University of Colorado - Boulder
MCEN 3025

Component Design

Ninja Star by the Colorado Creators

Instructor: Derek Reamon

Authors:

Ahmed Ferjani - Project Manager (785-956)

Sabrina Kurevija - Manufacturing Engineer (367-713)

Jack deBloois - Manufacturing Engineer (443-556)

Patrick Doyle - Systems Engineer (056-519)

Gabe Williams - Integration Engineer (594-720)

Jacob Allen - Test Engineer (091-641)

Kirollos Gerges - CAD Engineer (224-672)

April 29, 2021

Engineering & Applied Science
UNIVERSITY OF COLORADO **BOULDER**

Table of Contents

I. Introduction/ Background

For this project, the Colorado Creators (CCs) were challenged to create a kinetic sculpture that would use background information and knowledge gained from their time in engineering. The team had decided to create the Ninja Star for the kinetic sculpture. The Ninja Star is a kinetic sculpture that creates a stimulating kaleidoscope-like visual once the wheels are spun. When the wheels are set into motion, a “rocking effect” takes place and the wheels rotate to create a stimulating visual effect. Traditionally, the wheel would be spun by applying a force to one of the wheels, and then the wheels would spin in opposite directions, triggering a phenomenon of constantly changing patterns. However, due to the requirement of having an electrical component within the project, a 300 RPM motor will be incorporated into a gear system to drive the ninja star wheels.

The main purpose of the project is to challenge and force the team to use the knowledge about complex systems that were gained through past experiences and classes such as solids, circuits, etc. to create a sculpture. The Ninja Star takes the concepts learned from these classes and gives the team an opportunity to gain confidence with the procedure of design, analysis, and assembly, thus helping build the student’s intuition as scientists and engineers.

As the project started, the objectives the team had needed to accomplish were to create the sculpture, to meet the size requirement of at most one cubic foot, and to include an electrical component (a small DC motor). To include the motor and have the blades turn in opposite directions, the use of a pinion gear, bevel gears, and a mixture of stock and fabricated parts are needed. The designed model has a height of 11.2” and uses the electrical components that were purchased to drive the wheels and provide a kaleidoscope-like visual.

Along with the size objective, the Ninja Star design had to be created with the use of some machined parts that would use a water jet, lathe, and a milling machine. The Ninja Star’s components used a variety of different manufacturing techniques. The wheels were laser cut from acrylic and the base plate and the motor mount were manufactured with lathes and mills from aluminum. The stock components, including gears, motors, battery packs, and batteries, were purchased through online resources such as Amazon or McMaster Carr. The Ninja Star covers the project’s objectives and gives the CCs a unique project and strong motivation to complete a top tier project.

The main motivation behind this design is to allow a creative project using a variety of components and knowledge to create a kinetic sculpture that allowed for a stimulating visual effect. From the information gathered in Component Design lectures and through the assistance of Dr. Reamon, the TAs, and Chase, the Ninja Star was created.

II. Design

a. Conceptual designs

The conceptual design was centered around creating two wheels that would spin in opposite directions. The team thought having the wheels spin around an axle would be the simplest solution to move the wheels and avoid having to secure the wheels to a shaft. The team also determined using a gear system on the same axle as the wheels would be able to generate the opposite motion of the wheel desired. Finally, the motor would need to be raised up to the gear system to avoid a complex gear train and thus the motor mount solution was devised, with any other electronics left on the base of the design.

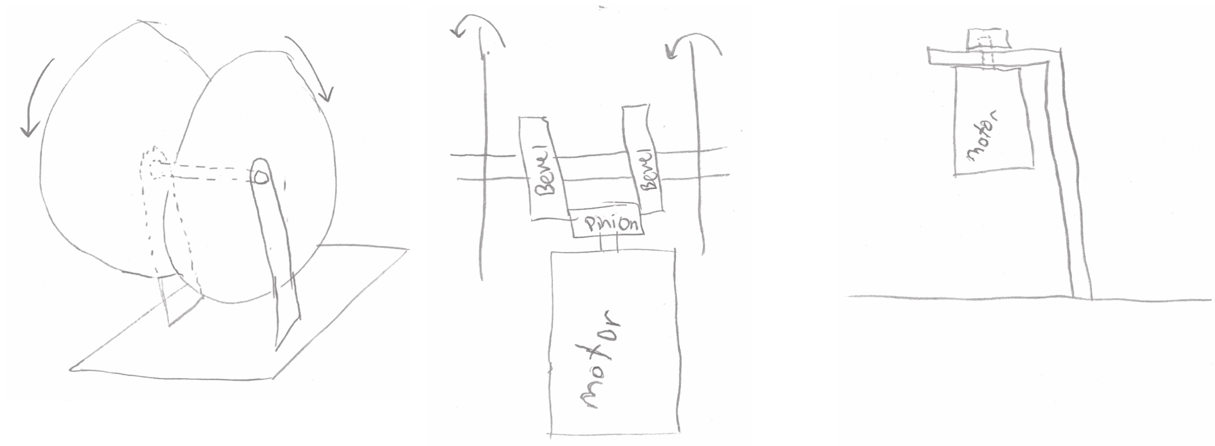


Figure 1: Conceptual Design Sketches

b. Selected design

The selected design reflects the above conceptual drawings. The wheels were designed to have many arms with two curves each. The wheels would spin in opposite directions to generate a pattern. To reverse the wheels' direction with one motor, bevel and pinion gears were used. The bevel gears spin on opposite sides of the pinion gear making the opposite rotation. The bevel gears and wheels were connected to the axle, held up by two aluminum arms extending from the base. The axle uses retaining rings to axially restrain the gears, wheels, and arms. The arms, wheels, bevel gears, and the axle make one structure.

The other structure was the motor mount. The mount has two parts, a vertical and horizontal piece, and was designed to bring the motor in contact with the pinion gear. The vertical part attaches to the base. The horizontal part is attached to the vertical mount and has mounting holes for the motor. The pinion gear was attached to the motor shaft with a set screw for torque transfer. The motor mount, motor, and pinion gear make up a second structure. The base has mounting holes for the arms and motor mount. The base holds the electronics required to power the motor. The base has small standoffs to avoid wobbling from resting on screws in the base. To operate, the motor spins the pinion gear, which then spins the bevel gears and attached wheels.

This project was one of three original project ideas. There was also an interlocking gear sculpture and a wind chime as project ideas. The interlocking gear project was the most complex project idea. It would have been challenging to create a set of custom working gears from scratch, due to limitations of the machine shop and the complexity of the associated math. The wind chime was too simple. It included a central pole and a set of radial rods. The wind chime would have been mostly ordering parts and not much engineering. The Ninja Star project was selected because it's difficulty was less extreme than the interlocking gears, but more challenging than the wind chime.

