MECHENG 350 WINTER 2020 DESIGN REPORT

Team 45

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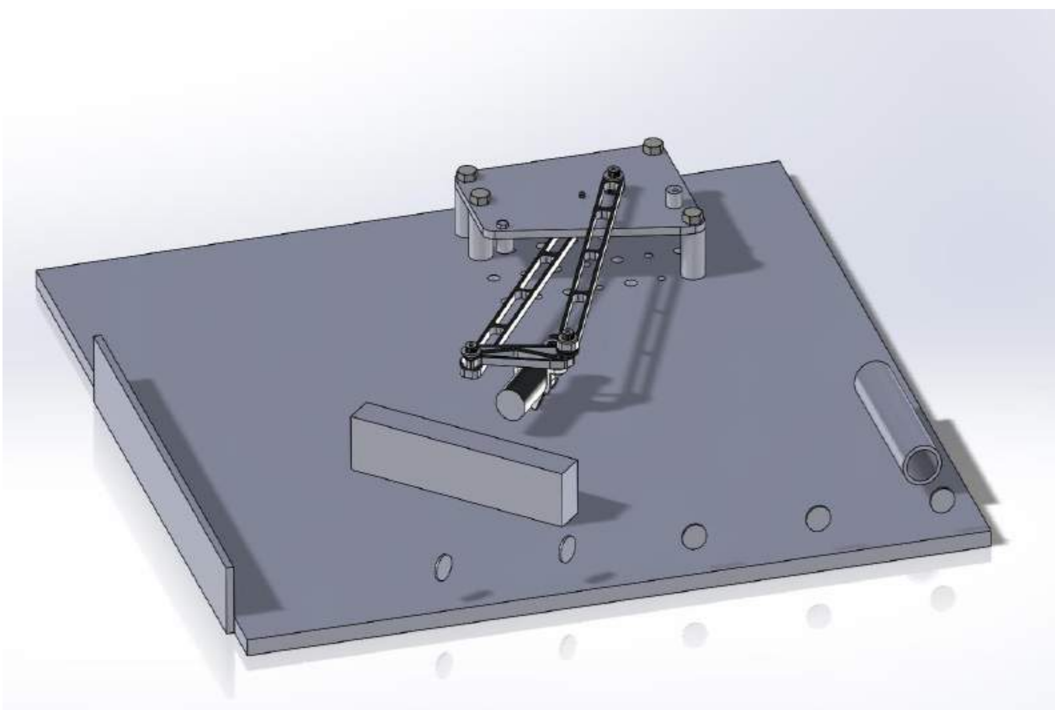


Edited by Jonah Shifrin

Section 1: Design Goals and Requirements

The goal of this project is to design, build and test a device that will use a single motor to move and shine a beam of light onto targets in designated positions on the playing field. Simultaneously, we have to pay attention to the weight, and geometry of the mechanism as well as the speed at which the mechanism can hit targets. The design must be robust, and able to survive many cycles of use before failing due to wear, so emphasis should be out on craftsmanship as well as surface finish of parts.

1.1 Design Restrictions

We have three main design restrictions: geometry, materials, and linkage specifications. Our restrictions around geometry include the 4-bar linkage and attached flashlight; these must be able to move freely without contacting playing field obstacles. The second geometric restriction includes the ground link, which must remain within the maximum ground plate dimensions (centered around the grounding holes in the playing field as shown below).

The second main design restriction is materials. All materials used outside of the provided kit will cost no more than $100 in total, shipping included. The third main design is linkage specifications: the linkage will be a 4-bar linkage with one degree of freedom; additionally, there will be hard stops attached to the ground plate defining the outer bounds of the linkage motion.

Finally, all parts will be designed with ease of manufacturability in mind and must be made in a timely manner and accurately with only the tools and machines available in the provided machine shop. All part drawings must be easy to understand and complete so any machinist would be able to manufacture the part if given. Evaluation Criteria and performance scoring metrics are described in Table 1 and Table 2, respectively.

Table 1. This table depicts the project scoring categories and their weightings.

Specification	Description	Target
Transmission Angle Deviation	| Transmission angle - *90°*| Measuring the largest angle	*0°*
Weight	Weight of only moving parts: links and attached pieces	Minimize using lightest / strongest material
Performance Score	Based on # of targets dropped and amt lights on targets	100% in each category

Performance Score was determined by two sub-metrics described in table 2 below. These are prescribed metrics with predetermined measurement and scoring.

Table 2. This table depicts the metrics used to generate a performance score.

Action	Measurement	Scoring
Shine Light	Measure by summing the analogue reading of each photosensor in each stage	Measurement / 1000
Drop Target	Sum of the # of targets dropped	Measurement x 10

Section 2: Design Selection

A Pugh Chart was used for design selection. Scoring four individual designs in four criteria on a scale of one to four, Table 4, by their measurements in each of the criteria, Table 3, each design could be quantitatively compared. The weightings in Table 4 were assigned according to the percentage of the project grade they were worth. The overall performance of our linkage is worth the largest percentage the project grade (represented in Table 4 as distance from target due to the metrics implications on speed of sensor recognition therefore enabling the linkage to hit more targets), followed by manufacturability and linkage weight, followed by maximum transmission angle. The relative weightings came out as 45%, 22%, and 11% respectively.

Table 3. This table shows the measured design parameters of each of the four, original, prototypes.

Category	Design 1	Design 2	Design 3	Design 4
Max Transmission Angle Deviation	14.5°	9°	18°	21°
Linkage Weight (length)	19.8418 in	28.2256 in	29.1108 in	29.7354 in
Average Distance from Targets	18.5100 in	15.1200 in	19.7500 in	19.8300 in

Table 4. This table shows a pew chart comparing designs two through four to design through the four weighted categories to the left.

Category	Weight	Actual Values	Design 1	Design 2	Design 3	Design 4
Max Transmission Angle Deviation	1	14.5°	0	+1	-1	-1
Linkage Weight (length)	2	19.8418 in	0	-2	-2	-2
Average Distance from Targets	4	18.5100 in	0	+4	0	0
Manufacturability	2	NA	0	0	+2	+2
Total score	9	NA	0	3	-1	-1

Section 3: Final Linkage Design and Analysis

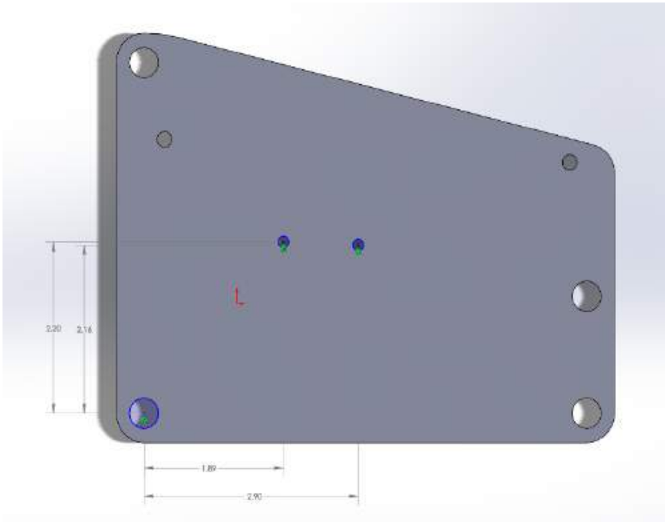
Based on the scores from the Pugh Chart, Design 1 and 2 had the highest scores and were the primary designs we decided to Continue iterating. Design 1 was designed with shorter links and a low max transmission angle deviation, but the shorter links, coupled with the fact the ground pivots were far from targets meant that, based on previously stated logic, would score lower in the average distance from targets than Design 2. Design 2 had longer links with ground pivots closer to targets. This meant, while much heavier, design 2 scored better in average distance from the targets. It also had very low transmission angle deviations. Design 3 made use of light-weighting.

Section 3.1: Physical Design

Using perpendicular cross bars in the linkage for lightweight and support, the design had well above the necessary strength with less mass. By comparing these design choices and acknowledging their strengths and weaknesses, we decided to combine them in a fifth design intended to better meet all the design objectives more thoroughly. This design is defined in Figure 2 below.

Figure 2. This figure defines the geometry of the final four bar linkage including a screengrab of the Ground Link referred to from here on as the base plate. The primary link lengths from joint center to joint center are 10.39", 3", 10.21", and 1.01". The final maximum transmission angle deviation of 12.61°.

Link	Input	Coupler	Follower	Ground
Length (hole to hole) [in]	10.39	3.00	10.21	1.01
Length (edge to edge) [in]	10.89	3.45	10.71	Not Relevant



The final task was to minimize weight through light weighting and hardware selection. The total mass of the final linkage, including all fasteners and other small components is 205.69 grams. The final geometry is shown in Figure 4 and Figure 5 below.

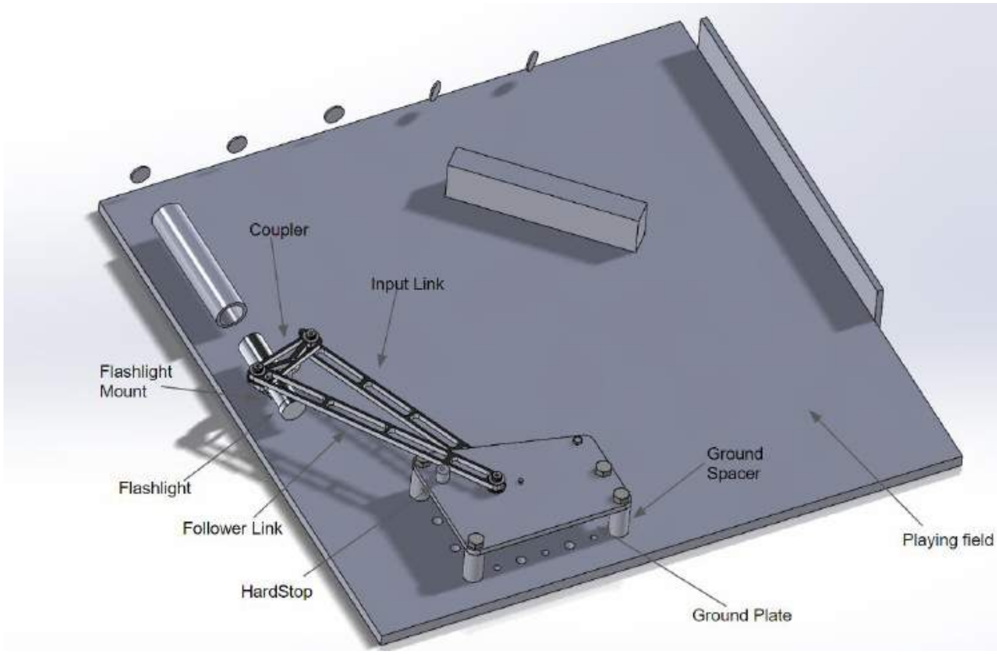


Figure 4. This figure shows an overview of a CAD model of the linkage mounted to the playing field with callouts annotated.

To save weight, nearly all materials used in the final design are made using aluminum, with the only exception being the flashlight mount, which was 3D printed, and any bearings, bushings, or nuts. The links are all made of aluminum sheet stock with the outer profiles and light weighting cut out by waterjet. The flashlight mount is meant to serve 2 purposes, one of them being exact location and angle control of the flashlight, and the other acting as a monopod to reduce bending moments in the links and friction increased on the aluminum shoulder bolt joints. Figure 5 below shows a closeup of the coupler link with the flashlight mounted on the playing field.

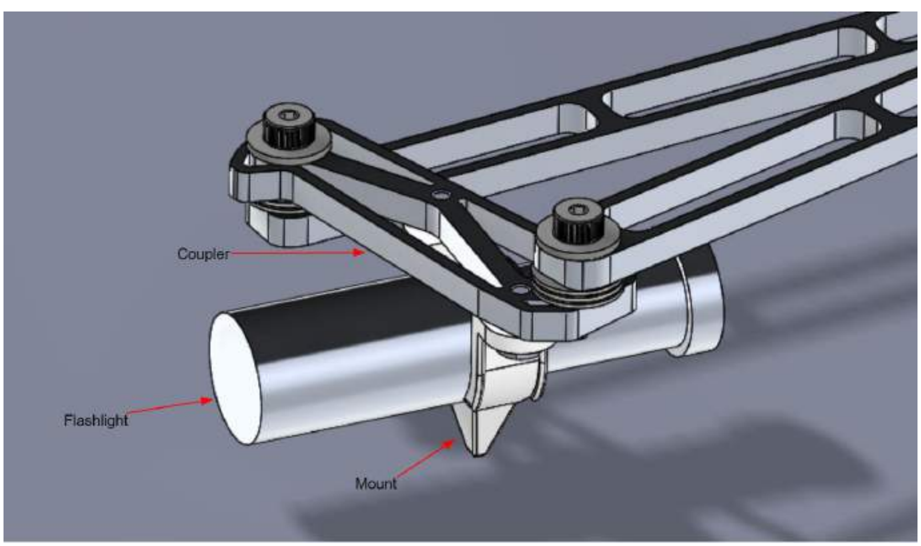


Figure 5. This figure shows the flashlight mounting and flashlight on the coupler, as well as the monopod leg.

Other crucial parts include the ground plate, whose final design is laid out above, ground plate spacers, and hard stops. The ground plate spacers are necessary because in our design, the ground plate is in between the input and follower links. The hard stops are aluminum cylinder stock cut to a minimum height. They are bolted down to the ground plate via an a-centric tapped hole. This allows us to rotate the hard stop and change the contact position of the linkage. This adjustability allows us to have great flexibility in the positioning of our hard stop without the creation of a complex part.

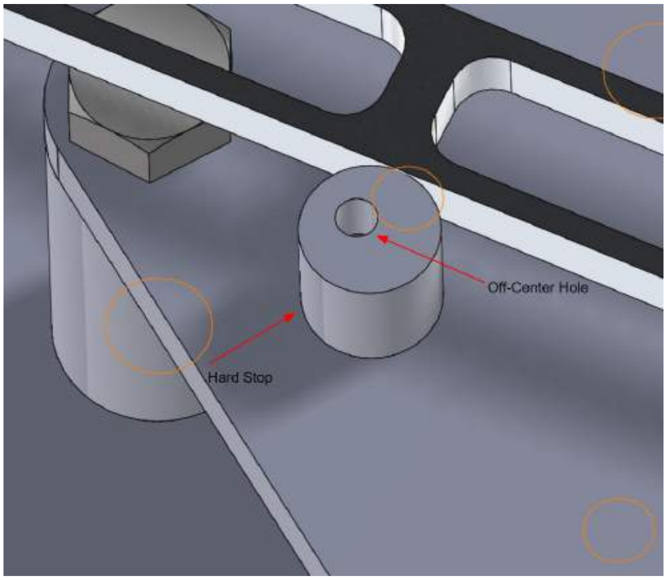


Figure 6. This is an image of the hard stop, with a specific call out for the “off-Center”, or a-centric hole that enables the linkage stop positions to me manually adjusted into position.

The joint design is methodical and follows a consistent logic. One of the components being linked must have an oil bushing press fit into it, and the other component in the joint will have a tapped 10-24 hole that the shoulder bolt will thread into. The shoulder bolt is placed the link with a bushing pressed in, with an oil washer under the bolt. A needle-roller bearing and appropriate washers are placed in between the links in order to ensure a perfect fit. All four of our joint designs are the same, shown in Figure 7 below.

