, design, innovation, men's and women's sprint, and endurance. The vehicle placed 2nd overall out of 26 teams. This overall score combined the scores from each of the five specific categories. The team received 2nd in design which was comprised of finished vehicle design and the team's report and presentation. The reverse mechanism earned 2nd place for the innovation category with its focus on enhanced vehicle safety. Pulaski reached a speed of 28.9 mph in the women's sprint race, placing 1st overall. Additionally, a speed of 27.8 mph was reached during the men's sprint, placing 6th overall. Pulaski completed 46 laps during the endurance course, equaling 36.3 miles. During which, the vehicle successfully maneuvered several obstacles each lap including three speed bumps, stop sign, slalom, quick turn, hairpin turn, and grocery delivery and pickup with minimal issues. The team experienced minor mechanical problems during the competition and feels that had those not occurred a first place finish would be been achieved. Overall, the team finished 0.11 points away from a 1st place finish.

7.0 COST ANALYSIS

7.1 BILL OF MATERIALS

To provide an accurate representation of the components and materials needed for vehicle construction the team created a bill of materials (BOM) for each subsection of the design. Each of these includes the application on the vehicle, the specific part, its manufacturer's suggested retail price (MSRP), the cost to the team, and the source of purchase.

Table 7.1-Frame BOM

Application	Product	Qty	MSRP	Actual Cost	Projected Total	Source
Center Tube	1.5"x1.5"x0.125" 6061-T6 Tube	6'	$22.91	$22.91	$22.91	Online Metals
Outriggers	1.5"x1.5"x0.125" 6061-T6 Tube	4'	$16.52	$16.52	$16.52	Online Metals
Roll bar	1.375"ODx0.125" 6061-T6 Tube	16'	$145.00	$145.00	$145.00	Online Metals
Roll bar	1"ODx0.125" 6061-T6 Tube	4'	$24.80	$24.80	$24.80	Online Metals
Roll bar	0.75"ODx0.125" 6061-T6 Tube	7'	$40.55	$40.55	$40.55	Online Metals
Gusset	0.25" Thick 6061-T6 Plate	2'	$28.54	$28.54	$28.54	Online Metals
Dropouts	Rear dropout with hanger	1	$55.89	$55.89	$55.89	Paragon Machine Works
Head Tubes	Front wheel head tubes	2	$15.00	$15.00	$30.00	Absolute Bikes
Bottom Bracket	Drivetrain bottom brackets	3	$20.00	$20.00	$60.00	Absolute Bikes
Overall	T6 Heat Treatment	1	$1,000.00	$0.00	$0.00	Phoenix Heat Treating
Roll bar	Computer bending	2	$300.00	$0.00	$0.00	Di-Matrix
	Totals				**$424.21**	

Table 7.2-Steering BOM

Application	Product	Qty	MSRP	Actual Cost	Projected Total	Source
Knuckle Stock	1.5"x 12" round stock 6061	4	$14.05	$14.05	$56.20	McMaster-Carr
Axle/Spindle Stock	7/8" x36" round stock	1	$15.54	$15.54	$15.54	McMaster-Carr
Bell Crank	.25"x12"x12"	1	$30.39	$30.39	$30.39	McMaster-Carr
Hiem Joints	hiem joints 1/4-28	8	$10.62	$10.62	$84.96	McMaster-Carr
Spacer Stock	3/8" x 12" round 4130 stock	1	$3.21	$3.21	$3.21	McMaster-Carr
Threaded inserts	1/4"-28 threaded insert x10	1	$8.75	$8.75	$8.75	McMaster-Carr
1/4" bolts	1/4" 28 1" grade 8 x50	1	$8.35	$8.35	$8.35	McMaster-Carr
Damper	steering damper	1	$24.45	$24.45	$24.45	McMaster-Carr
Bushing Stock	bearing grade bronze 1" x 6.5"	1	$26.29	$26.29	$26.29	McMaster-Carr
Tierod Material	.5" x.065" thick x72"	1	$28.44	$28.44	$28.44	McMaster-Carr
Bushing Bolts	1/2 20 castle nut x10	1	$7.98	$7.98	$7.98	McMaster-Carr
Steering Arms	1 sq yard 3k 2x2	1	$59.95	$59.95	$59.95	fibre glast
Knuckle Pivot	Headsets	2	$30.00	$30.00	$60.00	Absolute Bikes
Brakes	bb7 w/ 160mm rotors set of 2	1	$106.65	$106.65	$106.65	Absolute Bikes
Brake Handle	avid fr-5	1	$11.60	$11.60	$11.60	Absolute Bikes
Brake Splitter	brake splitter br3341	1	$39.60	$39.60	$39.60	Absolute Bikes
Tubes	20 inch tubes	4	$8.00	$5.00	$20.00	Absolute Bikes
Tire	20 inch tire	2	$60.00	$35.00	$70.00	Absolute Bikes
Hub Bearings	Kris King Hub Bearings	2	$45.00	$45.00	$90.00	Absolute Bikes
Assorted tools	Assorted tools	1	$50.00	$50.00	$50.00	
	Totals				**$802.36**	

Table 7.3-Ergonomics BOM

Application	Product	Qty	MSRP	Actual Cost	Projected Total	Source
Seat	Fiberglass recumbent seat	1	$165.00	$145.00	$145.00	Power On Cycling
Seat Cushion	Foam pad	1	$40.00	$30.00	$30.00	Power On Cycling
Back Support Beam	1.5" x 0.125" 6061 TS Square Tube - 1'	1	$5.16	$5.16	$5.16	Online Metals
Connection Beam	0.75" x 0.062" 6061 T6 Square Tube - 2'	1	$2.40	$2.40	$2.40	Online Metals
Bottom Bracket	1" x 4" 6061 Bar - 1'	2	$30.11	$30.11	$60.22	McMaster-Carr
Sliding Material	Black Delrin 0.062" x 12" x 12" Sheet	1	$11.86	$11.86	$11.86	Plastics International
Pin	3/8" dia., 1" Grip Lg., QR Lock Pin	1	$14.09	$14.09	$14.09	Reid Supply Company
Headrest	Stuffing	1	$5.00	$5.00	$5.00	Walmart
Headrest	Fabric	1	$5.00	$5.00	$5.00	Walmart
Seatbelt	Lap Belt (2 Point Seat Belt)	1	$17.95	$17.95	$17.95	SeatBeltsPlus.com
	Totals				**$278.73**	

Table 7.4-Drivetrain BOM

Application	Product	Qty	MSRP	Actual Cost	Projected Total	Source
Crank	SRAM Red 22 53-39	1	$620.00	$307.00	$307.00	Absolute Bikes
Cassette	SRAM xg1099	1	$510.00	$260.00	$260.00	Absolute Bikes
Step up	SRAM x7 26-39	1	$226.00	$113.00	$113.00	Absolute Bikes
Deruiler	SRAM X9 Type 2 Medium Cage	1	$150.00	$73.00	$73.00	Absolute Bikes
Shifter	SRAM X0 10 speed Trigger*	1	$180.00	$89.00	$89.00	Absolute Bikes
Chain	SRAM PC 1051	3	$40.00	$20.00	$60.00	Absolute Bikes
Gear	36 tooth 120 BPD	1	$40.00	$20.00	$20.00	Absolute Bikes
Rear Wheel	Stans ZTR Alpha 340 disk	1	$400.00	$200.00	$200.00	Absolute Bikes
Rear Tire	700c rear tire	2	$70.00	$35.00	$70.00	Absolute Bikes
Rear Tube	700c tube	2	$20.00	$10.00	$20.00	Absolute Bikes
Inner Bearing	Ball Bearing, 1/2" ID 1-1/8" OD	2	$9.51	$9.51	$19.02	McMaster-Carr
Cable Bearing	Ball Bearing, 2mm ID 6mm OD	1	$6.05	$6.05	$6.05	McMaster-Carr
Spring Bearing	Ball Bearing, 5/16" ID 1/2" OD	2	$6.20	$6.20	$12.40	McMaster-Carr
Spring	0.25 OD pack of 12	1	$9.80	$9.80	$9.80	McMaster-Carr
Tube	Aluminum 1.120" ID 1-1/4" OD	1	$10.62	$10.62	$10.62	McMaster-Carr
Spline	1 ft w/cut fee	2	$17.05	$8.53	$17.05	Grob
Spline Sleeve	Matching spline sleeve	2	$8.60	$4.30	$8.60	Grob
Bottom Bracket	External bottom bracket	1	$40.00	$20.00	$20.00	Absolute Bikes
Brake Cable	Shimano brake cable	1	$3.50	$3.50	$3.50	Absolute Bikes
Gear	Rear wheel	1	$40.00	$20.00	$20.00	Absolute Bikes
Idler Gear	Small gears on reverse shaft	2	$10.00	$5.00	$10.00	Absolute Bikes
	Total				**$1,349.04**	

Table 7.5-Fairing BOM

Application	Product	Qty	MSRP	Actual Cost	Projected Total	Source
Male Mold	Foam	19	$50.50	$50.50	$959.50	Homco
Male Mold	Fiberglass per yard 50"	18	$6.60	$6.60	$118.80	Aircraft Spruce
Male Mold	Bondo	2	$17.99	$17.99	$35.98	Homco
Male Mold	Wood 48X96X1/4	4	$17.99	$17.99	$71.96	Homco
Female Mold	Fiberglass per yard 50"	36	$6.60	$6.60	$237.60	Aircraft Spruce
Female Mold	Bleader Cloth	8	$7.95	$7.95	$63.60	Fibre Glast
Female Mold	Peel Ply	8	$8.95	$8.95	$71.60	Fibre Glast
Female Mold	Vaccum Bagging	8	$4.95	$4.95	$39.60	Fibre Glast
Female Mold	Sealant	1	$7.95	$7.95	$7.95	Fibre Glast
Fairing	Carbon Fiber 2x2 twill 50", per yard	18	$20.50	$20.50	$369.00	Soller Composites
Fairing	Bleader Cloth	8	$7.95	$7.95	$63.60	Fibre Glast
Fairing	Peel Ply	8	$8.95	$8.95	$71.60	Fibre Glast
Fairing	Vaccum Bagging	8	$4.95	$4.95	$39.60	Fibre Glast
Fairing	Sealant	1	$7.95	$7.95	$7.95	Fibre Glast
All	Resin 5.25 Gallons	1	$568.00	$568.00	$568.00	Aircraft Spruce
All	General: brushes, gloves, etc	1	$200.00	$200.00	$200.00	
	Totals				**$2,926.34**	

Table 7.6-Innovation BOM

Application	Product	Qty	MSRP	Actual Cost	Projected Total	Source
Closing Ducts	Driving servos	2	$20.00	$20.00	$40.00	servocity.com
Closing Ducts	Carbon composite flap	2	$20.00	$0.00	$0.00	Soller Composites
Closing Ducts	Resin for flaps	2	$5.00	$0.00	$0.00	NAU Machine Shop
Closing Ducts	FDM material	1	$100.00	$0.00	$0.00	Dr. Tester
Anti Fog Duct	FDM material	1	$20.00	$0.00	$0.00	Dr. Tester
Turn Signals	LED Strips	2	$20.00	$0.00	$0.00	sbLED.com (sponsor)
Brake Lights	LED Strips	2	$15.00	$0.00	$0.00	sbLED.com (sponsor)
Interior Light	LED Strip	1	$15.00	$0.00	$0.00	sbLED.com (sponsor)
Turn Signals	Button	2	$4.00	$4.00	$8.00	Radioshack
Brake lights	Switch	1	$1.00	$1.00	$1.00	Radioshack
Interior Light	Button	1	$1.00	$1.00	$1.00	Radioshack
Head Light	Lumia 500 light	1	$110.00	$0.00	$0.00	Niterider (sponsor)
Seat Belt Light	LED	1	$0.10	$0.10	$0.10	Radioshack
Sustainable Manf.	Test molds	1	$50.00	$0.00	$0.00	NAU Machine Shop
Sustainable Manf.	Test mold resins	1	$40.00	$0.00	$0.00	NAU Machine Shop
Onboard Electronics	Control panel	1	$15.00	$0.00	$0.00	Soller Composites
Onboard Electronics	Battery	1	$50.00	$50.00	$50.00	Radioshack
Onboard Electronics	Wiring (50ft)	1	$10.00	$10.00	$10.00	Radioshack
Onboard Electronics	Master control switch	1	$2.00	$2.00	$2.00	Radioshack
Onboard Electronics	Various connectors	1	$30.00	$30.00	$30.00	Radioshack
Onboard Electronics	Wire routing	1	$20.00	$20.00	$20.00	Radioshack
Onboard Electronics	Battery charger	1	$30.00	$30.00	$30.00	Radioshack
Onboard Electronics	Battery box/holder FDM material	1	$50.00	$0.00	$0.00	Dr. Tester
	Totals				**$192.10**	

To calculate the overall cost of the vehicle, the sum of each subsection was calculated and placed into Table 7.7.

Table 7.7-Overall Costs

Subsection	**Projected Total**
Frame	$424.21
Fairing	$2,926.34
Steering	$802.36
Drivetrain	$1,349.04
Ergonomics	$278.73
Innovation	$192.10
Vehicle Total	**$5,972.78**

The total cost of the vehicle comes to $5,972.78. This is well below the team's client given constraint of a $6,500 starting budget.

7.2 MANUFACTURING COSTS

To analyze the costs associated with a production run of ten vehicles a month for three years, the team first considered the labor costs required for vehicle construction. The labor costs for the vehicle include the positions of a machinist/welder, composite tech, general labor, and a manager. These labor costs can be seen in Table 7.8 below.

Table 7.8-Labor Costs

Title	**Number of People**	**Cost per person per hr**	**Hours per Vehicle**	**Total Cost per vehicle**	**Total Cost**
Machinist/Welder	3	$16.00	90	$1,440.00	$518,400.00
Composite Tech	2	$14.00	20	$280.00	$100,800.00
General Labor	4	$10.00	20	$200.00	$72,000.00
Manager	1	$20.00	30	$600.00	$216,000.00
Totals	**10**	**$60.00**	**160**	**$2,520.00**	**$907,200.00**

The team then considered the capital costs for machinery and tooling required for vehicle construction. These capital costs cover the initial cost of each piece of machinery needed as well as tooling costs to represent consumables needed for construction. The detailed breakdown of costs can be seen below in Table 7.9.

Table 7.9-Capital Costs

Tools	**Price**	**Quantity**	**Total**
Milling Machine	$9,999.00	2	$19,998.00
Lathe	$6,999.00	2	$13,998.00
CNC 4 Axis Machine	$26,789.99	1	$26,789.99
Sander	$399.99	2	$799.98
Drill Press	$569.99	2	$1,139.98
Grinders	$199.99	4	$799.96
Tig Welder	$7,837.00	2	$15,674.00
Sheet Metal Shear	$2,195.99	1	$2,195.99
Sheet Metal Break	$799.99	1	$799.99
Welding Tanks	$230.00	2	$460.00
Power Notcher	$2,995.99	1	$2,995.99
Powered Pipe Bender	$4,959.00	1	$4,959.00
Hydraulic Press	$399.99	1	$399.99
Horizontal Band Saw	$1,229.90	1	$1,229.90
Vertical Band saw	$1,999.99	1	$1,999.99
Bench	$549.99	4	$2,199.96
Welding Bench	$6,999.99	1	$6,999.99
Vacuum Pump	$1,219.95	2	$2,439.90
Fittings and Hoses	$500.00	1	$500.00
Air Compressor	$1,299.99	1	$1,299.99
3D printer	$57,899.99	1	$57,899.99
Tool Box	$2,103.97	2	$4,207.94
General Tooling	$20,000.00	1	$20,000.00
		Overall Total	**$189,788.53**

7.3 PRODUCTION COST

Along with the manufacturing costs, the team also calculated the overhead costs needed for the vehicle’s production. These included the rental of a building with appropriate capabilities and the utility costs for running the machines. These costs can be seen in Table 7.10 below.

Table 7.10-Overhead Costs

Overhead	**Cost per month**	**Yearly Cost**	**Overall Cost**
Building Rental	$1,000.00	$12,000.00	$36,000.00
Utilities	$500.00	$6,000.00	$18,000.00
Total	**$1,500.00**	**$18,000.00**	**$54,000.00**

Using the bill of materials costs created for this vehicle design, the capital costs of equipment and tooling, as well as labor and overhead costs, the team was able to predict the cost of a production run for the design. The cost to produce ten vehicles a month for three years, 360 vehicles total, was $3,305,566.93. The details can be seen below in Table 7.11.

Table 7.11-Total Costs

Costs	Total
Capital	$189,788.53
Labor	$907,200.00
Overhead	$54,000.00
Materials	$2,154,578.40
Total	**$3,305,566.93**

8.0 CONCLUSIONS

Team 9 was tasked with designing a human powered vehicle that can function as an alternative form of transportation that provides the benefits of bicycle commuting while maintaining the practicality of an automobile. This project was commissioned by the faculty advisor of NAU's ASME student chapter, Perry Wood, who has been involved in numerous human powered vehicle projects throughout his time as an engineer.

Vehicles of various forms and structures were considered, ultimately Team 9 chose to move forward with a recumbent position tadpole trike; a three wheeled design with two wheels in the front and one in the rear. Tadpole trikes are propelled with the use of a drivetrain that transfers rotational energy from the human operator's legs to forward movement at the ground. A drivetrain of traditional bicycle components makes the vehicle easily serviceable and minimizes the requirement of proprietary parts. An aluminum alloy frame was developed to carry the load of the occupant and protect the rider in the event of a rollover. This frame and drivetrain, in combination with an adjustable steering system, allow the vehicle to be safely operated from zero to 40 MPH, with skilled drivers capable of even higher speeds. In order to achieve these maximum speeds with a human power source, a streamlined, low drag fairing was designed to encompass the entire vehicle and operator. This shell is the result of over 15 iterations evaluated and optimized with computational fluid dynamics. The inclusion of this low drag shell gave this human powered vehicle aerodynamic forces one-fifth of those experienced on a traditional cyclist. A remote controlled air circulation system is integrated into the shell to keep operators comfortable in a variety of climate conditions. The reclined position of the operator was optimized through data collection experiments with the intention of placing occupants in a comfortable orientation without sacrificing power output. This was achieved with the use of a stationary power output monitoring fixture developed by Team 9. The prototype vehicle's total cost of development was $6000. However, projections for a multiyear production run were also calculated at 3.3 million dollars for a run of 360 vehicles during a three year span.

The vehicle's construction began in January of 2014 and was completed in April 2014. The designed vehicle had its performance as a traffic worthy vehicle evaluated and road tested at the Human Powered Vehicle Challenge (HPVC) hosted by the American Society of Mechanical Engineers (ASME). The vehicle successfully illustrated its superior design by placing 2nd overall in the international competition. Awards were presented to the design team for the vehicle's innovative reverse mechanism, its thorough overall design, and the vehicle performance in high speed and long distance tests.

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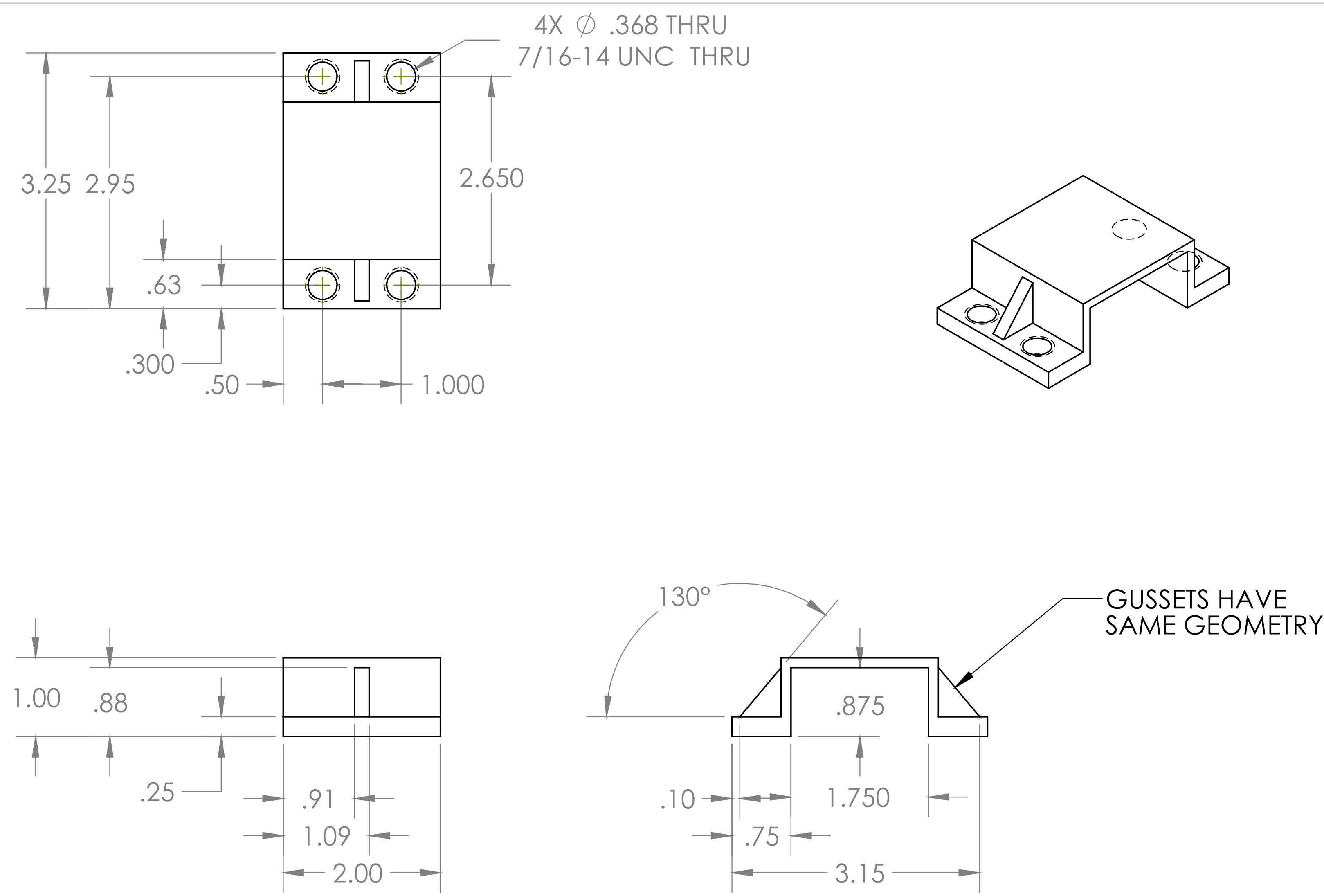
ENGINEERING DRAWINGS



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

TITLE:
BOTTOM BRACKET BACK

SIZE
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DATE DRAWN
12/12/2013

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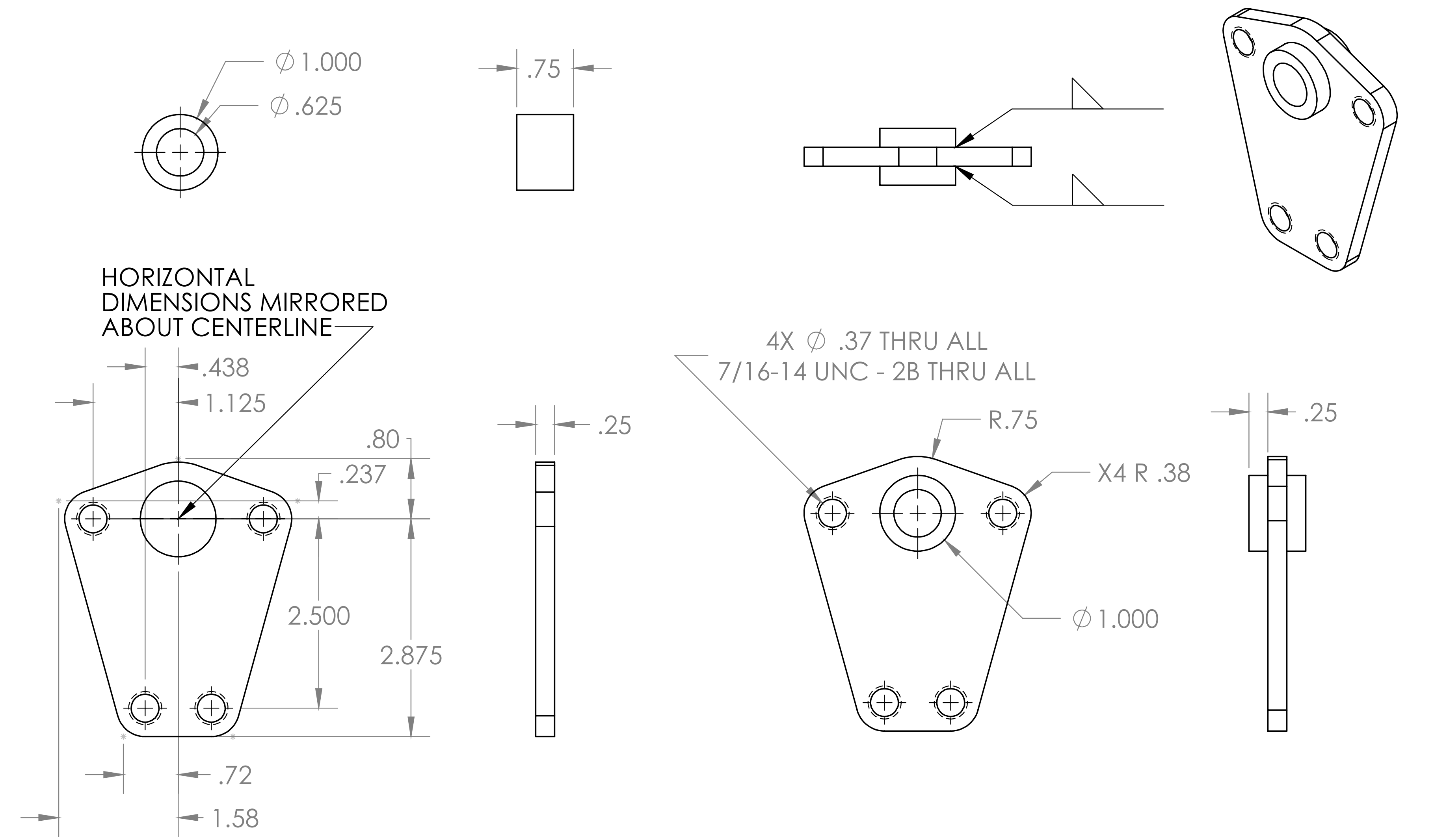

