Cal Poly Satellite Positioning Systems: "Thrust or Bust!"
Final Design Review

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Abstract

Satellites need a way to make precise corrections to their orbit and positioning. The purpose of this project is to design a gimbal mechanism for Astranis that orients an ion thruster along a requested vector. The gimbal must produce any vector within a 2.5° cone in a thirty-minute window. Current systems are expensive and not well suited to this application. The design must be operable in a space environment and optimize mass, size, and reliability.

Our design toggles between four discrete positions to achieve an average thrust vector. The gimbal accomplishes this using four solenoids that tilt a plate about a central hinge. The hinge allows for low friction rotation in only two axes. It also contains an integrated restoring force, which will passively restore the thruster to center in event of actuator failure. A linkage assembly connects the solenoids to the thruster plate, allowing for mechanical advantage and a low profile. Four hard stops in the linkage assembly physically define the actuation angles.

We initially pursued several designs in parallel before narrowing down to a single design for our confirmation prototype. After manufacturing this prototype, we tested our design to verify range and accuracy of the vector and the ability of the gimbal to move an ion thruster on Earth. The gimbal produced a 2.445° cone with a vector precision of ±0.01° and successfully actuated a 5kg load with a similar center of mass. The gimbal has an envelope of 199x199x44mm and a total mass of 0.926kg. Future testing should include environment tests and complete system tests to ensure full functionality in the intended application.

Although our final prototype is not intended to be launch ready, the work accomplished for this project will benefit Astranis as they pursue a flight ready design.

Statement of Disclaimer

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1.0 Introduction

The goal of the project is to design and prototype a device to position a low-force thruster on a satellite for our sponsor, Astranis Space Technologies Corp. Astranis is a start-up that designs telecommunications satellites to provide internet access to rural areas. Our point of contact with the company for this project is Jay Miley, a structural engineer at Astranis.

The team working to solve this problem is composed of four mechanical engineering students at California Polytechnic State University, San Luis Obispo for a senior design project. This project lasted for three quarters culminating in a final prototype and a design expo.

This document first discusses the results of the team's research, then addresses the scope of the project and clearly defines requirements that a successful design must meet. The document proceeds to give an overview of our ideation process and initial concepts presented in the preliminary design review. It then describes our idea refinement process and development of structural prototypes to influence the final design direction. After presenting the details of our final design, the report covers our manufacturing procedures, and design verification procedures and results. Finally, it discusses conclusions drawn from the project and recommendations for future iterations.

2.0 Background

To fully understand the project presented to us, our team studied the technical background and current relevant literature. This initial analysis helped us to clearly define the problem and develop an effective solution process. Through meetings, observations, and research, we generated a list of requirements to fit the needs of our sponsor, Astranis. We then performed a patent search and discovered ways we could improve on existing products while noting the reasons that those products were successful. We also conducted technical research to better understand the potential challenges posed by working in a space environment and the relevant standards that the mechanism should be able to fulfill.

2.1 Customer Research

Astranis is a start-up company working to develop technology that provides lower cost telecommunications to the world. They specifically focus on bringing online rural areas with little access to the internet. In pursuit of this goal, they are creating smaller and lower cost telecom satellites. If successful, our system may be integrated onto a future satellite iteration. The gimbal will enable small adjustments, making the overall satellite positioning system more efficient.

Our sponsor provided us the following baseline requirements for our design:

- Minimize mass
- Minimize complexity
- Ensure reliability

• All materials vacuum compatible
• Survive a temperature range of -100 °C to 200 °C
• Minimize volume within a boundary of 200x200x80mm, particularly the 80mm height
• Accommodate mounting system and selected thruster

We also received guidance on how to approach each requirement. The priority for Astranis is simple and reliable positioning. The design of the satellite is not yet defined, so specific volume, mass, cost, and pointing range are not hard requirements. However, our system must be able to survive the space environment. Although our design is not required to survive launch considerations, we should consider how it will accommodate a support mechanism during launch. Design and accommodation of this constraint system is out of the scope of this project.