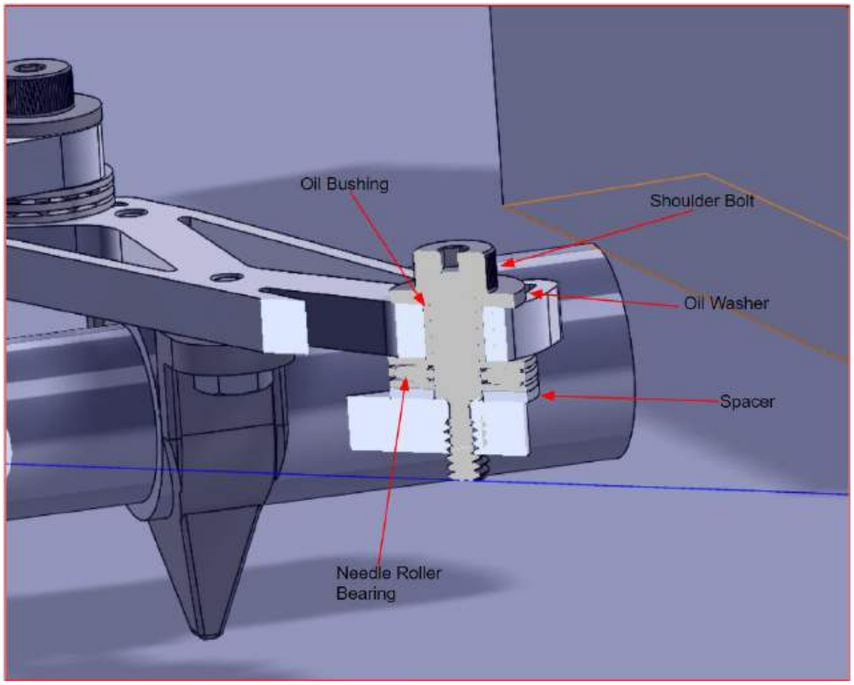


Figure 7. This figure depicts a labelled CAD cross section screenshot of the joint assembly. While some vary in vertical orientation all linkage joints follow the same design.

Section 3.2: Motion

The linkage driving arm follows an 84.52 degree sweep to complete its full range of motion from target 1 to target 5. The ends of its range of motion are show in Figure 8 below.

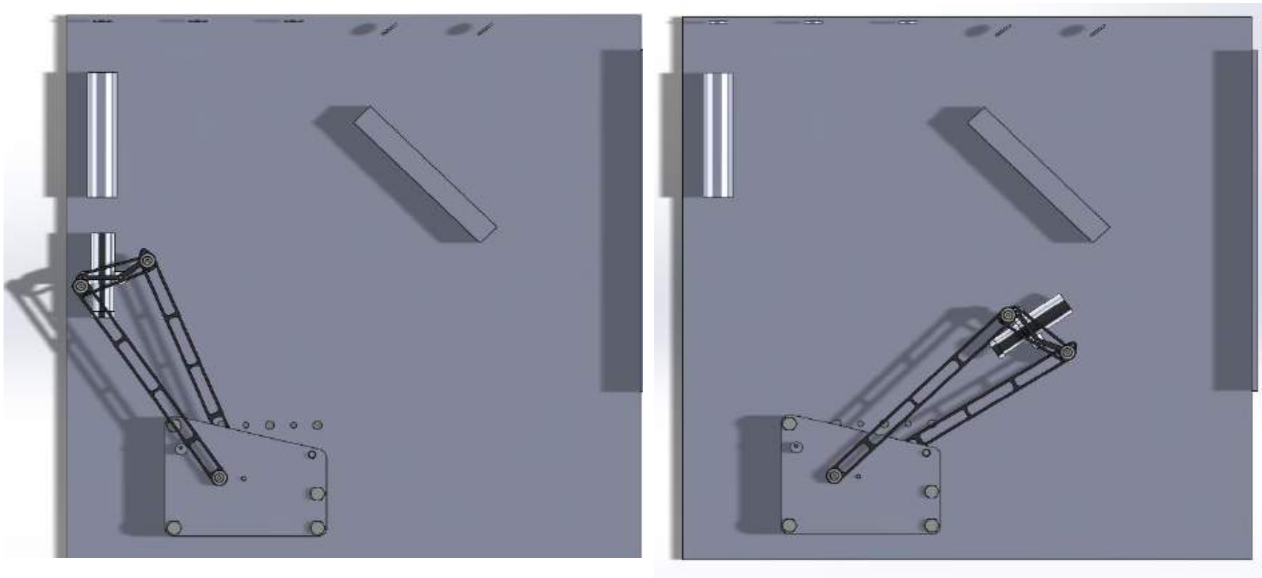


Figure 8. This figure depicts the starting, position 1, on the left and farthest rotational position, position 5, on the right.

The team performed a preliminary analysis of the linkage in ADAMS to determine the power and torque required to move the mechanism, as well as how quickly the linkage can move through its entire range of motion, while staying within the power boundaries of the motor. The time shown below was derived empirically by testing the power consumption necessary to cause the acceleration needed to sweep the linkage through its entire range of motion. The power consumption was not to exceed 2.75W, which is the power the motor can sustainably generate. The power necessary to drive this motion in the time below is also given below.

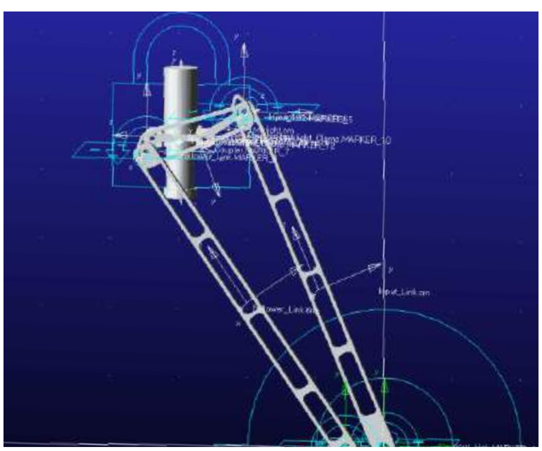


Figure 9. This figure displays a screenshot of the Linkage assembly inside and set up on the ADAMS dynamic simulation software. The simulation estimated the time required to pass through the full motion at 0.425 seconds with a maximum power consumption of 2.6 watts.

The goal of the ADAMS trials was to determine the functional limitations of the linkage and the power train design requirements thereof. These metrics are summarized by angular position, angular velocity, power consumption, and the input torque, summarized in Figure 10 on the following page.

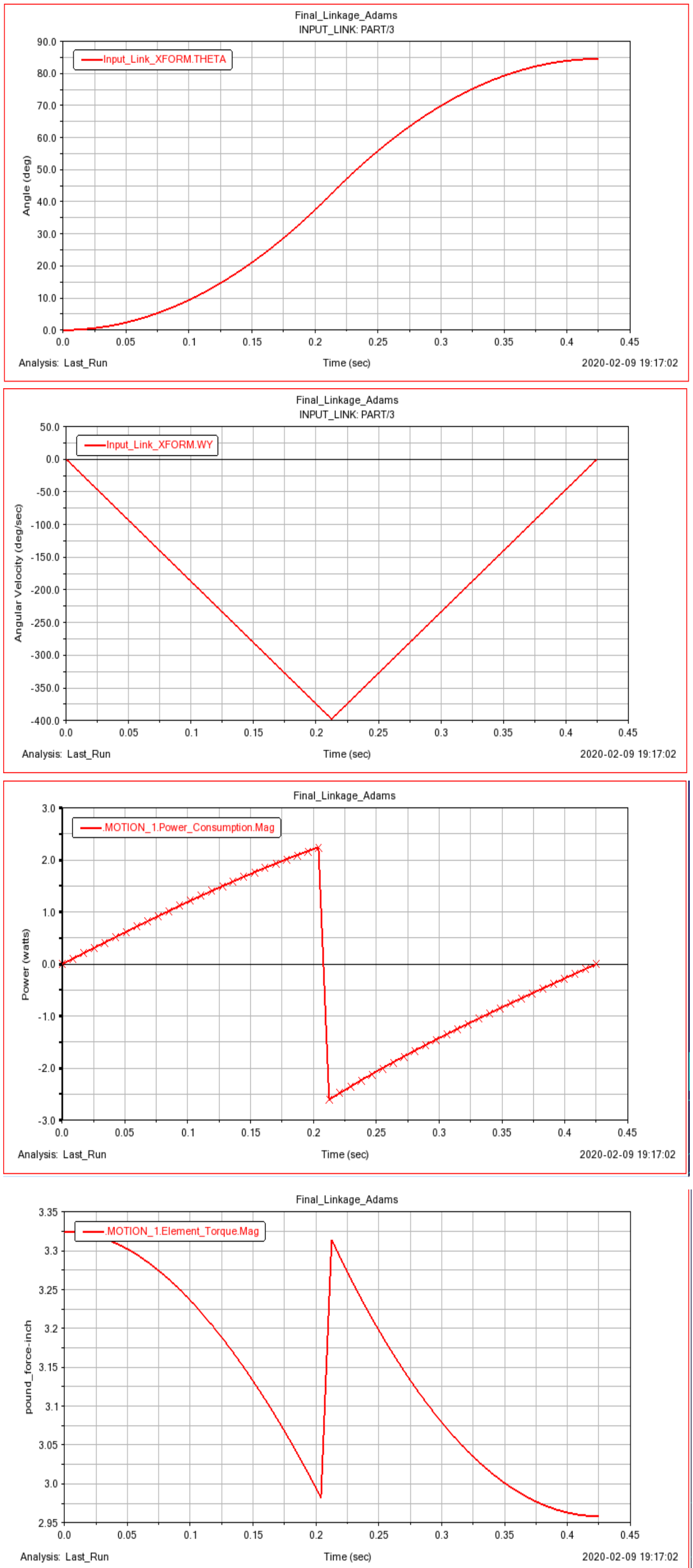


Figure 10: This figure depicts the angular position, angular velocity, angular velocity, power, and necessary input torque, over time. position

The top graph to the left shows the angular position, starting in position 1. The total time to sweep through the largest potential motion of the linkage, 84.52°, was 0.425 seconds. The Second Graph shows the angular velocity through the range of motion over time. Here positive velocity is defined as counterclockwise. The maximum velocity reached is -400 deg/sec while beginning and ending at 0 deg/sec. The third graph shows the power through the motion reaching maxima and minima at 2.2 watts and -2.55 watts. The final, bottom, graph shows the torque on the input link that will have to be applied by the driving motor and gearing with a maximum torque of 3.325 lbf-in.

Section 4: Late Design Changes

After further review two additional design changes were made to improve the linkage's manufacturability and functionality. The first modification was to reduce the size and number of manually milled spacers. The second modification was made to better control the flashlights positioning relative to the playing field and coupler link. By adding a monopod and shelf, we were able to ensure the light would shine parallel to the field and not apply unwanted friction to the shoulder bolted joints. Figure 11 below shows the before and after of this design modification.

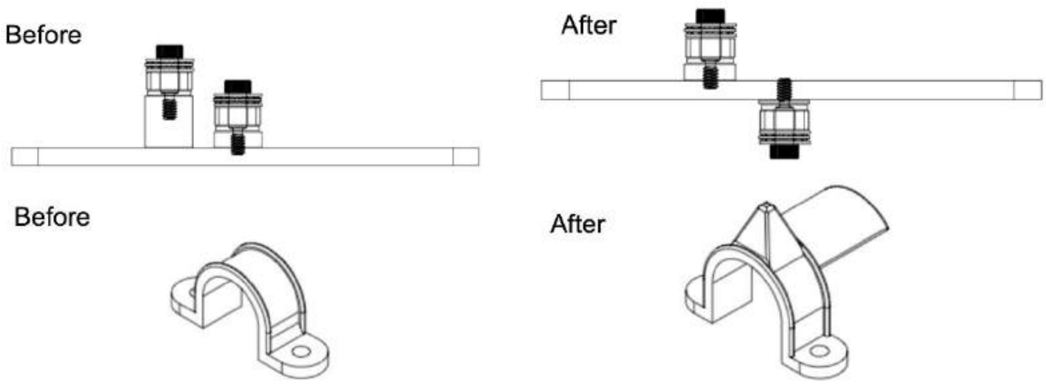


Figure 11. This figure shows line drawings comparing the described changes made to joint spacers and the flashlight mount.

Section 5: Transmission Design

For transmission ratio, describe the methods used to generate the transmission ratio (inertia matching, and light beam resolution) and the rationale behind using them. Include justification of the methods and explain their validity (calculation vs. reality). Introduce relevant equations, variables, and given values (such as motor inertia, encoder resolution, etc.).

Section 5.1: Transmission Ratio

To determine the best gear ratio for optimal performance of our linkage, we used two different methods. The first method was the inertia matching method. The idea behind this method is that as the linkage moves, the relative center of mass of individual links changes the inertia of the linkage relative to the ground pivot, which changes the amount of torque necessary to move the linkage at different positions. In this method, we define the "optimal" transmission ratio as the ratio that minimizes the torque required by the motor. From minimizing the torque, we get that the optimal transmission ratio $N = \sqrt{IL/IM}$. This means that we must calculate the moments of inertia of the linkage. This can be done by using the Parallel Axis Theorem, $I = Icm + m \cdot r^2$, where I is the inertia about a point, Icm is the inertia of the object about its center of mass, m is the mass of the object, and r is the distance of the center of mass of the object from the point. In order to calculate the I value of the entire linkage, we use the parallel axis theorem to calculate the inertias of each link and then add them up. This must be done at each position 1-5, and then the maximum of these will be used in calculations. Figure 12 and 13 below shows the r values for each position and the values that go into the transmission ratio calculations.

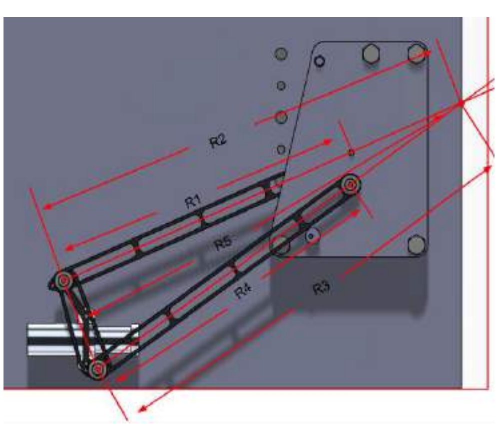


Figure 12. This figure defines the variables used in the inertial matching method R1, R2, R3, R4, and R5. Each represents a distance, in cm, and vary as the linkage sweeps through its range of motion.

Fixed Variables		
Variable	**Value**	**Units**
minput	34.93	(gram)
moutput	30.64	(gram)
mcoupler	116.5	(gram)
Iinput_CG	2818.34	(gram*cm^2)
Ioutput_CG	2232.84	(gram*cm^2)
Icoupler_CG	884.73	(gram*cm^2)

Position 1		
Geometric Variables		
Variable	**Value**	**Units**
R1 (input link)	26.46	cm
R2	39.19	cm
R3	40.06	cm
R4 (output link)	25.93	cm
R5	39.39	cm
Total Inertias of a Link (via Parallel Axis)		
Variable	**Value**	**Units**
Iinput	8932.239197	(gram*cm^2)
Ioutput	7383.155134	(gram*cm^2)
Icoupler	181642.8797	(gram*cm^2)
Scale Factors		
R1/R2	0.6751722378	(unitless)
(R1*R3)/(R2*R4)	1.043092937	(unitless)
Total Inertia		
Itotal	99768.70675	(gram*cm^2)

Position 2		
Geometric Variables		
Variable	**Value**	**Units**
R1	26.46	cm
R2	38.52	cm
R3	38.88	cm
R4	25.93	cm
R5	38.38	cm
Total Inertias of a Link (via Parallel Axis)		
Variable	**Value**	**Units**
Iinput	8932.239197	(gram*cm^2)
Ioutput	7383.155134	(gram*cm^2)
Icoupler	172492.0726	(gram*cm^2)
Scale Factors		
R1/R2	0.6869158879	(unitless)
(R1*R3)/(R2*R4)	1.029976464	(unitless)
Total Inertia		
Itotal	98155.64783	(gram*cm^2)

Position 3		
Geometric Variables		
Variable	**Value**	**Units**
R1	26.46	cm
R2	39.66	cm
R3	39.41	cm
R4	25.93	cm
R5	39.22	cm
Total Inertias of a Link (via Parallel Axis)		
Variable	**Value**	**Units**
Iinput	8932.239197	(gram*cm^2)
Ioutput	7383.155134	(gram*cm^2)
Icoupler	180086.0086	(gram*cm^2)
Scale Factors		
R1/R2	0.6671709531	(unitless)
(R1*R3)/(R2*R4)	1.014007222	(unitless)
Total Inertia		
Itotal	96683.03632	(gram*cm^2)

Position 4		
Geometric Variables		
Variable	**Value**	**Units**
R1	26.46	cm
R2	35.81	cm
R3	33.54	cm
R4	25.93	cm
R5	34.36	cm
Total Inertias of a Link (via Parallel Axis)		
Variable	**Value**	**Units**
Iinput	8932.239197	(gram*cm^2)
Ioutput	7383.155134	(gram*cm^2)
Icoupler	138425.7484	(gram*cm^2)
Scale Factors		
R1/R2	0.7388997487	(unitless)
(R1*R3)/(R2*R4)	0.9557538593	(unitless)
Total Inertia		
Itotal	91253.19503	(gram*cm^2)

Position 5		
Geometric Variables		
Variable	**Value**	**Units**
R1	26.46	cm
R2	35.09	cm
R3	32.69	cm
R4	25.93	cm
R5	33.57	cm
Total Inertias of a Link (via Parallel Axis)		
Variable	**Value**	**Units**
Iinput	8932.239197	(gram*cm^2)
Ioutput	7383.155134	(gram*cm^2)
Icoupler	132173.8109	(gram*cm^2)
Scale Factors		
R1/R2	0.754060986	(unitless)
(R1*R3)/(R2*R4)	0.95064611	(unitless)
Total Inertia		
Itotal	90759.68578	(gram*cm^2)

Transmission Calculations		
Variable	**Value**	**Units**
Maximum Linkage Inertia (IL)	99768.70675	(gram*cm^2)
Imotor	25000	(gram*cm^2)
Transmission Ratio (N)	[illegible]	**(unitless)**

Figure 13. This figure shows the datum at each linkage position necessary to calculate gear ratio using inertial matching. this method produced a recommended transmission ratio of 1.99768.