TEAM 9 HUMAN POWERED VEHICLE CHALLENGE			
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS: MAIN BODY WILL BE INPUT INTO CAMWORKS FOR G-CODE GENERATION	DRAWN BY: ALEX HAWLEY	
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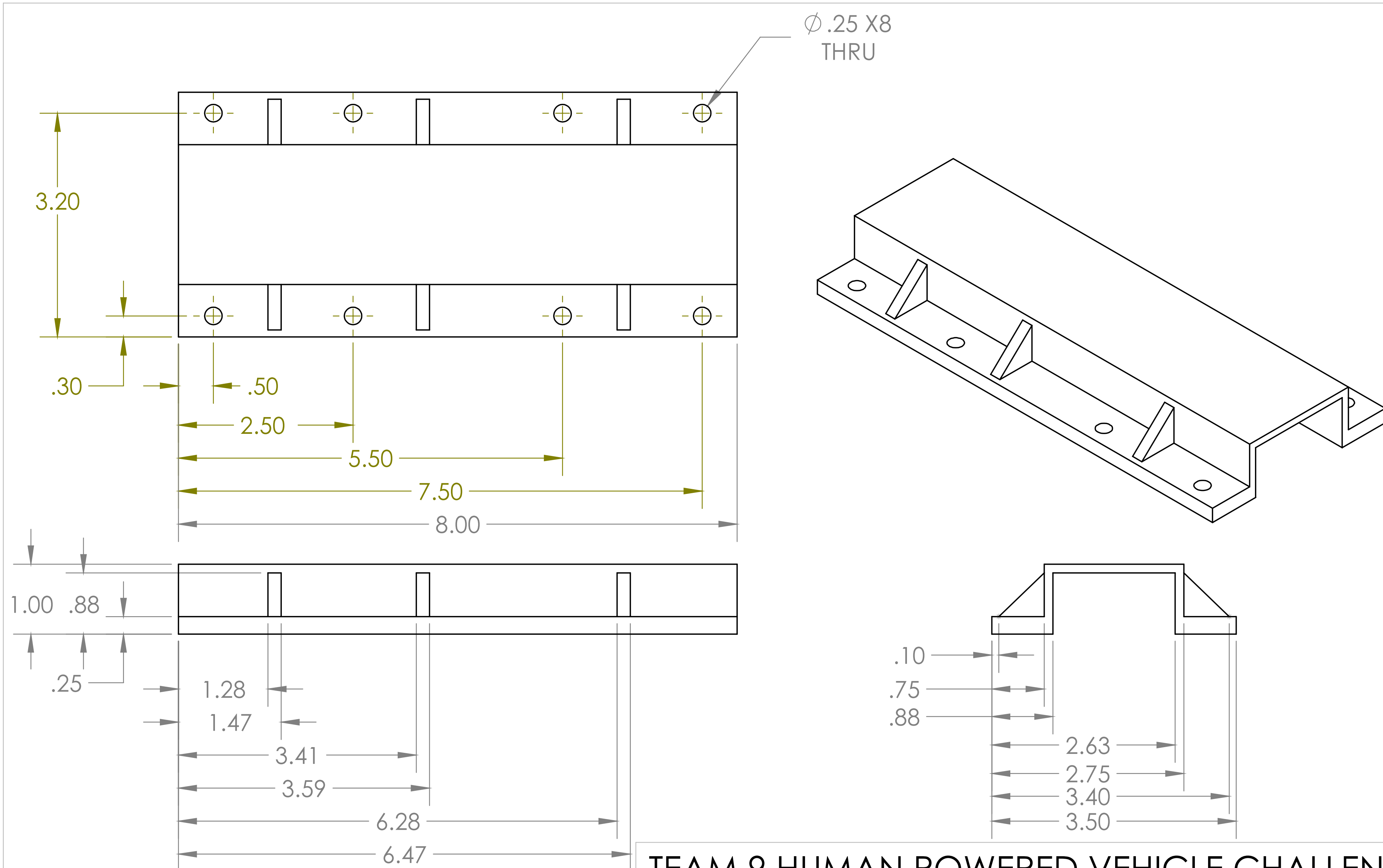
SolidWorks Student Edition.
For Academic Use Only.



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
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GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

TITLE:
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SIZE A | DATE DRAWN 12/12/2013

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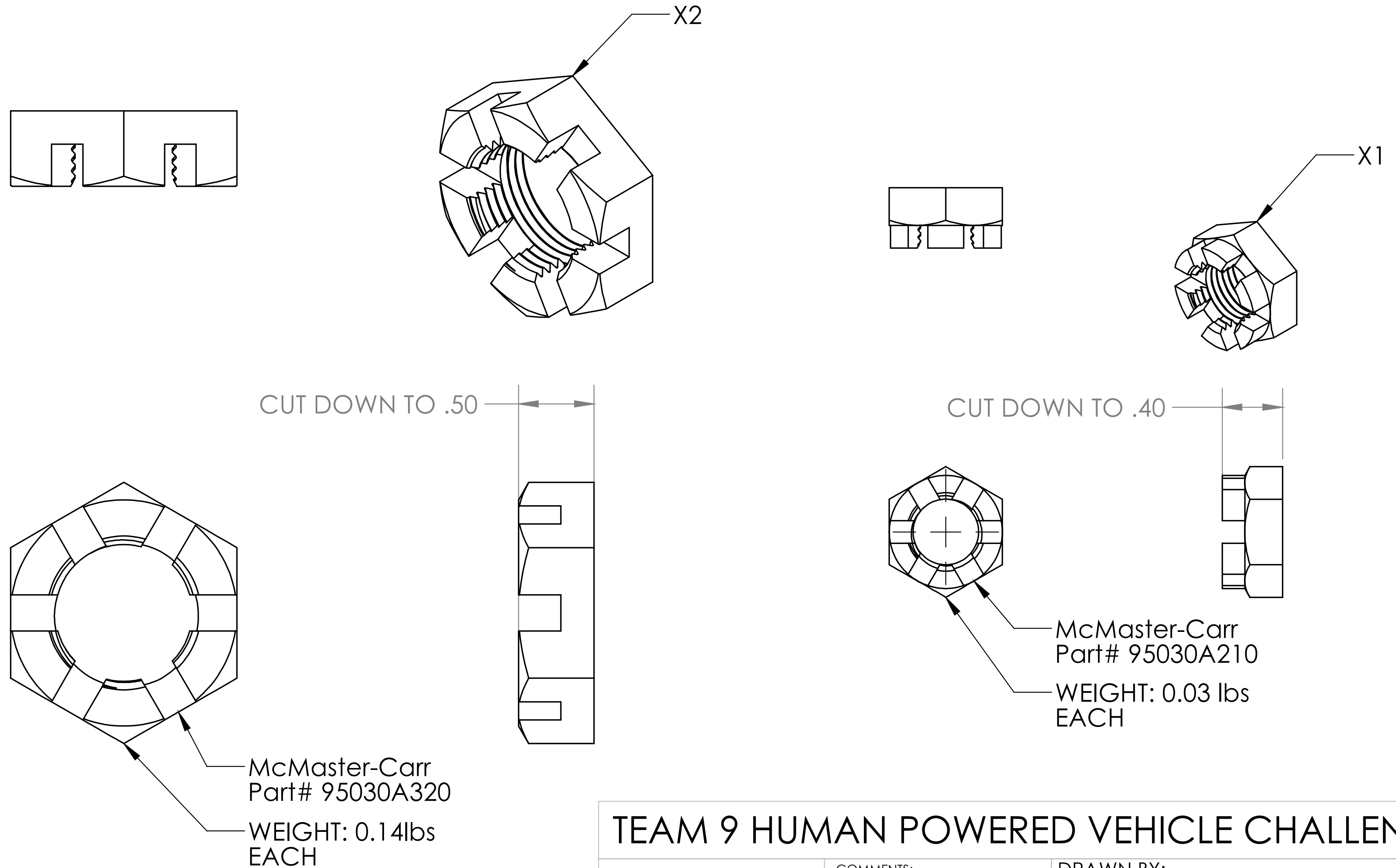

TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
Zinc-Plated Grade 2 Steel

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

TITLE:
CASTLE NUTS

SIZE
A

DATE DRAWN
12/12/2013

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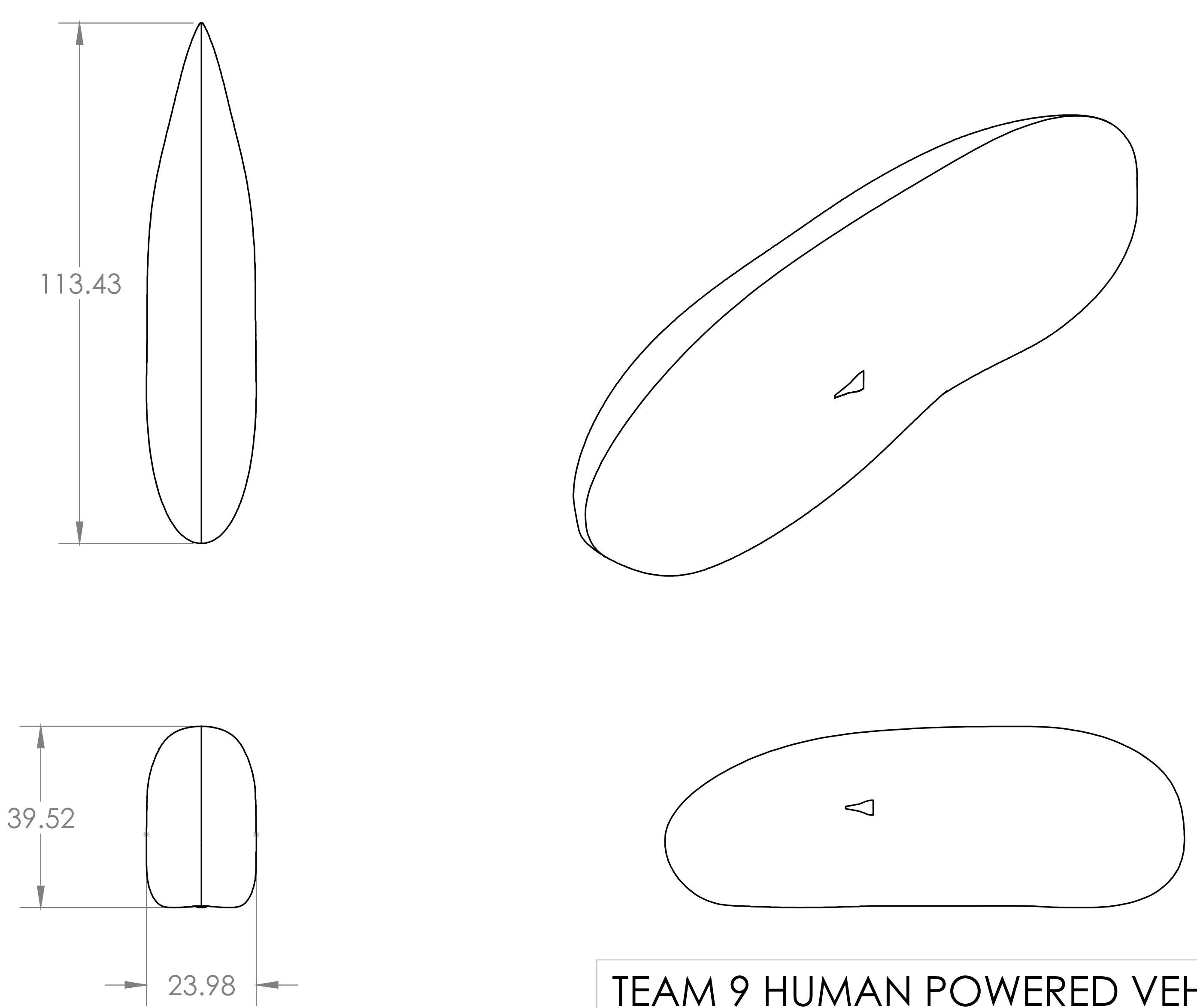

TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

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GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

COMMENTS:

DRAWN BY: KEVIN MONTOYA

TITLE: FAIRING

MATERIAL: Carbon Fiber 2X2 3K

FINISH

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DATE DRAWN: 12/12/2013

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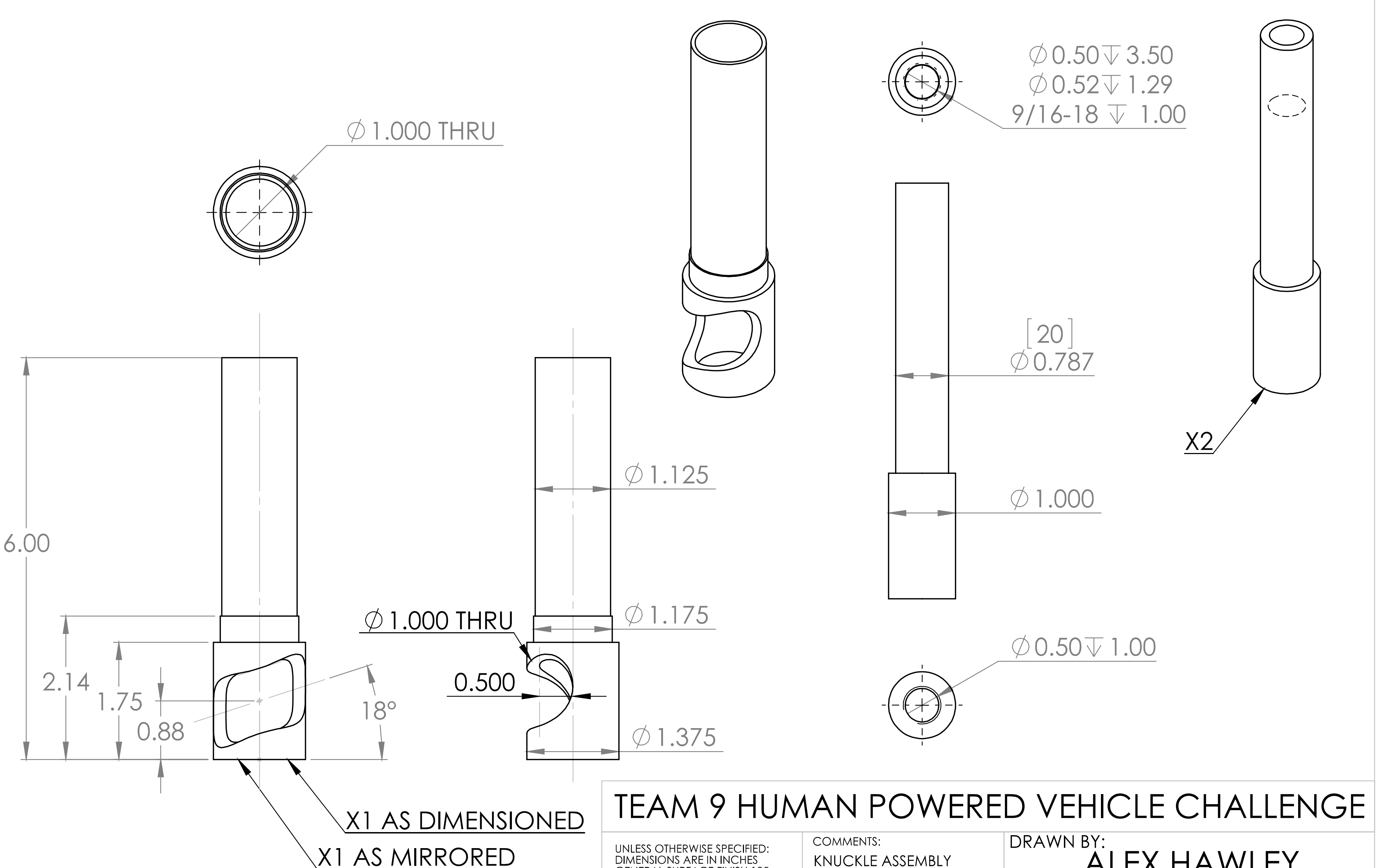

TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
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GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:
KNUCKLE ASSEMBLY

DO NOT SCALE DRAWING

DRAWN BY:
ALEX HAWLEY

TITLE:
KNUCKLES

SIZE
A

DATE DRAWN
12/12/2013

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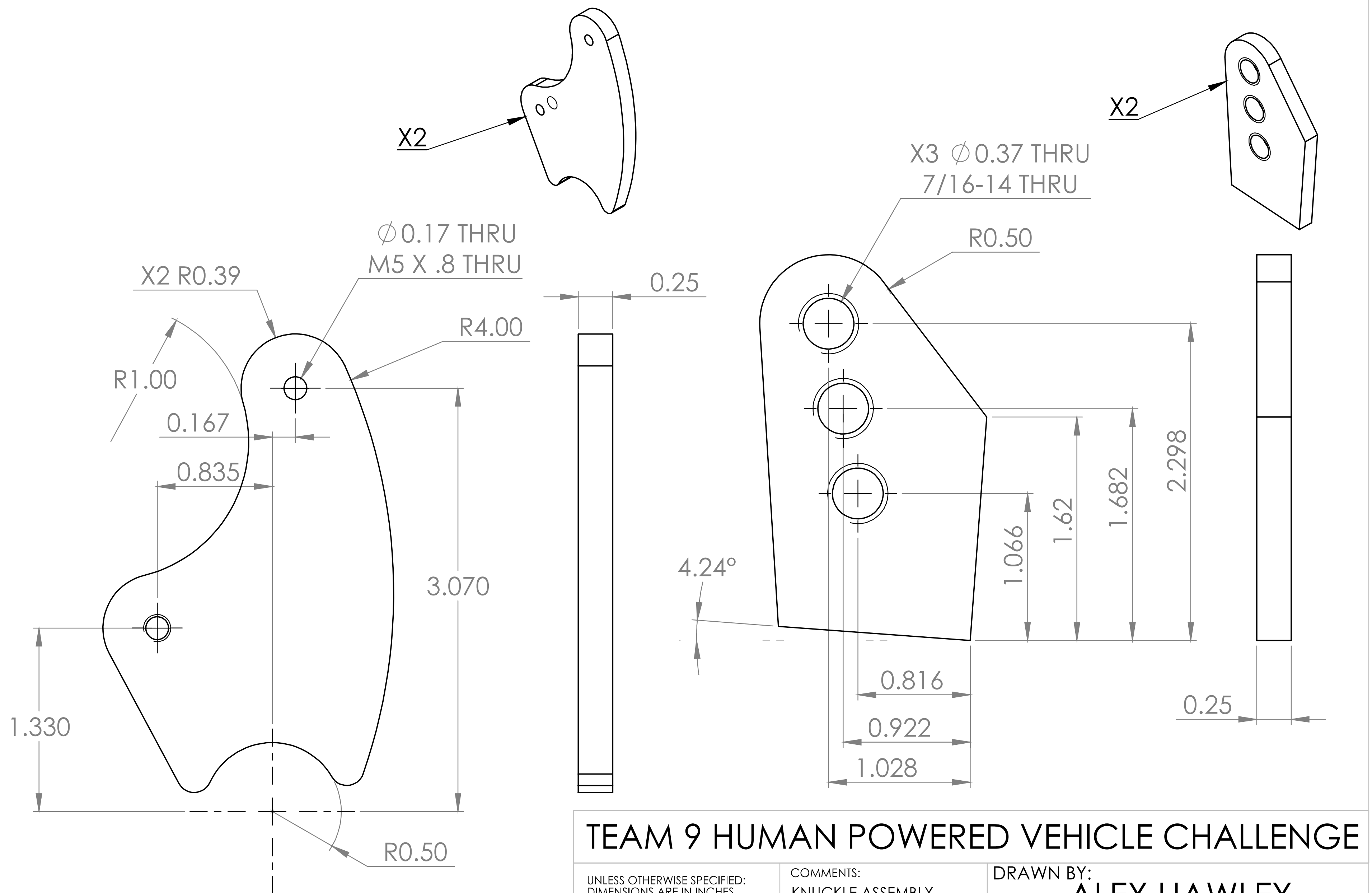

TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS: KNUCKLE ASSEMBLY	DRAWN BY: ALEX HAWLEY
		TITLE: KNUCKLES
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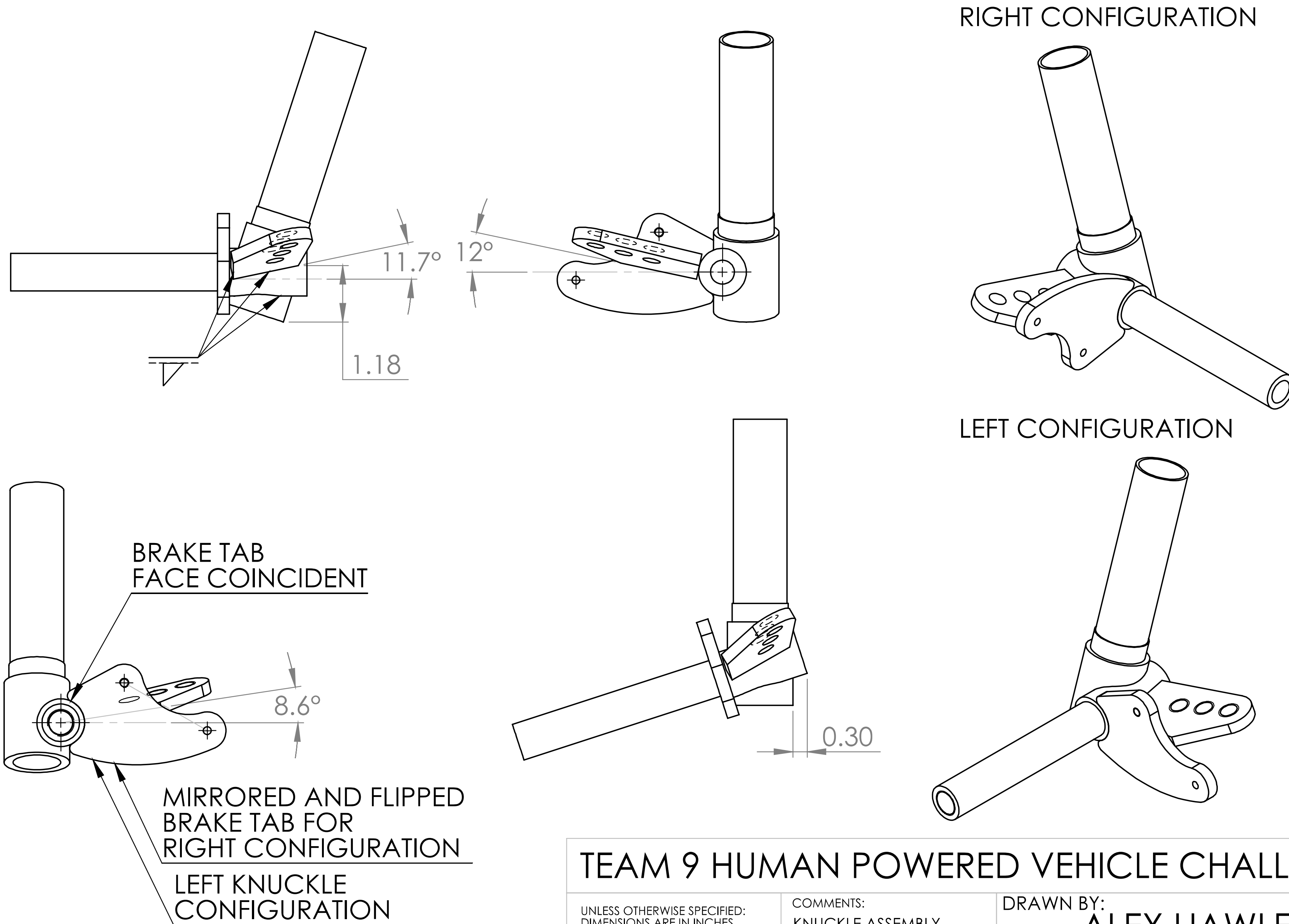