2.1.1 Ongoing Changes to Design Requirements

Over the course of the project, the baseline requirements were modified to reflect the challenges discovered by the project. The initial 5° cone was reduced to a 2.5° cone due to the challenges posed by actuating the gimbal with the chosen mechanism. Additionally, there were concerns about external forces on the gimbal, particularly the hose that will attach to the gimbal. Finally, in the case of a failure Astranis wanted the gimbal to either be at or passively return to a known position. These changes are summarized as:

• 2.5° cone as the range of actuation
• 0.2Nm holding torque
• Have a known no power reset position in the case of failure

2.2 Product Research

As part of the background research, we found existing products and examined their potential for solving our sponsor’s needs and wants. The following are four categories of products we discovered through an extensive online search that could potentially be useful for our design.

2.2.1 Dual Axis Gimbals

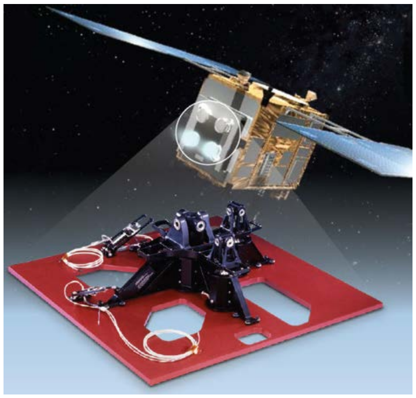


Figure 1: MOOG Ion Thruster Gimbal [1]

Moog developed a gimbal mechanism (Figure 1) to provide vector maneuvering for thrust of the Hayabusa satellite which used four gimbaled ion thrusters. Hayabusa was a robotic spacecraft launched in 2003 by the Japanese Aerospace Exploration Agency (JAXA) to return sample material from a near-Earth asteroid [1]. This gimbal was specifically designed for Hayabusa's ion thruster, which is a method of electric propulsion. The device is a dual axis gimbal actuated by linear actuators. It uses stepper motors with lead-screw actuation for positioning. The gimbal has a vector range of ±5° in both X and Y axes, an operating temperature range of -20° to 80°C and has envelope dimensions of 16x16x7 inches.

2.2.2 Three Arm Gimbal

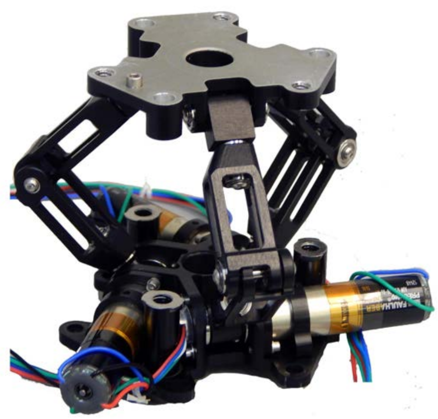


Figure 2: Tethers Unlimited COBRA Gimbal [2]

The second type of gimbal we found is the three-armed gimbal. Tethers Unlimited makes the COBRA gimbal (Figure 2), a three degree of freedom mechanism designed for precision pointing of thrusters or sensors. The device uses three stepper motors to define its degrees of freedom [2]. The COBRA line provides three models, COBRA-C, COBRA-HPX, and COBRA-UHPX, with an open-loop stepper, closed-loop stepper and brushless closed-loop stepper respectively. These models have a hemispherical range of 2πsr. The envelope dimensions for the gimbals ranges from 100 to 165 mm in diameter and 26 to 40 mm in stack height.