The transmission ratio calculated from the inertia matching method was 1.99768 which was rounded to 2. To further confirm or reject the results of this analytical method a second form of analysis was used referred to as the light beam resolution method.

The light beam resolution method calculates transmission ratio based on how responsive the system is to changes in position. At each target position, the light beam's angle with respect to the horizontal was measured. The minimum angle measurement refers to when the light beam covered only the left half of the target, while the maximum angle measurement refers to when the light beam covered only the right half of the target. This range, along with the specs of the encoder and motor, are used to determine a transmission ratio that will prevent the light beam from moving past the target before the system recognizes that it is at the target location. Table 5 below shows the quantitative inputs and output resulting from the light beam resolution transmission analysis method.

Table 5. This shows the inputs and outputs of the light beam resolution transmission analysis method for the final 4 bar linkage.

Position	Minimum Angle [deg]	Maximum angle [deg]	Difference
1	65.34	68.73	3.39
2	79.02	82.36	3.34
3	92.51	96.08	3.57
4	142.55	145.07	2.52
5	147.81	149.99	2.18
Minimum difference	2.18		
Desired Count Range	30		
Desired Ratio	2.580275229		

The desired transmission ratio was calculated Using Equation 1 below.

$$Ratio = Desired\ count\ range/((minimum\ difference/360) * Encoder\ Resolution * Gearbox\ ratio)$$ [Eqn. 1]

The encoder resolution is 64 bits; the gearbox ratio is 30. It is possible that the angle measurements have a small amount of error, but not enough to significantly impact the final “Desired Ratio” value.

The transmission ratio of 2.58 obtained from the light beam resolution method is greater than the transmission ratio of 2 obtained from the inertia matching method. The higher ratio provides a greatest safety factor for achieving the required torque and speed, therefore 2.58 was chosen as the target transmission ratio.

Section 5.2: Transmission Type

The next step in selecting the mechanism’s transmission was to decide the transmission type. Each transmission type was evaluated on its relative price, manufacturability (how many parts would have to be made and how long it would take to manufacture those parts), and backlash reduction. Each identified assembly type, belt and pully, gear and pinion, and chain and sprocket, were given a point value of 1, 2, or 3 in each category based on their expected achievement relative to one another. The lowest achieving transmission type was given a 1 and the highest a 3.

Each evaluation category was then weighted based on a group consensus of its importance to the operation of our linkage. Price was given a low 2x weighting because while under a budget we had allotted a conservative 70% of our total budget to spend on the linkage transmission. Manufacturability was given a 7x due to two factors: the deadlines to have the linkage mechanically operational by March 20th and the common tradeoff between the complexity and precision wherein a long list of complex parts will likely be made with less precision than a short list of simple parts. Backlash reduction was given a 4x multiplier because high backlash has the potential to greatly reduce transmission efficiency and therefore impede the linkage performance during competition**.**

Transmission Type 1, Belt and Pulley: Based on the pricing from McMaster-Carr, a nylon bearing embedded round belt pulley costs approximately $14-$19 per unit based on unit size and a round belt with a cross sectional diameter of 1/8” costs approximately $5. In order to approximate cost, we evaluate the price of a belt and pulley we estimated 2 small diameter gears (input and tensioner) at $14 each, 1 larger diameter gear, priced at $19, and 1 1/8” belt would be required to complete the transmission. This put the estimated cost at $52. The main hindrance to the manufacturability of a rack and pinion is the number of shafts and therefore braces (bracing each shaft on two ends to keep backlash down) this means the assembly would require 2 additional shafts and at least 1 extra plate with 2 high precision bore holes and spacers to secure each shaft. This transmission would also require one of these shafts to be on a variable mount which would also increase manufacturing complications. A strength of belt and pulley transition is low backlash. Though if inadequately tensioned there could be slipping of the belt around the tensioning wheels the which would cause a reduction in efficiency. This problem while not insurmountable offers a high potential for future complications in design and assembly.

Transmission Type 2, Gear and Pinion: Based on the pricing from McMaster-Carr a 24 pitch 20-degree pressure angle imperial gear set with a speed reduction ratio 2 < N < 3 would cost approximately $41us, $16 for the pinion and $25 for the output gear. This transmission system would only require 1 additional shaft and 1 extra support plate with 1 bore hole and spacers. The Downside to this Transmission is a relatively high backlash and lower efficiency.

Transmission Type 3, Chain and Sprocket: Based on pricing from McMaster-Carr a 2.5 reduction ratio would cost approximately $35 for 2 smaller and 1 larger sprocket and another $11 for 2' of chain and a connecting link, making the total cost approximation $46. The manufacturability of the chain and sprocket is quite like the belt and pulley except that the tensioner does not need to tension the chain nearly as much as the belt in order to transmit the same force. Backlash for the chain and sprocket is quite like the gear and pinion except that due to tensioning we expect it may be slightly lower having a slightly high efficiency than the gear and pinion.

The relationships between these different transmission types are described in Table 6 below where the %Score represents the point value a transmission type divided by the total possible number of points, 39.

Table 6. This table shows the transmission type selection pew chart used to select between belt and pully, gear and pinion, and chain and sprocket transmissions.

	Multiplier	**Type 1**	**Type 2**	**Type 3**
Price	x2	1	2	3
Manufacturability	x7	1	3	2
Backlash Reduction	x4	3	1	2
%Score	N/A	53.8%	74.4%	71.79%

As seen by the %Score values in Table 6 transmission type 2, pinion and gear, proved the most promising. The final step in transmission selection was choosing a specific set of gears. Having decided to purchase from McMaster-Carr to be able to have reliable cad and tolerance specks for each purchased part to lower the possibility of misalignment and manufacturing error to inaccuracies in CAD files, we then had to establish our selection criteria. After discussion and skimming through McMaster-Carr's metal gear options we established that we wanted to select from the 48 pitch gears to reduce backlash as much as possible, as backlash was established this transmission type's weakest feature.

Section 5.3: Gear and Pinion Selection

Within the gear and pinion design space we determined three metrics for part selection. First, the gear set must be as close to the conservative gear ratio estimate of 2.56 as possible. Second the output gear must have a large enough face outside of its hub to secure 2 4-40 screws. Third, the input gear must have a large enough hub diameter to securely drill a ¼" hole on the face and still have enough mass left on the hub to drill and fit a 1/16 diameter spring pin through to secure the gear to the drive shaft.

Using these criteria, we narrowed down the pair options to two, N=2.667 and N=2.400. These gear pairs are described in Table 7 on the following page.

Table 7. This table shows the two gear sets in consideration for use in the linkage transmission. The four gears are separated into two groups the input and output of a 2.667 transmission ratio and 2.400 transmission ratio.

	N = 2.667		**N = 2.400**	
	input	output	input	output
Part Number	7880K19	6832K45	7880K18	6832K44
Teeth	18	48	15	36
Hub Diameter	0.28"	0.50"	0.22"	0.5"
Pitch Diameter	0.375"	1.000"	0.312"	0.750"
Price	15.78	23.38	14.47	21.38

While the N=2.400 gear pair is cheaper the output gear only has 0.125" radially to mount the 4-40 screws and the input gear could not be mounted to a ¼" shaft by a spring pin due to its small hub diameter. Therefore, we selected a pinion and gear transmission purchased from McMaster-Carr made from an input gear 7880K19 and output gear 6832K45 with a speed reduction ratio of N=2.667.

Section 5.4: Final Transmission Design

Given the transmission type and specific parts selected the linkage must be redesigned to fit the necessary motor gears drive shaft and support bushings needed for the transmission to operate smoothly. A screengrab of the modified linkage design is shown in Figure 14 below.

Figure 14. This figure depicts a wide-angle view of the linkage design with the added transmission.

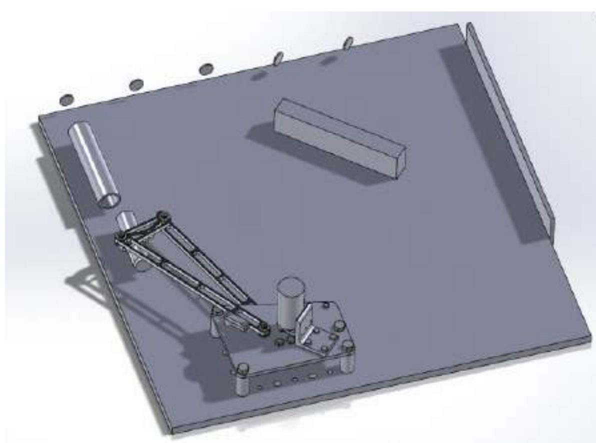


Figure 15, on the next page, shows the finalized transmission design that will be used to drive the input link. The parts that had to be added to the linkage design include, the motor, motor mount, motor shaft extension, motor shaft support and spacers, and two gears used to increase the torque from the motor and achieve the maximum acceleration of the linkage while being able to accurately hit each target. Other components also added were places to mount the limit switches, which will be attached to the hard-stop. All parts are labeled in figures below.

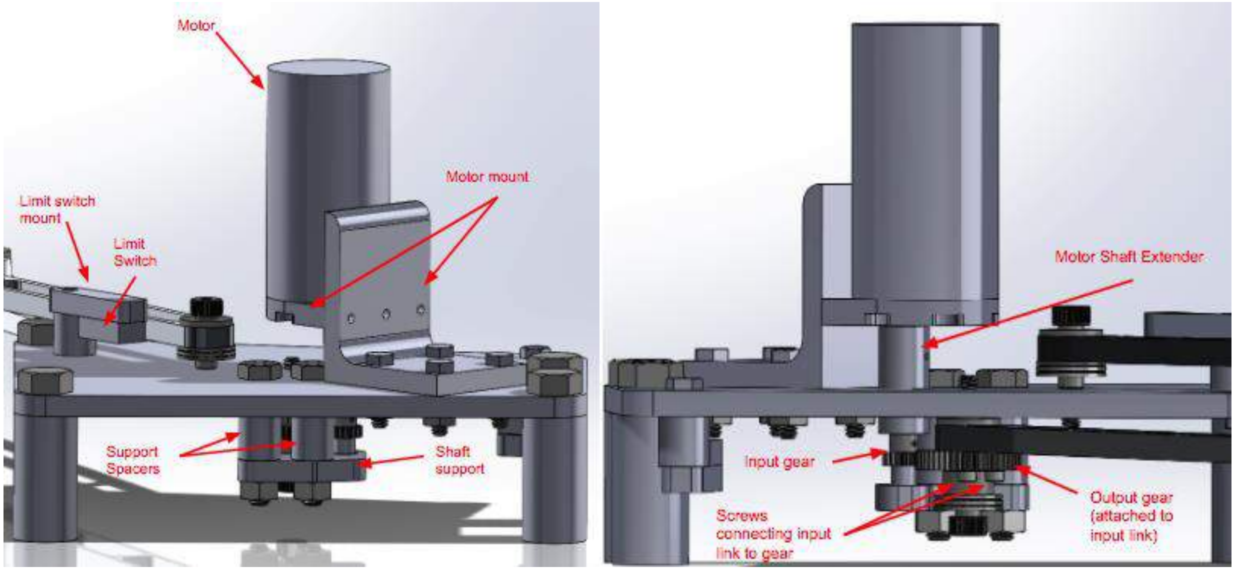


Figure 15. This figure shows a close-up view of the transmission assembly from 2 angles. Each image is annotated with part labels in red. The playing field is hidden for ease of viewing.

There are a few components of the assembly that transfer torque and require special attention. The motor shaft extender transfers torque from the motor to the motor shaft to the input gear and will be connected to both using spring pins to effectively transfer this force. The input gear then must transfer torque to the output gear, which is accomplished by the teeth of the gears meshing. Our transmission has a gear ratio (N) of 2.66. This means the torque from the input gear will be multiplied by 2.66 in the output gear. Finally, the output gear must transfer the torque to the input link, which is done so by rigidly attaching the output gear to the input link with two screws.

To reduce backlash an additional support plate was added. This plate will support rotation of the shaft extender on the other side of the gears and transmission. This is done by spacing a water jetted piece of ¼ inch aluminum plate from the bottom of the ground plate and be press fit onto an oil bushing which the end of the drive shaft will rotate in, pictured below in Figure 16. Angle stock will be used as a means of mounting the motor to the ground plate. The design is rigid and is not meant to be adjustable. We do not want much motion or vibration in our transmission to prevent misalignment issues, so tolerances must be high for all additional holes added to the ground plate.

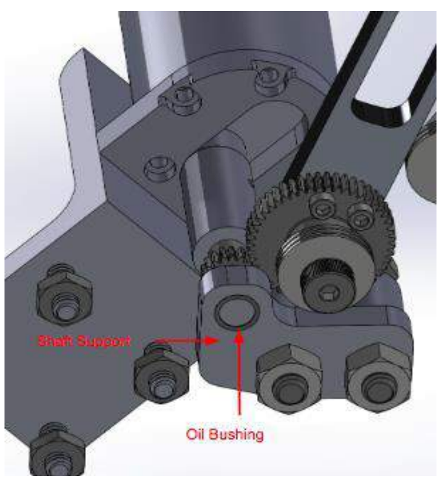


Figure 16. This figure shown a screengrab highlighting the shaft support plate, labeled shaft support. This is a view from the bottom of the assembly with the base plate hidden to reduce confusion.

The additional weight added by the transmission will mostly be due to the motor, gears, and mounting brackets. The motor weighs the most, around 200 grams, which is almost as much as our entire linkage. We expect the additional weight added to the ground plate to be somewhere between 300 and 400 grams. This should not affect any torque/power calculations done on the linkage however, as this additional weight is not part of the moving linkage.

The final addition to the design is a mounting plate that will be used to mount the limit switch in the hard stop. Like the hard stop itself, the limit switch mount will be adjustable, so we may position the limit switch exactly as needed in order to be switched when the link hits the boundary of its desired range of motion. An image of the limit switch mount can be seen in Figure 17 below.