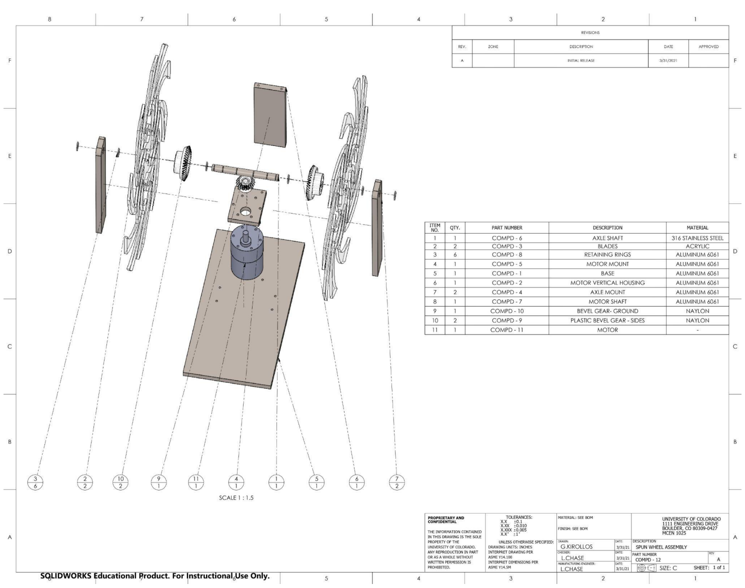
The machinability of materials is very important and crucial to component material selection. How machinable a metal is depends on the physical properties of the metal and the cutting conditions. Therefore, the Colorado Creators selected the components' materials based on the machinability of a material and limitations of the Idea Forge's machine shop.

In the machine shop, aluminum is readily available, strong, and easily machinable because it chips easily. The other factor that drove the team to choose aluminum for most of the components is that aluminum is easy to shape; meaning that aluminum machining can be done much quicker than other comparable metals. In fact, Aluminum can be machined at speeds up to 3x or 4x faster than iron or steel.

The other materials are acrylic, plastic, and stainless steel. These materials are used in the following ways:

- Acrylic: Acrylic was chosen to make up the wheels because of its appearance, light-weight, so it wouldn't too heavily impede the motor; while also being very easy to laser cut into a complex shape.
- Plastic: Plastic is the material of both the pinion and bevel gears and was chosen to facilitate torque transmission from the gear as opposed to a heavier metal option, which would impede the motor's rotational velocity. The plastic gears also made for a cheaper overall design compared to metal gears.
- Stainless steel - Stainless steel was used for the axle. The team chose stainless steel because of its smooth finish to help reduce friction between the coupled gears and ninja stars. The only modifications to the axle were small grooves to attach retaining rings so it wouldn't too heavily impact the machinist's work.

Below is an exploded view for the Ninja Star's assembly with an attached Bill of Materials:



ITEM NO.	QTY.	PART NUMBER	DESCRIPTION	MATERIAL
1	1	COMPD - 6	AXLE SHAFT	316 STAINLESS STEEL
2	2	COMPD - 3	BLADES	ACRYLIC
3	6	COMPD - 8	RETAINING RINGS	ALUMINUM 6061
4	1	COMPD - 5	MOTOR MOUNT	ALUMINUM 6061
5	1	COMPD - 1	BASE	ALUMINUM 6061
6	1	COMPD - 2	MOTOR VERTICAL HOUSING	ALUMINUM 6061
7	2	COMPD - 4	AXLE MOUNT	ALUMINUM 6061
8	1	COMPD - 7	MOTOR SHAFT	ALUMINUM 6061
9	1	COMPD - 10	BEVEL GEAR- GROUND	NAYLON
10	2	COMPD - 9	PLASTIC BEVEL GEAR - SIDES	NAYLON
11	1	COMPD - 11	MOTOR	-

Figure 2: Exploded view of the Ninja Star assembly and BOM table.

c. Design iteration

The motor was originally designed to be attached to one of the larger bevel gears on the side of a mounting arm. This design made mounting the pinion gear easier, but mounting the axle harder. This design would've made the axle a shaft, complicating the direction inversion of the wheels. The motor placement was redesigned to attach to the small pinion gear under the center of the axle and an alternate motor mounting solution was developed. The base was originally a full enclosure with a cutout to see the wheel designs. This enabled hiding the motor and electronics. The enclosure was changed to a simple base to save on materials and simplicity at the cost of exposing the electronics. The wheels were originally mounted on the hubs of the bevel gears and were to be attached with adhesive. This was changed to connecting the wheels on the hubs with screws for better clearance of the motor and stronger clamping to the gears, since adhesive wouldn't hold up well to the required shear stresses. The final change was for the mounting between the motor shaft and pinion gear. The first concept was to create an adapter for a force fit between the motor's d-shaft and the pinion gear. The team learned this also wouldn't have held up well in rotational shear stresses and wouldn't have efficiently transferred torque from the motor to the gear system. Instead, a small tapped hole in the pinion gear was machined for the placement of a set screw. This design better transferred torque to the gear system and wheels. These were the fundamental changes made during the design process.

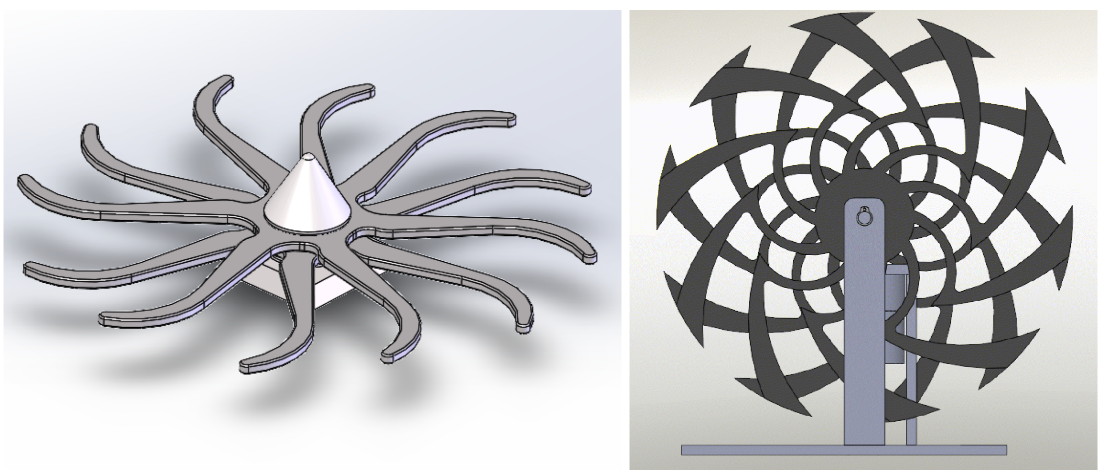


Figure 3: Older, Conceptual Design (left) and Final Design (right)

III. Component Analysis – Critical Components

The two most critical components of the project are the axle and the gear system. These components are critical to the design because they enable the unique motion of the ninja stars. Without the axle and gear system, the ninja stars would be unable to spin in opposite directions and the stability of the motion would be compromised. The axle is critical because it allows the ninja stars and gear system to move uniformly. It provides a balanced foundation for the gear system and ninja stars to rotate about. In addition, the gear system is fundamental because it connects to the motor which drives motion. The gear system was designed specifically to enable the ninja stars to rotate in opposite directions and create the desired visual effect. The gears also serve a purpose in having a place to mount the ninja stars and have them spin at uniform speeds.

Analysis on the axle began with analyzing the forces and torques created due to the supports on the end of the gears and wheels rotating about the axle. After spinning the gears around the axle, it was determined that the torque was negligible and analysis was focused on the forces from components' weights and resulting moments.