2.2.3 Ball Joint and Rotary Actuators

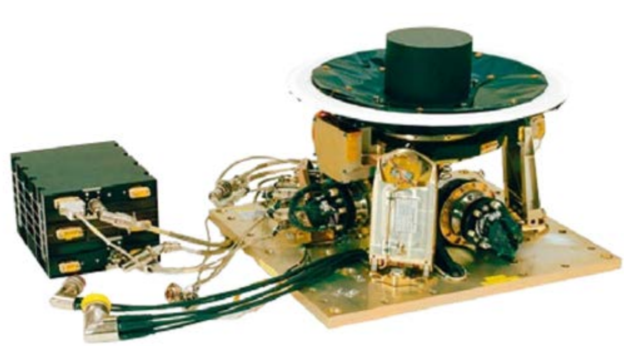


Figure 3: RUAG Electric Propulsion Mechanism (EPMEC) [3]

RUAG created an electric propulsion pointing mechanism (Figure 3) for the SMART-1 spacecraft developed by the Swedish Space Corporation. The spacecraft used an electric propulsion system as the main thruster power source for the mission, with EPMEC used as the steering mechanism. The EPMEC design uses two rotary actuators, which drive the thruster via a strut-linkage around a spherical joint [3]. The EPMEC enables pointing within a half-cone angle of 10°. The mechanism has an operating temperature range of -45° to 65° C.

2.2.4 Full Sphere of Motion Gimbals

Figure 4: NEA Electronics G35 Gimbal [4]

NEA Electronics has developed actuators specifically for precision spacecraft pointing applications. NEA's G35 gimbal (Figure 4) is comprised of two P35 actuators combined with brackets to create a multi-axis gimbal [4]. The P35 actuators provide two step angle options, 0.0075° output step angle and a 0.0024° output step angle for very fine positioning. A single P35 actuator is 4.75 inches in diameter and 3.90 inches in height. Each P35 actuator can provide voltage telemetry over the entire 360 degrees of travel. The mechanism has an operating temperature range of -50° to 105°C.

Figure 5: Aerotech AMG100-LP Low-Profile Direct-Drive Gimbal [5]

High precision gimbals have been designed for precision applications. Aerotech develops gimbals to provide ultra-precise angular positioning. The AMG100-LP gimbal (Figure 5) is designed for directing optics, lasers, antennas, and sensors to very precise pointing angles [5]. The AMG-LP utilizes Aerotech's high torque S-series brushless, slotless servomotors. The gimbal provides 360 degrees of rotation about the azimuth and elevation angles. The gimbal provides an accuracy up to ±24 µrad when calibrated or ±192 µrad when uncalibrated. The envelope dimensions for the gimbal are 292 mm in diametral clearance and 243 mm in height.

2.2.5 Patent Search Results

A patent search was conducted to examine current technologies related to gimballed thrust control. The primary purpose of this investigation was for industry research and idea generation. The secondary purpose is to be aware of what patents may be incorporated or referenced in our final design. We identified five relevant patents in Table 1 along with a short description of their contents.

Table 1: Relevant Patents

Patent Title	Patent Number	Description
Ion Thruster Support and Positioning System [6]	US 5,738,308 A	Linkage that allows ion thruster positioning using three rotary actuators
Spacecraft Attitude Control And Momentum Unloading Using Gimballed And Throttled Thrusters [7]	US 5,349,532 A	Single axis gimbals positioned on the corners of the satellite allow for attitude control
Gimbaled Thruster Control System [8]	US 6,481,672 B1	Calculation of gimbal angle required for torque adjustments
Mechanism For Thrust Vector Control Using Multiple Nozzles [9]	US 5,662,290 A	Mechanism to control angle of nozzle
Attitude Slew Methodology For Space Vehicles Using Gimbaled Low-Thrust Propulsion Subsystem [10]	US 9,522,746 B1	System of four gimballed thrusters for attitude control in the event of reaction wheel failure

The Ion Thruster Support and Positioning System patent was helpful to us because it addresses the differences in requirements for a gimbal mechanism for liquid fuel thruster and ion thruster systems. It also discusses how these differences guided the design of the system being patented. The patents Spacecraft Attitude Control and Momentum Unloading and Mechanism for Thrust Vector Control Using Multiple Nozzles are not as helpful for our project because they rely on the thrusters having certain characteristics that we cannot assume. The Attitude Slew Methodology patent also relies on aspects of the satellite beyond our control for this project, namely that it requires the satellite to have four thrusters dedicated to attitude control. These patents were useful in helping us further understand the scope of our project, but none met all the specifications of our application.