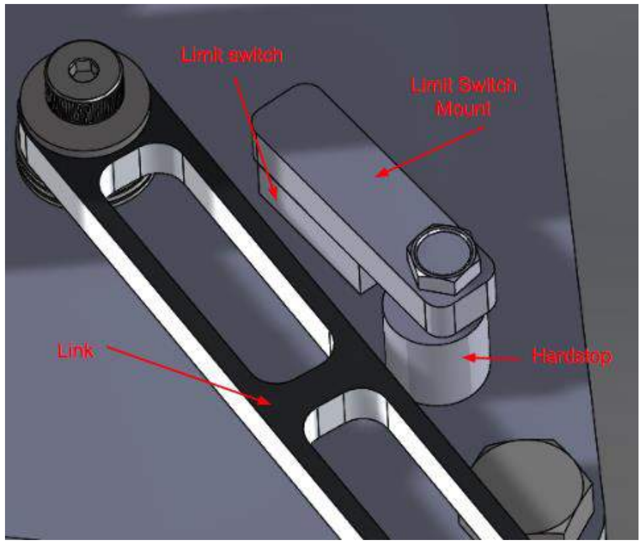


Figure 17. This figure shows a close up of the assembly highlighting the limit switch mount and its relation to the limit switch link and hard stop.

Section 6: Power Analysis

After determining the transmission ratio and making addition to the linkage assembly we recalculated the time it takes the linkage to move though its full range of motion. The step-by-step method used to calculate the time of motion (T_{motion}) is demonstrated in the procedure below.

1. Compute total inertia J of the system
   a. $J = J^L + J^m = 99768.707gcm^2 + 25000gcm^2 = 124{,}768.707gcm^2$
2. Assuming triangular velocity profile, $\theta = 0.5 \cdot base \cdot height = 0.5 \cdot (0.425s) \cdot (2.222rad/s) = 0.472rad$
   a. $\omega_{max} = \frac{2\theta}{Tmotion} = \frac{2(0.472rad)}{0.425s} = 2.222rad/s$
   b. $\omega\frac{d}{dt} = \frac{2\omega_{max}}{Tmotion} = \frac{2(2.222rad/s)}{0.425s} = 10.458rad/s^2$
3. Compute the load torque τ_L
   a. $\tau = J\omega\frac{d}{dt} = \frac{2J\omega_{max}}{Tmotion} = \frac{4\Theta J}{Tmotion} = \frac{4(0.472rad)(124{,}768.707gcm^2)}{(0.425s)^2} = 0.1304Nm$
4. Relate τ_L to T_m
   a. $n = \frac{\tau^L}{Tm} \Rightarrow T_m = \frac{\tau^L}{n} = \frac{0.1304Nm}{2.580} = 0.05054Nm$
5. Use the general equation for a linear torque speed curve to relate the motor's T to ω
   a. $\frac{T^L}{n} = \frac{T_{nom}V_S}{V_{nom}} - Kn\omega_{max} = \frac{0.1304Nm}{2.580} = \frac{(0.14kgm)V_S}{12V} - 0.00405(2.580)(2.222rad/s) \Rightarrow V_s = 6.322V$
6. Limiting V_s to 10V, find the smallest T_{motion}
   a. $T_L = n(\frac{T_{nom}V_S}{V_{nom}} - Kn\omega_{max}) = 2.580(\frac{(0.14kgm)(10V)}{12V} - 0.00405(2.580)(2.222rad/s) = 0.2411Nm$
   b. Two Cases
      i. $\omega_{max} = \frac{2\theta}{Tmotion} \Rightarrow T_m = \frac{2(0.472rad)}{2.222rad/s} = 0.425s$
      ii. $T_L = \frac{4\Theta J}{(T_m)^2} \Rightarrow T_m = \sqrt{\frac{4\theta J}{T_L}} = \sqrt{\frac{4(0.472rad)(0.012477kgm^2)}{0.2411Nm}} = 0.3126s$
   c. The shortest time is observed in Case II, 0.3126s

Section 7: Torque Transfer Analysis

Torque is being transferred in two places. As seen below, first is from the motor's adapter shaft, through gear to the spring pin. The second is from the link to the output gear. Torque transfer is important to know the size of the spring pin needed to withstand the maximum force of the motor. The torque transfer points described are marked in red annotation in Figure 18 below.

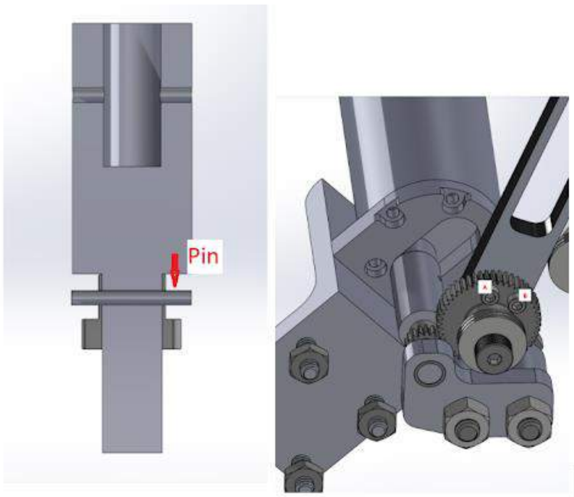


Figure 18. This figure shows a cross section of the motor shaft and input gear assembly where the pic transfers the torque from the drive shaft to the gear. The right image is a bottom view of the transmission highlighting the two screws that will be transferring the drive shaft torque, through the transmission gears, into the driving link.

Quantitative torque transfer analysis was then conducted as described in the procedure below.

1. Looking up the motor specs, T_s = 0.14kgm*g. Knowing 350 will operate the motor at 10V scaling to the correct $T_s = \frac{10V*0.14kgm}{12V} = 1.167kgm*g$
2. To find the force on the motor, $F_m = \frac{T_S}{radius\ of\ shaft_m} = \frac{1.167kgm*g}{0.003m} = 389kg*9.81m/s^2 = 3{,}816.09N$
3. Two analysis:
   a. Shear stress acting on 1/16" (1.5875mm→ radius is 0.79375mm) pin, τ is $\tau = \frac{F_m}{cross\ area\ of\ pin} = \frac{3{,}816.09N}{\pi(0.00079375m)^2} = 1{,}927{,}974{,}384.23Pa \Rightarrow 1.927MPa$
   b. Torque transfer to force analysis to the output gear $F = \frac{T_S N}{2radius_A} = \frac{1.167kgm*9.81m/s^2*2.66}{2*(0.00014732m)} = 103{,}354.59N \Rightarrow 103kN$
   $\tau = \frac{F}{A} = \frac{103{,}354.59N}{\pi(0.14732mm)^2} = 1.5159*10^6 Pa = 1.52MPa$

The above calculations assume that the torque will be transferred with 100% efficiency. Additionally, it is assumed that the force will be distributed evenly between A and B due to the same radii and the spring pin is made from steel.

These stresses will not cause failure. Assuming the spring pin is made from general steel, the yield stress is 350 MPa, and the 303 steel for the output gear has a yield stress of 207 MPa as well as a tensile strength of 517 MPa. As these stresses are two orders of magnitude greater than calculated stresses, one can assume these stresses will not cause failure.

Section 8: Evaluation of Received Manufactured Parts

As the project syllabus outlined each team was to design their linkage with the expectation that we would be outsorcing manufacturing to a different team. With this in mind we made sure to allot for a quality assurance phase in our project schedule. This quality assurance was to evaluate the acceptability of the outsourced parts. Table 8 on the following page shows the parts that were outsources and whether they were accepted by our design team.

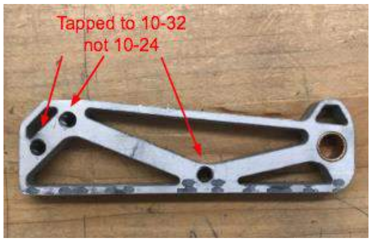
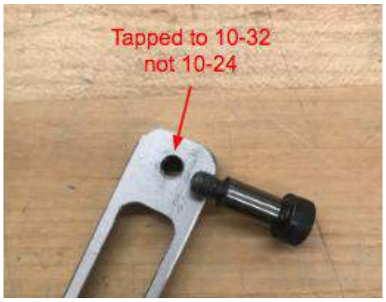
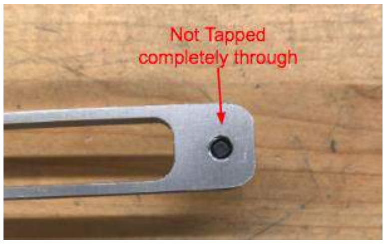
Table 8. This table shows the outsourced parts and their quality assurance evaluations.

Part	**Quantity**	**Critical Dimension**	**Meets Critical dimension tolerance?**	**All other dimensions met?**	**Accepted?**
Ground Spacer	4	Height	Yes	Yes	Yes (All)
Hard Stop	2	Height	Yes	Yes	Yes (All)
Input Link	1	Center to center hole distance	Yes	No (Tapped hole incorrect)	No
Coupler	1	Center to center hole distance	Yes	No (Tapped holes incorrect)	No
Follower	1	Center to center hole distances	Yes	Yes	Yes
Ground Plate	1	Center to center hole distances	Yes	Yes	Yes

Parts made by the manufacturing team were almost all within tolerance of our defined specifications. All links were the correct length and had center to center hole distances within tolerance. Spacers and hard stops were all made to the correct dimensions within tolerance and had a good surface finish, however, there were some errors that had to be fixed to move forward with assembly. The main issue with some of the links was that the holes were tapped to an incorrect screw thread. All holes in the coupler were meant to be tapped in 10-24 thread but were instead tapped to 10-32 thread. The threaded holes on the coupler meant for the flashlight mount were also threaded incorrectly to 10-32 instead of 10-24. The same mistake with incorrect threading was also made on the one tapped hole on the input link. For this reason, we requested that both links be remade by the manufacturing team to align with the drawings given to them by the design team.

The last issue that arose in the outsourced manufacturing was that some tapped holes were not tapped entirely through the part. This made the design team only able to thread screws into the parts through one side of the hole, which was not always possible with the orientation of the parts in the final assembly. This was an issue with both holes tapped on the coupler to which the flashlight mount would be attached, and the tapped hole on the input link. These holes were all tapped to the incorrect screw size, so they will be rejected and remade. Table 9, on the following page, shows more specifics on the rejected parts.

Table 9. This table shows the issues identified with the outsourced parts during quality assurance and the subsequent actions taken to resolve the errors.

Issue	Photo	Resolution
Incorrect tap thread on all holes in the coupler link- Tapped to 10-32 instead of 10-24 as specified on the drawing		Reject part due to issues with not having correct 10-32 stock for assembly
Incorrect tap thread on singular tapped hole on the input link - Tapped to 10-32 instead of 10-24		Find and use 10-32 shoulder bolt for range of motion review. Reject part to ease assembly in final stages
Holes tapped for flashlight mount on coupler not tapped all the way through the part		Return to machine shop and use easy-tapper to finish tapping hole through the part
Hole on input link not tapped all the way through the part		Flip input link over and thread in through the other side for range of motion review. Return to machine shop and use easy-tapper to finish tapping hole through the part

Appendix A: Bill of Materials

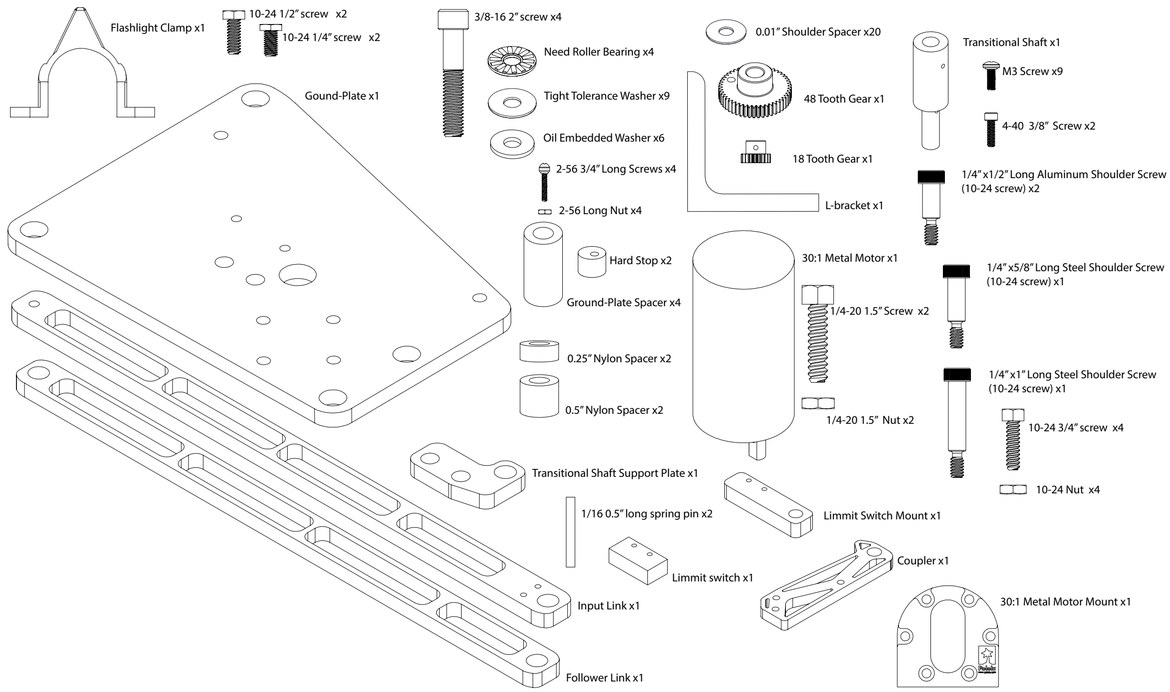
Part Name	Supplier	Part #	Price per unit($)	Amount
Aluminum Plate	Alro Steel	21430300	Kit- 0.13/sq. in.	35 sq. in.
Aluminum round stock, ½ in. Diameter	Alro Steel	Custom	Kit- 0.59/in.	4.25 in.
Aluminum round stock, ¾ in	Alro Steel	Custom	Kit- 3.62/in.	6.5 in.
Aluminum Angle, 2.5" x 2" x 1/4" thick, 6" long	Alro Steel	Custom	Kit- 0.57/in.	2.0 in.
Oil-Embedded Thrust Bearing (Washer) for 1/4" Shaft Dia., 5/8" OD, 1/16" Thk.	McMaster-Carr	5906K531	Kit- 0.97	6
SAE 841 Sleeve Bushing for 1/4" Shaft Dia., 1/4" Lg.	McMaster-Carr	6391K126	Kit- 0.51	5
Needle roller thrust bearing, Bore 2.50	McMaster-Carr	5909K23	Purchased- 2.80	4
Thrust washer for ¼" Shaft Dia, 11/16" OD, 0.032" Thk.	McMaster-Carr	5909K231	Purchased- 1.12	9
Aluminum Shoulder Screw, ¼" Diameter x ½" Shoulder, 10-24 Thread	McMaster-Carr	97381A303	Purchased- 5.46	2
Shoulder Screw, ¼" Diameter x 5/8" Shoulder, 10-24 Thread	McMaster-Carr	91259A539	Kit- 1.21	1
Shoulder Screw, ¼" Diameter x 1" Shoulder, 10-24 Thread	McMaster-Carr	91259A542	Kit- 1.31	1

10-24, ½” long screw*	McMaster-Carr	91255A242	Crib- 0.16	2
10-24, 1/4” long screw*	McMaster-Carr	91306A269	Crib- 0.08	2
10-24, ¾” long screw*	McMaster-Carr	91255A245	Crib- 0.18	4
10-24 nut*	McMaster-Carr	90480A011	Crib- 0.02	4
Socket Head Cap Screw, ⅜-16 Thread, 2” Length	McMaster-Carr	91251A632	Kit- 0.49	4
AR-100 LED Flashlight	AR Happy	B01CB2ZTYQ	Kit- 3.50	1
2-56 ¾” screw*	McMaster-Carr	91255A018	Crib- 0.38	4
2-56 nut*	McMaster-Carr	90480A003	Crib- 0.01	4
3-D printed Flashlight mount (PLA)	Duderstadt Center	Custom	Purchased- 5.00	1
.01” shoulder spacers	McMaster-Carr	91124A059	Purchased- 0.19	20
48 tooth gear	McMaster-Carr	6832K45	Purchased- 23.38	1
18 tooth gear	McMaster-Carr	7880K19	Purchased- 15.78	1
Bracket for 37D mm Metal Gearmotors (w/ 9 M3 screws)	Pololu	1995	Kit- 7.95	1
4-40 ⅜” screw	McMaster-Carr	90272A108	Purchased- 0.02	2

Nylon Unthreaded Spacers, 5/8" OD, ½" Length, for ¼" ID	McMaster-Carr	94639A694	Kit- 0.45	2
Nylon Unthreaded Spacers, 5/8" OD, 1/4" Length, for ¼" ID	McMaster-Carr	94639A674	Kit- 0.42	2
¼-20 1.5” screw*	McMaster-Carr	90272A546	Crib- 0.18	2
¼-20 nut*	McMaster-Carr	95462A029	Crib- 0.05	2
1/16 0.5” long spring pin*	McMaster-Carr	98296A027	Crib- 0.02	2
Snap Action Switch	Jameco	187733	Kit- 2.19	1
30:1 Metal Gearmotor 37Dx68L mm with 64 CPR Encoder	Pololu	4752	Kit- 39.95	1
PTFE shim stock 8”x12”x.001”	McMaster-Carr	1192N11	Purchased- 3.18 for entire sheet	¼ sq. in.
Total Purchase cost- $80.11				

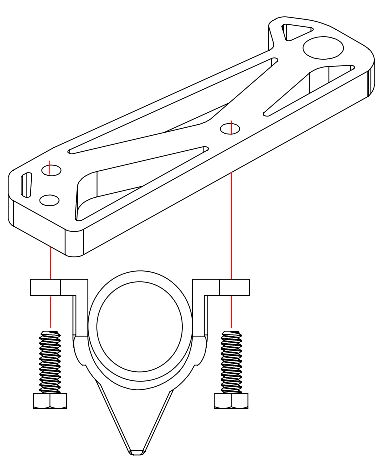
* All starred items were obtained second hand from the university. We assumed these parts to be purchased from McMaster-Carr and used the part number and price of the product that most closely resembled the part received from the crib.