By approximating the axle as fixed end beam, shear and moment diagrams were created to determine the max moment based on the following beam analysis:

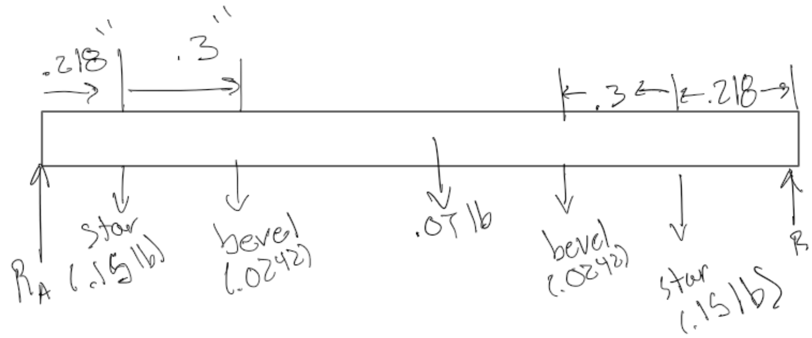


Figure 4: Fixed Beam Approximation FBD for Axle

This beam analysis enabled determination of the shear and moment diagrams used to calculate the σ_{nom} with the following equation:

$$\text{Eq. 1: } \sigma = \frac{My}{I}$$

Then using Fig. C-6 [1], a value for K_t of 3.7015 was determined, the geometric stress-concentration factor, resulting from the machined grooves for retaining rings. With this value and Table 6.6 [1], using the known values for 316 stainless steel, the fatigue stress-concentration factor, K_f, was calculated and found to be 1.852.

Next, the modified fatigue endurance limit was calculated with the following equation:

$$\text{Eq. 2: } S_f = C_{load} C_{size}\ C_{surf} C_{temp} C_{reliab} S_f'$$

Using equations 6.7a-f and Table 6.4 and 6.3 [1], the C values were determined. The estimated fatigue strength was calculated using the approximation:

$$S_f' = .5 S_{ut} \text{ for } S_{ut} \leq 200\ kpsi$$

Using the found value of 75 kpsi for S_{ut}. The modified fatigue endurance limit was estimated to be 22.75 kpsi. Finally, the safety factor of the axle was calculated using the equation:

$$\text{Eq. 3: } N_f = \frac{S_f S_{ut}}{\sigma_a' S_{ut} + \sigma_m' S_{ut}}$$

Since there is no fluctuating applied stresses, the $\sigma_a' S_{ut}$ term was neglected and the max moment was taken as the σ_m' with the modified stress-concentration factor applied. The safety factor was determined to be about 3656. This is much higher than normal but is expected given the use of a steel axle for the team's small and lightweight design.

Analysis of the gear system is dependent on the torque being delivered from the motor. Using the techniques developed in class for DC motors, the torque delivered is able to be calculated based on the rotational speed of the motor and its no-load current and stalled current. Using the determined torque and analysis of the gears applied rotational stresses the analysis of the axle and the gear system will be able to be completed. The stall current and no load current will be measured using a .375 Ω connected to ground. The Colorado Creators decided to calculate the factor of safety of the bevel gears using the following equations:

$$\text{Eq. 4: } T = F * L$$

The Colorado Creators used equation 1 to calculate the force of the motor. Where T is torque, F is force, and L represents radial length.

$$\text{Eq. 5: } P = T * \omega$$

After calculating the force, the power was found using equation 2 where P is the power, T is the torque, and ωis the angular velocity of the motor.

$$\text{Eq. 6: } \alpha_G = tan^{-1}(\frac{N_G}{N_p})$$

$$\text{Eq. 7: } \alpha_p = 90 - \alpha_G$$

Given the number of teeth of the bevel gear and pinion gear, the Colorado Creators found the values of the pitch cone angles α_G and α_p using equations 3 and 4.

$$\text{Eq. 8: } L = \frac{d_p}{2*sin(\alpha_p)}$$

Since the Colorado Creators were given the diametrical pitch d_p from McMaster-Carr and found the pitch cone angles, the group was able to determine a pitch cone length L.

Using figure 4 below, the Colorado Creators, approximated a value for the geometry factor that will be used later to calculate the bending stress of the bevel gear.

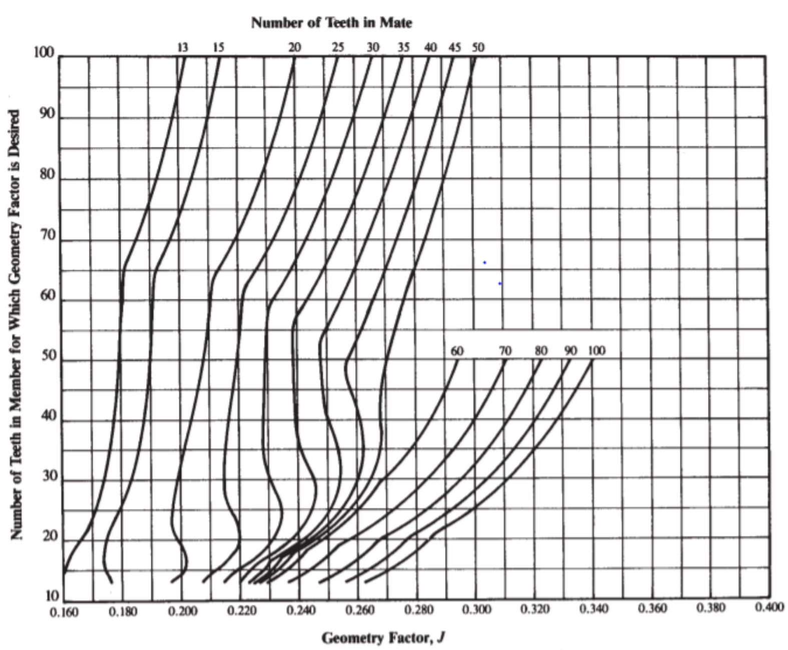


Figure 5: Determining the geometry factor

$$\text{Eq. 9: } F = L/3$$

After determining the pitch cone length, the Colorado Creators calculated a suitable face width, F.

$$\text{Eq. 10: } m = \frac{P_d}{n}$$

Equation 8 was needed to find the module, m given a diametrical pitch and the number of bevel teeth.

$$\text{Eq. 11: } \sigma_b = \frac{2000*T_p}{P_d} * \frac{1}{F*m*J} * \frac{K_a*K_m*K_s}{K_v*K_x}$$

Given all the values calculated in the equations 4-10, the Colorado Creators determined the bending stress of a bevel gear and made common assumptions used for bevel gears to represent K_a, the application factor, K_m, the load distribution factor, K_s, the size factor, K_v, the dynamic factor, and K_x, the curvature factor.

$$\text{Eq. 12: } S_{fb} = 27000 + 364 * HB\text{(psi)}$$

Assuming the material of the gear was made of polyethylene, the Colorado Creators made an assumption that the Brinnell Hardness (HB) had a value of 2, and calculated the corrected bending-endurance strength (S_{fb}).

$$\text{Eq. 13: } N = \frac{S_{fb}}{\sigma_b}$$

After calculating the corrected bending endurance strength and the bending stress of the bevel gear, the Colorado Creators determined the safety factor of the gear system was approximately 6.8.