2.3 Technical Research

In orbit, satellite systems are exposed to low pressures, high doses of radiation, thermal cycling, atomic oxygen, and impacts from micrometeoroids and other debris. The mechanism will need to maintain its accuracy under these conditions. The vacuum environment limits material selection, as outgassing will occur in certain materials. This removes cadmium, zinc, magnesium, and many plastics from the list of viable material options. Some that work well under these conditions are aluminum, nickel, titanium, and steel. [11] Atomic oxygen can cause corrosion in some materials such as aluminum which requires a coating. Astranis provided a survival temperature cycle for this project of +200℃/-100℃, although we will select a more moderate temperature requirement for mechanism operation. Designing for high radiation dosage beyond material selection is outside the scope of what is feasible to test for this project and Cal Poly does not have the facilities or equipment to test these requirements.

Objects sent into space are subject to multiple standards to ensure safety, reliability, and quality. The Air Force Space Command published the Space and Missile Systems Command Standard, known as SMC-S-016, which contains the testing requirements for our system. The device must pass both the electrical and structural standards [12]. Additionally, the General Environmental Verification Standard published by the NASA Goddard Space Flight Center contains requirements for the testing of mechanical elements, including strength qualifications, mechanical shock tests, and vibration tests [13]. Finally, for material selection, the American Society of Testing and Materials prescribes the Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment. The object or system is exposed to a near vacuum ($7x10^{-3}$ Pa) for 24 hours at 125℃. For use on spacecraft, a Total Mass Loss of <1% and a Collected Volatile Condensable Material of <0.1% has been used to validate previous spacecraft components [14].

As with the environmental requirements, not all specifications set by these standards can be tested using equipment available at California Polytechnic State University. Certain tests, such as extended life tests, will not be possible given these restrictions.

2.4 Actuator Research

Actuator selection proved to be a critical factor in selecting a final design, so it is worth discussing the merits of each type. Astranis desired that the design should passively return to center so that in case of a failure, the ion thruster would remain useable at a known direction. Table 2 summarizes the benefits and problems for several types of linear actuators. The viability ranking was chosen for our design and requirement set. Should the requirements or the design change, the viability would change as well. For example, if the requirement of a passive return to center was not included, piezoelectric actuators would have a higher viability.

Table 2: Linear actuator selection summary

Actuator Type	Benefits	Problems	Viability
Pull Solenoid	Simple construction Free when not powered	Single direction of force Lower max force Low actuation distance	Viable
Push Solenoid	Simple construction Free when not powered	Single direction of force Lower max force Plunger pin is prone to wear Difficulty of force transfer Low Actuation Distance	Not Viable
Nitinol Memory	Lighter construction Retracted when not powered	Lower force Fragile High temperature sensitivity Exposed electronics Low actuation distance	Not Viable
Pin Pullers	Extremely high force Retracted when not powered	Extremely low life Single direction of force Low actuation distance	Not Viable
Rack and Pinion	High, dual direction force High potential load Low power usage High actuation distance	Large envelope Requires a gearbox Additional motor requirements Heavy construction	Not Viable
Screw Mechanism	High force High potential load Low power usage High actuation distance	Actuator extends beyond the motion envelope Potential screw failure Additional motor requirements Heavy construction	Not Viable
Piezoelectric	Extremely precise actuation Adequate force High actuation distance	Extremely high price Potential temperature sensitivity No passive return Locked when not powered	Not Viable
Voice Coils	Dual direction force Centered when not powered	Lower max force Requires lower force Low actuation distance	Viable