Appendix B: Assembly Manual



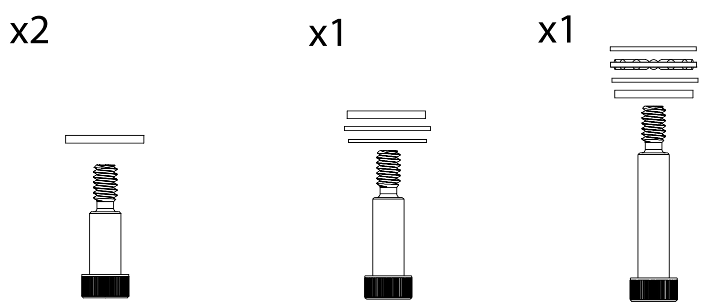
1) Assemble coupler.
    a. Place flashlight in flashlight clamp.
    b. Screw flashlight clamp onto coupler using 10-24 ¼"long screws x2 onto the off center holes of the coupler.

Step 1



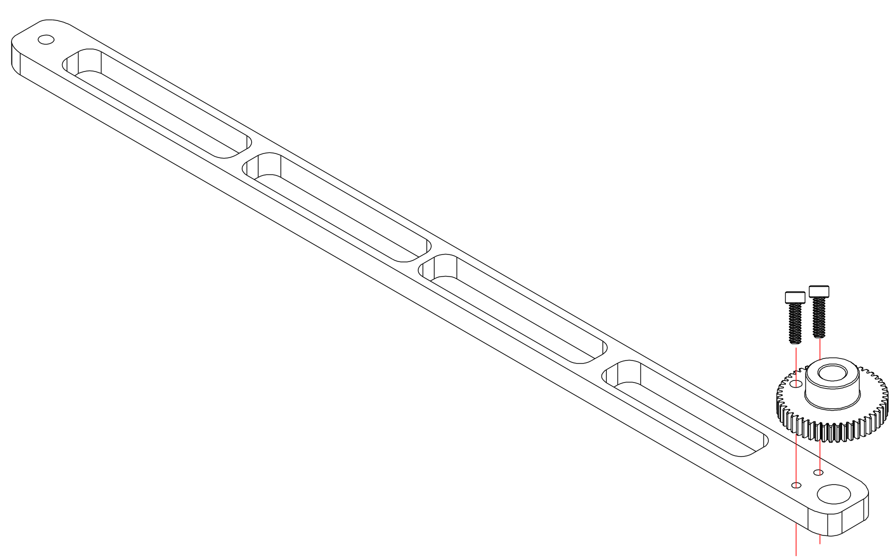
2) Prepping joints (4 oil embedded thrust washers, 2 ½" long sleeve aluminum shoulder bolt, 1 5/8" long sleeve steel shoulder bolt, 1 1" long sleeve steel shoulder bolt, 3 tight tolerance washers, 1 needle roller bearing, 1 0.01" shoulder spacer).
   a. Place an oil embedded thrust washer onto an aluminum shoulder bolt (repeat for second aluminum bolt).
   b. Place 1 0.01" shoulder spacer, 1 tight tolerance washer and an oil embedded thrust washer onto the 5/8" steel shoulder bolt, in order.
   c. Place 1 oil embedded thrust washer, a precision steel washer, needle roller bearing, then another steel washer onto the 1" shoulder bolt, in order.

Step 2



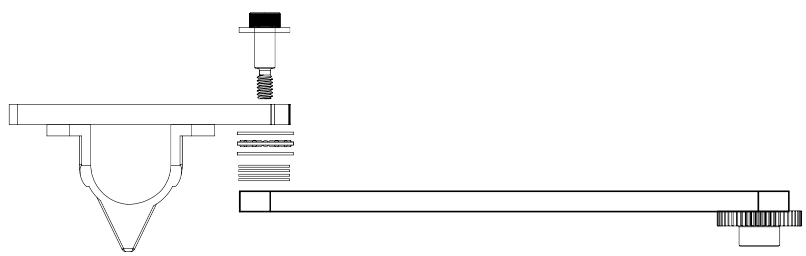
3) Fix the output gear onto the input Link (1 input link, 1 48 tooth gear, 2 4-40 3/8" long screws).
   a. Using two 4-40 screws fix the 48 tooth gear to the bottom of the input link

Step 3



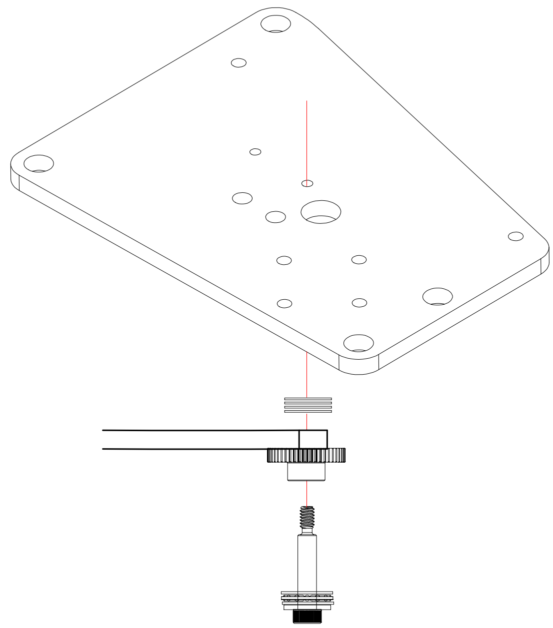
4) Create the input to coupler joint (2 tight tolerance steel washers, 3-5 .01” shoulder spacers, 1 needle roller bearing, 1 #2.a joint, 1 #3 assembly, 1 #1 assembly, 1 micrometer).
    a. Measure the shoulder bolt’s sleeve length and all of the parts to be added to this joint using a micrometer.
    b. Subtract the summed height of the parts and subtract that from the measured sleeve length. Then select an additional 3-5 .01” spacers that most accurately reduces the remaining gap to 0 without going over.
    c. On a shoulder bolt from step 2.a, slide the bushing embedded hole of the coupler onto the assembly.
    d. Place a steel washer then needle roller bearing then another steel washer onto the bolt.
    e. Place the chosen number of .01” shoulder spacers onto the stack.
        i. Determined in step b.
    f. Screw on the tapped end of the input link until flush.
        i. Make sure the gear mounted side is down.

Step 4



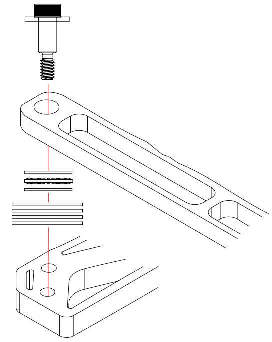
5) Create the input to baseplate joint (2 oil embedded thrust washer, 1 #2.c assembly, 1 #4 assembly,1 base plate, 1 micrometer).
    a. Measure the shoulder bolt’s hardened sleeve length and all of the parts to be added to this joint using a micrometer.
    b. Subtract the summed height of the parts and subtract that from the measured sleeve length. Then select an additional 3-5 .01” shoulder spacers that most accurately reduces the remaining gap to 0 without going over.
    c. On the shoulder bolt from 2.c slide the bushing embedded hole of the input link onto the assembly.
    d. Place the oil embedded thrust washer onto the assembly.
    e. Place the chosen number of .01” shoulder spacers onto the stack.
        i. Selected in step b.
    f. Screw the baseplate’s right center tapped hole onto the assembly.

step 5



6) Create the coupler to follower joint (2 high tolerance steel washers, 1 needle roller bearing, 3-5 0.01” shoulder spacers, 1 #2.a assembly, 1 #4 assembly,1 micrometer)
    a. Measure the shoulder bolt’s sleeve length and all of the parts to be added to this joint using a micrometer.
    b. Subtract the summed height of the parts and subtract that from the measured sleeve length. Then select an additional 3-5 .01” shoulder spacers that most accurately reduces the remaining gap to 0 without going over.
    c. On a shoulder bolt from step 2.a, slide the bushing embedded hole of the follower link onto the assembly.
    d. Place a steel washer then needle roller bearing then another steel washer onto the bolt.
    e. Place the chosen number of .01” shoulder spacers onto the stack
        i. Selected in step b.
    f. Screw the assembly into the correct tapped coupler hole

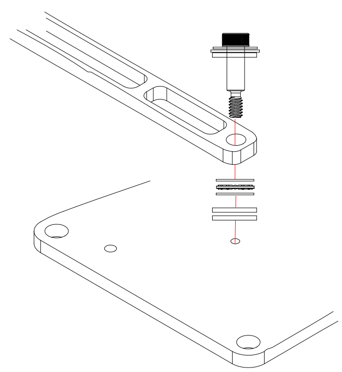
Step 6



7) Complete the linkage assembly by completing the follower to ground joint (2 tight tolerance washers, 1 needle roller bearing, 3-5 0.01” shoulder spacers, 2 oil embedded thrust washers, 1 #2.b assembly, 1 #5 assembly, 1 micrometer).

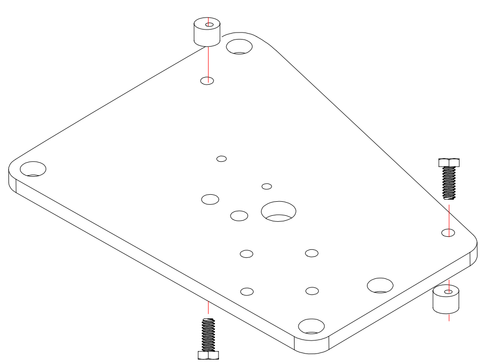
a. Measure the shoulder bolt's sleeve length and all of the parts to be added to this joint using a micrometer.
b. Subtract the summed height of the parts and subtract that from the measured sleeve length. Then select an additional 2 oil embedded thrust washers that most accurately reduces the remaining gap to 0 without going over.
c. On a shoulder bolt from step 2.b, slide the bushing embedded hole of the follower link onto the assembly.
d. Place a steel washer then needle roller bearing then another steel washer onto the bolt.
e. Place the chosen 2 oil embedded thrust washers onto the stack.
    i. Chosen in step b.
f. Screw the joint into the correct tapped hole on the baseplate.

Step 7



8) Screw on hard stops (2 acentric hard stops, 2 10-24 ½" screws).
    a. Attach 1 acentric hard stop to top side of the leftmost remaining tapped hole using a 10-24 screw from the bottom of the plate.
    b. Attach 1 acentric hard stop to the bottom side of the leftmost remaining tapped hole using a 10-24 screw from the top of the plate.

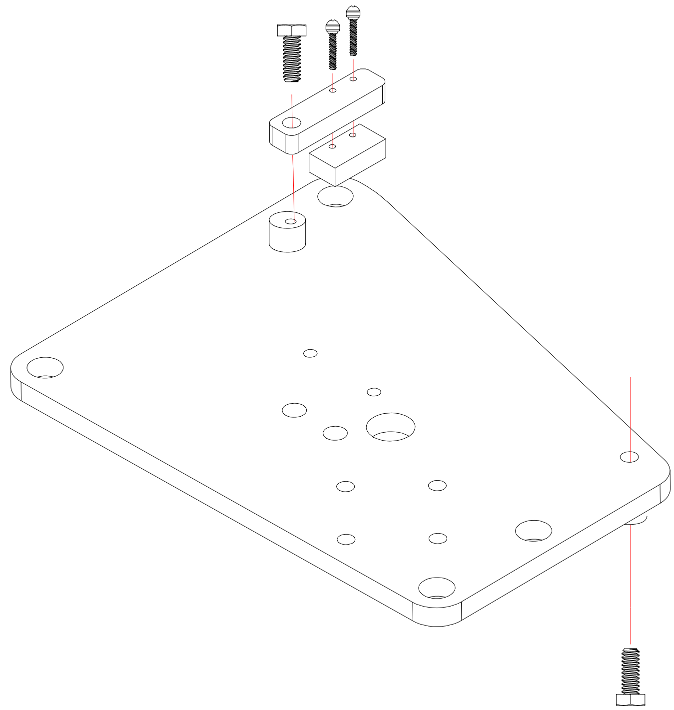
Step 8



9) Attach the limit switches to the hard stops (1 limit switches, 1 limit switch mounts, 1 #11 assembly, 2 10-24 screws).
    a. Using two 10-24 screw attach a limit switch mount to the exposed end of each hard stop.
    b. Screw the limit switches to the inside face of each limit switch mount using two 2-56 ½" long screws.
    c. Calibrate the limit switches.

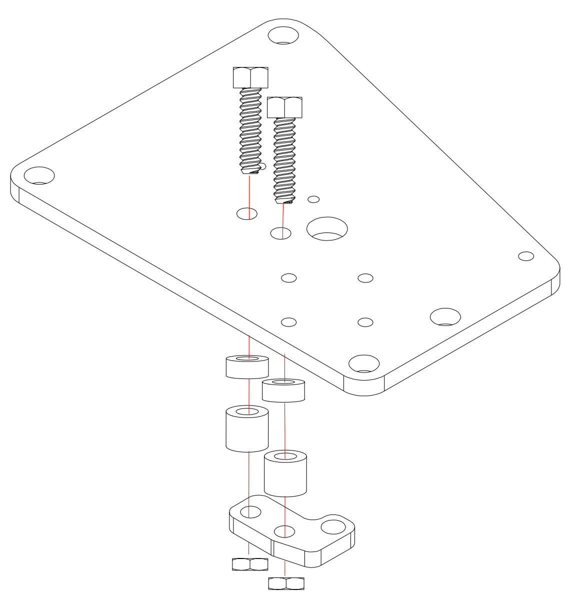
i. Loosen the screws from step a and adjust the limit switch to the correct angle.
ii. Tighten the screw back down to fix the limit switch in place.

Step 9



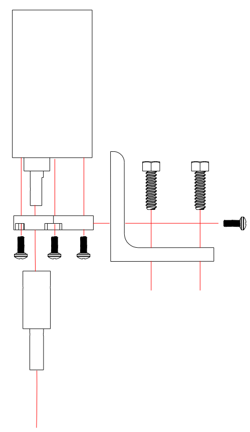
10) Mount transitional shaft support to the ground-plate (1 #9 assembly, 2 ¼-20 bolts 1.5” long, 2 ¼-20 nuts, 1 transitional shaft support plate).
    a. Using two 1.5” ¼-20 screws line up the support plate to the correct holes on the ground plate spacing the two aluminum parts apart by two sets of a .5 and .25 stacked nylon spacers.
        i. making sure to run the bolt with its head on the top of the plate.
    b. Using two ¼-20 nuts bolt the support plate into place.