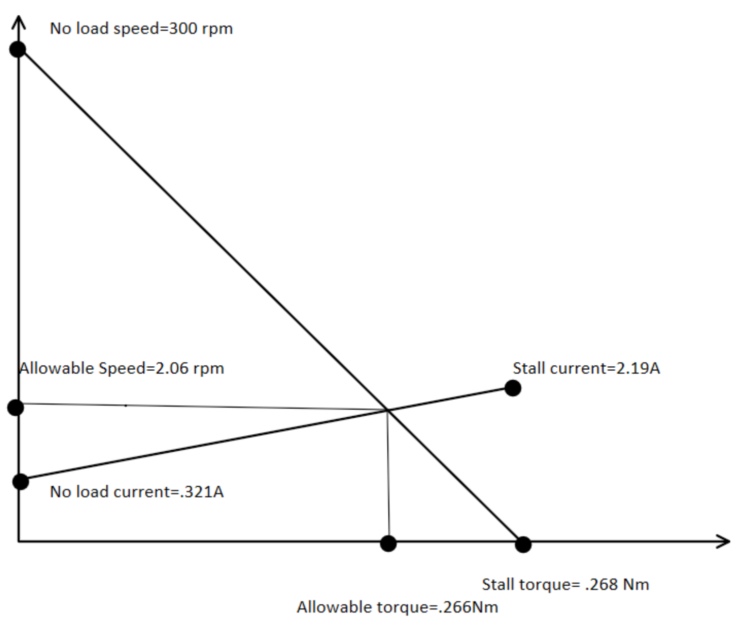


Figure 6: Motor Specs

Using the circuit that the Colorado Creators created, the group was able to measure the no load current and stall current. Using the angular speed of the motor, the current, and the 12 volts supplied, our group was able to find the stall torque. With two sets of lines, the Colorado Creators found the maximum allowable torque to be a value of .266 Nm which is a tenth of what the group found using the measurements found in a dc motor table. After completing the calculations again with the new allowable torque, the group determined a safety value of 6 relative to the value of 6.8 calculated using the allowable torque found in the dc motor table.

Some of the basic design constraints the team faced were a maximum size of one cubic foot, a required electrical component, and at least two machined components. The critical components used that were crucial to the design were the axle that the ninja stars rest on and the system of gears that drive their motion. The team's original conceptual design was changed to meet the project's requirements and constraints.

The axle that holds up the wheels was originally designed without retaining rings, and after the team's first meeting with Chase from the machine-shop, the team learned that keeping the parts coupled along the axle would be very difficult to maintain. The team redesigned the axle to have several grooves in it to hold retaining rings. When performing a force analysis on the axle, the stress concentrations from the added grooves had to be taken into account and were heavily utilized in determining the safety factor of the shaft. Given the size constraints on the project, the team chose to use a small axle to match up with the system of gears for aesthetic purposes, as the team did not want obtrusive gears being overly visible in the kinetic sculpture.

The gear system was chosen and designed as the team's way to incorporate the electrical component of the system, the motor. The rotation from the motor was translated to the wheels, allowing for the kinetic aspect of the sculpture. The team needed a way to lock the motor's rotation to the gear system. Originally the team designed a forced fit system to lock the gear to the motor's rotation. Upon further analysis, without an incredibly high friction between the motor and the gears, the team realized this plan wouldn't work well at even low rotational velocities. The team consulted with the machine shop on this issue and realized using a set-screw between the gear and the motor would be the best route. The ninja stars were designed to be about as large as the size constraints would allow, the team designed a motor housing to bring the motor's D-shaft directly into contact with the first gear of the system, the pinion gear.

While neither of the team's critical components were designed or machined, to meet the project's requirements of machined components the motor's housing and the arms that hold up the axle allowed for more than enough machined components to meet the requirement. Some modification was done via the machine shop to the critical components such as, the hole drilled into the first gear for the set screw, drilling holes into the back of the gears that rest on the shaft to be connected to the ninja stars, and adding grooves into the axle to allow for retaining rings be added and thus axially constrain the components on the axle.

IV. Fabrication

The Colorado Creators used a combination of standard parts from manufacturers such as McMaster Carr with custom manufactured parts to assemble the project. The parts that the team needed to get custom made were the blades, motor mount pieces, the base, the axle mount pieces, and an axle with grooves for retaining rings.

For the custom parts used in the assembly, the Colorado Creators used a unique pattern to laser cut the blades from acrylic. A 2 axis mill was used to make the motor mount, base, and axle mounts, all out of ¼” sheet aluminum, along with a bandsaw to cut the edges to the correct dimensions. To make the retaining ring grooves in the 8mm diameter stainless steel axle, a lathe was used. The drawing for each machined component is included in the appendix.

In addition to the machined parts, the Colorado Creators also used a number of standard parts from McMaster Carr, Amazon, and Home Depot. These parts included the pinion and bevel gears, the axle, the 300 RPM motor, retaining rings, batteries, switches, and fasteners. Some of these parts were modified, including adding a set screw hole in the pinion gear and adding retaining ring grooves in the axle.

Upon receiving the parts, the team realized that bevel gears did not have the holes that were intended to be there. In order to attach the two bevel gears to the rotating wheels, the bevel gears had to be modified. This fabrication was critical to the design because in order for the wheels to rotate synchronously with the gears, the two parts had to be attached. A drill press was used to create three holes (No. 43 tap drill size) to attach the gears to the wheels via #4-40 UNC size screws.

Figure 7: Competed assembly of the Ninja Star

V. Testing and Results

In the previous section, Component Analysis, the team outlined the most critical components of the Ninja Star and how they were designed. In order to make sure that the team completed the calculations correctly and that the designed parts will be functional when assembled, a test plan was created to verify the theoretical results after the project is assembled. The parts that the Colorado Creators considered to be the most crucial were the gear system and the axle.

With this project, there is not a good way to verify the theoretical calculations that were performed for the axle and gear system without expensive testing equipment. Therefore the metrics that the team will use to determine if the axle and gear system were designed properly will be if the wheels spin at the desired rate and with little friction and are aligned properly on the axle. If the team observes that the wheels spin freely and produces the optical effect desired when viewed from the side, then the team will be able to conclude that the overall design was successful and that the correct considerations were taken into account when designing the critical components.

Because the team decided to use a stainless steel axle along with plastic gears and acrylic, the factor of safety is much higher than needed. Therefore, the team is not worried about the strength of the axle, and will instead ensure that the gears, attached to the wheels, are able to spin freely around the axle and do not lose much angular velocity due to friction.

In order to test the strength of the axle, the Colorado Creators would have had to perform a test where the team bends the axle until it breaks. This was not possible due to the lack of access to a material tester and the fact that the team needed the axle intact to use it in the final assembly. However, the theoretical safety factor that the team calculated indicated that the strength of the axle was not a concern.

Using a circuit with a known resistance value, .375 Ω, the team was able to calculate the no load current and stalled current. By connecting the resistor from the negative terminal of the motor to ground and measuring the voltage across that resistor and applying Ohm's Law, the currents were determined. To stall the motor the Ninja Stars were manually stopped and the no-load calculations were done when the motor was at maximum RPM. The small resistance value was used to minimize the impact on the motor and still get an accurate voltage reading. Using these values calculated from the circuit, the team calculated the actual safety factor, which was found to be 6, which is close to the theoretical value to 6.8.

VI. Design Iteration

Upon assembly of the project, the team was able to verify that the design works as intended. The team minimized friction in the system so that the blades spin freely and do not put extra strain on the motor. Overall, the team met the design requirements and goals for this project, as the team was able to produce a final kinetic sculpture that spins as it was designed to.