Of the linear actuators, pull solenoids, piezoelectrics, and voice coils are the most promising linear actuators. Solenoid are the most favored due to their extremely simple construction, low cost and adequate throw. They also have the highest forced when fully retracted. Piezoelectric actuators are promising for both force and life cycles, but are self-locking. This is useful for other designs, but since a passive return to center was desired piezoelectric actuators will not work for this application. Voice coils are also good choices, as they are similar construction to solenoids. Voice coils and piezoelectric actuators can provide the necessary force with the ability to actuate in both directions, reducing the required number of actuators to two. Both piezoelectric actuators and voice coils are worth pursuing for future designs but are significantly more expensive than solenoids.

For rotary actuator selection, we searched primarily for brushless DC motors. Brushed motors brought life concerns and stepper motors require full power to hold at a single position. Additionally, any force will move the location of a stepper motor. Gearboxes were eliminated after conversations with Astranis due to their multiple potential failure modes. It was possible to select a motor with enough torque without a gearbox, but motors without a gear reduction do not perform well at stall, having high power draw and low life. One other notable actuator is rotary solenoids. These actuators have binary or ternary positions that they are designed to maintain a position, rather than rotate through a set of positions like a motor. However, rotary solenoids are low force but some do produce enough torque for this application.

3.0 Objectives

For this project, we will design and prototype a precise positioning system for an ion thruster to allow the satellite to stay in orbit longer. Astranis has provided us with requirements that we will attempt to meet by completing following objectives.

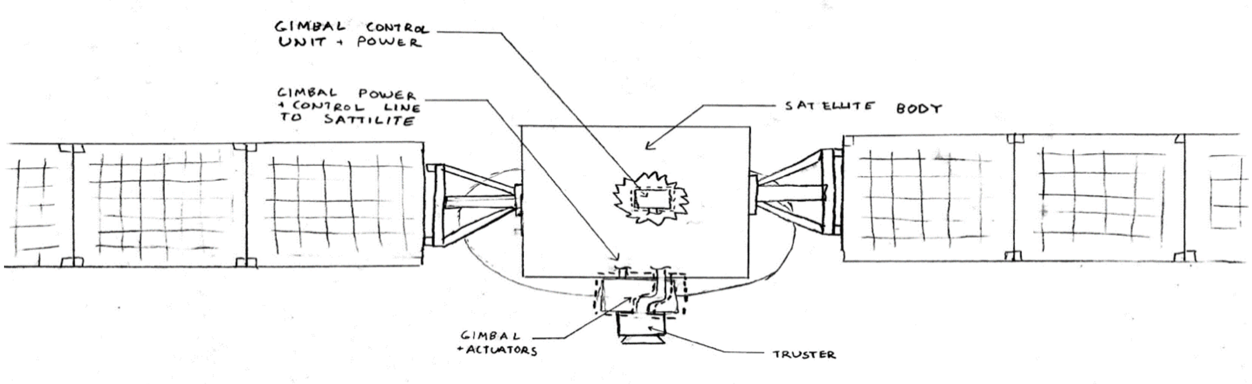


Figure 6: Boundary Drawing

The boundary drawing in Figure 6 shows our system integrated into a satellite. The dashed lines represent the gimbal boundary. We will accommodate the mounting interface of the satellite and the thruster on both ends of our boundary. This will be in the form of a bolt pattern and thruster specifications. We will also accommodate any cables from the thruster to the satellite. The gimbal itself will also have electrical connections to the satellite. In a full satellite, the gimbal power and control system would be integrated into the satellite hardware. For our prototype, we will have a 'breakout board' to simulate these systems and actuate the gimbal.