Step 10



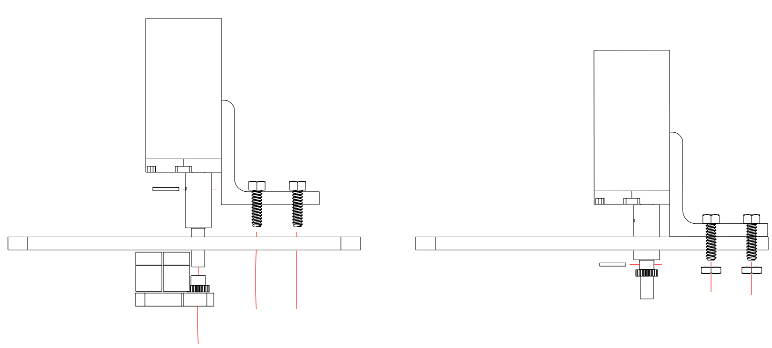
11) Assemble the motor sub assembly (1 30:1 metal motor, 1 metal motor mount, 1 L bracket, 1 transitional shaft, 9 3M screws).
    a. Using the 6 3M screws mount the 30:1 metal motor onto the motor mount.
    b. Using 3 3M screws mount the metal motor facing down onto the L bracket 2" long non milled side.
        i. This side will have a much more rounded top edge.

Step 11



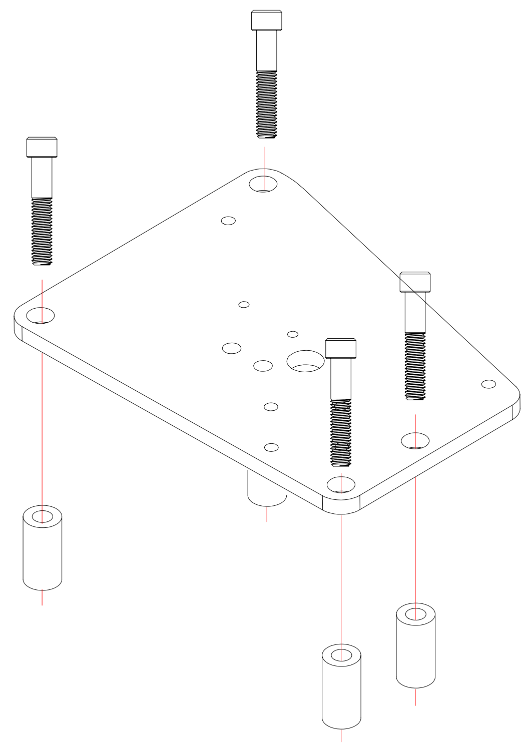
12) Mount and complete the transmission assembly (1 #11 Assembly, 1 #10 Assembly, 4 10-24 .75" long bolts, 1 18 tooth gear, 2 1/16 diameter 0.5" long spring pins, 4 10-24 nuts).
    a. Using a spring pin secure the transitional shaft to the metal motor shaft.
    b. Place the 18 tooth gear concentrically onto of the transitional shaft support's bearing.
    c. Align assembly #11 to its corresponding holes on the ground plate using the 4 10-24 bolts.
    d. Using a second spring pin fix the 18 tooth gear to the corresponding spring pin hole on the transitional shaft.
    e. Fix the transmission assembly in place by tightening by screwing 4 10-24 nuts onto the bolts from step c.
        i. This may require you to loosen the nuts from step 10 in order to center the shaft with the bushing.
        ii. After realigning you should then tighten the support plate back to a locked position.

Step 12

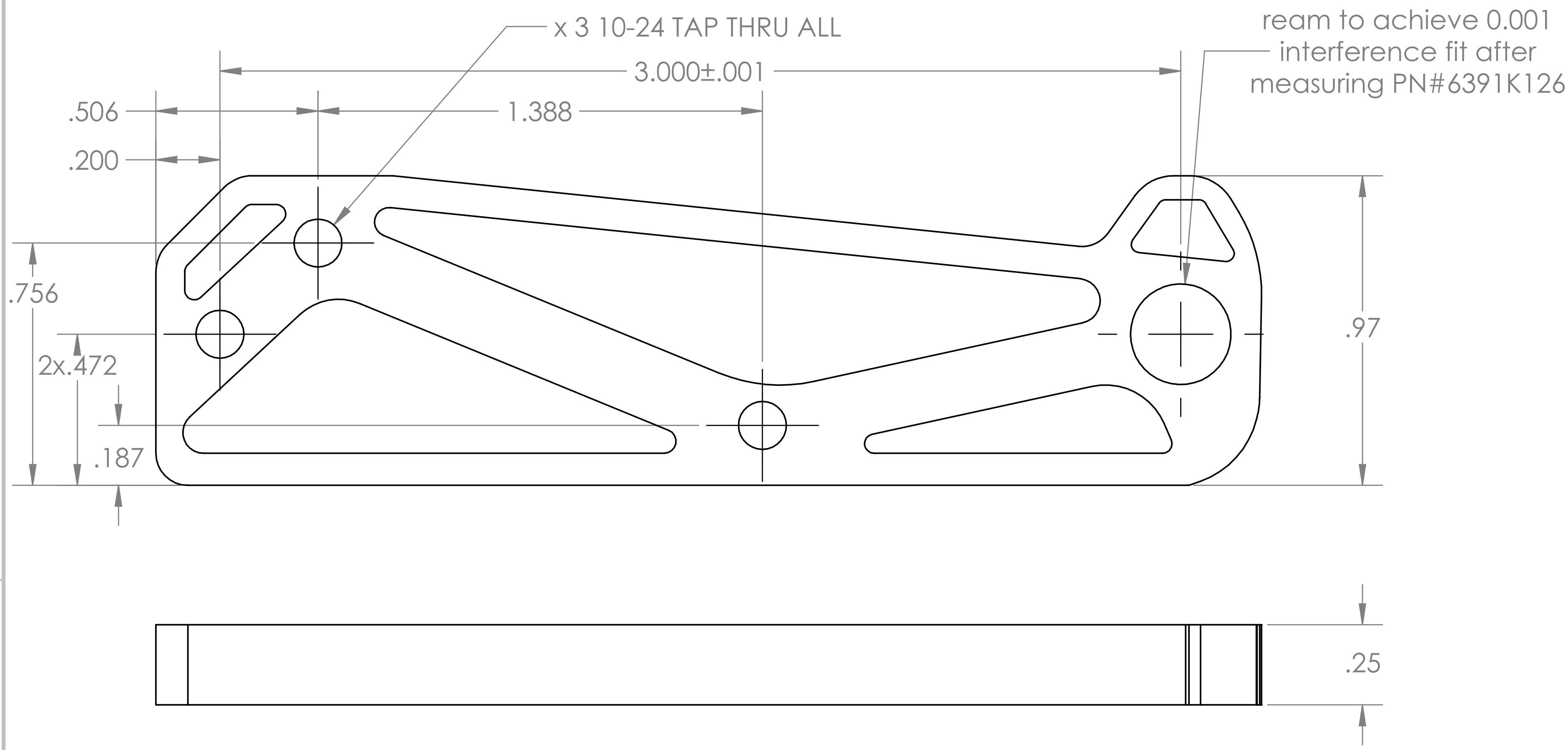


13) Attach to gameboard (assembly #7, 4 ground-plate spacers, 4 2" long 3/8-16 screws).
    a. Stack the 4 bolts onto the ground-plate.
    b. Place spacers onto the bolt shafts and tighten place to threaded board holes.

Step 12



Appendix C: Drawings and Manufacturing Guide



DRAWING & MANUF. PLAN CHECKS:
- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.0025

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL
0.25" ALUMINUM

FINISH
STOCK
BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MARISSA	02/04/2020
CHECKED	JAKE	02/04/2020
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:
TOLEERANCE DOWN TO 0.001"

ME 350 TEAM 45

TITLE:

COUPLER

SIZE	DWG. NO.	REV
A	P45_06	01

SCALE: 2:1 | QUANTITY: 1 | SHEET 1 OF 2

2 1

MANUFACTURING PLAN
RAW MATERIAL STOCK: 0.25" Aluminum Plate Stock

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Water jet lightweighting and outer contour then deburr	water jet	water jet clamps	Metal file	N/A
2	place component in clamp with long continuous edge parallel to x axis on the near side of the vice	Mill	Vise	1.5" paralels	N/A
3	zero x axis on left facing flat face of the part by using the edge finder. Then turning the mill off and manually adjusting for the edgefinder's radius	Mill	Vise	edge finder, chuck	1000
4	Zero y axis to the near edge using the edge finder. Then turning the mill off and manually adjusting for the edgefinder's radius	Mill	Vise	edge finder, Chuck	1000
5	rezero axis to the farthest left 10-24 tap hole (left center hole) and center drill	Mill	Vise	center drill, chuck	N/A
6	through drill with a #25 drill bit	Mill	Vise	#25 drill bit, chuck	1400
7	turn off the mill and tap hole with 10-24 tap	Mill	Vise	10-24 tap	0
8	Repeat steps 6-7 on remaining 10-24 tap holes making sure to slide parallels part way out when drilling close to the edges to ensure they are not dammaged	Mill	Vise	center drill, #25 drill bit,10-24 tap, chuck	see steps 6-7 respectively
9	center drill then through pilot drill the interference fit hole using 19/64" drill bit (right most hole)	Mill	Vise	center drill, 19/64 drill bit, chuck	900
10	measure selected sleeve bearing OD and ream the hole from step 8 to OD-0.001"	Mill	Vise	Reamer, chuck	100
11	remove part from vice and debur	N/A	N/A	Metal File	N/A
12	Use 10-24 tap to manually tap #25 holes from step 5	Easy Tapper	Easy Tapper	10-24 tap	N/A
13	press bushing into reamed hole	Arbor Press	N/A	Arbor Press	N/A

B B

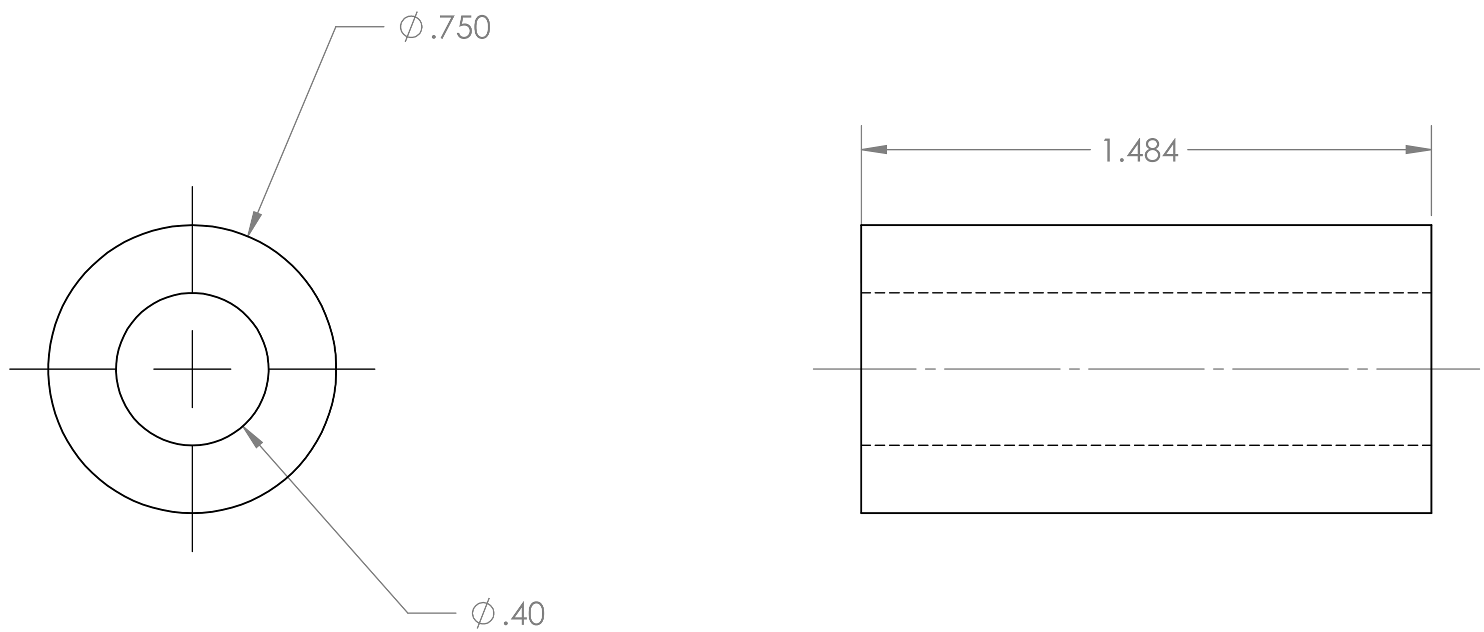
A A

SHEET 2 OF 2

2 1

2 | 1

B | B



A | A

DRAWING & MANUF. PLAN CHECKS:
- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL
3/4" Al Round Stock

FINISH
BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JAKE	2/4/20
CHECKED	XX	XX/XX/XX
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:

ME 350 TEAM 45

TITLE:

GROUND SPACER

SIZE	DWG. NO.	REV
A	P45_04	01

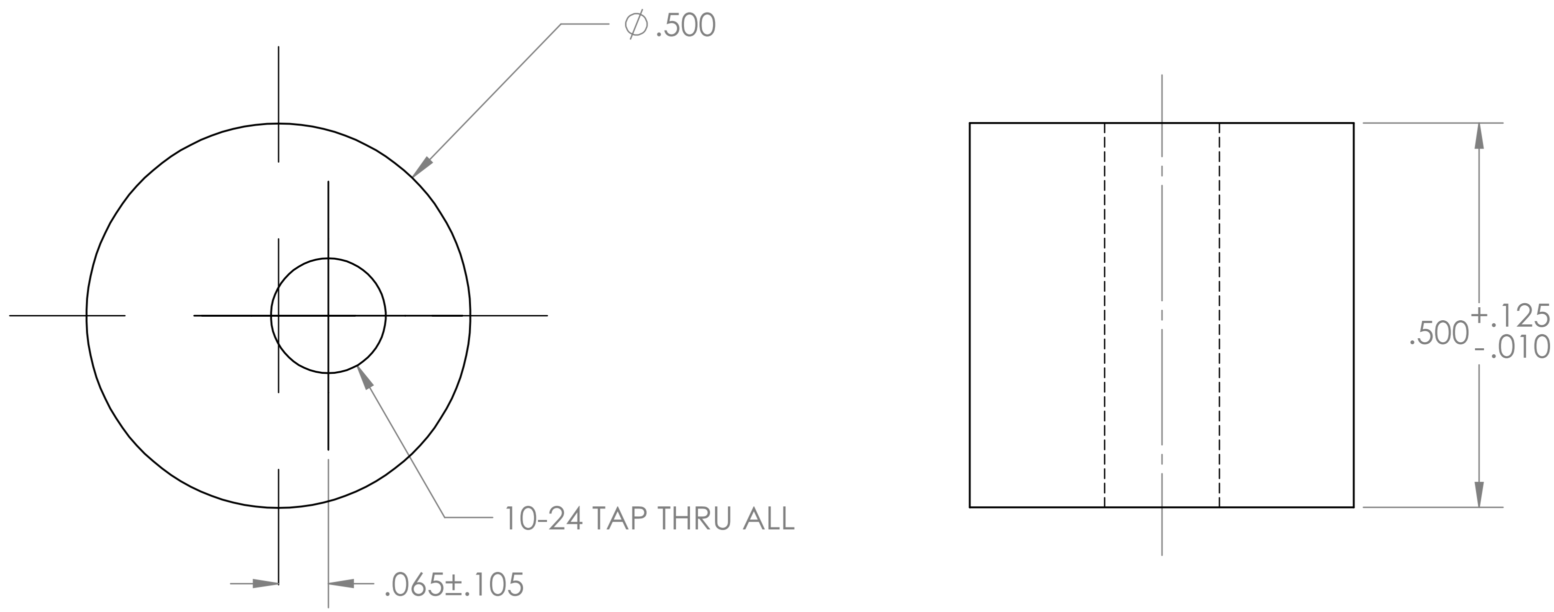
SCALE: 2:1 | QUANTITY: 4 | SHEET 1 OF 2

2 | 1

MANUFACTURING PLAN
RAW MATERIAL STOCK: 0.75" Aluminum Cylinder Stock

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	cut 0.75" cylinder stock to approximately 1.6" and deburr	Band saw	Vice	File	300
2	place in lathe and machine one end flat taking off as little material as required	Lathe	Head Stock	3/4" collet, Facing tool, collet stop	750
3	flip part and and repeat step 2 then zero horozontal axis	Lathe	Head Stock	3/4" collet, facing tool	750
4	remove component and measure its length 3 times and not the average	N/A	N/A	Micrometer (or calliper if there is not a large enough micrometer)	N/A
5	place part back into collet and face component down to 1.484" in passes no larger than 0.020"	Lathe	Head stock	3/4" collet, Facing tool	750
6	peck drill centered clearence through hole using X drill bit	Lathe	head stock	3/4" collet, X drill bit, remove collet stop	750
7	remove component and deburr	N/A	N/A	File	N/A