TEAM 9 HUMAN POWERED VEHICLE CHALLENGE			
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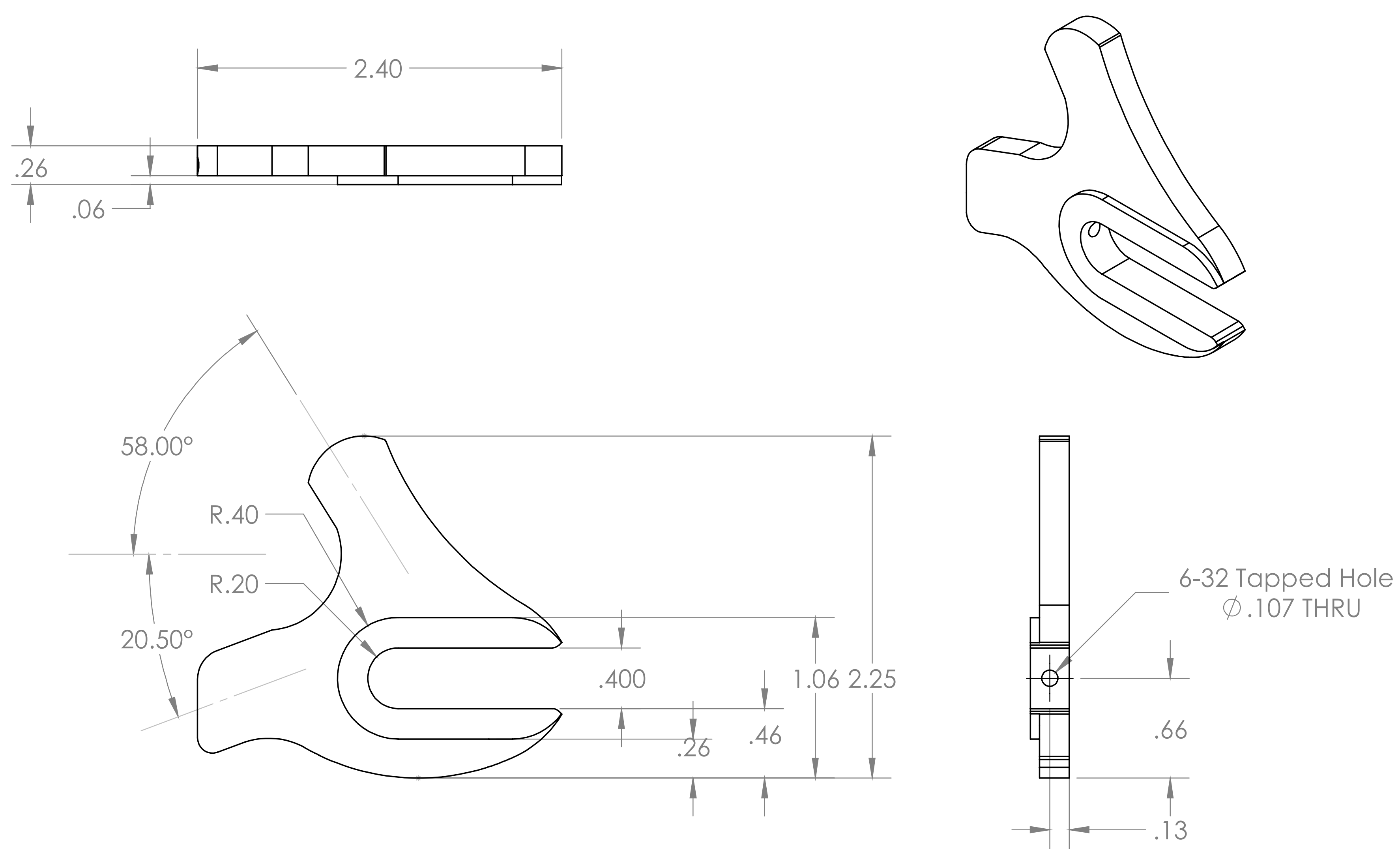

TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:
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DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

TITLE:
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SIZE
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DATE DRAWN
12/12/2013

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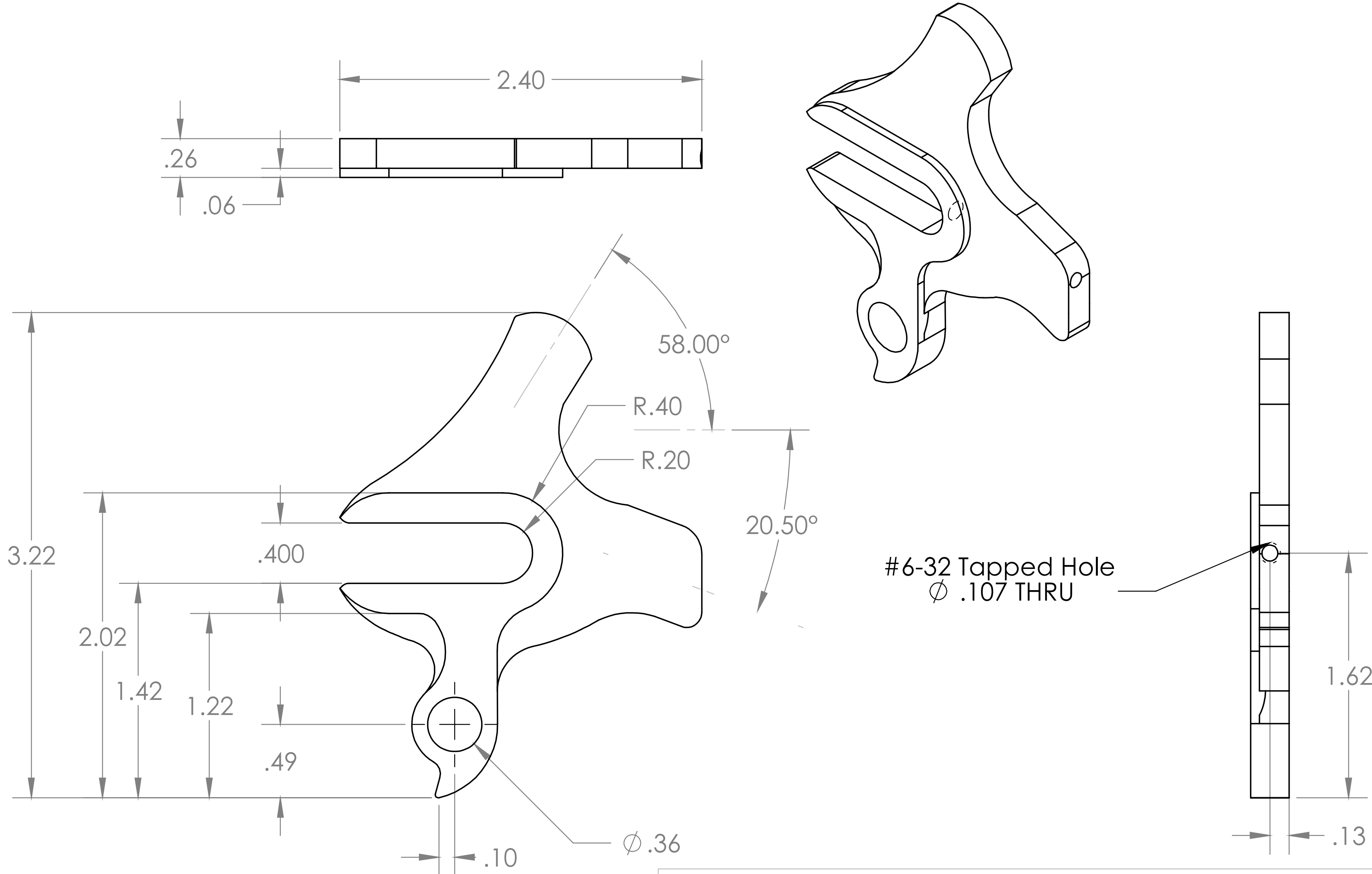


TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:
This part will be machinced in a CNC machine. The code will be produced with a program called CAMWORKS.

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

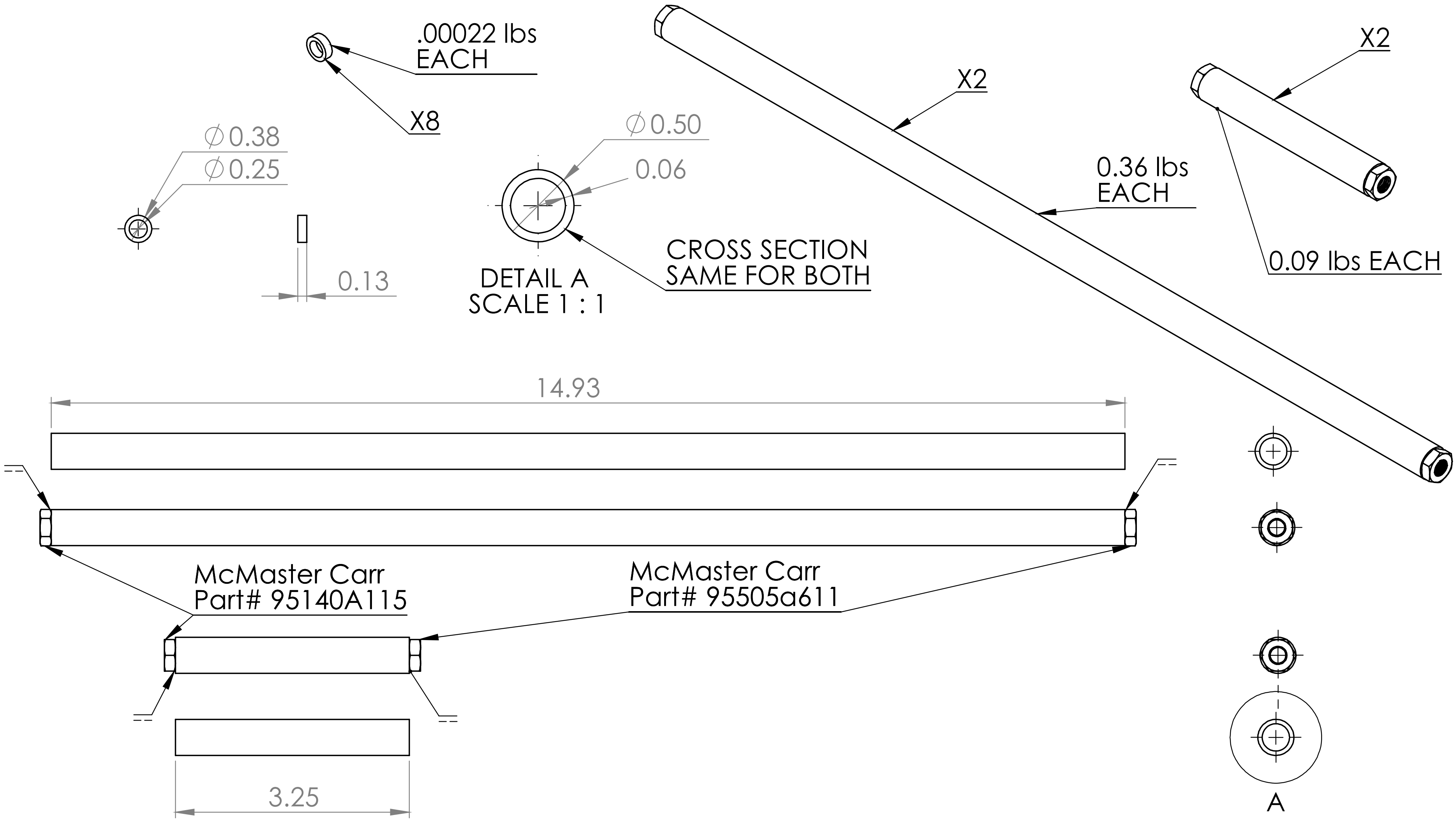
TITLE:
RIGHT DROPOUT

SIZE
A

DATE DRAWN
12/12/2013

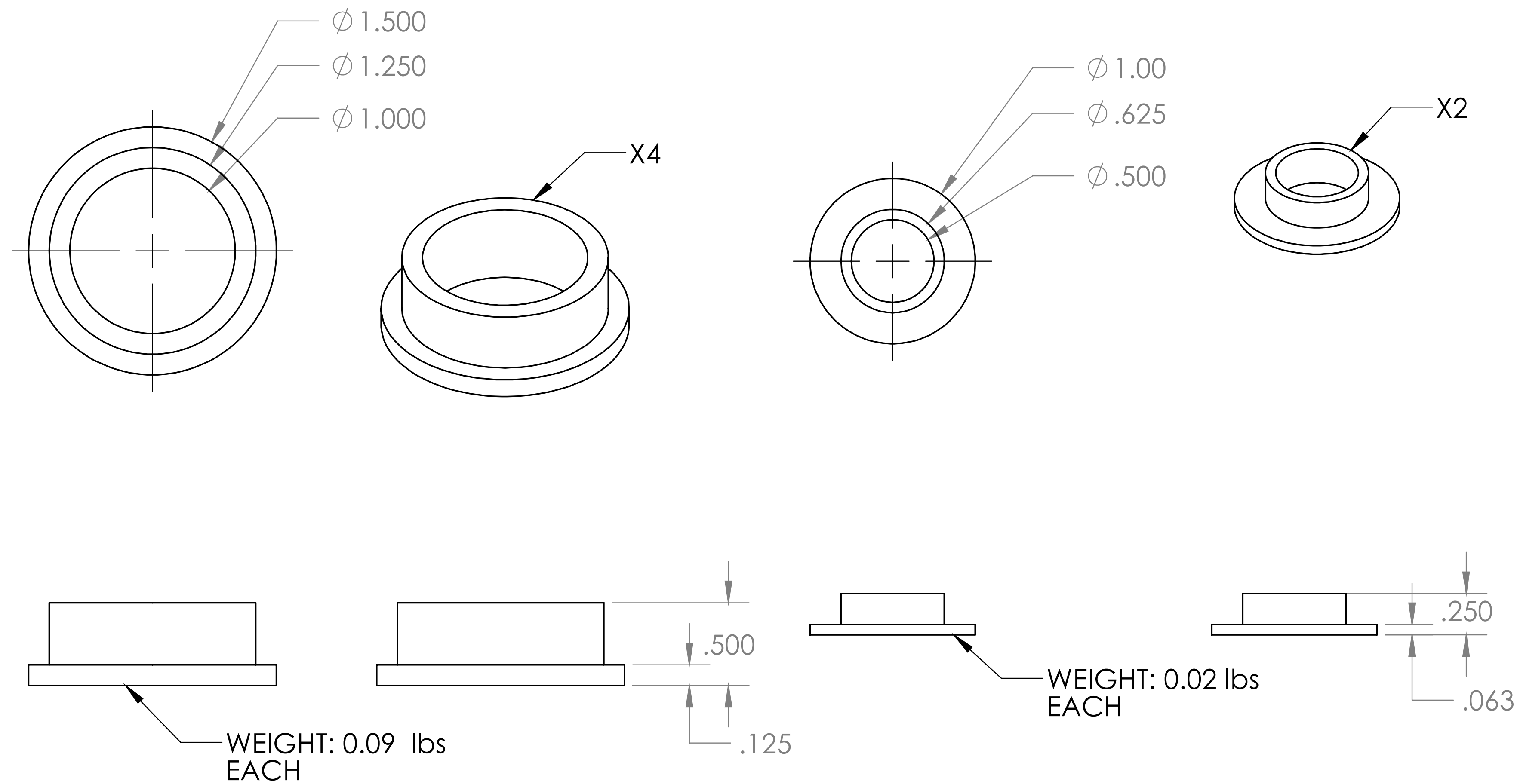
SCALE: 1:1 | WEIGHT: 0.06 lbs | SHEET 1 OF 1

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE			
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: ALEX HAWLEY	
		TITLE: Linkages and Spacers	
MATERIAL 4130 CHROMOLY		SIZE A	DATE DRAWN 12/10/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: 0.46 lbs SHEET 1 OF 1

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
Bronze (Alloy 936)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