The device must fit within a 200x200x80 mm envelope. It must also be as lightweight as possible to reduce the amount of fuel needed, thus reducing launch cost. There will be no way to repair the system once launched so it must be reliable for the lifetime of the satellite. The device must be able to angle the thruster within a ±2.5° cone of the neutral position. The gimbal does not need to produce an instantaneous vector but must produce an accurate net vector within a 30- minute time window. We can move the thruster to multiple positions for different durations during the window to obtain this average thrust. A larger angular range is allowable if we can obtain the same positioning requirements.

Since the device will be operated in space, it needs to function in a vacuum. It also needs to withstand extreme temperatures, so a survival temperature range of -100 °C to 200 °C must be met. In one of the later design stages, we will specify the optimal temperature operating range for the gimbal. Our sponsor has stated that we are not responsible for considering launch loads and vibrations. In order to reduce cost and complexity, it is desirable for the device to be easily manufacturable. It is also desirable for the device to be energy efficient, actuate quickly, and position precisely.

3.1 Quality Function Deployment

In order to ensure we are meeting the correct customer needs we have created a House of Quality chart, shown in Appendix A. We identified system reliability and accuracy as the highest priority requirements for our customer. This chart also identifies how we can test whether each design meets customer requirements. Based on our initial research our highest priority specifications are vector precision, temperature resistance, actuation time, and the lifetime hours of operation. Vector precision is a test of how accurately and repeatedly we can output a given vector.

3.2 Engineering Specifications

A successful design will follow the specifications listed in Table 3. The highest risk specifications, denoted by (H) in the Risk column are the survival temperature, cycle life, accuracy, and off-axis holding torque; these are the specifications that will be most difficult for us to meet. The Compliance column shows whether we will determine if the specification is met by either inspection (I), analysis (A), or testing (T). Specifications 9 through 12 were added over the course of the design process as we became more familiar with the project and its goals.

Table 3: Thruster Gimbal Design Specification Targets

Spec. #	Parameter	Requirement or Target	Tolerance	Risk	Compliance
1	Mass	1.5kg	Max	M	I, A
2	Product Size	200x200x80mm	Max	M	I
3	Vector Precision	±0.5°	Max	H	T, A
4	Cost	$3500	Max	M	I
5	Operational Temperature	-40°C to 100°C	Min	M	A

Spec. #	Parameter	Requirement or Target	Tolerance	Risk	Compliance
6	Survival Temperature	-100°C to 200°C	Min	H	A
7	Operational in Vacuum	10^{-8} Pa	Min	M	A
8	Cycle life	10 Years	Min	H	A
9	Vector Cone	2.5°	Min	M	T
10	On- Axis Holding Torque	0.2Nm	Min	M	T
11	Off-Axis Holding Torque	0.2Nm	Min	H	T
12	Actuation in 1G	Go/No-go	N/A	M	I

Specification Descriptions:

1. Mass
   System mass will include the mass of the gimbal mechanism, the gimbal-thruster interface, and the gimbal-satellite interface. Mass will be tested weighing these components on a scale
2. Product Size
   Product size will be measured by determining what the size would be of the smallest three-dimensional envelope the system could fit within.
3. Vector Accuracy
   We will measure vector accuracy by placing a laser at the center of the mechanism and comparing the resultant angle with the expected.
4. Cost
   The total cost of the system is the sum of the cost of each of the components in the system; when products are purchased in bulk and only some are used, we will calculate the cost of the individual parts for use in the total.
5. Operational Temperature
   The operational temperature range is the range of temperatures at which the system is fully functional during operation.
6. Survival Temperature
   The survival temperature range is the range of temperatures at which the system does not suffer any permanent damage.
7. Operational in Vacuum
   This specification determines whether the system will operate at extremely low pressures.