B



B

A

DRAWING & MANUF. PLAN CHECKS:

- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE
REVISION BLOCK	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.05
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL
0.50" ALUMINUM

FINISH
STOCK
BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MARISSA	02/04/2020
CHECKED	JAKE	02/04/2020
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:

ME 350 TEAM 45

TITLE:

HARD STOPS

SIZE	DWG. NO.	REV
A	P45_05	01

SCALE: 4:1 | QUANTITY: 2 | SHEET 1 OF 2

A

2 1

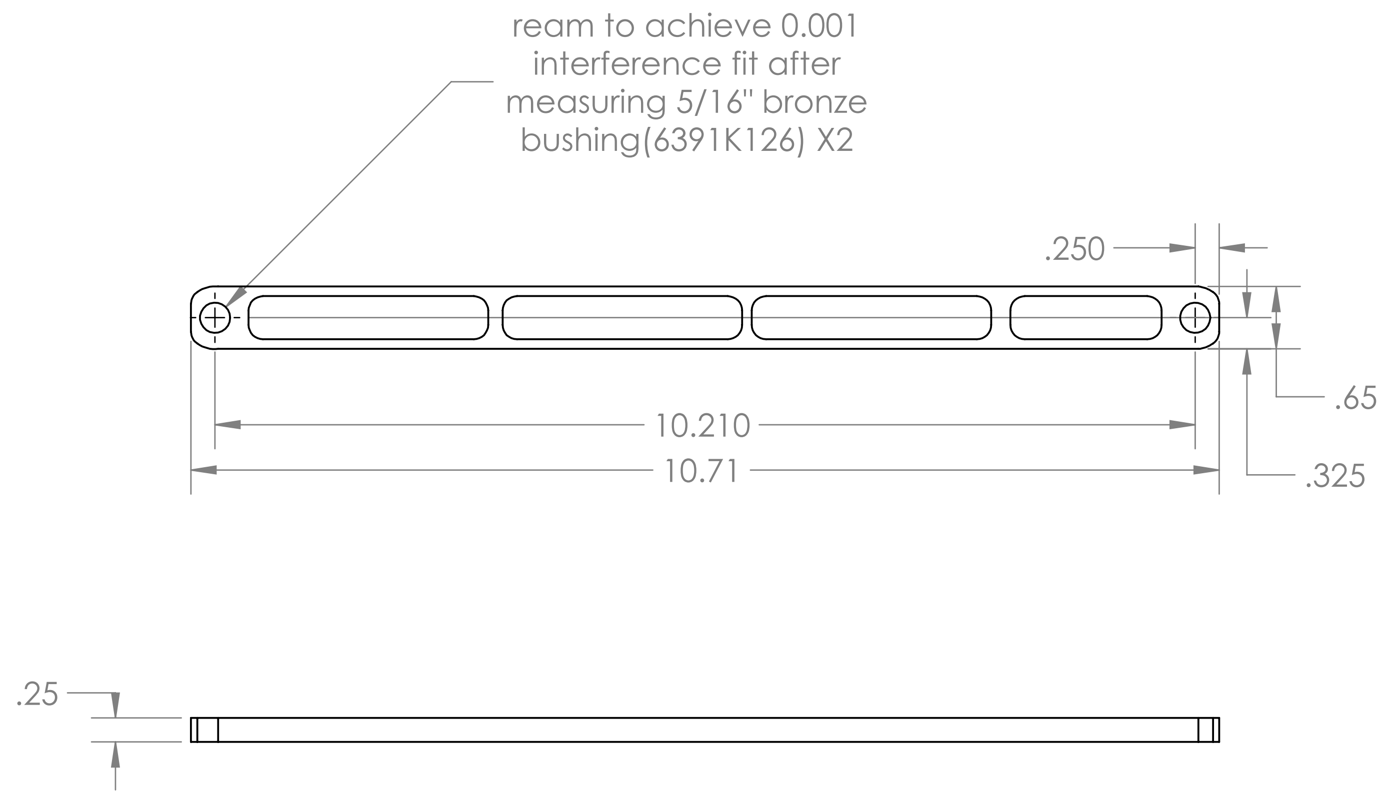
MANUFACTURING PLAN
RAW MATERIAL STOCK: 0.50" Aluminum Cylinder Stock

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	cut 0.50" cylinder stock to approximately 0.50" and deburr	Band saw	Vice	File	300
2	place in lathe and machine one end flat taking off as little material as required	Lathe	Head Stock	1/2" collet, Facing tool	750
3	flip part and and repeat step 2 then zero horozontal axis	Lathe	Head Stock	1/2" collet, facing tool	750
4	measure to make sure the part is still within tolerance	N/A	N/A	calliper	N/A
5	remove any necesary excess material	Lathe	Head stock	1/2" collet, Facing tool	750
6	use height guage to mark, then center punch inner tapped hole	Drill press	vise	height guage, center punch, mallet	1000
7	center drill then peck drill inner tapped hole using #25 drill bit	Drill Press	vise	#25 drill bit	1200
8	remove component and deburr and tap with 10-24 tap"	Easy Tapper	Easy Tapper	File, 10-24 tap	N/A

B B

A A

2 1



DRAWING & MANUF. PLAN CHECKS:

- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE
REVISION BLOCK	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL
0.25" ALUMINUM

FINISH
STOCK
BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MARISSA	02/04/2020
CHECKED	JAKE	02/04/2020
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:
MEASURE THE OIL BUSHING AND REEM TO 1 THOU UNDER OUTSIDE DIAMETER FOR PRESS FIT

ME 350 TEAM 45

TITLE:

FOLLOWER LINK

SIZE	DWG. NO.	REV
A	P45_01	01

SCALE: 1:2 | QUANTITY: X | SHEET 1 OF 2

2 1

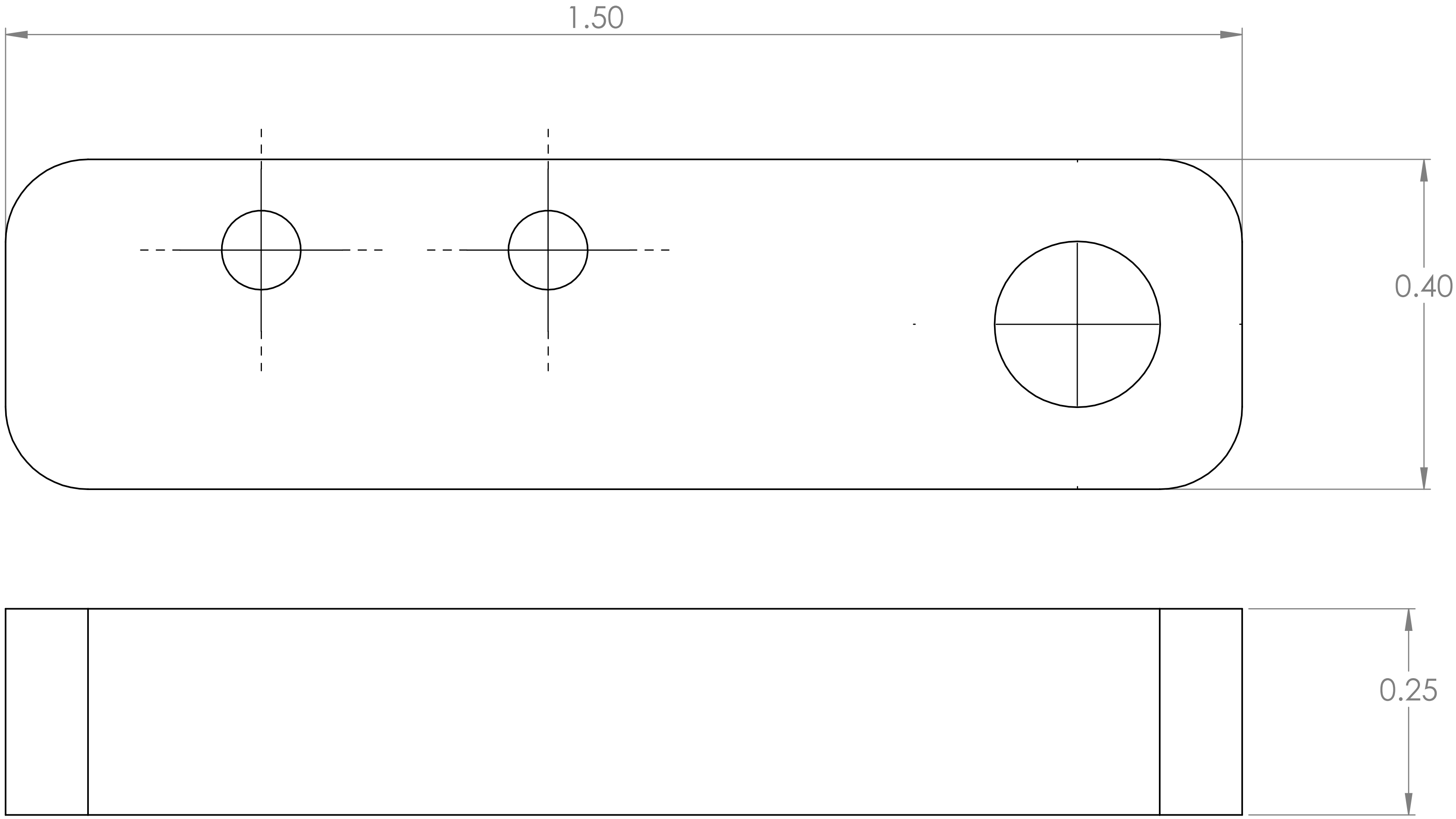
MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/4" aluminum plate

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	water jet outer contour and light-weighting then deburr	water jet	water jet clamps	File	N/A
2	Use strap clamps on the with a piece of disposable wood to clamp part to mill keeping both ends adequatly exposed to allow for desired holes to be through drilled	Mill	strap clamp	support material, dowel pins,2 strap clamps	N/A
3	Zero the x axis to the left face of the part using the edge finder and adjusting for the edge finder's radius	Mill	strap clamp	Edge finder, Chuck	1000
4	Zero the y axis to the near face of the part using the edge finder and adjusting for the edge finder's radius	Mill	strap clamp	Edge finder, Chuck	1000
5	move to center of the called interference fit hole, rezero y axis and center drill	Mill	strap clamp	center drill	1000
6	center drill then through drill with a 5/16 drill bit	Mill	strap clamp	Center drill, 19/64 drill bit, chuck	900
7	measure the respective sleeve bearing OD and ream hole from step 5 to OD-0.001"	Mill	strap clamp	Reamer, chuck	100
8	Repeat steps 6&7 for the hole on the right side of the part	Mill	strap clamp	Center drill, 5/16 drill bit, Reamer, Chuck	900/100
9	Deburr part and press fit repective sleeve bearing into component	Arbor Press	N/A	File	N/A
10					
11					
12					
13					
14					

B B

A A

2 1

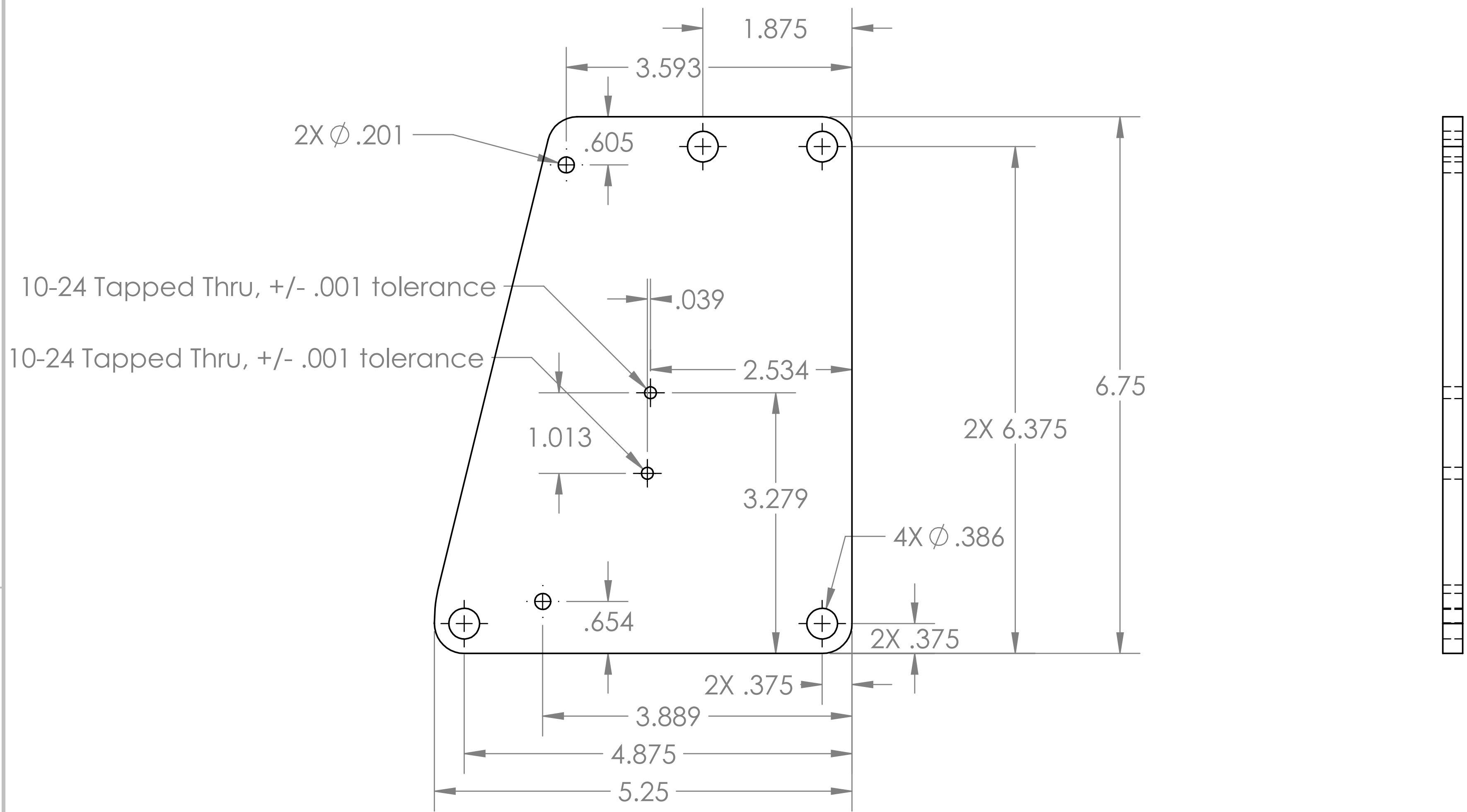


		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	ME350 Team 45
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR MACH ± 1° Angular BEND ± 3° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.0025	DRAWN	Jonah S	2/29/2020	TITLE:
			CHECKED			Limit Switch Mount
			GSI APPR			
			SHOP APPR			
		INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5-2009	Q.A.			
		MATERIAL: 0.25" Aluminum Plate Stock	COMMENTS:			SIZE A · DWG. NO. P45_15 · REV
		FINISH: Burr Free				
Revision Block		DO NOT SCALE DRAWING				SCALE: 5:1 · Quantity: 1 · SHEET 1 OF 2