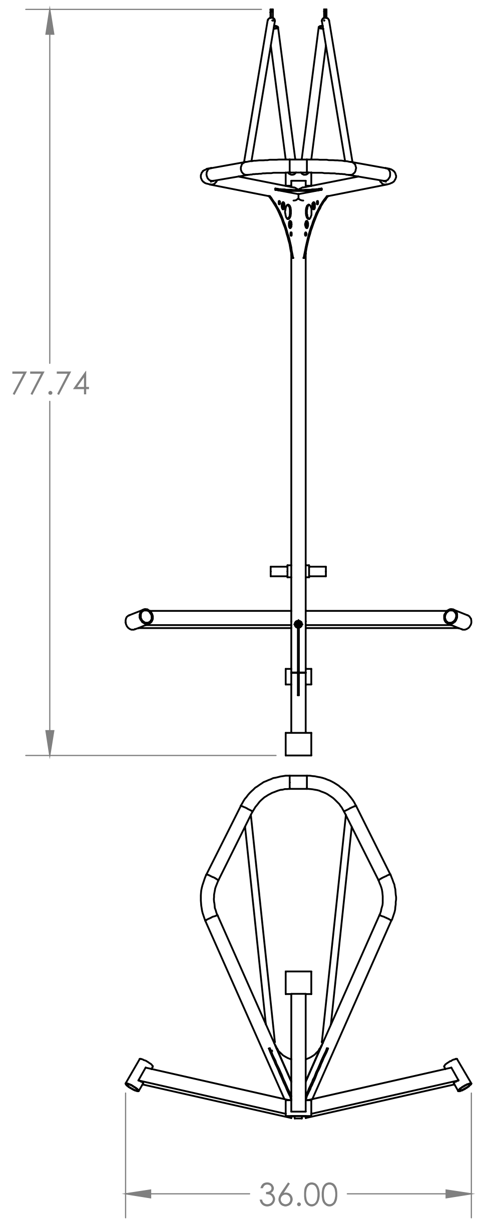
TITLE:
STEERING BUSHINGS

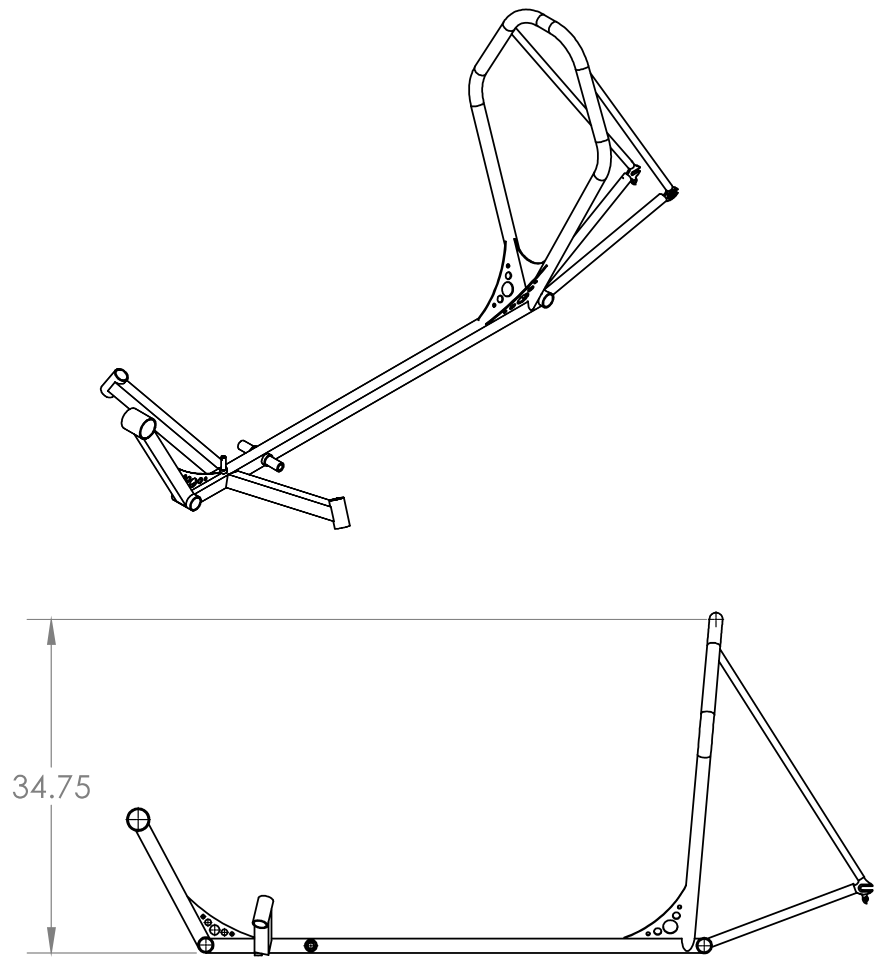
SIZE
A

DATE DRAWN
12/12/2013

SCALE: 1:1 | WEIGHT: 0.4 lbs | SHEET 1 OF 1

5 4 3 2 1

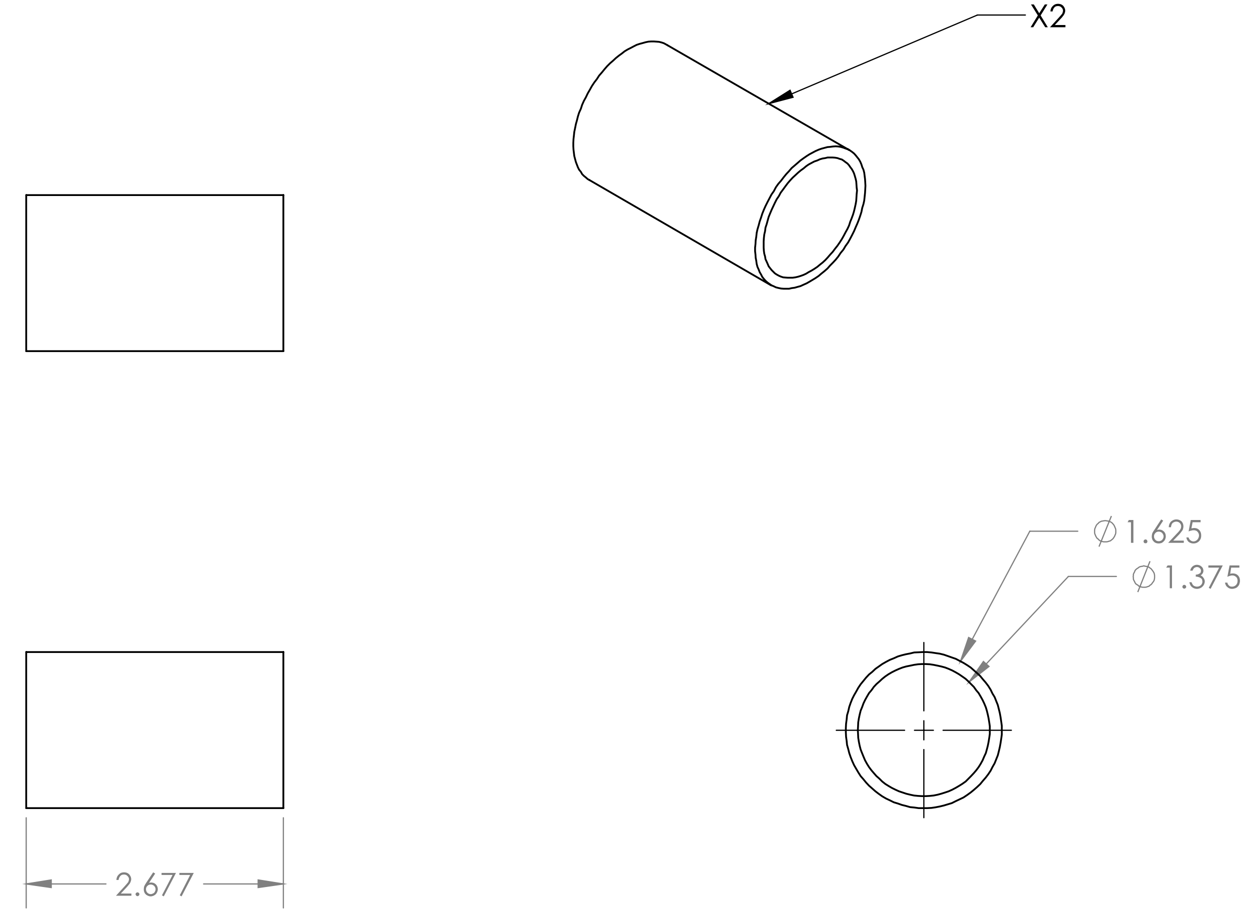




TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

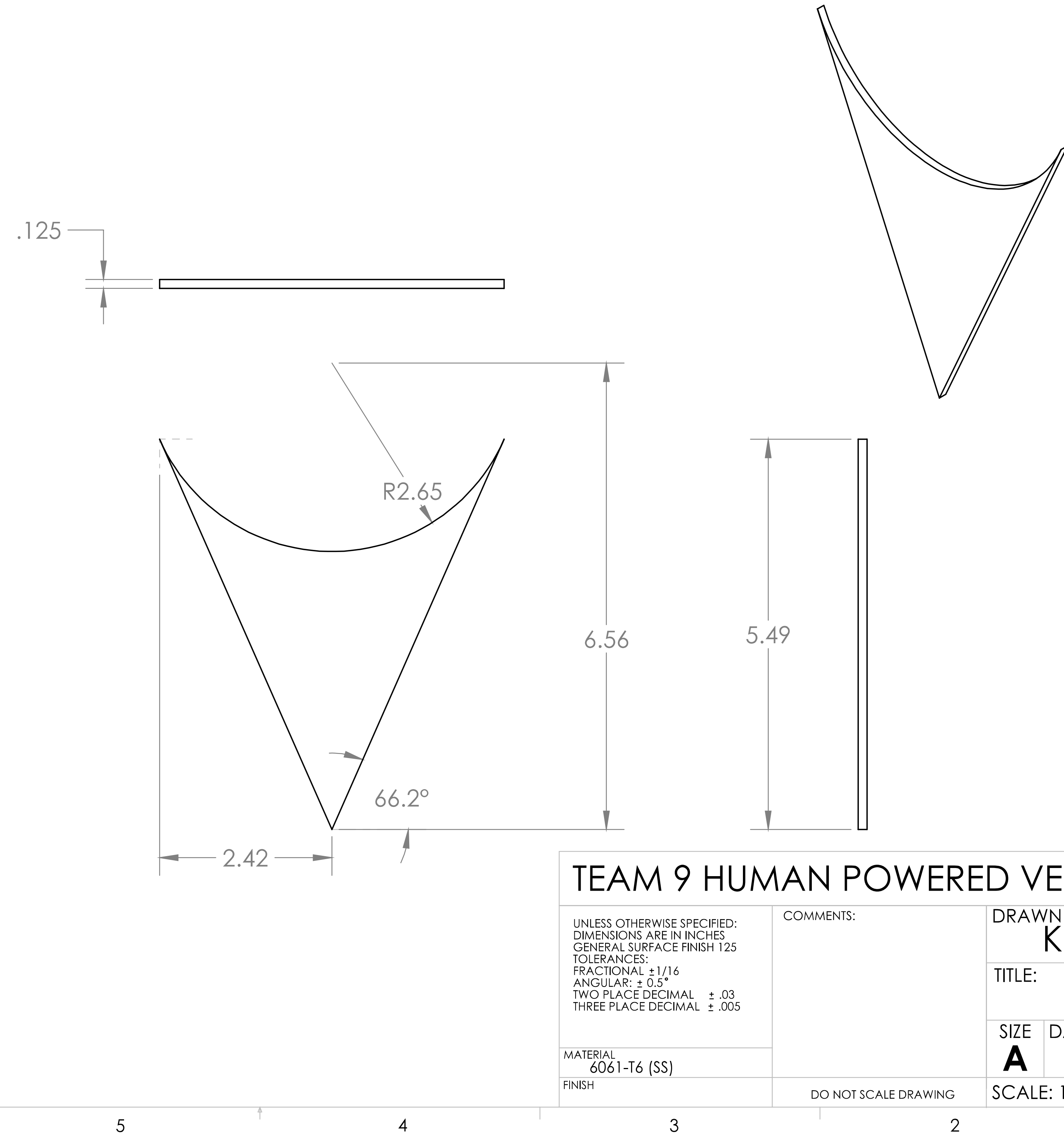
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS: Frame for 2013-2014 HPVC Capstone Designed and Created by Matt Gerlich Sketches completed by Kevin Montoya	DRAWN BY: KEVIN MONTOYA TITLE: FRAME SIZE A DATE DRAWN 12/12/2013
MATERIAL 6061-T6 (SS)		
FINISH	DO NOT SCALE DRAWING	SCALE: 1:20 | WEIGHT: 14.50 lbs | SHEET 1 OF 14

5 4 3 2 1

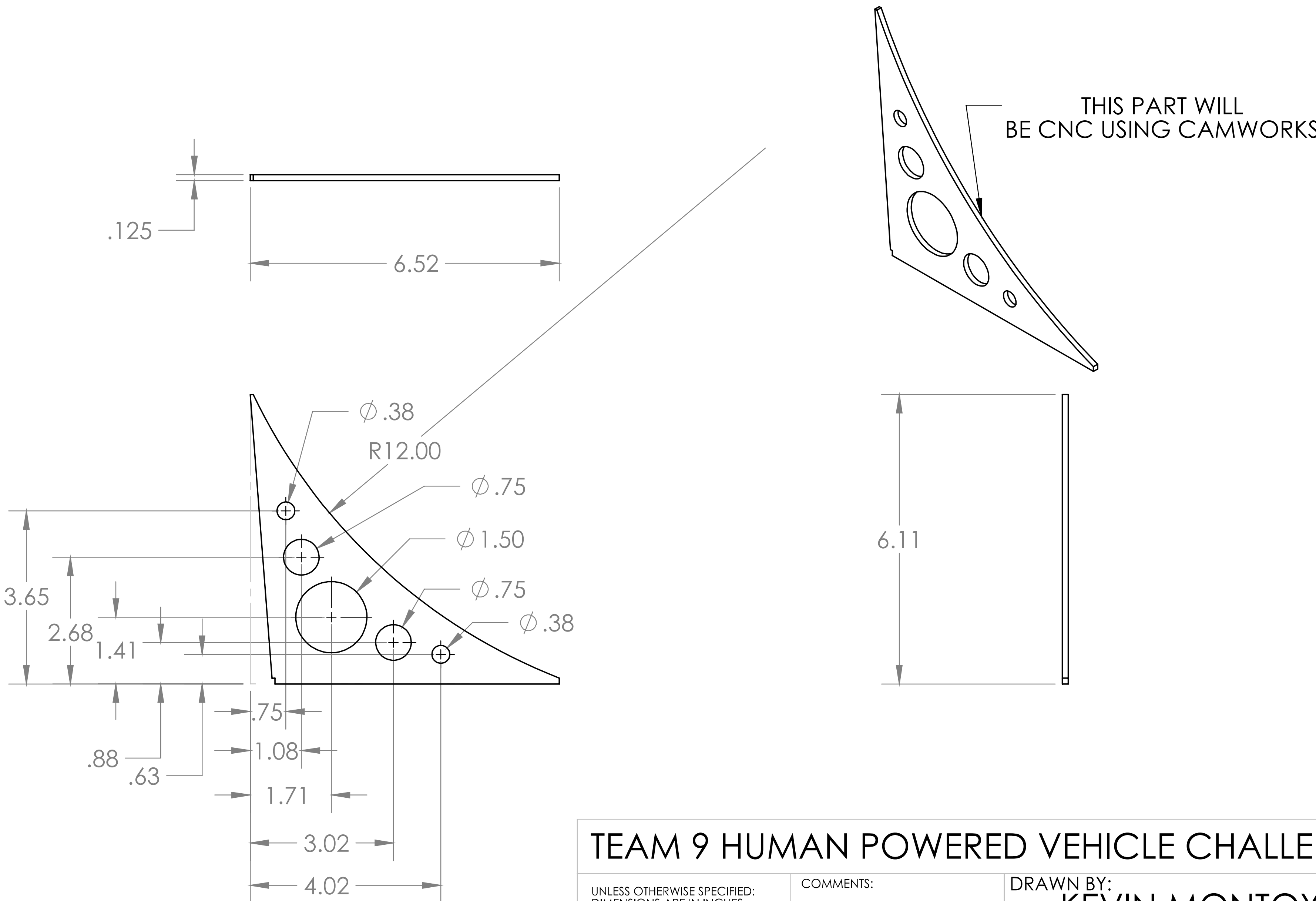


TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA		
		TITLE: FRAME		
MATERIAL 6061-T6 (SS)		SIZE A	DATE DRAWN 12/12/2013	
FINISH	DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: 14.50 lbs	SHEET 2 OF 14



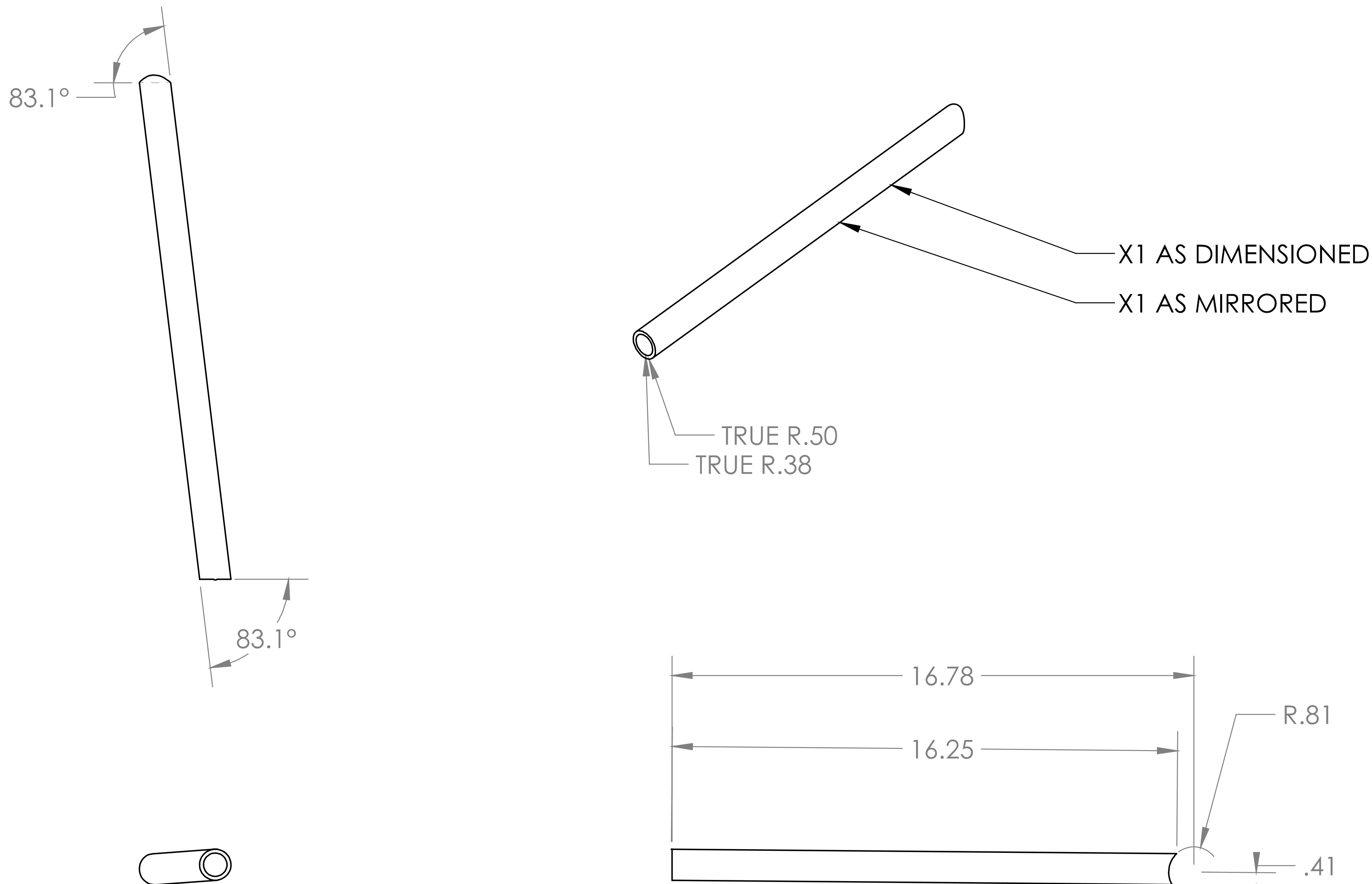
TEAM 9 HUMAN POWERED VEHICLE CHALLENGE			
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA	
		TITLE: FRAME	
MATERIAL 6061-T6 (SS)		SIZE A	DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: 14.50 lbs SHEET 3 OF 14



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA TITLE: FRAME SIZE A — DATE DRAWN 12/12/2013
MATERIAL 6061-T6 (SS)		
FINISH	DO NOT SCALE DRAWING	SCALE: 1:3 — WEIGHT: 14.50 lbs — SHEET 4 OF 14

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

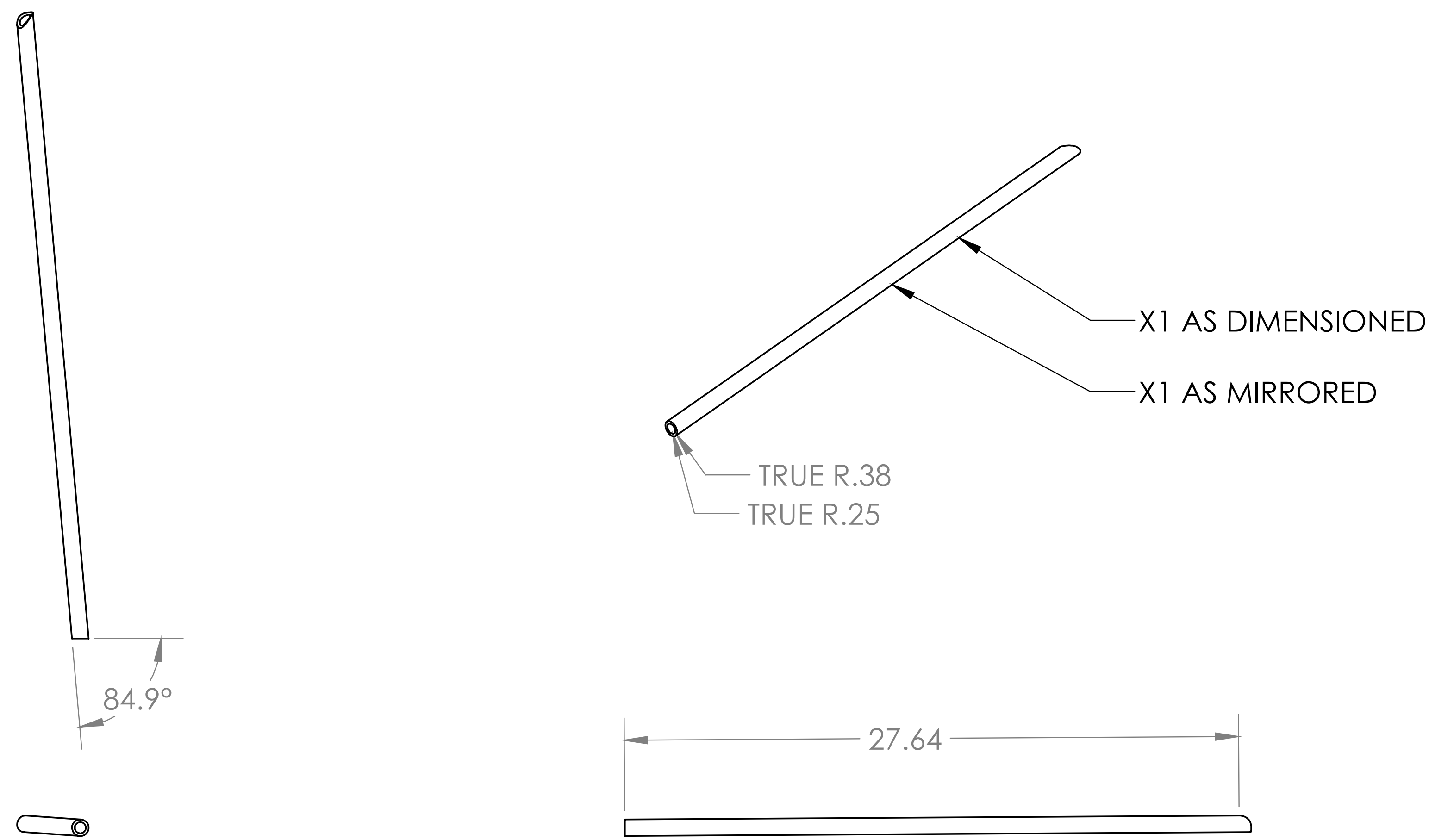
TITLE:
FRAME

SIZE
A

DATE DRAWN
12/12/2013

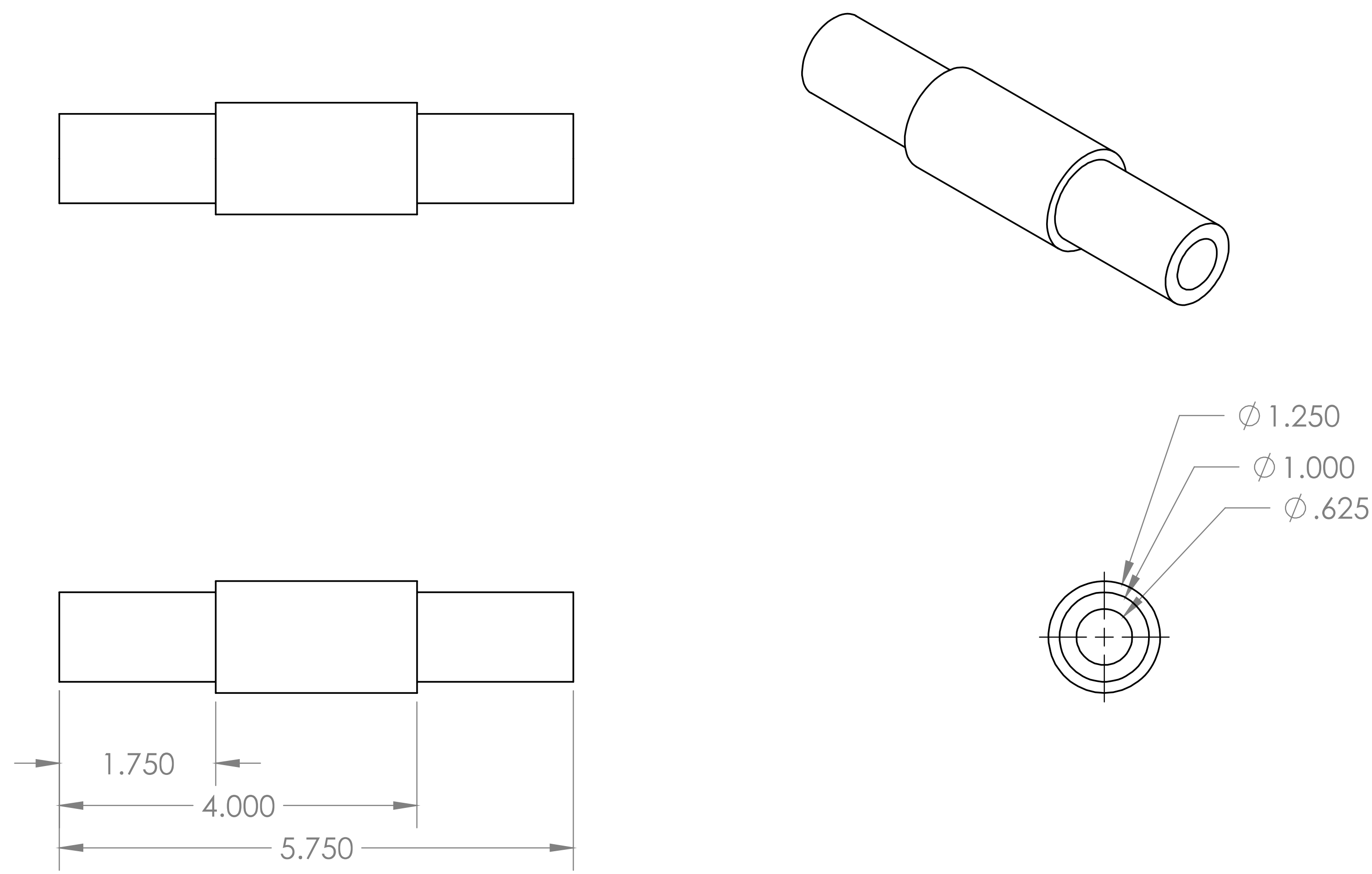
SCALE: 1:5 | WEIGHT: 14.50 lbs | SHEET 5 OF 14

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE				
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA		
		TITLE: FRAME		
MATERIAL 6061-T6 (SS)		SIZE A	DATE DRAWN 12/12/2013	
FINISH	DO NOT SCALE DRAWING	SCALE: 1:8	WEIGHT: 14.50 lbs	SHEET 6 OF 14

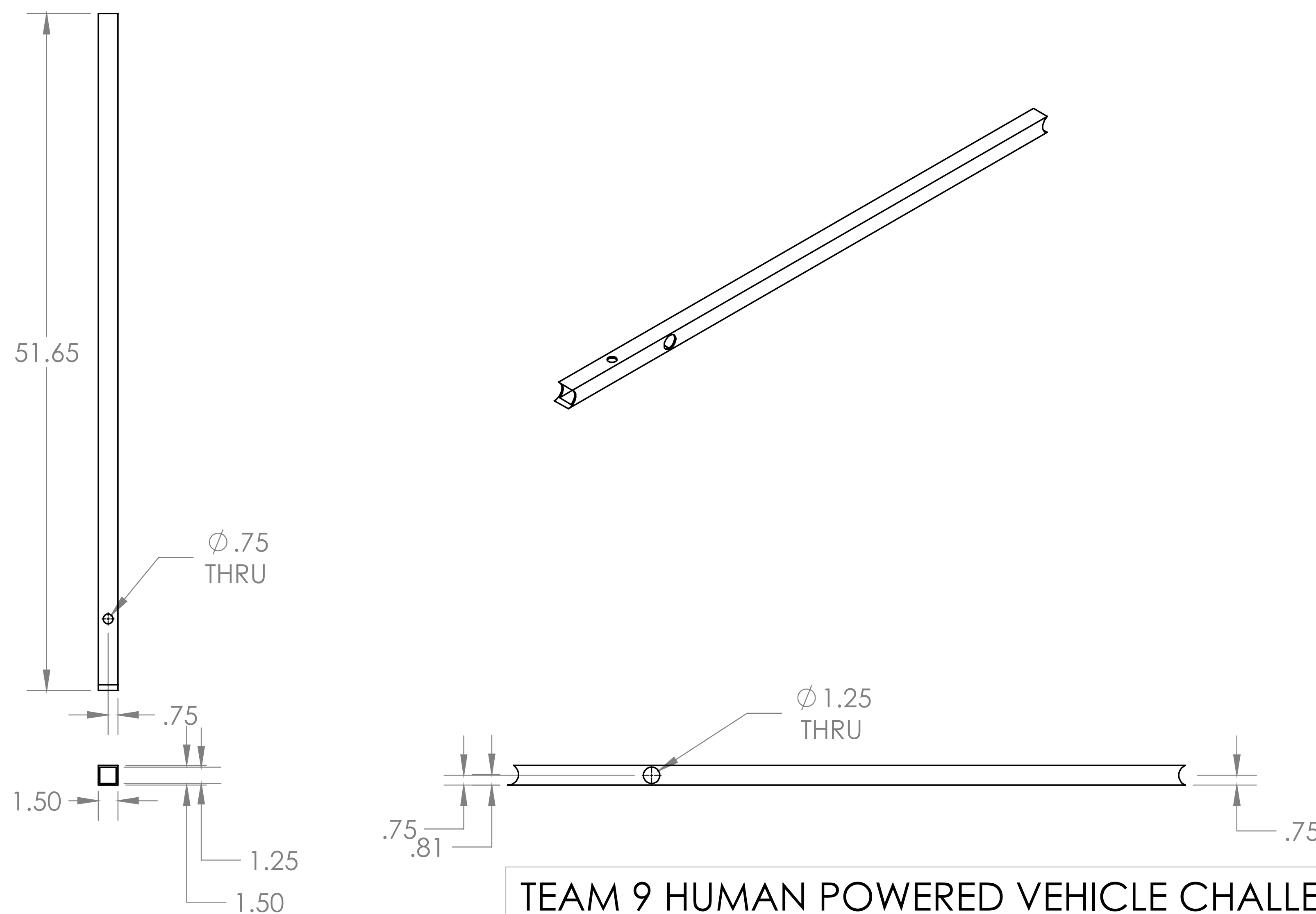
5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