Once the team finished the set up of our overall system and did some tests, they realized that one of our retaining rings continued to get caught on the side of the screw and would not allow the system to move. To negate the effect of this ring, the team took it out. Along with that, the Colorado Creators noticed that the selected motor had an excessive amount of RPM. For this part of the lab, the team had to set up a circuit on the side that allows users to control the speed of the motor. A circuit diagram for this is shown below:

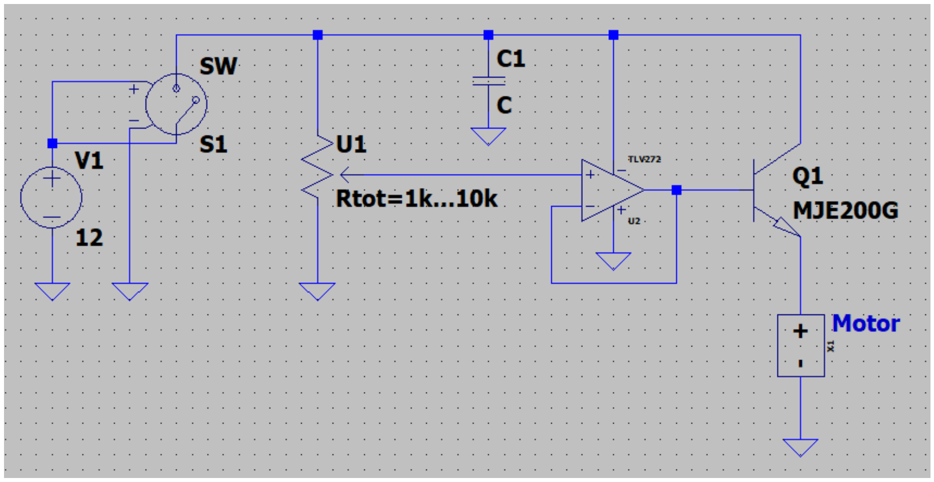


Figure 8: Variable Power Supply Circuit to limit the motor's rotational velocity

VII. Budget and Bill of Materials

For this project, the overall cost came out to be $205.92. As a team, the Colorado Creators did not include the costs of the aluminum sheet or cost of shop time in these calculations. A breakdown of costs is below:

Name of Part	Quantity	Vendor	Cost	Description
Retaining rings	6	McMaster Carr	$0.67/unit	Aluminum rings
Blades	2	ITLL	$25/sheet	Acrylic
Bevel gear	2	McMaster Carr	$41.12/unit	Nylon Plastic
Pinion Gear	1	McMaster Carr	$24.37	Nylon Plastic
Motor	1	Amazon	$13.99	Iron
Motor Mount	1	IdeaForge	N/A	Aluminum
Axle	1	McMaster Carr	$20.55	Stainless Steel
Base	1	IdeaForge	N/A	Aluminum
Vertical Motor Mount	1	IdeaForge	N/A	Aluminum
Axle Mount	2	IdeaForge	N/A	Aluminum
4-40 screws	8	HomeDepot	$0.12/unit	Steel
Switches	1	Amazon	$2.60/unit	N/A
Battery Pack	1	Amazon	$5.66	Plastic

Batteries	8	Amazon	$1.30/unit	Duracell
M3-5 screws	6	HomeDepot	$0.26/unit	Stainless Steel
2-56 ¼ inch screw	1	HomeDepot	$.25/unit	Stainless Steel

VIII. Team Timeline:

Week Feb 22-28 (Week 5)

- Start CAD design (simple layout)
- BOM
- Meeting with Chase

Week Mar 1- 7th (Week 6)

- Small scale model should be created with video
- March 5 -- First Part order submission deadline

Week Mar 8-14 th (Week 7)

- 4:30-5 PM (3/10/21) Meeting with Chase
    - Needs Preliminary B.o.M and CAD model

Week Mar 15-21 st (Week 8)

- Need completed drawings and finalized CAD models
- Submit initial fabrication requests

Week March 22 - 28th -- Week April 12 - 18 (Week 9 - 12)

- Start assembling product
- All initial fabrication requests due 4/2

Week 4/19 - 4/25 (Week 13)

- The project should be completed
- Hardware demonstrations in lab // everything should be done and operating at this point

Report draft due 4/1

- Include suggestions/revisions from PDR and Major DR

6-10 minute Virtual Expo due 4/29

Final Report due 4/29

IX. Appendix

References:

[1] Norton, R., 2010. *Machine Design: An Integrated Approach*. 4th ed. Pearson.
[2] Engineers Edge, LLC. *Preferred Force SHRINK Fits CHART ANSI B4.1 Calculator: GD&T Tolerances*. www.engineersedge.com/calculators/mechanical-tolerances/force-fit-tolerances.htm.

Equations:

$\sigma = \frac{My}{I}$ Eq. 1

$S_f = C_{load} C_{size} C_{surf} C_{temp} C_{reliab} S_f'$ Eq. 2

$N_f = \frac{S_f S_{ut}}{\sigma_a' S_{ut} + \sigma_m' S_{ut}}$ Eq. 3

$T = F * L$

Eq. 4

$P = T * \omega$ Eq. 5

$\alpha_G = tan^{-1}(\frac{N_G}{N_p})$

Eq. 6

$\alpha_p = 90 - \alpha_G$ Eq. 7

$L = \frac{d_p}{2*sin(\alpha_p)}$ Eq. 8

$F = L/3$ Eq. 9

$m = \frac{P_d}{n}$ Eq. 10

$\sigma_b = \frac{2000*T_p}{P_d} * \frac{1}{F*m*J} * \frac{K_a*K_m*K_s}{K_v*K_x}$

Eq. 11

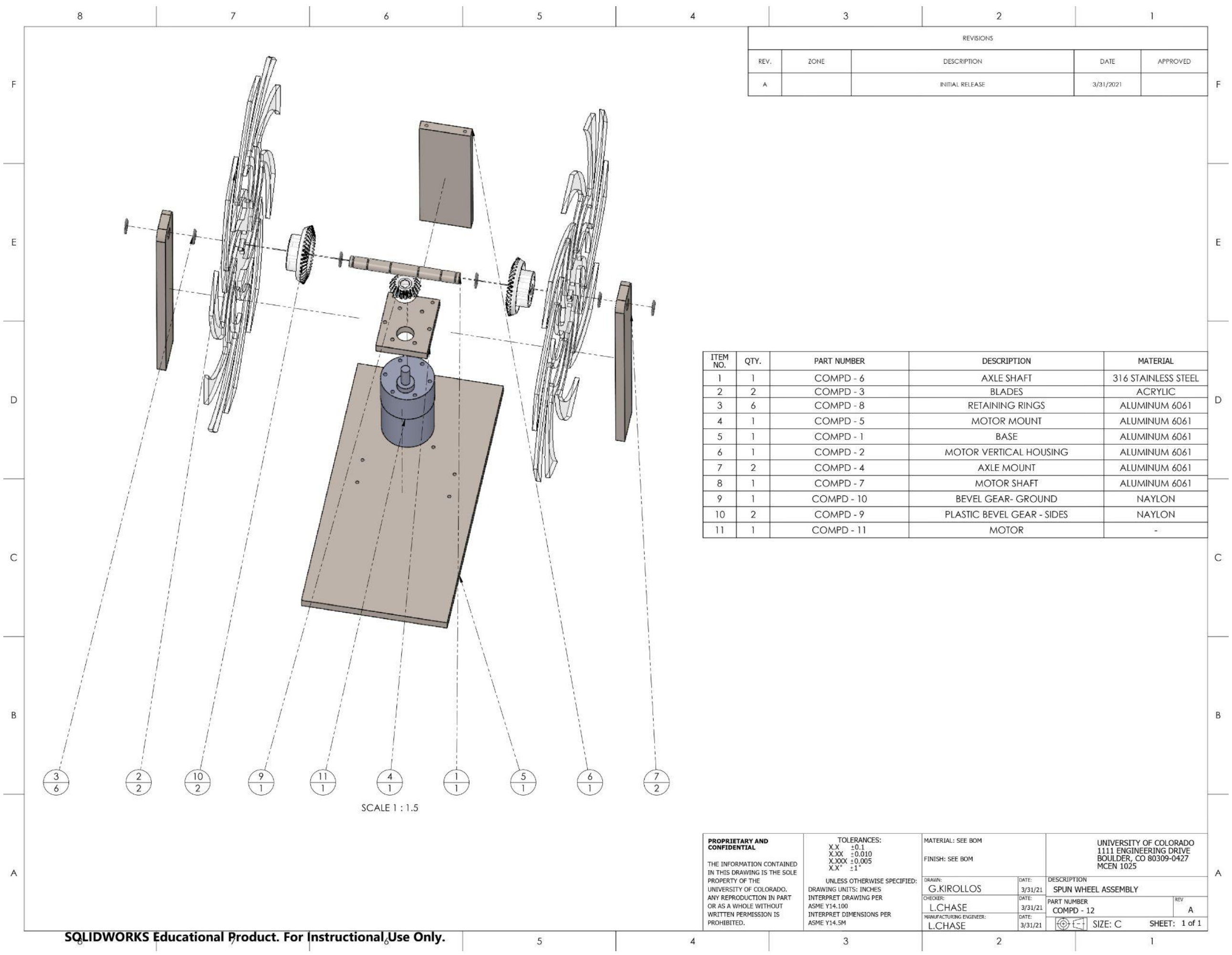
$S_{fb} = 27000 + 364 * HB$(psi)