Step	Process Description	Machine	Fixture	Tools	Speed (RPM)
1	waterjet and deburr	Water Jet	Water Jet Clamp	File	N/A
2					
3					
4					
5					
6					
7					
8					
9					

2 1

B B



A A

DRAWING & MANUF. PLAN CHECKS:

- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE
REVISION BLOCK	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.0025

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL
1/4" Aluminim PLate

FINISH
BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JAKE	2/4/20
CHECKED	MARISSA	02/06/20
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:

ME 350 TEAM 45

TITLE:

GROUND PLATE

SIZE	DWG. NO.	REV
A	P45_02	01

SCALE: 1:4 QUANTITY: 1 SHEET 1 OF 2

2 1

2 1

MANUFACTURING PLAN

RAW MATERIAL STOCK: 1/4" aluminum plate

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Water jet outer contour, then deburr.	water jet	water jet clamps	File	N/A
2	Place part in the mill vise, clamping the parallel sides.	Mill	vise	1.5" parallels	N/A
3	Zero the x-axis to the right face of the face of the part using the edge finder and adjusting for the edge finder's radius.	Mill	vise	Edge finder, Chuck	1000
4	Zero the y-axis to the bottom face of the face of the part using the edge finder and adjusting for the edge finder's radius.	Mill	vise	Edge finder, Chuck	1000
5	Center drill the #9 hole at the bottom right corner of the ground plate.	Mill	vise	Center drill, Chuck	1200
6	Drill all the way through the hole. Repeat steps 5&6 for the other 3 #9 holes.	Mill	vise	W drill bit, Chuck	750
7	Recenter from the bottom right hole.	Mill	vise	Edge finder, Chuck	1000
8	Center drill the #7 hole at the top left corner of the ground plate.	Mill	vise	Center drill, Chuck	1200
9	Drill all the way through the #7 hole. Repeat steps 8&9 for the other #7 hole.	Mill	vise	#7 drill bit, Chuck	1300
10	Center drill the 10-24 tapped hole at the center of the ground plate.	Mill	vise	Center drill, Chuck	1200
11	Drill all the way through the 10-24 tapped hole. The tolerance should be +/- .001.	Mill	vise	#25 drill bit, Chuck	1500
12	Tap the 10-24 hole. Recenter from the tapped hole, then repeat steps 11&12 for the other 10-24 tapped hole.	Mill	vise	10-24 tap, Chuck, tap wrench	N/A

B B

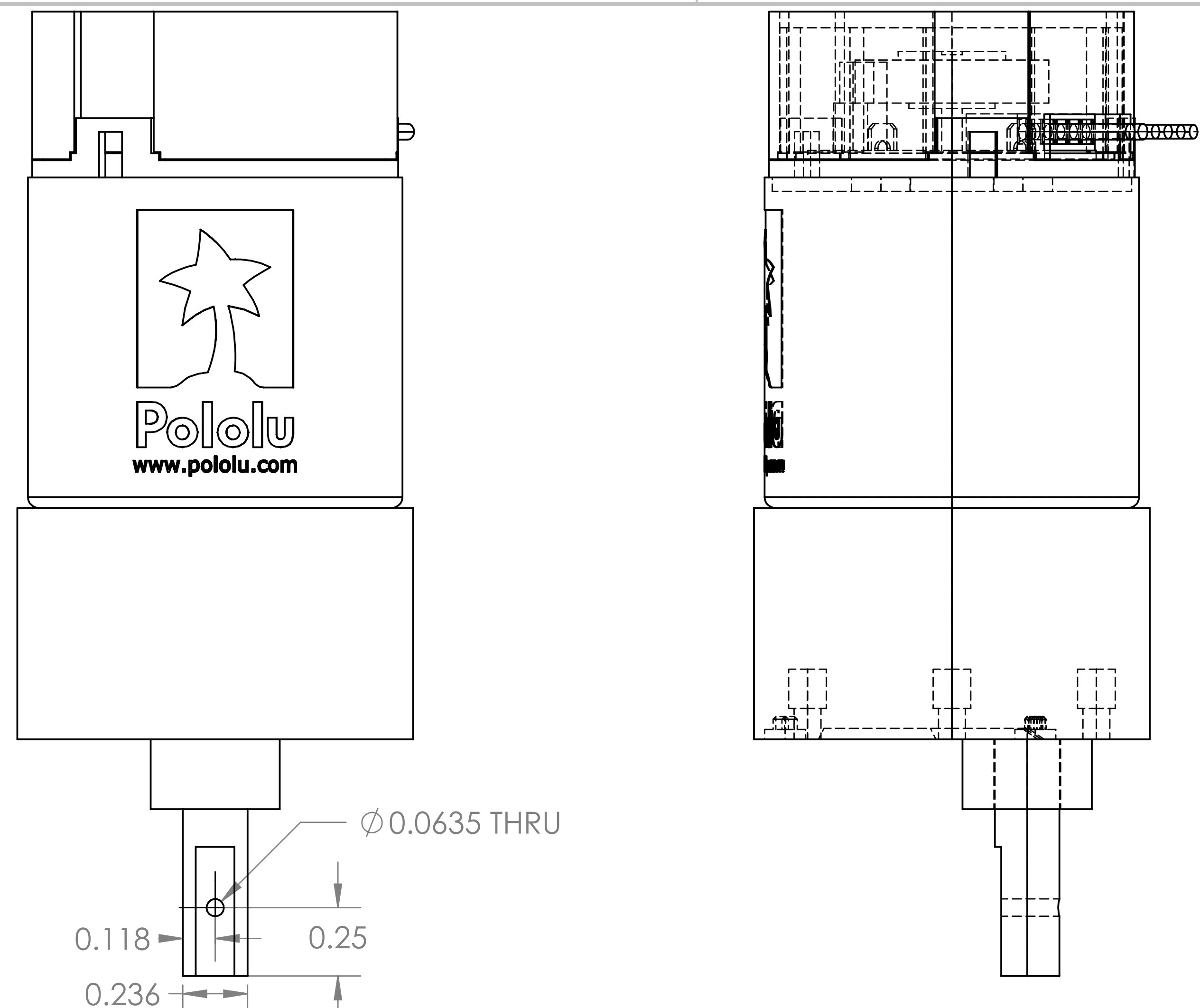
A A

SHEET 2 OF 2

2 1

2 1

B B



A A

DRAWING & MANUF. PLAN CHECKS:
- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL
Pololu DC Motor

FINISH
BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MATT	03/22/20
CHECKED	JONAH	03/23/20
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:

ME 350 TEAM 45

TITLE:

MOTOR W/ HOLE

SIZE	DWG. NO.	REV
A	P45_012	1

SCALE: 3:2 QUANTITY: 1 SHEET 1 OF 2

2 1

2 1

B B

MANUFACTURING PLAN
RAW MATERIAL STOCK:

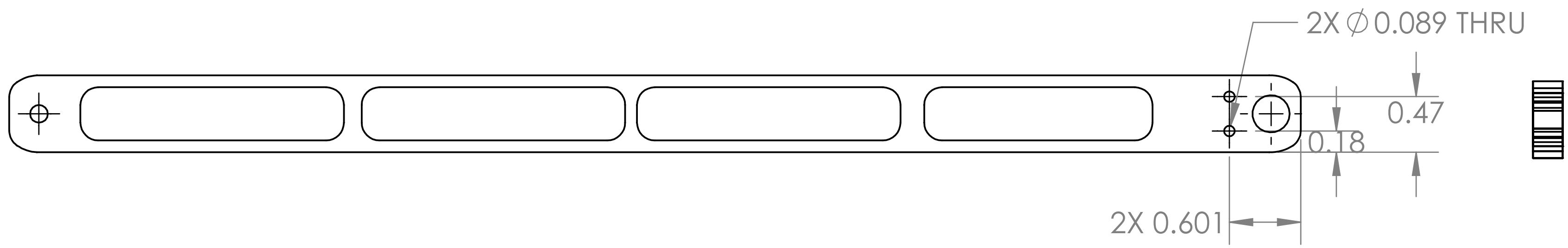
STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Gently clamp motor in the vise using motor fixture	Mill	Motor fixture		
2	Use the edge finder to zero the x and y axes to the bottom left of the motor shaft.	Mill	Motor fixture	Drill chuck, Edge finder	1000
3	Center drill the #52 hole.	Mill	Motor fixture	Drill chuck, #1 Center drill	1200
4	THRU drill the #52 hole.	Mill	Motor fixture	Drill chuck, #52 Drill bit	1500
5	Carefully remove part from vise and deburr			File, Deburring tool	

A A

2 1

2 1

B B



A A

DRAWING & MANUF. PLAN CHECKS:

- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL
Input Link

FINISH
BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MATT	03/01/20
CHECKED	JONAH	03/01/20
GSI/IA APPR.	DW W2020	
SHOP APPR.	3/24/2020	
INSPECTED		

COMMENTS:

ME 350 TEAM 45

TITLE:

INPUT LINK V2

SIZE	DWG. NO.	REV
A	P45_003	02

SCALE: 2:3 QUANTITY: X SHEET 1 OF 2

2 1

2 1

MANUFACTURING PLAN

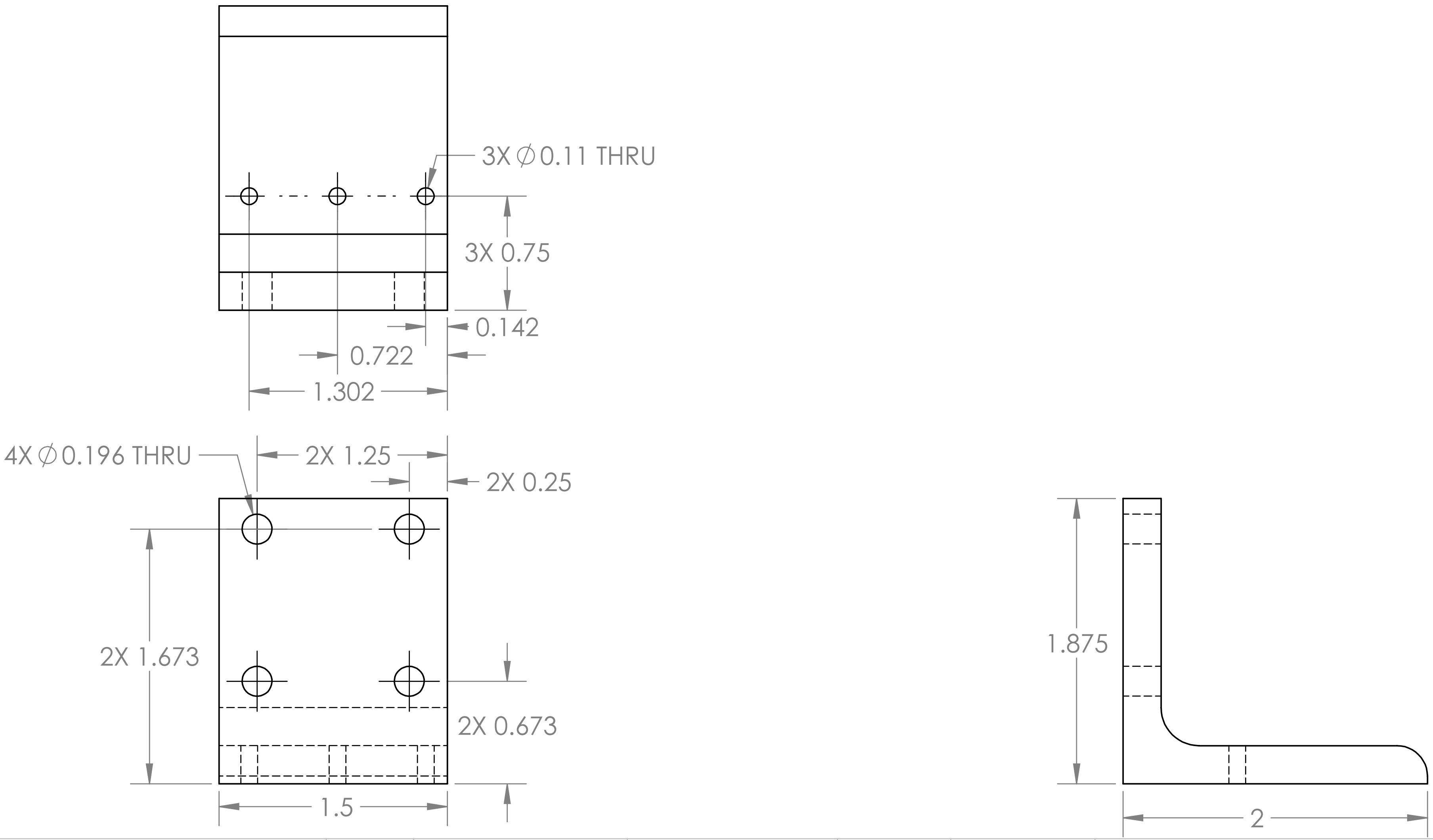
RAW MATERIAL STOCK: Input Link

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Secure the right end of the part on the mill using the vise.	Mill	Vise	1.5" parallels	
2	Zero the x-axis to the right face of the part using the edge finder and adjust for the edge finder's radius.	Mill	Vise	Edge finder, Chuck	1000
3	Zero the y-axis to the bottom face of the part using the edge finder and adjust for the edge finder's radius.	Mill	Vise	Edge finder, Chuck	1000
4	Center drill the #43 hole at the bottom right side of the part.	Mill	Vise	Center drill, Chuck	1200
5	Drill all the way through the #43 hole. Repeat steps 4&5 for the other #43 hole.	Mill	Vise	#43 drill bit, Chuck	1600
6					
7					
8					
9					
10					

B B

A A

2 1



DRAWING & MANUF. PLAN CHECKS:

- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL
2.5x2x.25" aluminum

FINISH
angle stock
BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MATT	03/4/20
CHECKED	JONAH	03/5/20
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:

ME 350 TEAM 45

TITLE:

L-BRACKET

SIZE	DWG. NO.	REV
A	P45_011	01

SCALE: 1:1 | QUANTITY: 1 | SHEET 1 OF 2

2 1

MANUFACTURING PLAN

RAW MATERIAL STOCK: **Aluminum Angle, 2.5" x 2" x 1/4" thick**

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Use vertical and horizontal band saws to cut length and height of part to 0.1" larger than the specified dimensions.	Vertical band saw, Horizontal band saw		Calipers	
2	Clean the long edge by making 0.01" passes with the long 3/4" end mill until the part is the specified length	Mill	Vise	Workholding block, .250" end mill	500
3	Clean the short edges by making 0.01" passes with the long 3/4" end mill until the part is the specified length	Mill	Vise	1.5" parallels, long 3/4" end mill	500
4	Zero the x and y axes to the bottom right corner using the edge finder.	Mill	Vise	Edge finder, Chuck	1000
5	Center drill the #9 hole in bottom right of the part.	Mill	Vise	Center drill, Chuck	1200
6	Thru drill the #9 hole. Repeat steps 5&6 for the other 3 #9 holes.	Mill	Vise	#9 drill bit, Chuck	1300
7	Flip the part and rezero the x and y axes to the top right corner using the edge finder.	Mill	Vise	Edge finder, Chuck	1000
8	Center drill the #35 hole on the right side of the part.	Mill	Vise	Center drill, Chuck	1200
9	Thru drill the #35 hole. Repeat steps 5&6 for the other 2 #35 holes.	Mill	Vise	#35 drill bit, Chuck	1600
10	File and deburr part			File, deburring tool	

B B

A A

2 1