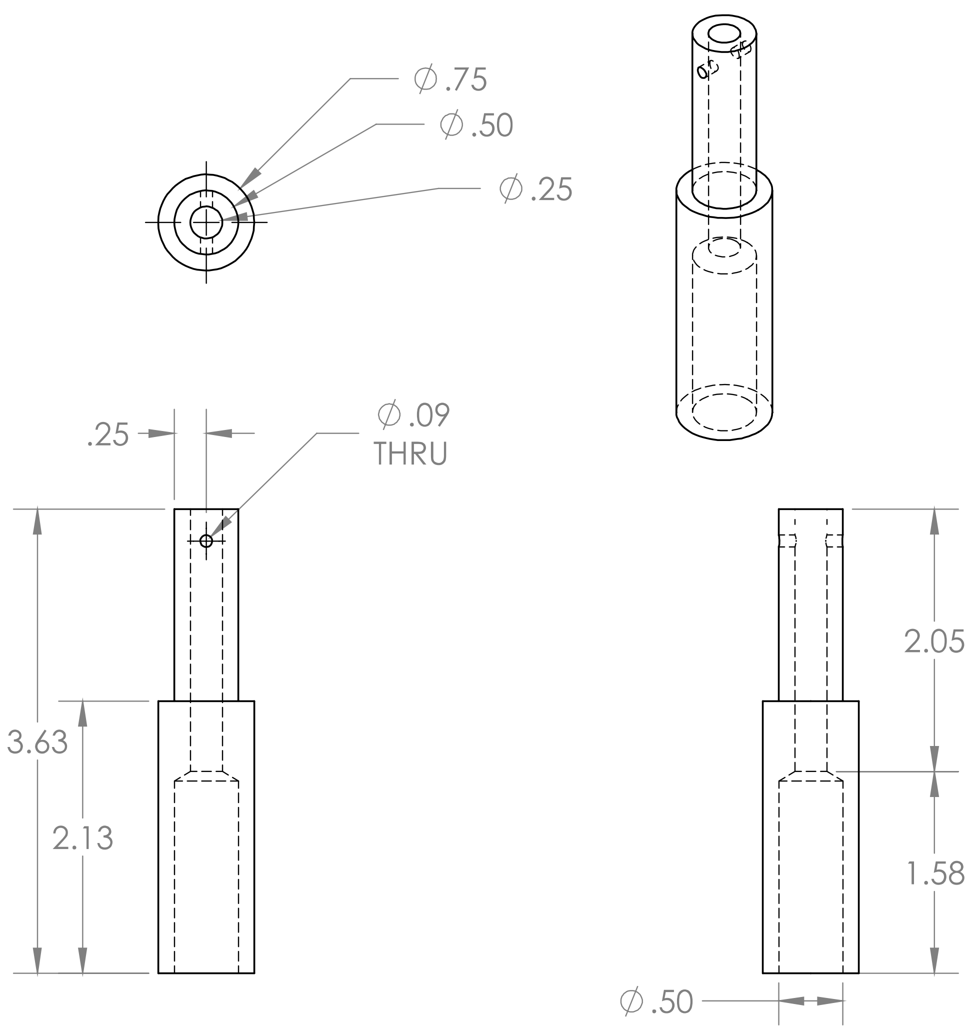
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA TITLE: FRAME
MATERIAL 6061-T6 (SS)		SIZE A / DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:2 / WEIGHT: 14.50 lbs / SHEET 7 OF 14

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE		
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA
		TITLE: FRAME
MATERIAL 6061-T6 (SS)		SIZE **A** DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:12 WEIGHT: 14.50 lbs SHEET 8 OF 14

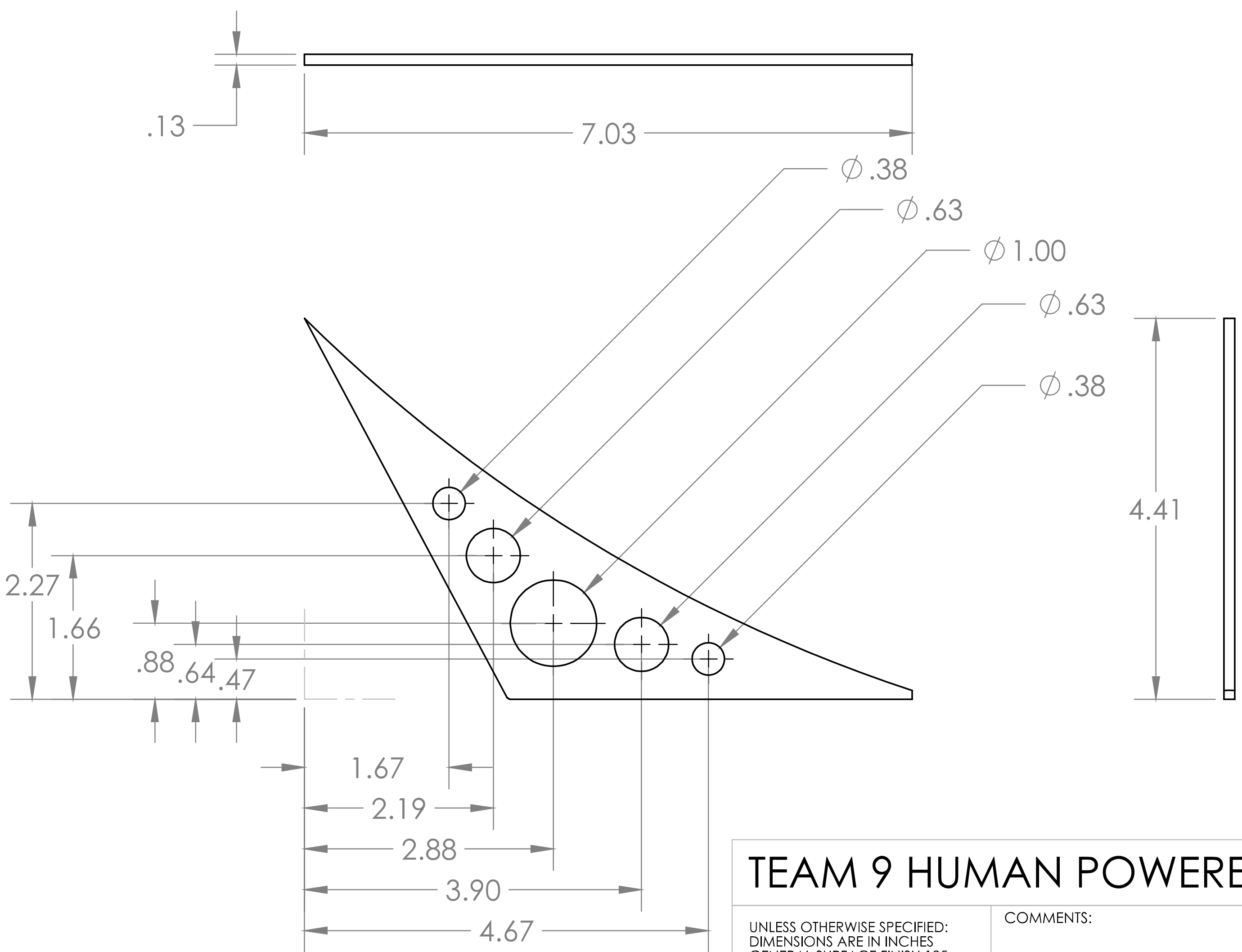
5 4 3 2 1

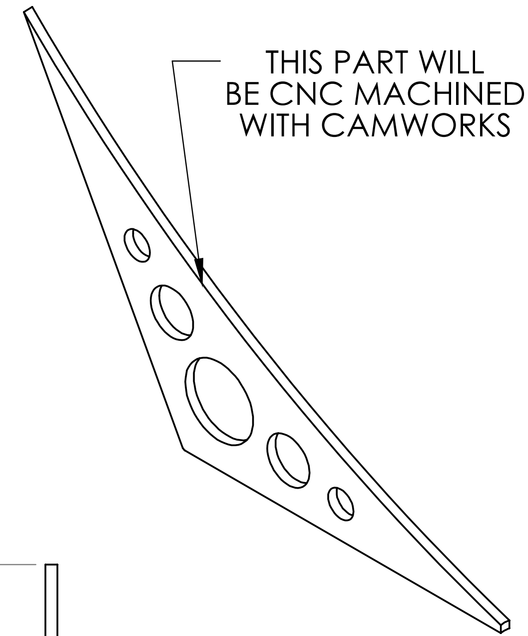


TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA TITLE: FRAME	
MATERIAL 6061-T6 (SS)		SIZE **A**	DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 2:3	WEIGHT: 14.50 lbs SHEET 9 OF 14

5 4 3 2 1





TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

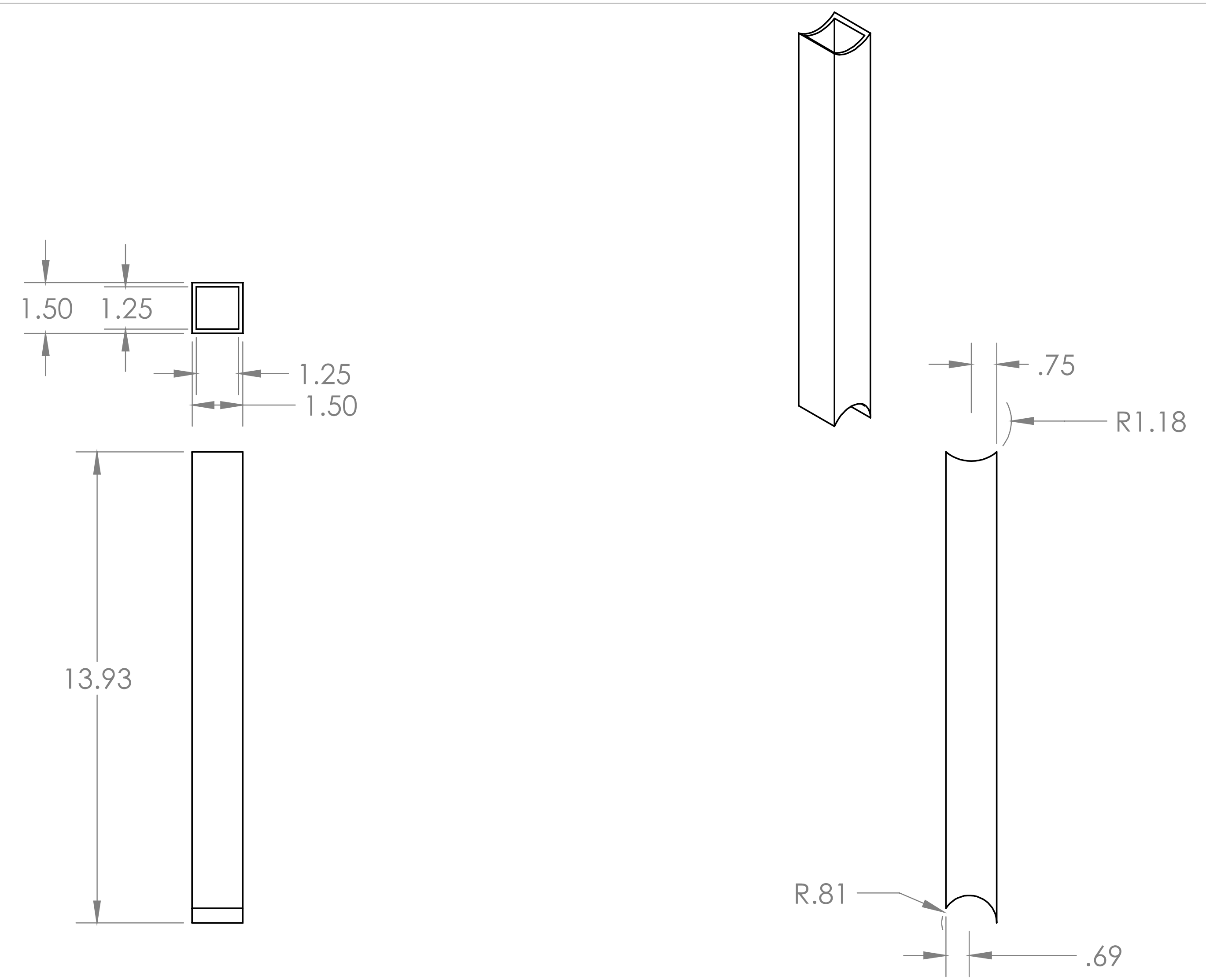
TITLE:
FRAME

SIZE
A

DATE DRAWN
12/12/2013

SCALE: 1:2 | WEIGHT: 14.50 lbs | SHEET 10 OF 14

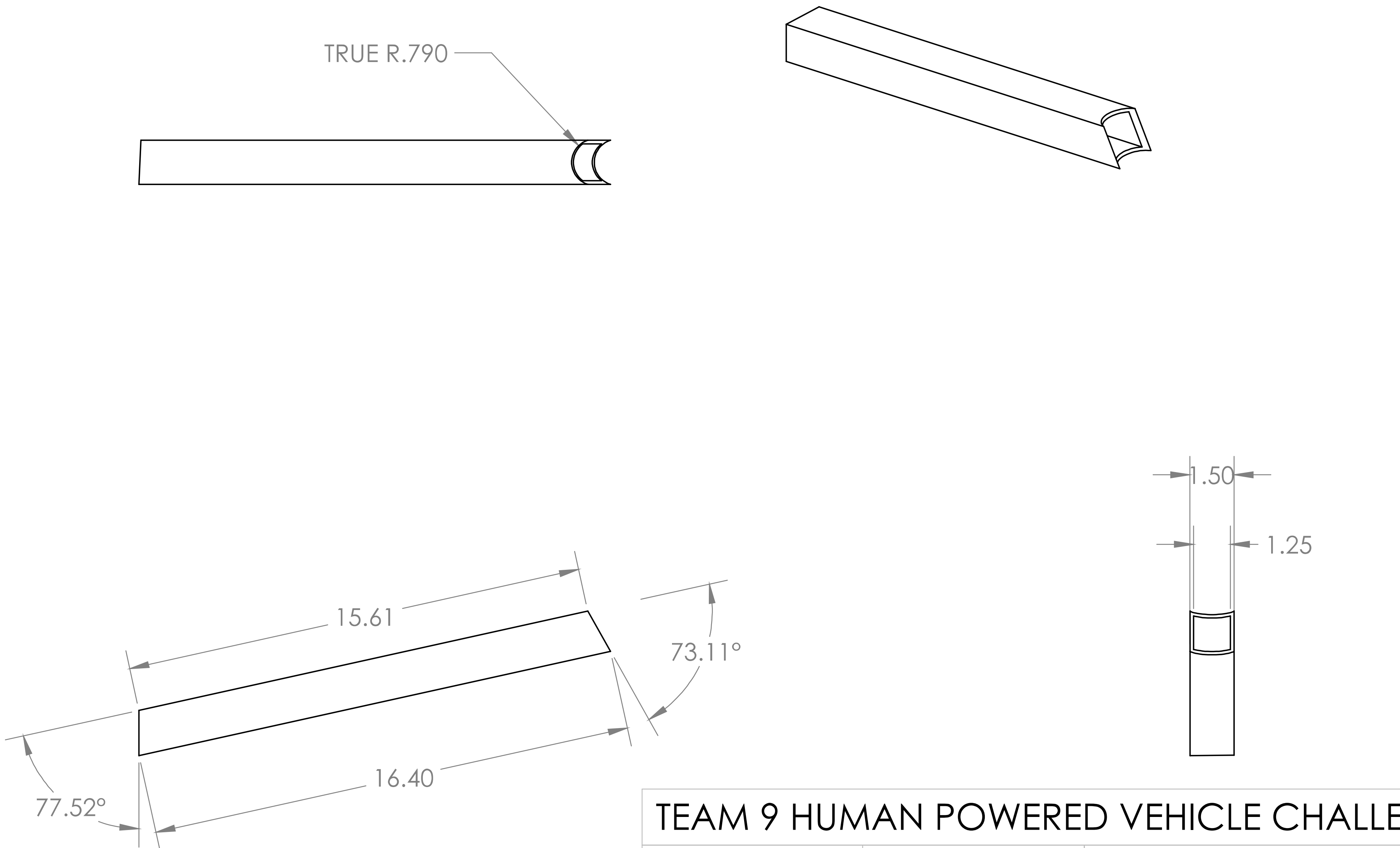
5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

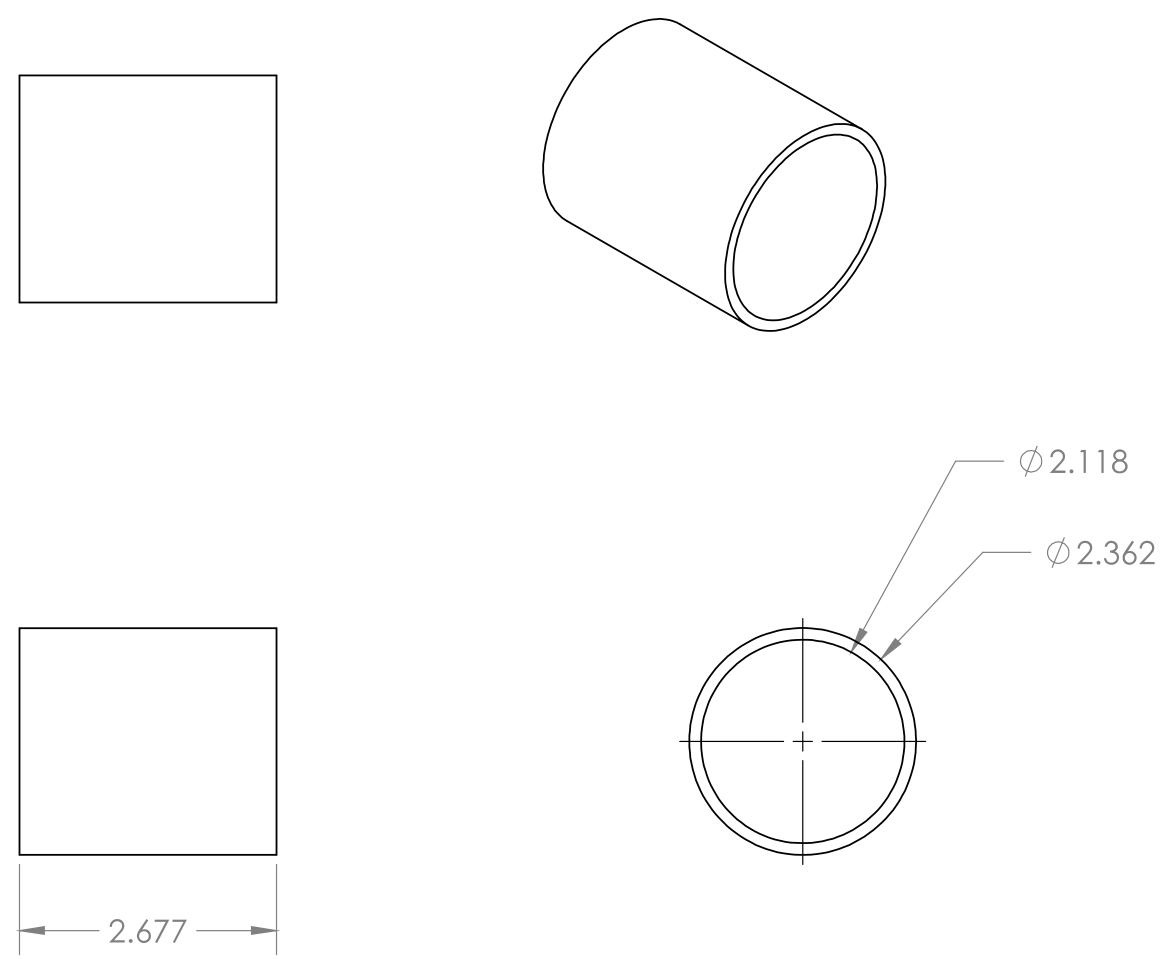
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA
		TITLE: FRAME
MATERIAL 6061-T6 (SS)		SIZE **A** — DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:5 — WEIGHT: 14.50 lbs — SHEET 11 OF 14

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA
		TITLE: FRAME
MATERIAL 6061-T6 (SS)		SIZE A · DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:5 · WEIGHT: 14.50 lbs · SHEET 12 OF 14