Eq. 12

$N = \frac{S_{fb}}{\sigma_b}$

Eq. 13

Exploded view of product assembly:



ITEM NO.	QTY.	PART NUMBER	DESCRIPTION	MATERIAL
1	1	COMPD - 6	AXLE SHAFT	316 STAINLESS STEEL
2	2	COMPD - 3	BLADES	ACRYLIC
3	6	COMPD - 8	RETAINING RINGS	ALUMINUM 6061
4	1	COMPD - 5	MOTOR MOUNT	ALUMINUM 6061
5	1	COMPD - 1	BASE	ALUMINUM 6061
6	1	COMPD - 2	MOTOR VERTICAL HOUSING	ALUMINUM 6061
7	2	COMPD - 4	AXLE MOUNT	ALUMINUM 6061
8	1	COMPD - 7	MOTOR SHAFT	ALUMINUM 6061
9	1	COMPD - 10	BEVEL GEAR- GROUND	NAYLON
10	2	COMPD - 9	PLASTIC BEVEL GEAR - SIDES	NAYLON
11	1	COMPD - 11	MOTOR	-

Calculations:

Gear and Motor:

allowable torque from table → .245

$T = F \times L \Rightarrow F = \frac{T}{L} = 61.25$

$P = T \cdot w \Rightarrow 73.5W$

Need: $J, K_a, K_m, K_s, K_v, K_x$

Pitch diameter → $P_d = 20mm$

Pitch cone angles $= \alpha_g = \tan^{-1}\left(\frac{N_g}{N_p}\right) = \tan^{-1}\left(\frac{40}{20}\right) = 63^\circ$

$\alpha_p = 90 - \alpha_g = 26^\circ$

Pitch cone length:

$$L = \frac{d_p}{2\sin\alpha_p} = \frac{20}{2\sin(26)} = 22\,mm$$

Pitch width: $F = L/3 = 7.33mm$

looking up bending geometry factor, J, using fig 13.5

$J_p = .237$, $J_g = .201$

$$\text{module} = \frac{P_d}{\#\,\text{teeth}} = \frac{20mm}{40} = .5$$

$$\sigma_b = \frac{2000\,T_p}{d}\,\frac{1}{J F m}\,\frac{K_a K_m K_s}{K_v K_x} = \frac{(2000)(.245)}{20}\,\frac{1}{(7.33)(.5)(.237)}\,\frac{(1)(1.6)(1)}{(.652)(1)}$$

$\sigma_b = 28.2\ MPa$

$S_{fb} = 27000 + 364 \cdot HB \rightarrow 27000 + 364 * 2 = 27727\ psi = 191\ MPa$

$$\boxed{N = \frac{191}{28.2} = 6.82}$$

No load current → .321 A

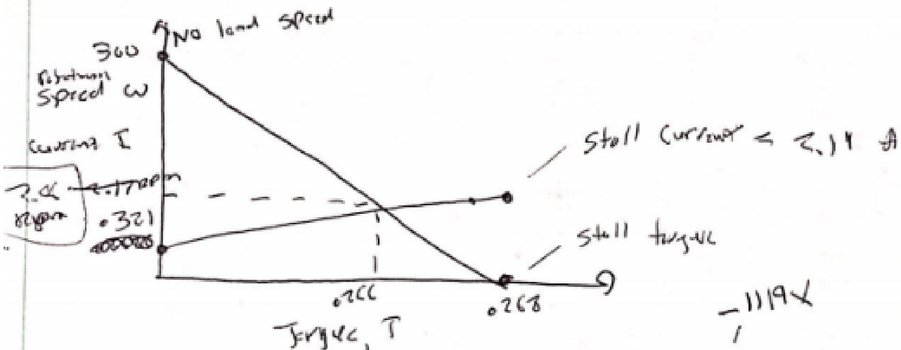
Stall current → 2.19 A

No load speed → 300 rpm

Stall torque →

$$P = T\omega = VI$$

$$T = \frac{VI}{\omega} = \frac{(12V)(2.19A)}{300\ rpm} = .2628$$



$-1119x$

$\frac{.268}{300}$ → ~~$y = 6.9 \times 10^{-4} x + 300$~~ $y = \frac{-300}{.268}x + 300$

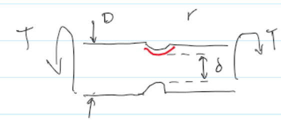
$$y = \left(\frac{2.19 - .321}{.268}\right)x + .321$$

$$y = 6.97x + .321$$

$$x = \frac{249}{1125} \rightarrow .266$$

Axle:

Appendix: Fig. C-5



$D = .3150$

$\delta = .3150 - .008 \times 2$

$= .307$

$\underline{K_t = A\left(\frac{r}{\delta}\right)^b}$ approximate r w/ $\left(\frac{D-\delta}{2}\right)$

$r = \frac{.315 - .307}{2} = .004$

$D/\delta = 1.26 \approx 1.3$

$A = .8946$

$b = -.232$

$K_t = .8946\left(\frac{.004}{.307}\right)^{-.232} = 2.4488 \longrightarrow$ torsion

mass of stars = .15 lb =

mass of retaining rings = .001 lb

" " bend gear = .0242 lb

moment: $K_t = .94299\left(\frac{.004}{.307}\right)^{-.31504} = 3.7015 \longrightarrow$ use greater K value

$E = 1.93\text{E}11\ N/m^2$ $m = .07$ lb $= .0317515$

$S_y = 172368932\ N$

Fig 6-26/27 + eq. 6.7d $\longrightarrow$ machined

$$S_e = \underset{6.7a}{C_{load}}\ \underset{6.7b/c/d}{C_{size}}\ C_{surf}\ C_{temp}\ C_{reliab}\ S_e'$$

C_{size}: $\downarrow$ .315" Ø

C_{temp}: $\downarrow$ 6.7f

C_{reliab}: $\searrow$ Table 6-4

$C_{size} = .869\, d_{eq}^{.097}$

w/ $d_{eq} = \sqrt{A_{95}/.0766}$

$A_{95} = .0105\,\delta^2$

$A_{95} = .0010418625$

$d_{eq} = .116624$

$\boxed{C_{size} = .7055}$

$\boxed{C_{load} = 1 \quad \text{(Bending)}}$

change S_{ut} to kpsi (75 kpsi)

$C_{surf} = A(S_{ut})^b$ $A = 2.7$ $b = -.265$

$\boxed{C_{surf} = .86}$

$S_e' = .5\,S_{ut} = 37.5$ kpsi

$\boxed{C_{temp} = 1}$

$\boxed{C_{reliab} = 1}$

$\boxed{S_e = 22.75 \text{ kpsi}}$

$$N_f = \frac{S_e S_{ut}}{\cancel{\sigma'_a} S_{ut} + \sigma'_m S_e}$$

$K_f = 1 + q(K_t - 1)$

w/ $q = \frac{1}{1 + \sqrt{a}/\sqrt{r}}$ $\rightarrow$ $q = \frac{1}{1 + .865/\sqrt{.315/2}} = .315$

$\sqrt{a}$ b/w 70 + 80 kpsi values

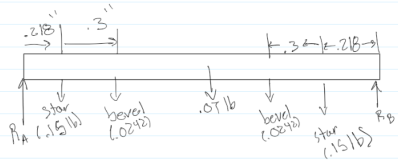
Table 6.6: $\sqrt{a} = .93 - \left(\frac{.93 - .8}{2}\right) = .865$

$\sqrt{r} = \sqrt{.315/2}$

.8''

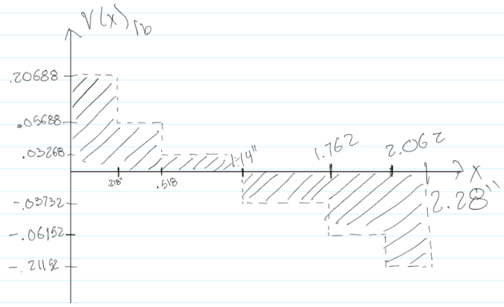
$\rightarrow K_f = 1 + .315(3.705 - 1)$

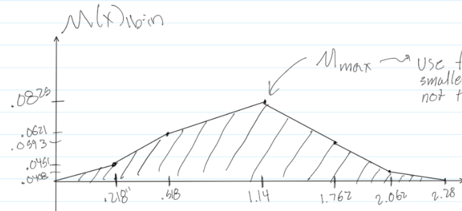
$K_f = 1.852$



$$\Sigma M_A = -.15\text{lb} \cdot .218'' - .0242\text{lb} \cdot .3'' - .07\text{lb} \cdot \frac{2.28''}{2} - .0242\text{lb}(2.28 - .518)$$
$$- .15\text{lb}(2.28 - .218) + R_B \cdot 2.28'' = 0$$

$R_B = .20688$ lb $= R_A$ by symmetry





M_{max} $\rightarrow$ use for σ_m (will generate smallest safety factor even if it's not the mean value)

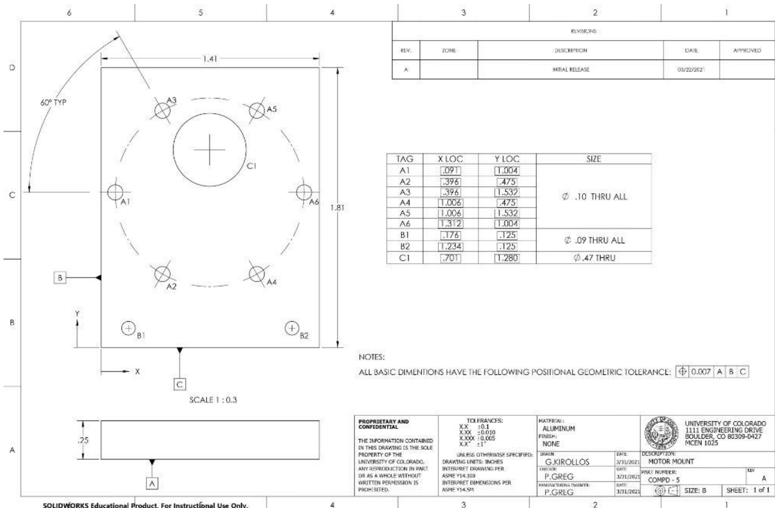
$\sigma = \frac{My}{I}$ ← r, ← $\frac{\pi r^4}{4}$ $\rightarrow$ $\sigma = \frac{M}{\frac{\pi r^3}{4}}$

$\sigma_{nom} = \frac{.0825\text{ lb}\cdot\text{in}}{\frac{\pi(.315)^3}{4}} = 3.36$ psi

$$N_f = \frac{S_e S_{ut}}{\cancel{\sigma'_a S_{ut}} + \sigma'_m S_{ut}} = \frac{22.75\text{ kpsi} \cdot 75\text{ kpsi}}{.006223\text{ kpsi} \cdot 75\text{ kpsi}} = \boxed{3655.8}$$

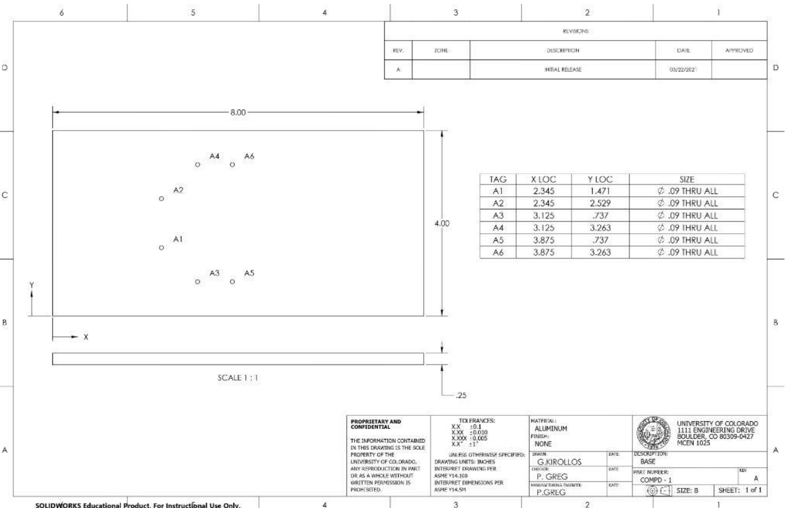
0 no fluctuating stress

Drawings



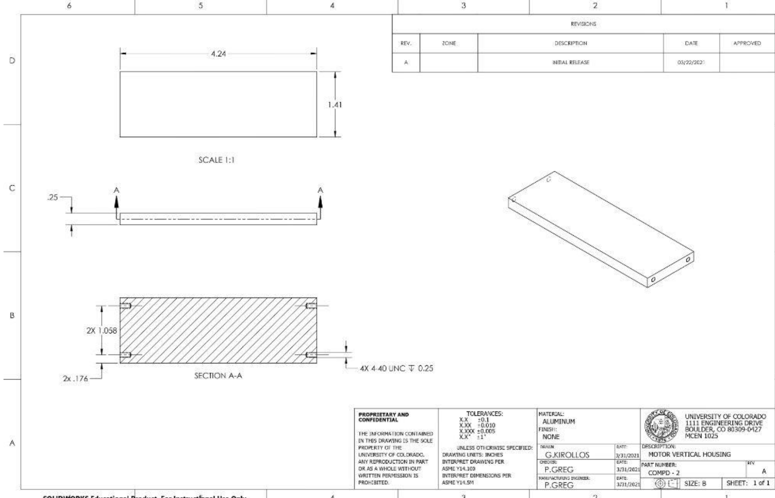
TAG	X LOC	Y LOC	SIZE
A1	.091	1.004	Ø .10 THRU ALL
A2	.396	.475	
A3	.396	1.532	
A4	1.006	.475	
A5	1.006	1.532	
A6	1.312	1.004	
B1	.176	.125	Ø .09 THRU ALL
B2	1.234	.125	
C1	.701	1.280	Ø .47 THRU