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

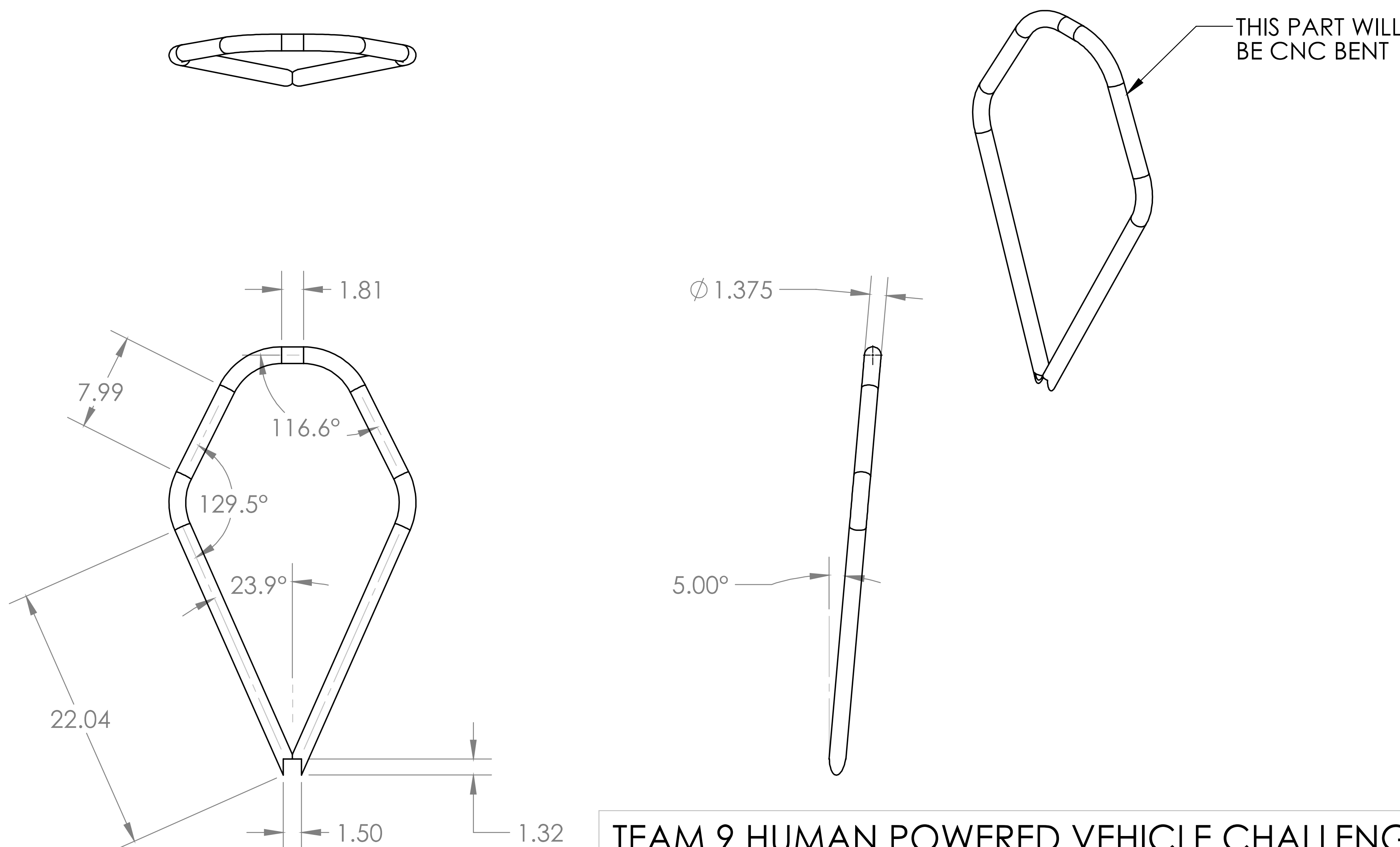
TITLE:
FRAME

SIZE
A

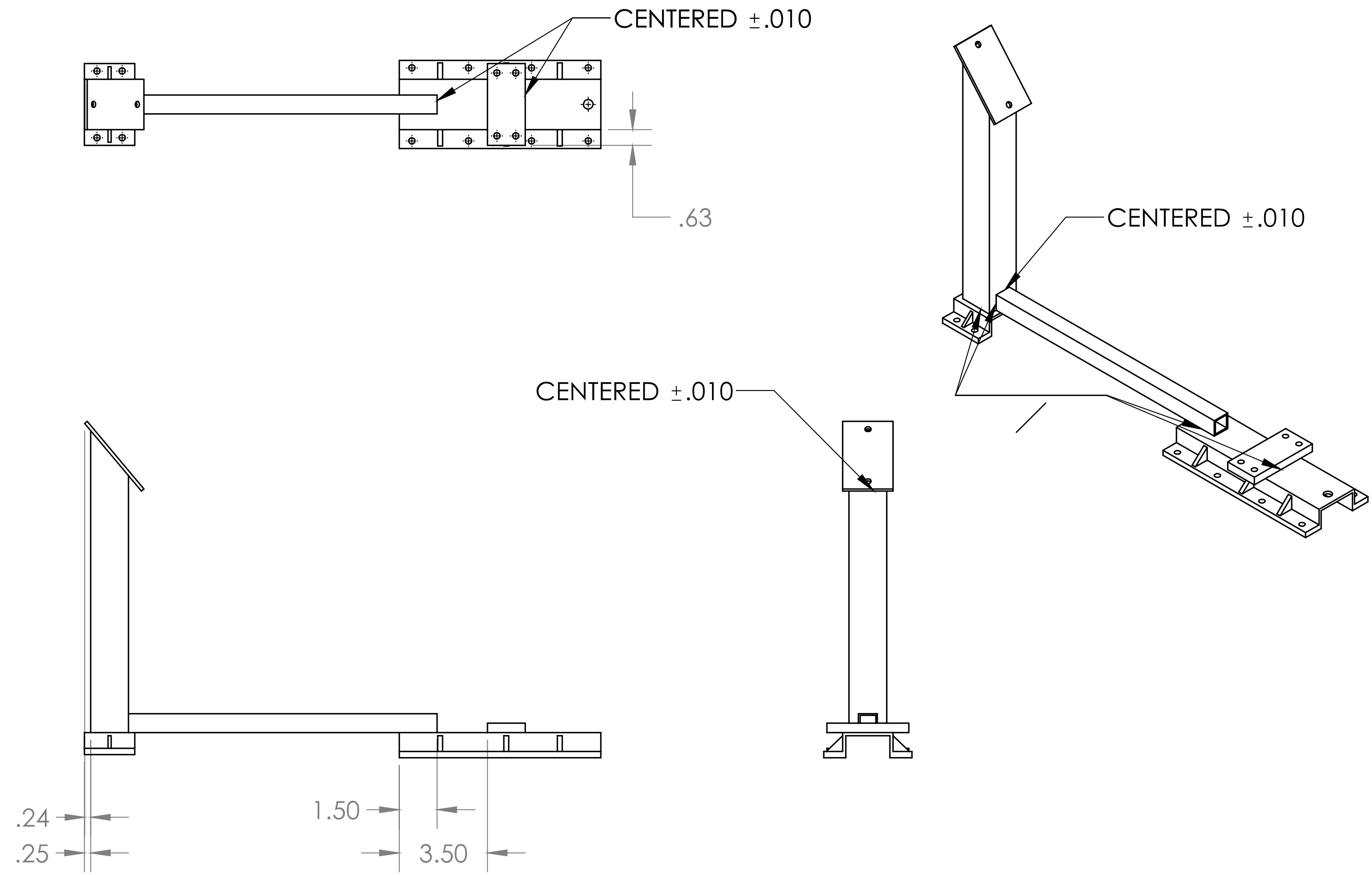
DATE DRAWN
12/12/2013

SCALE: 1:2 | WEIGHT: 14.50 lbs | SHEET 13 OF 14

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE			
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA	
		TITLE: FRAME	
MATERIAL 6061-T6 (SS)		SIZE A	DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:12	WEIGHT: 14.50 lbs — SHEET 14 OF 14



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

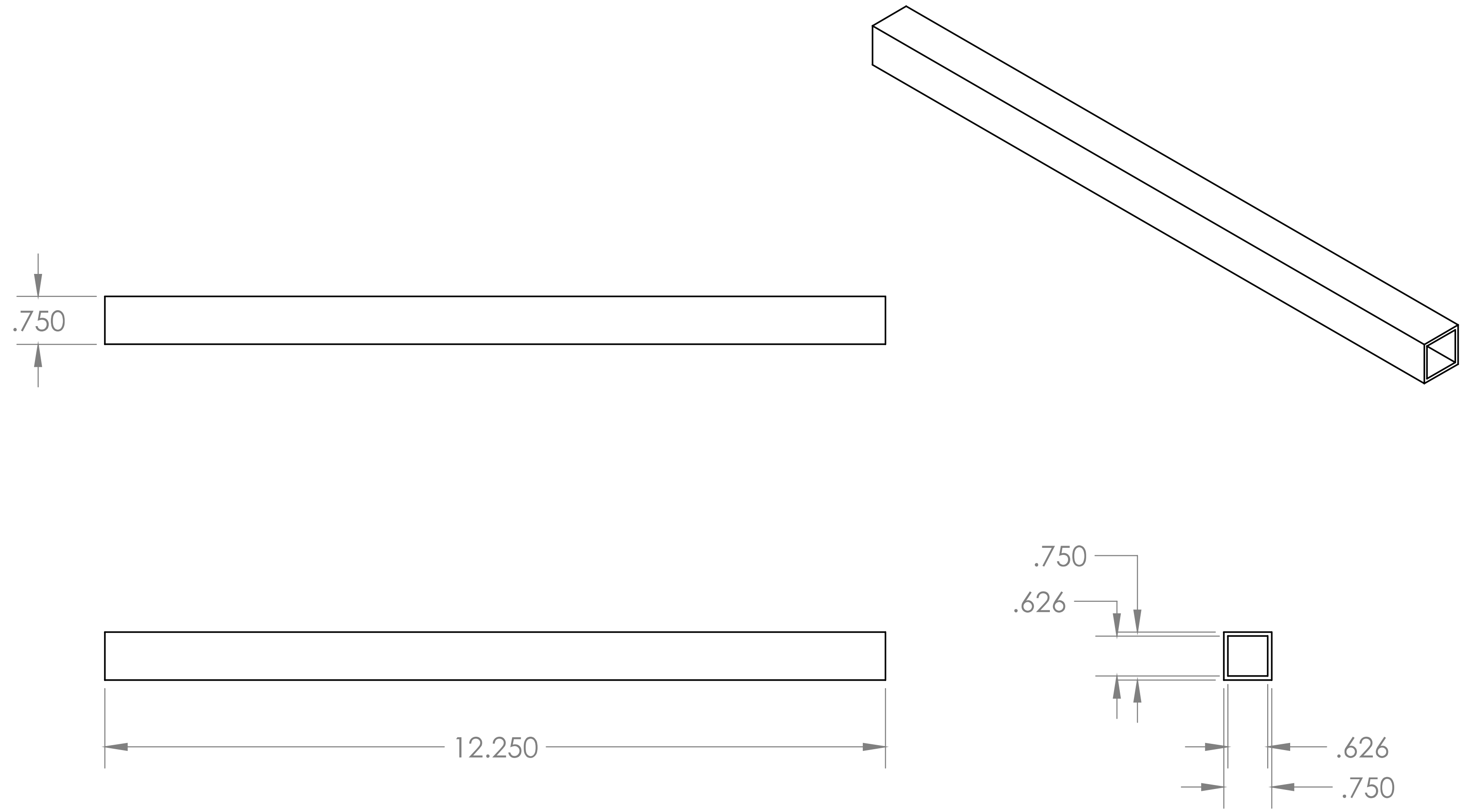
TITLE:
SEAT BRACKET

SIZE
A

DATE DRAWN
12/12/2013

SCALE: 1:6 | WEIGHT: 2.02 | SHEET 1 OF 7

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

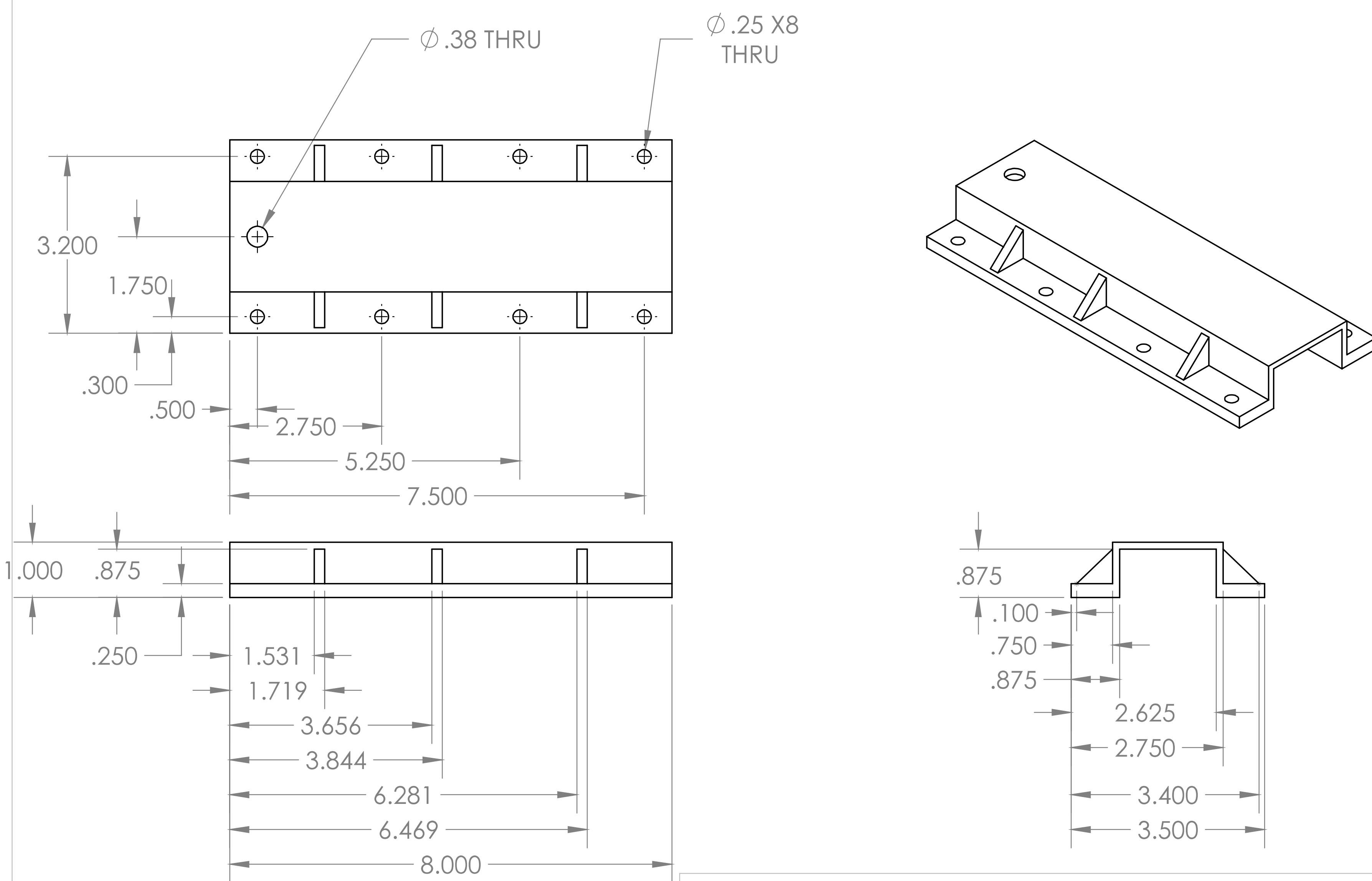
TITLE:
SEAT BRACKET

SIZE
A

DATE DRAWN
12/12/2013

SCALE: 3:8 | WEIGHT: 2.02 | SHEET 2 OF 7

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

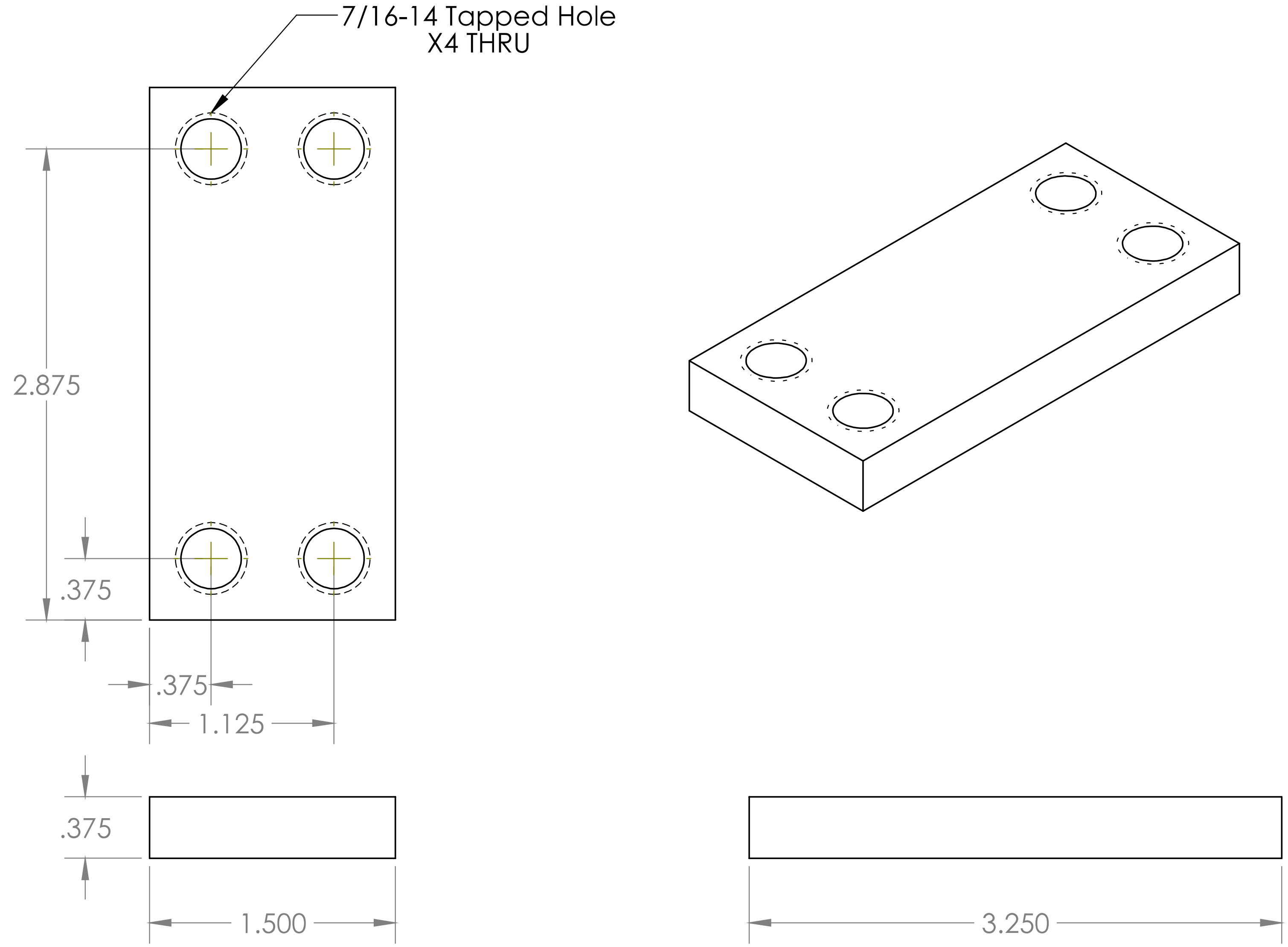
TITLE:
SEAT BRACKET

SIZE
A

DATE DRAWN
12/12/2013

SCALE: 3:8 | WEIGHT: 2.02 | SHEET 3 OF 7

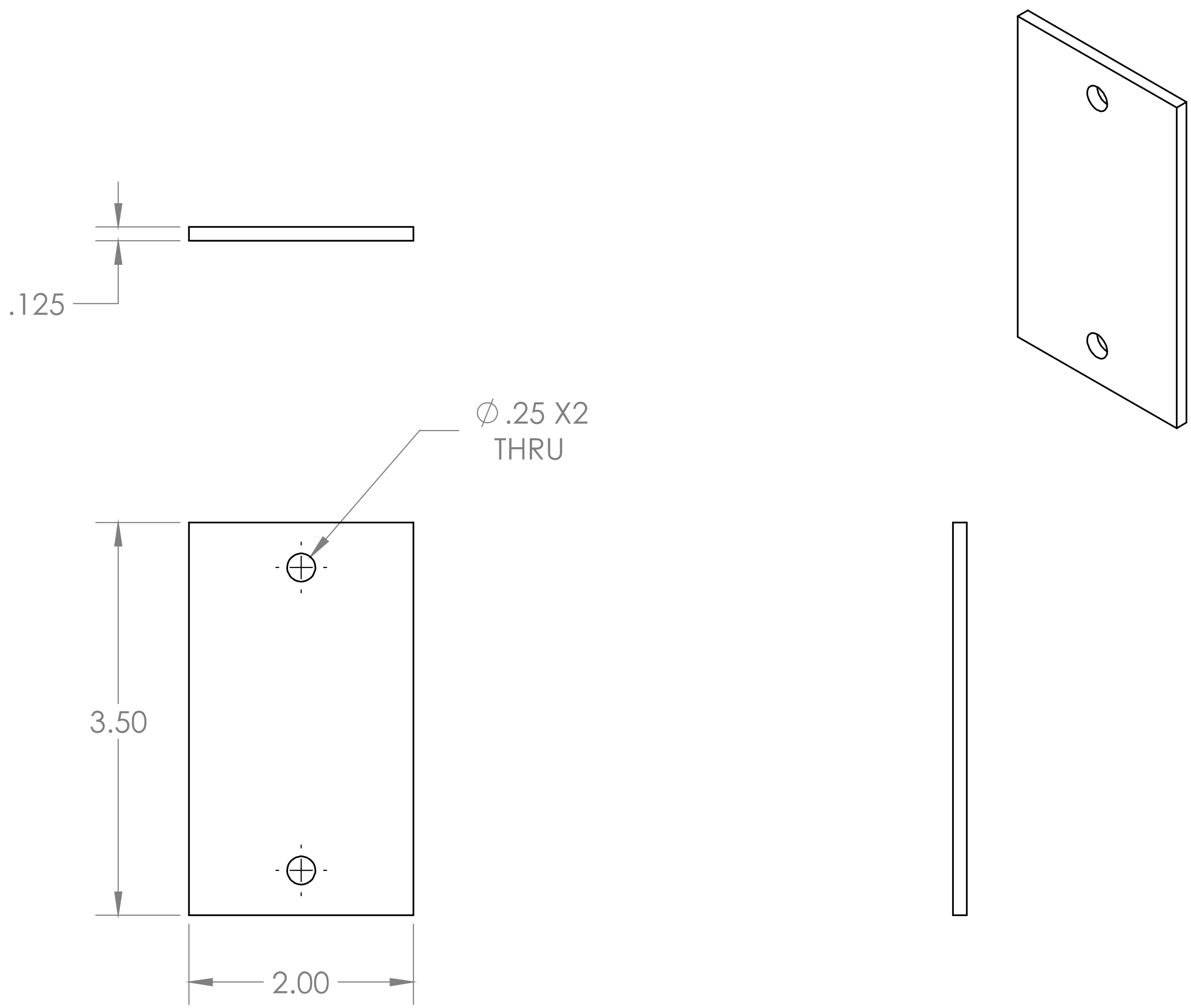
5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA
		TITLE: SEAT BRACKET
MATERIAL 6061-T6 (SS)		SIZE **A** DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:1 WEIGHT: 2.02 SHEET 4 OF 7

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

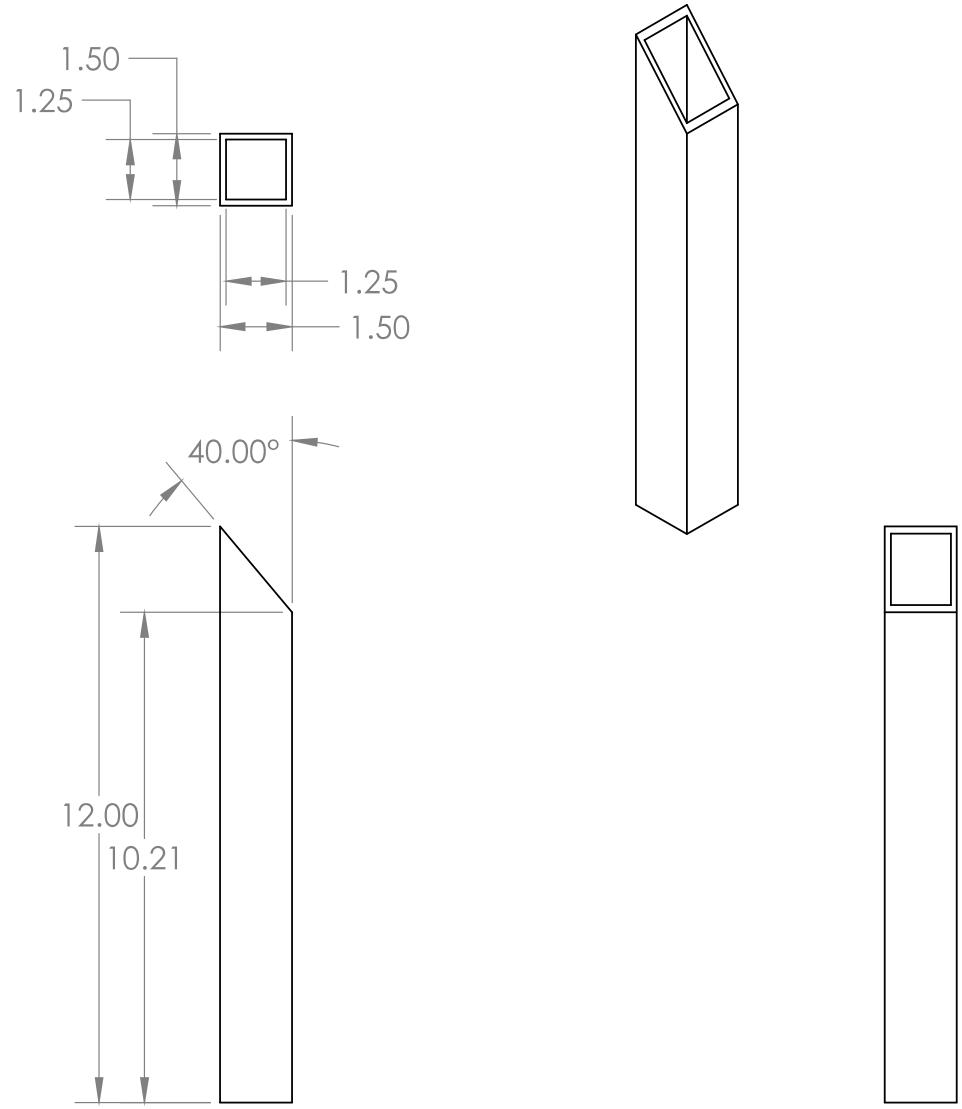
TITLE:
SEAT BRACKET

SIZE
A

DATE DRAWN
12/12/2013

SCALE: 5:8 | WEIGHT: 2.02 | SHEET 5 OF 7

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

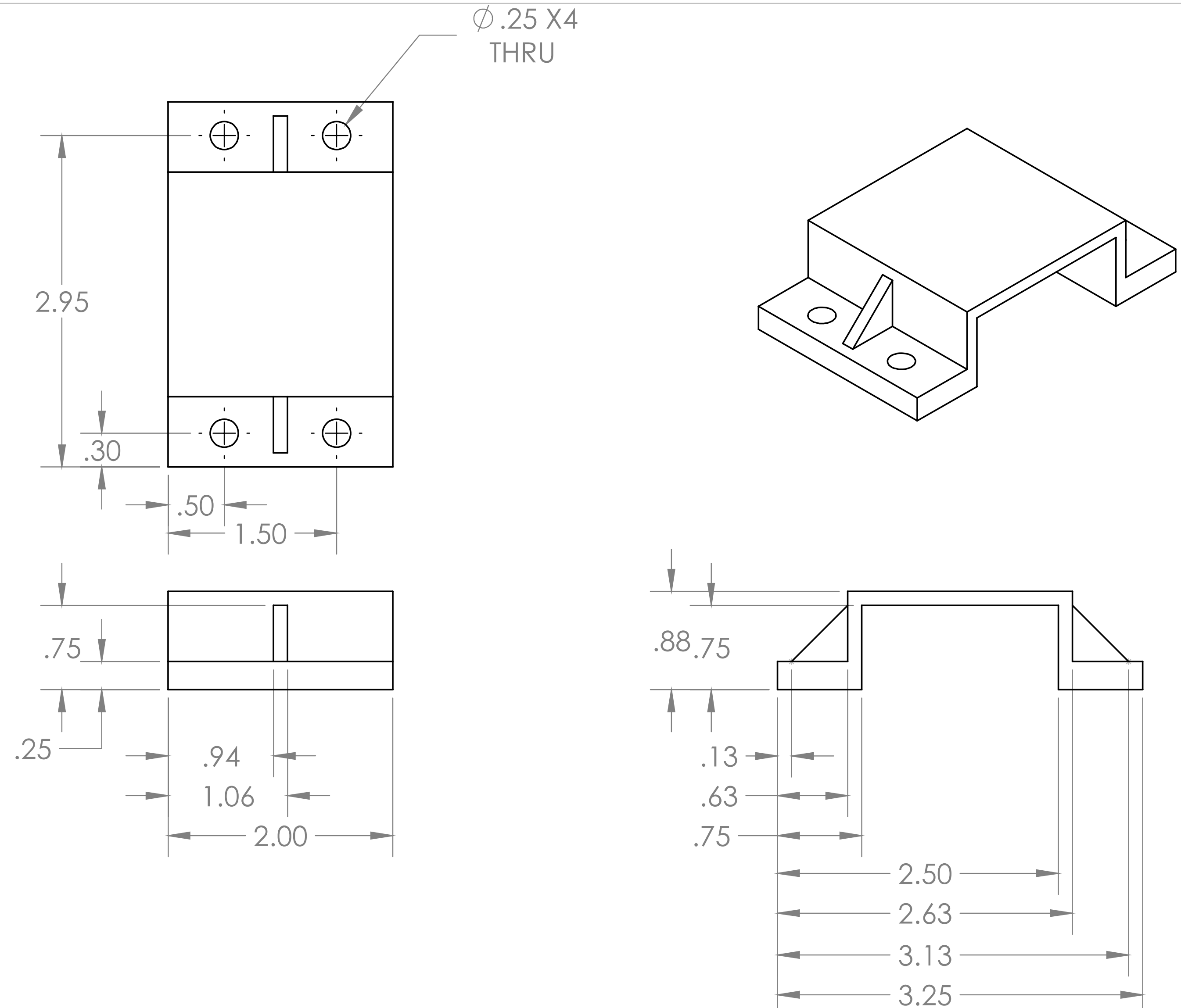
TITLE:
SEAT BRACKET

SIZE
A

DATE DRAWN
12/12/2013

SCALE: 1:4 | WEIGHT: 2.02 | SHEET 6 OF 7

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

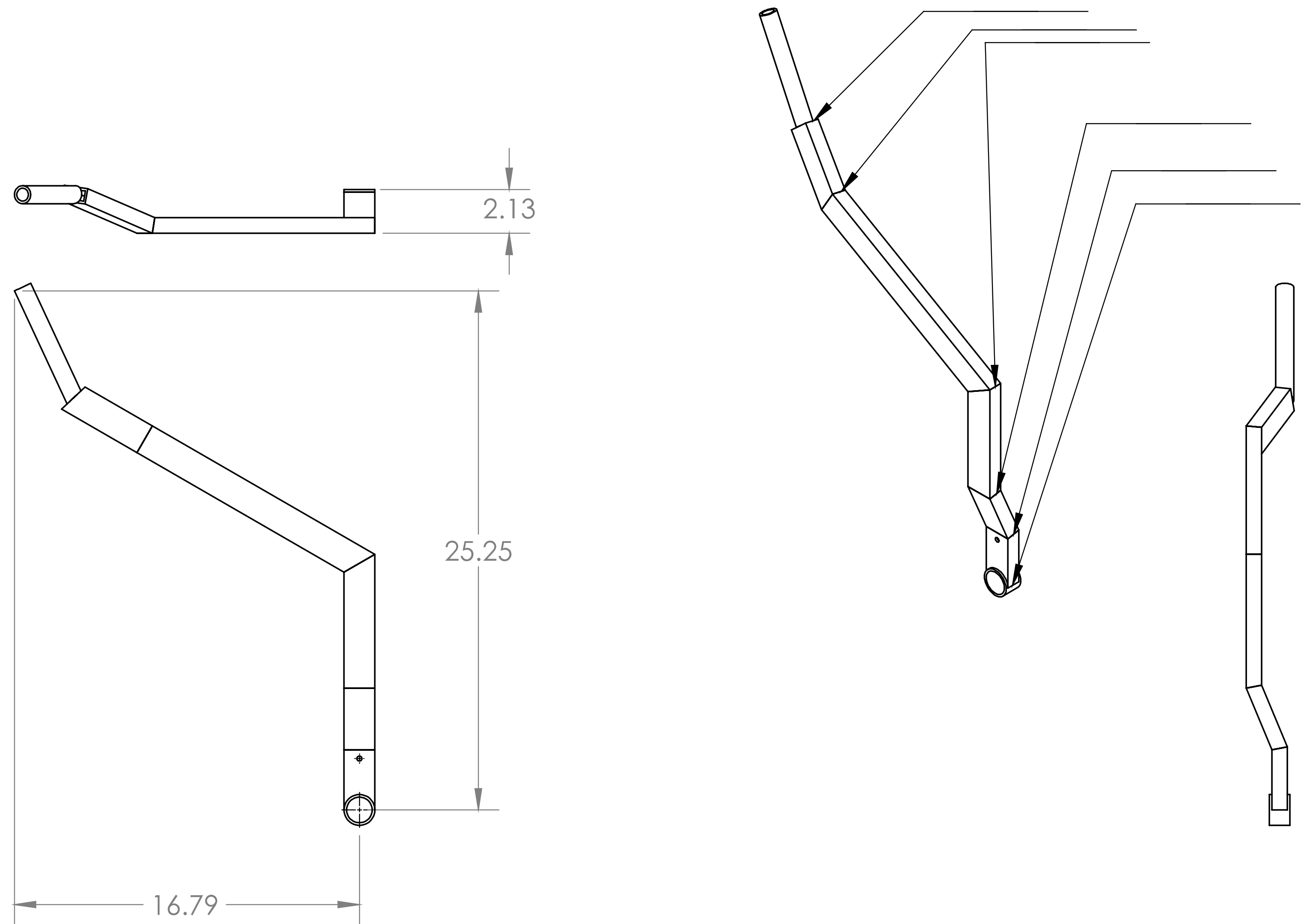
TITLE:
SEAT BRACKET

SIZE
A

DATE DRAWN
12/12/2013

SCALE: 2:3 | WEIGHT: 2.02 | SHEET 7 OF 7

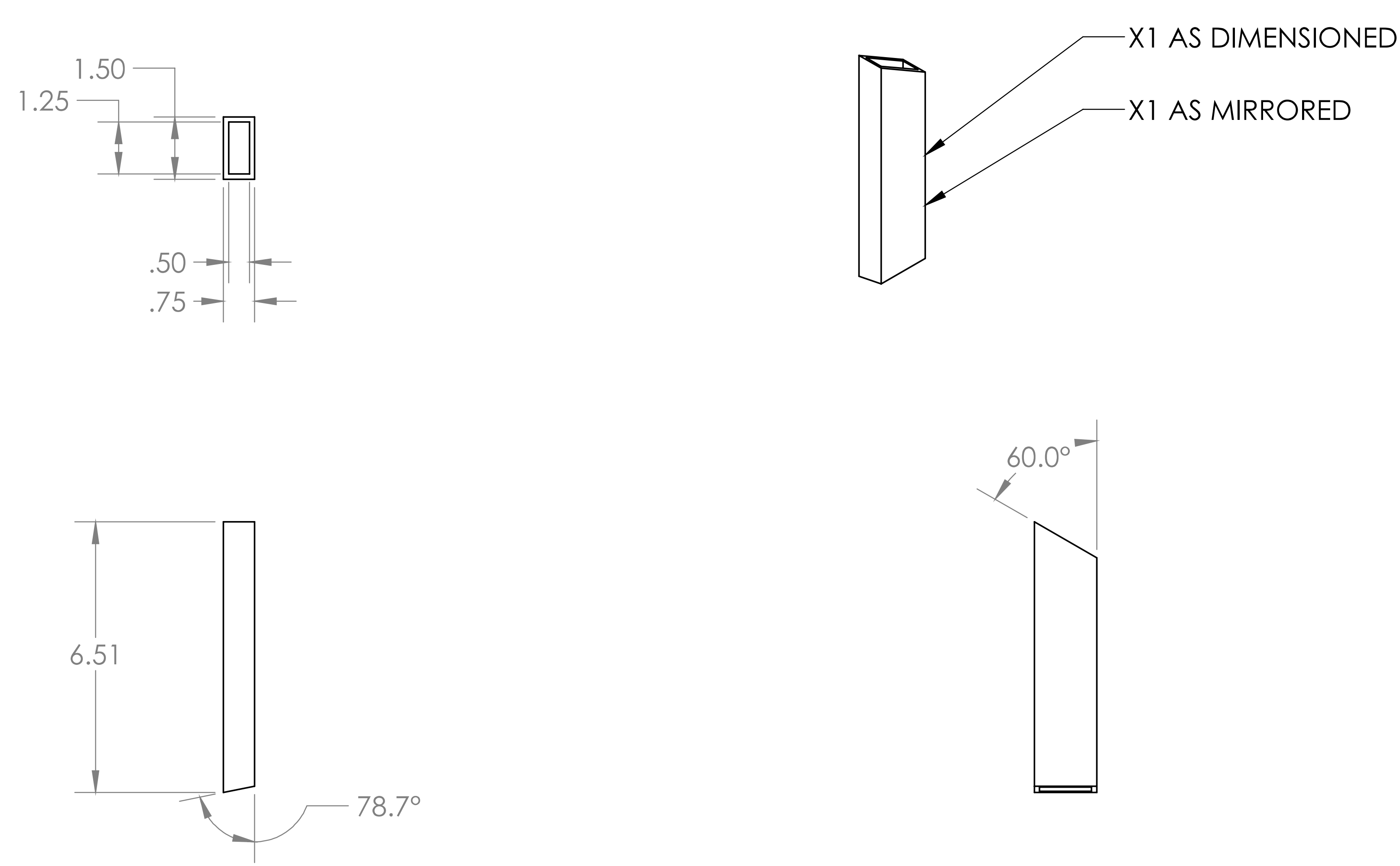
5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA TITLE: STEERING ARMS SIZE A DATE DRAWN 12/12/2013
MATERIAL 6061-T6 (SS)		
FINISH	DO NOT SCALE DRAWING	SCALE: 1:8 | WEIGHT: 1.59 lbs | SHEET 1 OF 9

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

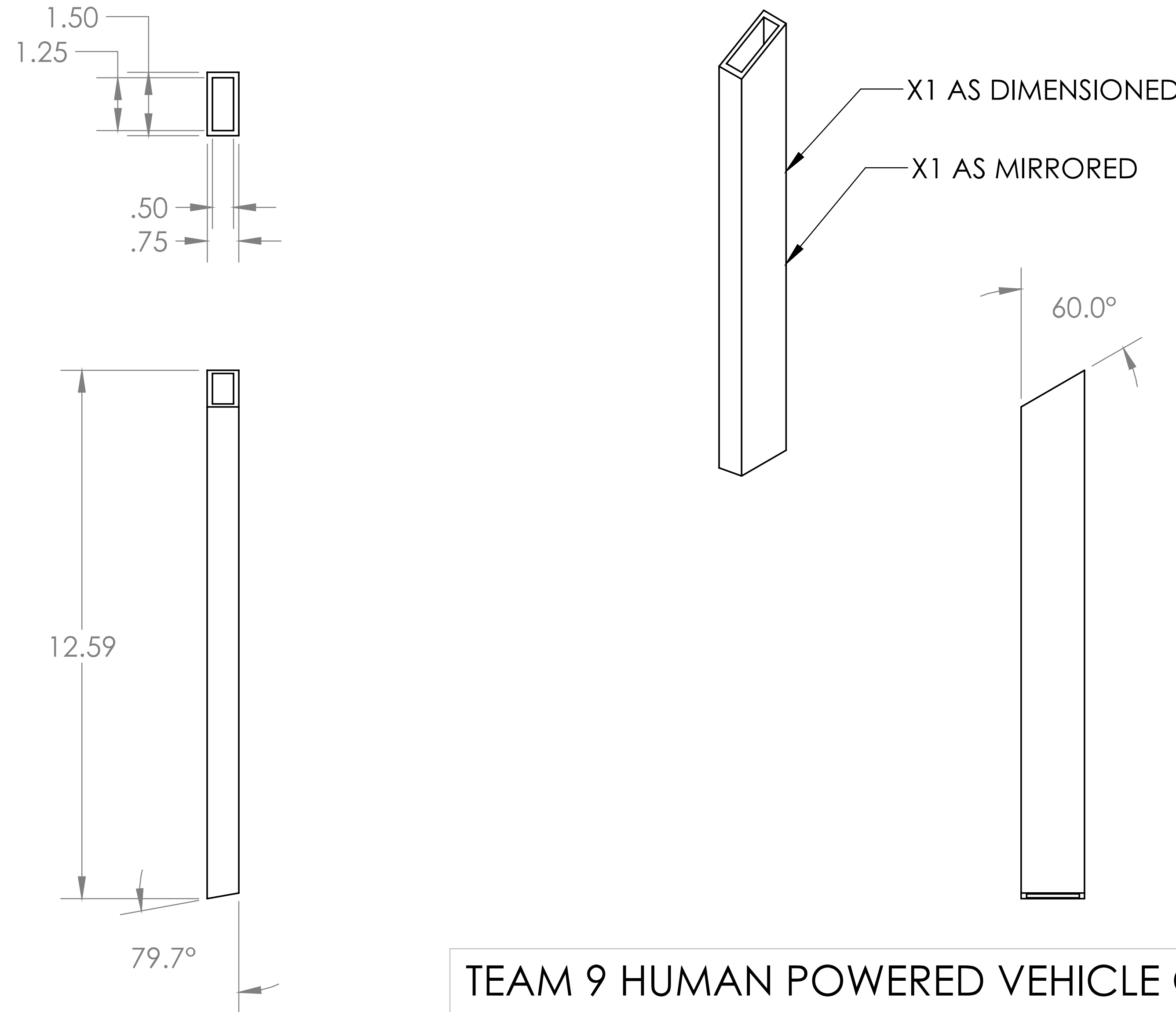
TITLE:
STEERING ARMS

SIZE
A

DATE DRAWN
12/12/2013

SCALE: 1:4 | WEIGHT: 1.59 lbs | SHEET 2 OF 9

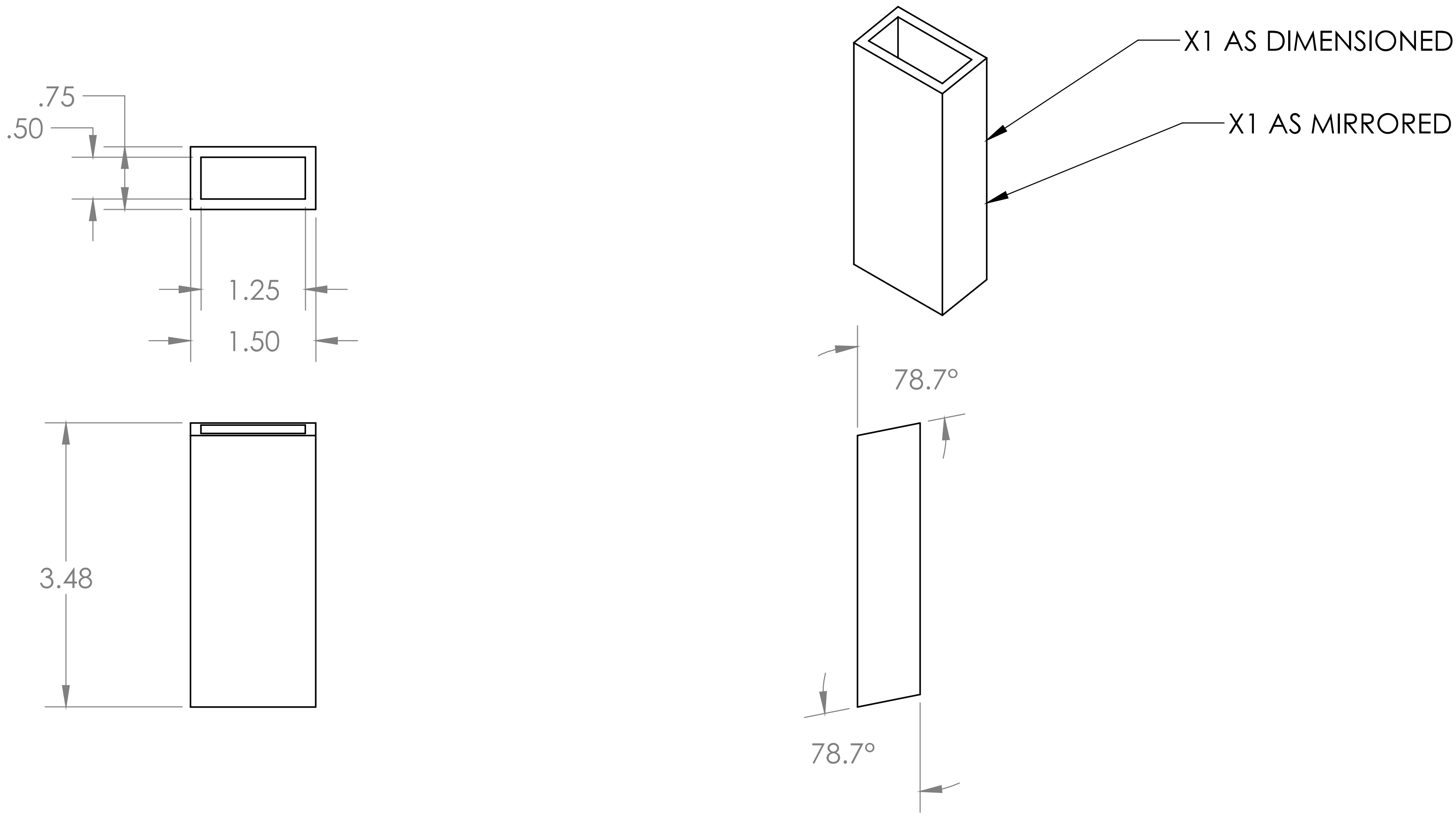
5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA TITLE: STEERING ARMS SIZE A · DATE DRAWN 12/12/2013
MATERIAL 6061-T6 (SS) FINISH	DO NOT SCALE DRAWING	SCALE: 1:4 · WEIGHT: 1.59 lbs · SHEET 3 OF 9

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

COMMENTS:

DRAWN BY:
KEVIN MONTOYA

TITLE:
STEERING ARMS

SIZE
A

DATE DRAWN
12/12/2013

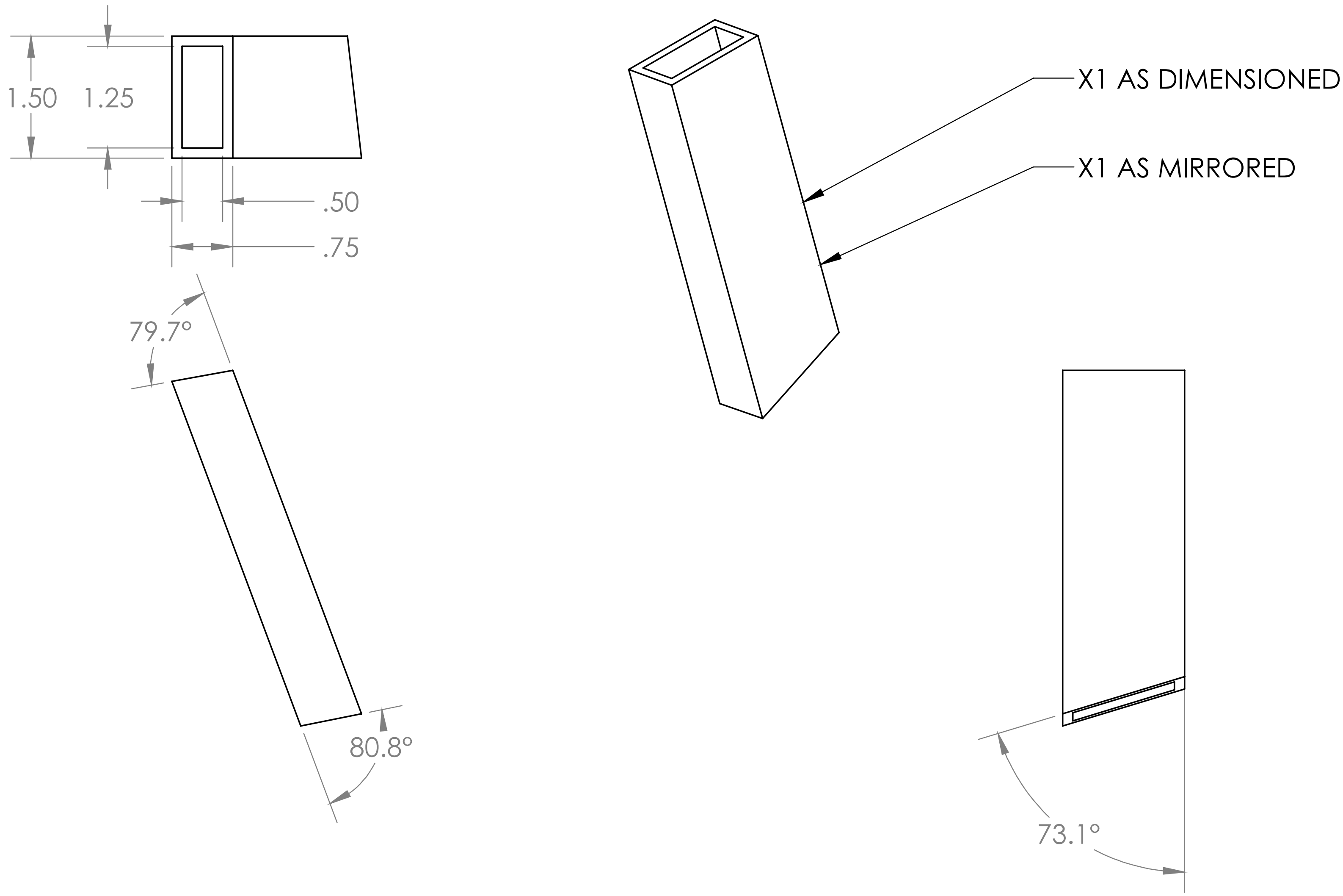
MATERIAL
6061-T6 (SS)