NOTES:
ALL BASIC DIMENTIONS HAVE THE FOLLOWING POSITIONAL GEOMETRIC TOLERANCE: 0.007 A B C
SCALE 1 : 0.3
MOTOR MOUNT
COMPD - 5
SOLIDWORKS Educational Product. For Instructional Use Only.

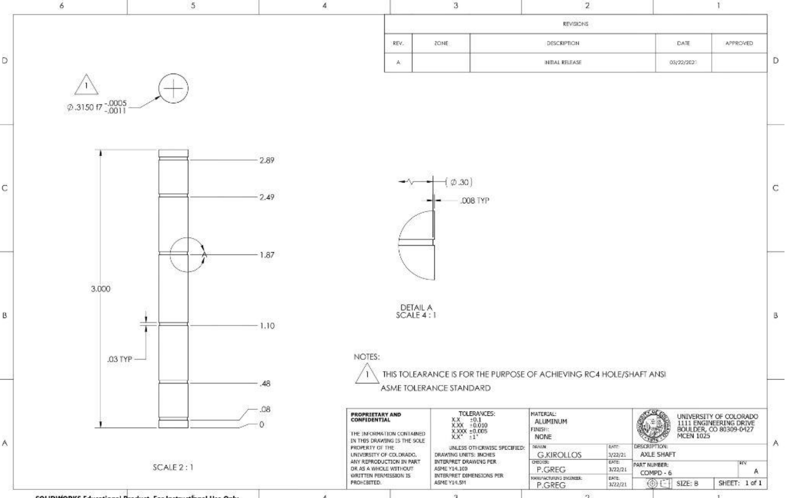


TAG	X LOC	Y LOC	SIZE
A1	2.345	1.471	Ø .09 THRU ALL
A2	2.345	2.529	Ø .09 THRU ALL
A3	3.125	.737	Ø .09 THRU ALL
A4	3.125	3.263	Ø .09 THRU ALL
A5	3.875	.737	Ø .09 THRU ALL
A6	3.875	3.263	Ø .09 THRU ALL

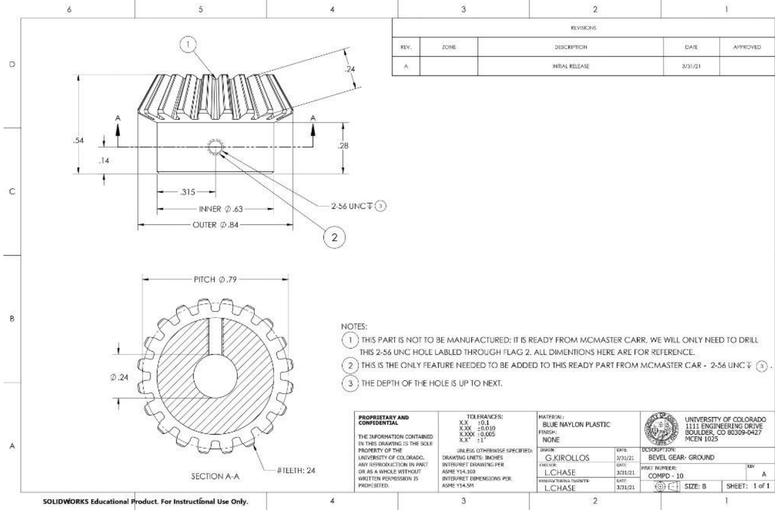
SCALE 1 : 1
BASE
COMPD - 1
SOLIDWORKS Educational Product. For Instructional Use Only.



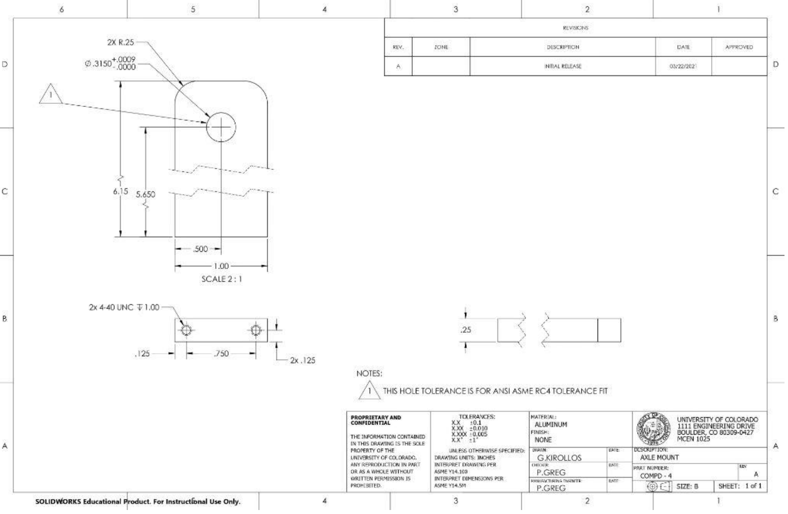
SCALE 1:1
SECTION A-A
4X 4-40 UNC ⊽ 0.25
MOTOR VERTICAL HOUSING
COMPD - 2
SOLIDWORKS Educational Product. For Instructional Use Only.



DETAIL A
SCALE 4 : 1
NOTES:
THIS TOLEARANCE IS FOR THE PURPOSE OF ACHIEVING RC4 HOLE/SHAFT ANSI ASME TOLERANCE STANDARD
SCALE 2 : 1
AXLE SHAFT
COMPD - 6
SOLIDWORKS Educational Product. For Instructional Use Only.



NOTES:
THIS PART IS NOT TO BE MANUFACTURED; IT IS READY FROM MCMASTER CARR. WE WILL ONLY NEED TO DRILL THIS 2-56 UNC HOLE LABLED THROUGH FLAG 2. ALL DIMENTIONS HERE ARE FOR REFERENCE.
THIS IS THE ONLY FEATURE NEEDED TO BE ADDED TO THIS READY PART FROM MCMASTER CAR - 2-56 UNC
THE DEPTH OF THE HOLE IS UP TO NEXT.
SECTION A-A
#TEETH: 24
BEVEL GEAR- GROUND
COMPD - 10
SOLIDWORKS Educational Product. For Instructional Use Only.



SCALE 2 : 1
NOTES:
THIS HOLE TOLERANCE IS FOR ANSI ASME RC4 TOLERANCE FIT
AXLE MOUNT
COMPD - 4
SOLIDWORKS Educational Product. For Instructional Use Only.