FINISH

DO NOT SCALE DRAWING

SCALE: 1:2 | WEIGHT: 1.59 lbs | SHEET 4 OF 9

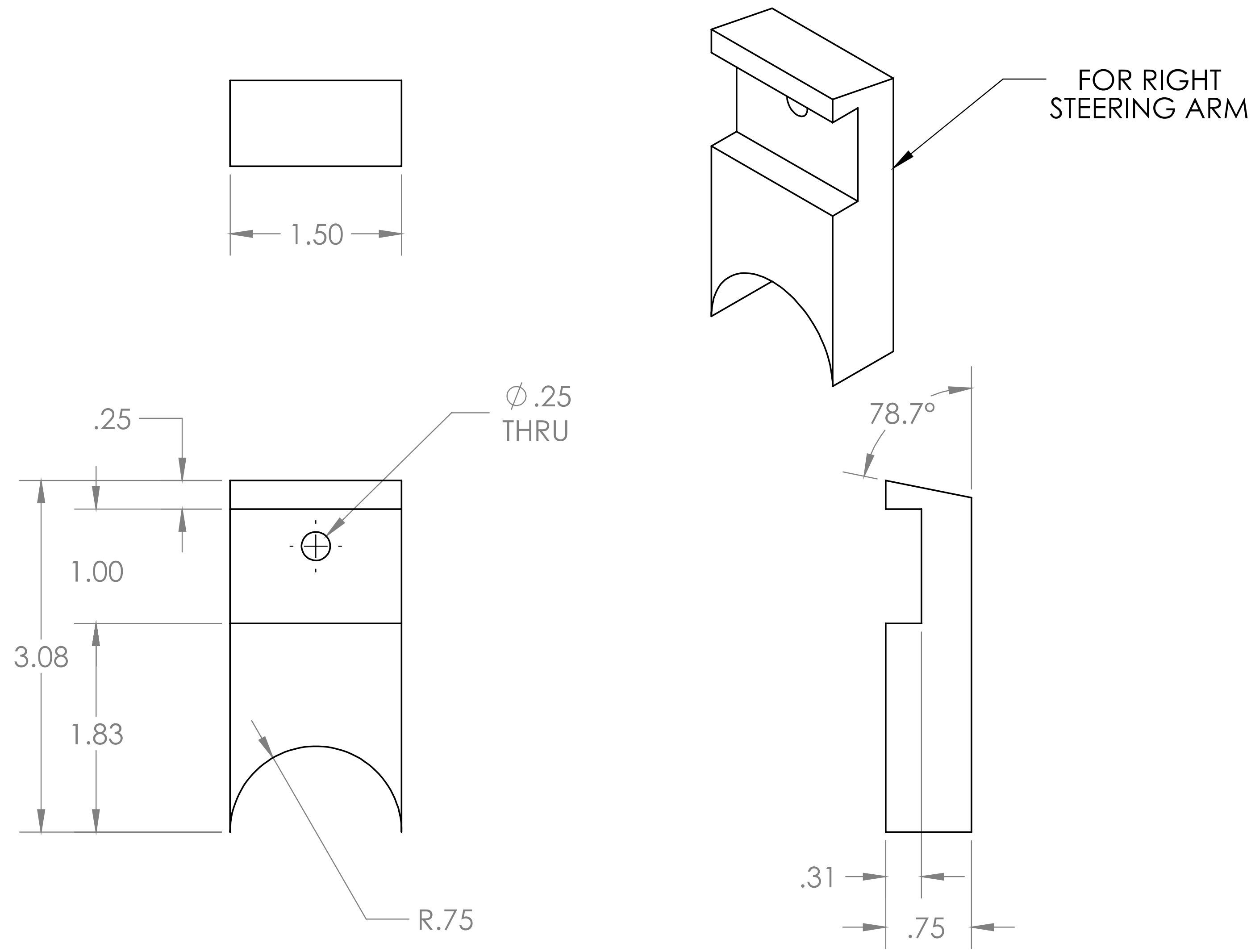
5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA		
		TITLE: STEERING ARMS		
MATERIAL 6061-T6 (SS)		SIZE **A**	DATE DRAWN 12/12/2013	
FINISH	DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: 1.59 lbs	SHEET 5 OF 9

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

DRAWN BY:
KEVIN MONTOYA

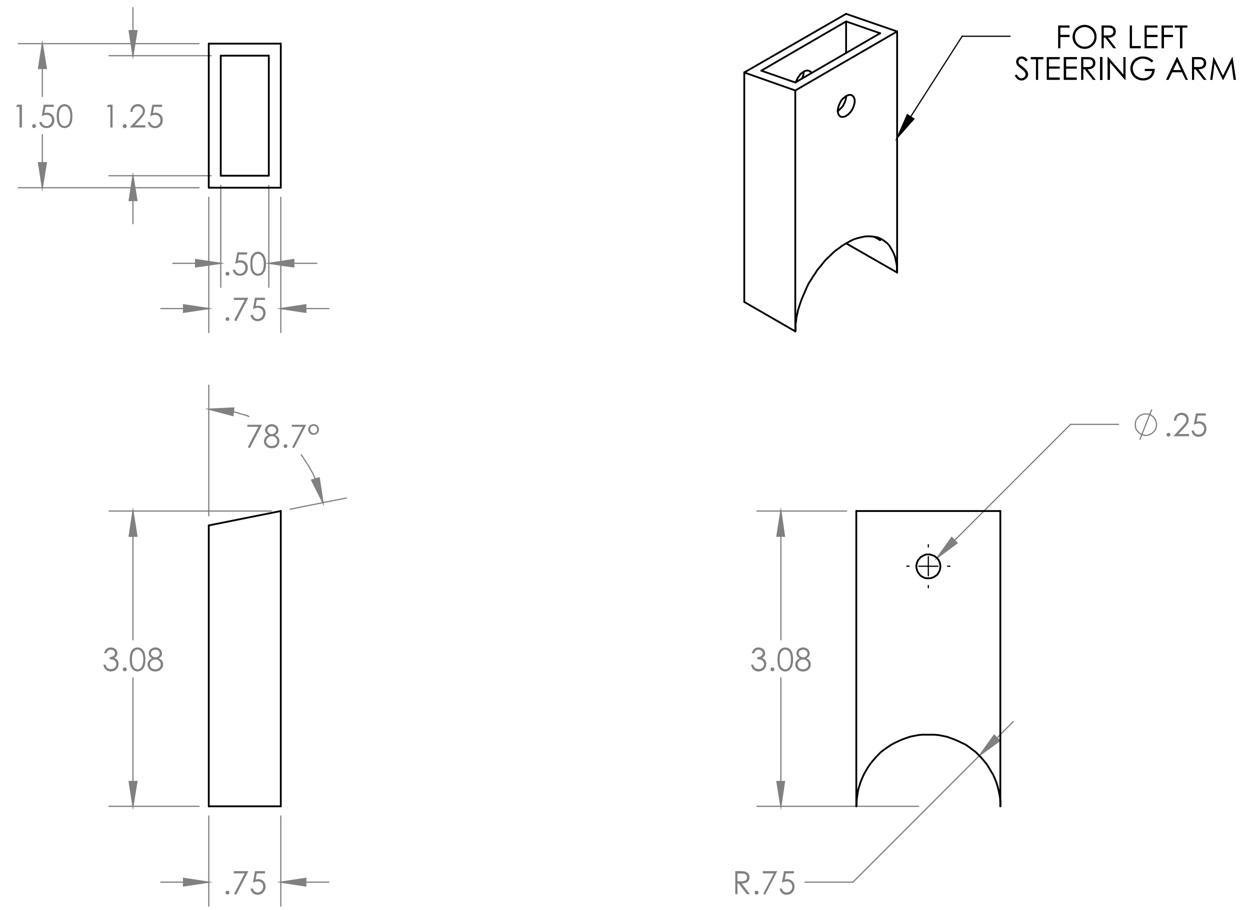
TITLE:
STEERING ARMS

SIZE
A

DATE DRAWN
12/12/2013

SCALE: 2:3 | WEIGHT: 1.59 lbs | SHEET 6 OF 9

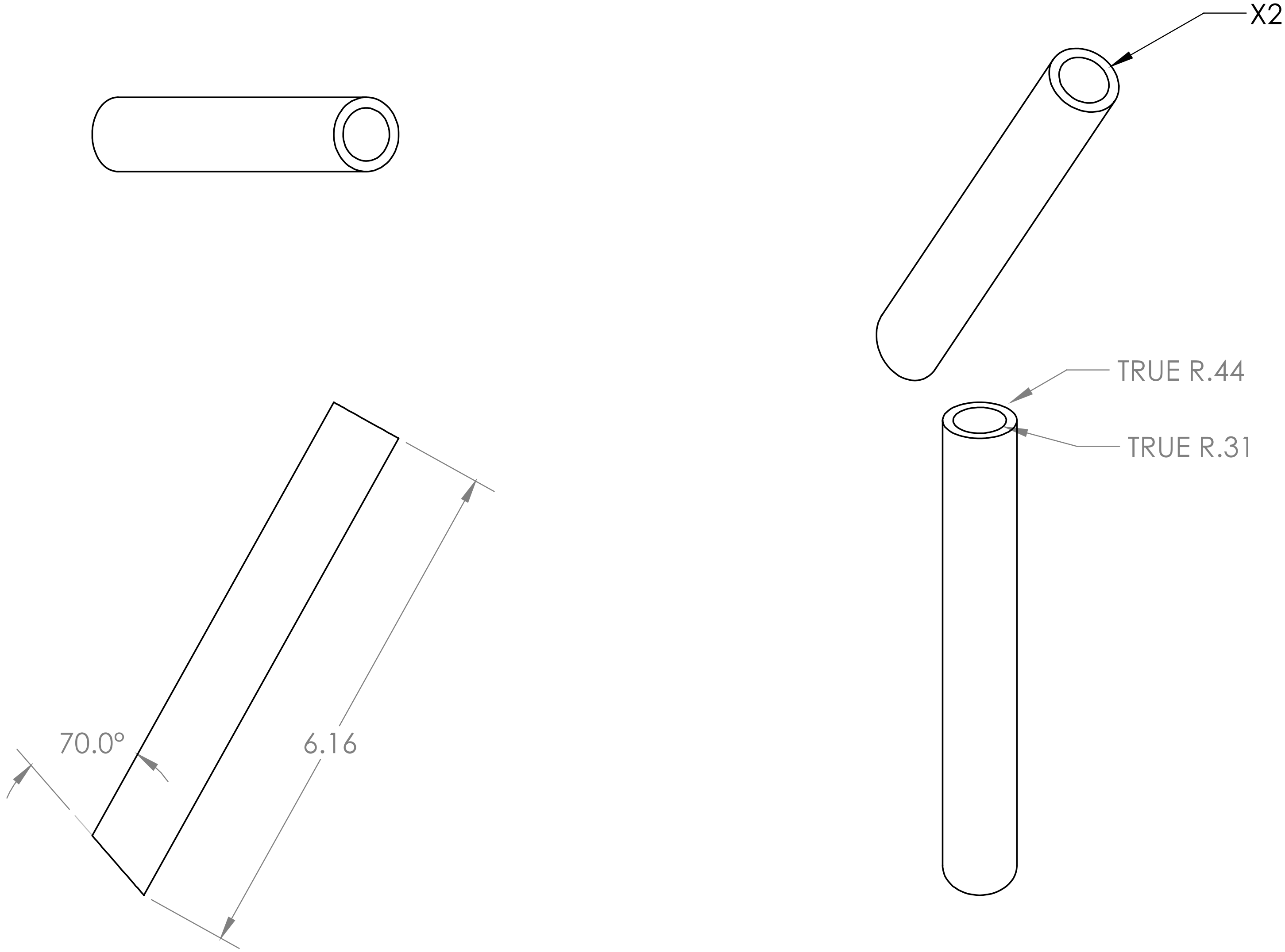
5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA
MATERIAL 6061-T6 (SS)		TITLE: STEERING ARMS
		SIZE A | DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:2 | WEIGHT: 1.59 lbs | SHEET 7 OF 9

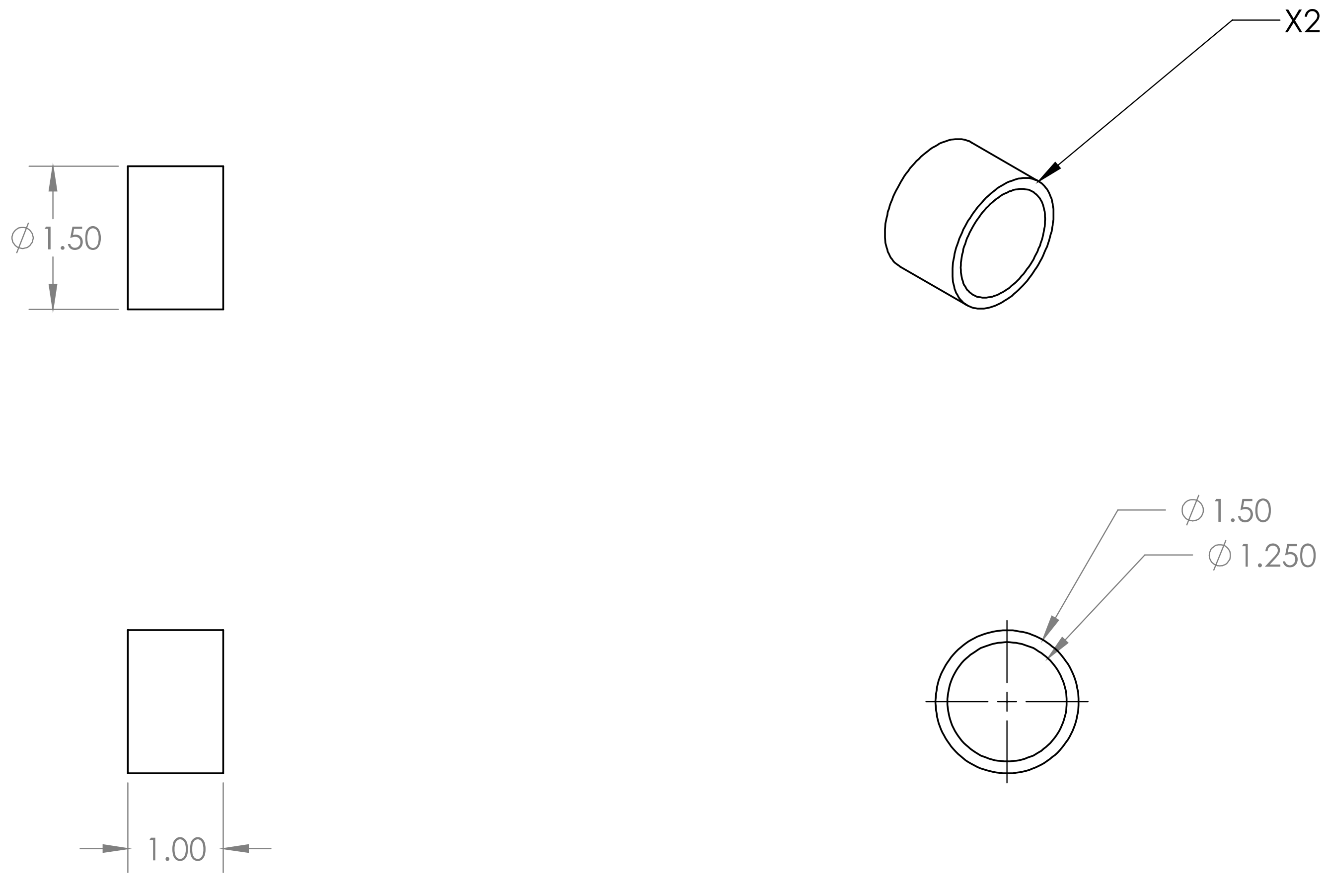
5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS:	DRAWN BY: KEVIN MONTOYA TITLE: STEERING ARMS
MATERIAL 6061-T6 (SS)		SIZE A / DATE DRAWN 12/12/2013
FINISH	DO NOT SCALE DRAWING	SCALE: 1:2 / WEIGHT: 1.59 lbs / SHEET 8 OF 9

5 4 3 2 1



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
6061-T6 (SS)

FINISH

COMMENTS:

DO NOT SCALE DRAWING

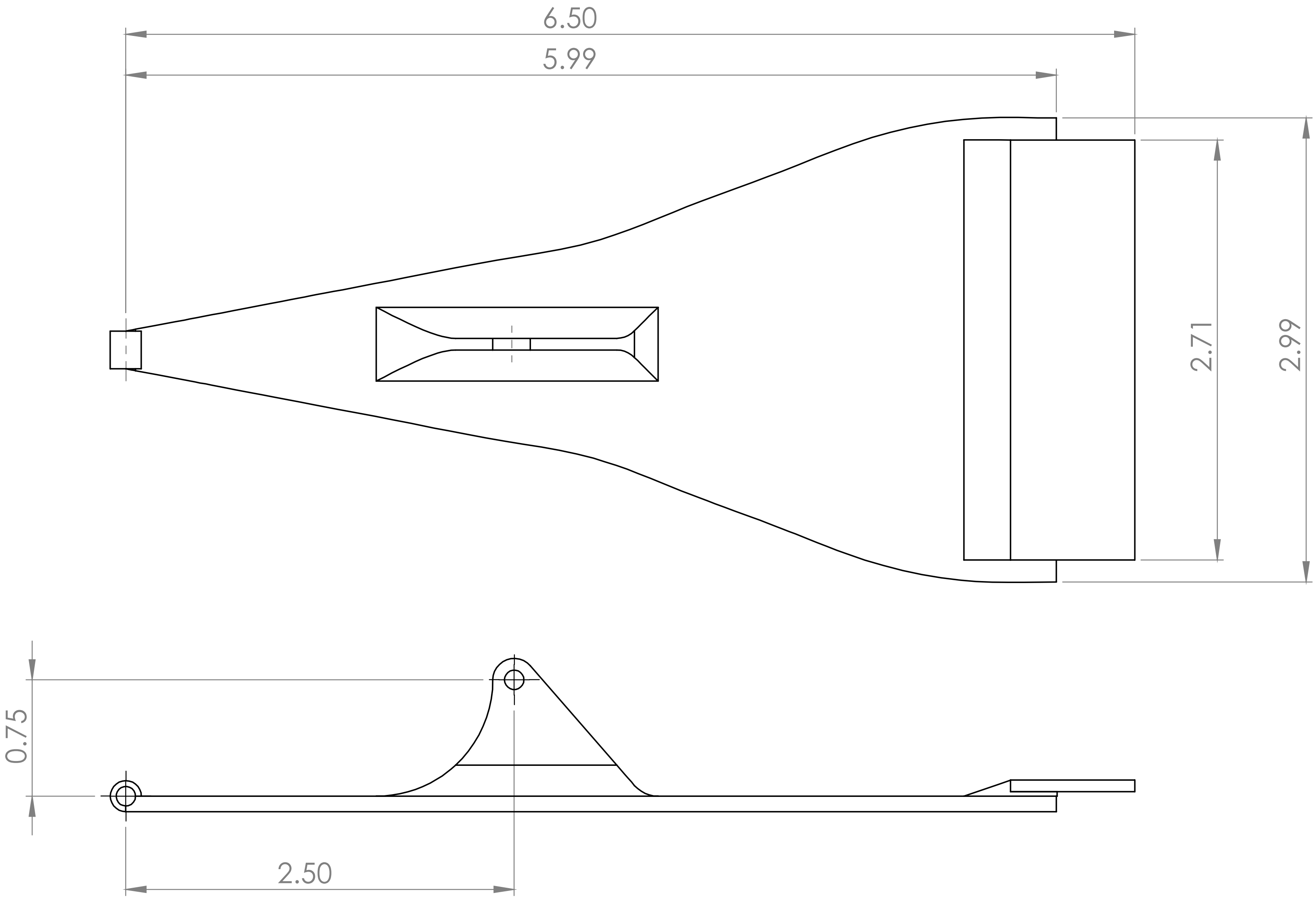
DRAWN BY:
KEVIN MONTOYA

TITLE:
STEERING ARMS

SIZE
A

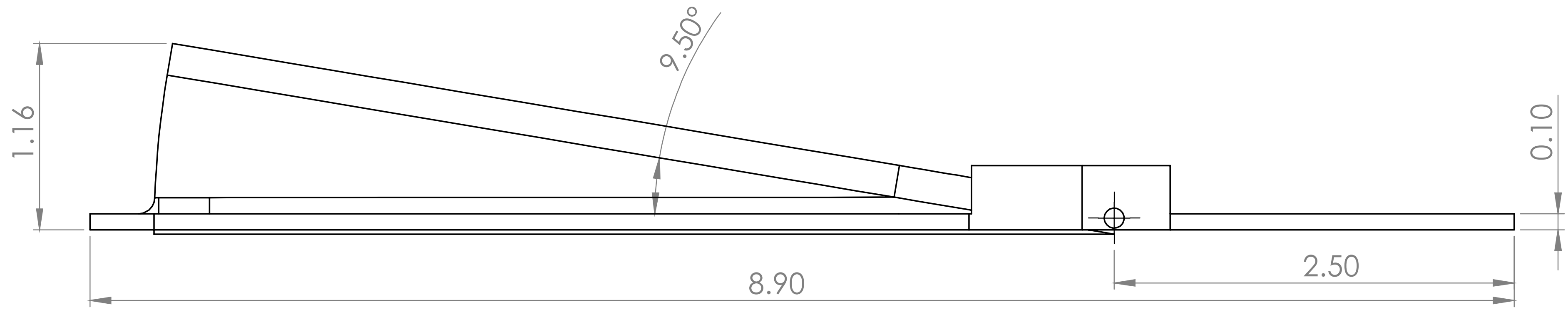
DATE DRAWN
12/12/2013

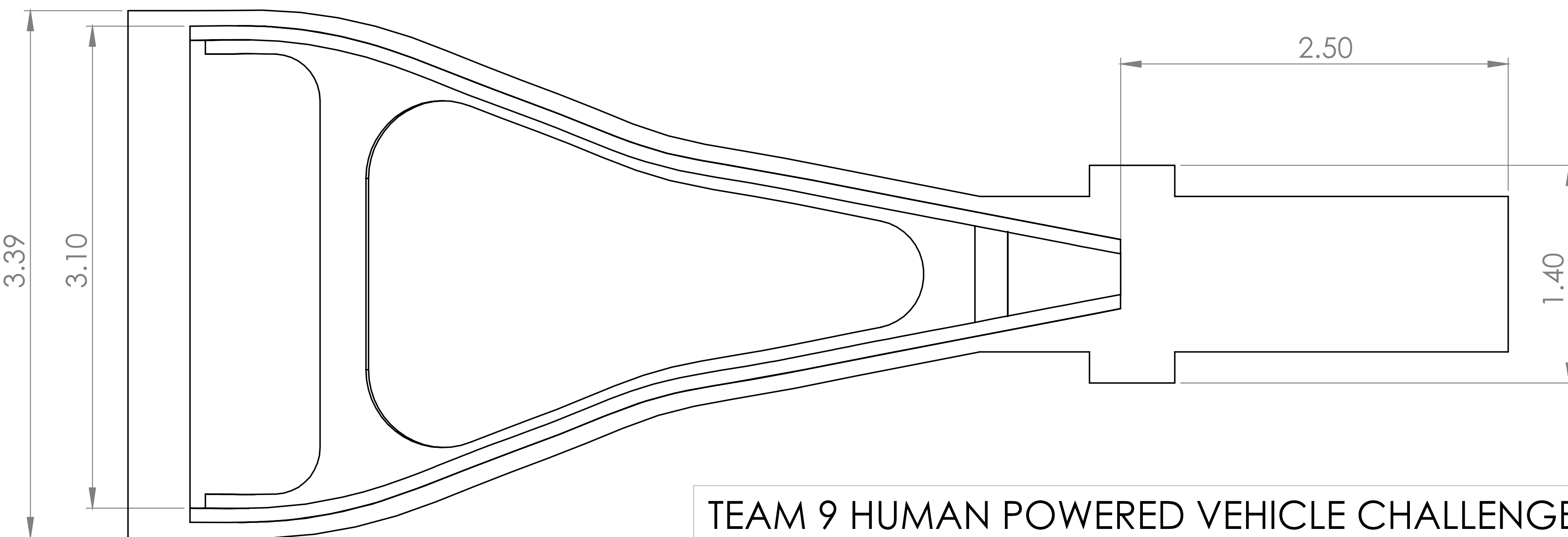
SCALE: 1:2 | WEIGHT: 1.59 lbs | SHEET 9 OF 9



TEAM 9 HUMAN POWERED VEHICLE CHALLENGE			
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES GENERAL SURFACE FINISH 125 TOLERANCES: FRACTIONAL ±1/16 ANGULAR: ± 0.5° TWO PLACE DECIMAL ± .03 THREE PLACE DECIMAL ± .005	COMMENTS: FDM Rapid Prototyped Part	DRAWN BY: Erik Nelson	
MATERIAL ABS		TITLE: Closing Duct Flap	
FINISH	DO NOT SCALE DRAWING	SIZE A	DATE DRAWN 12/8/2013
		SCALE: 1:1	WEIGHT: 0.05 / SHEET 1 OF 1

5 4 3 2 1





TEAM 9 HUMAN POWERED VEHICLE CHALLENGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL SURFACE FINISH 125
TOLERANCES:
FRACTIONAL ±1/16
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± .03
THREE PLACE DECIMAL ± .005

MATERIAL
ABS

FINISH

COMMENTS:
FDM Rapid Prototyped Part

DO NOT SCALE DRAWING

DRAWN BY:
Erik Nelson

TITLE:
Closing Duct Frame

SIZE
A

DATE DRAWN
12/8/2013

SCALE: 1:1 | WEIGHT: 0.07 | SHEET 1 OF 1

5 4 3 2 1