8. Cycle Life
   We will not test for the life of our design; it is beyond the scope of the project.
9. Vector Cone
   Vector cone is the physical measurement of the maximum cone angle we can achieve. This angle occurs between two corner vectors, so it is defined as the smallest corner angle times √2.
10. On- Axis Holding Torque
   Holding torque is defined as the torque required to break the thruster away from its hard stop while it is actuated. For on-axis, a force is applied directly opposite to the actuated side.
11. On- Axis Holding Torque
   Holding torque is defined as the torque required to break the thruster away from its hard stop while it is actuated. For on-axis, a force is applied in the corner adjacent to the actuated side.
12. Actuation in 1G
   The gimbal must move a 5 kg mass in the vertical position into and out of each corner location under standard Earth gravity.

4.0 Concept Design

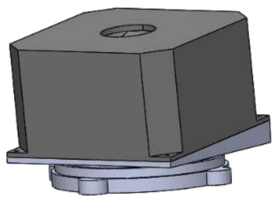
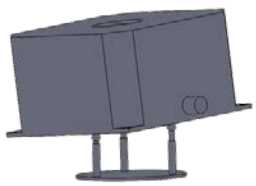
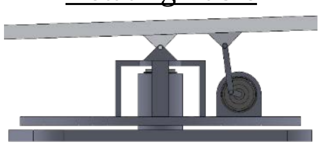
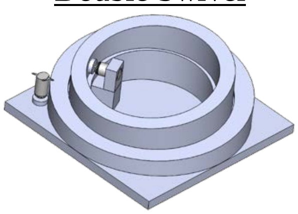
Before pursuing a single design option, our team spent time brainstorming and investigating potential solutions to determine their feasibility and identify their benefits, as well as areas of concern. Our concept development resulted in multiple solutions. We selected three top concepts for further development, which we reduced to two and then eventually a single concept. In this chapter, we detail our ideation methods, initial concepts, and design direction.

4.1 Preliminary Ideation

Our design selection process began with initial brainstorming sessions. In these sessions, we allowed all ideas to be on the table regardless of how outlandish or infeasible the ideas seemed. After amassing a large stack of initial idea sketches and concepts, we down-selected for those ideas which were impossible or beyond our abilities. We then selected the best ideas from the list using a Pugh Matrix included in Appendix B. A Pugh matrix uses a design idea as the datum and evaluated ideas based on their relative performance on a given criteria compared to a datum idea. The datum we used in this case was a two degree of freedom rotating arm. These tools allowed us to decide which ideas best fit the requirements for the project and eliminate ideas that performed poorly relative to the others.

We repeated this process of ideating and down-selecting several times and we noticed several classes of ideas beginning to emerge. At this point, we decided to each individually research and ideate on a different idea class to determine any initial problems or challenges. This resulted in some preliminary concepts (Table 4) that we presented to Jay Miley on November 8th.

Table 4: Initial Concepts

Concept	Description	Advantages	Disadvantages
Single DOF 	Thruster is mounted on a plate at fixed angle. The plate can then be rotated by a motor between two calculated positions to achieve the desired vector.	- simplicity - potential for high reliability - single actuator - few failure modes	- difficult cable routing - requires many actuations
Three Linear Actuators 	The thruster can be directed to any angle in the 5° cone extending the linear actuators to different lengths.	- instantaneous pointing - no gear reduction required - simple cable routing	- requires three precise actuators - no redundancy - actuators are structural components
Rotating Table 	Two mechanisms make up this design, a rotating table and a hinged platform. The rotating table is free to spin 360°.	- instantaneous pointing - ability to point to normal if bottom motor fails	- requires two actuators - difficult cable routing - complicated linkage system
Double Swivel 	Two concentric rings are each sloped 2.5° on one face. A motor mounted to the base drives the bottom ring and a motor mounted to the bottom ring drives the upper ring.	- instantaneous pointing - ability to point to normal if bottom motor fails	- requires two actuators - difficult cable routing - requires many sliding surfaces

4.2 Design Path

After presenting these ideas to our sponsor, Jay informed us that rotating the thruster was not a viable solution due to the complexities of cable routing. With this knowledge, we eliminated or refined our preliminary concepts. The flowchart in Figure 7 details the evolution of our preliminary designs into three major design concepts.

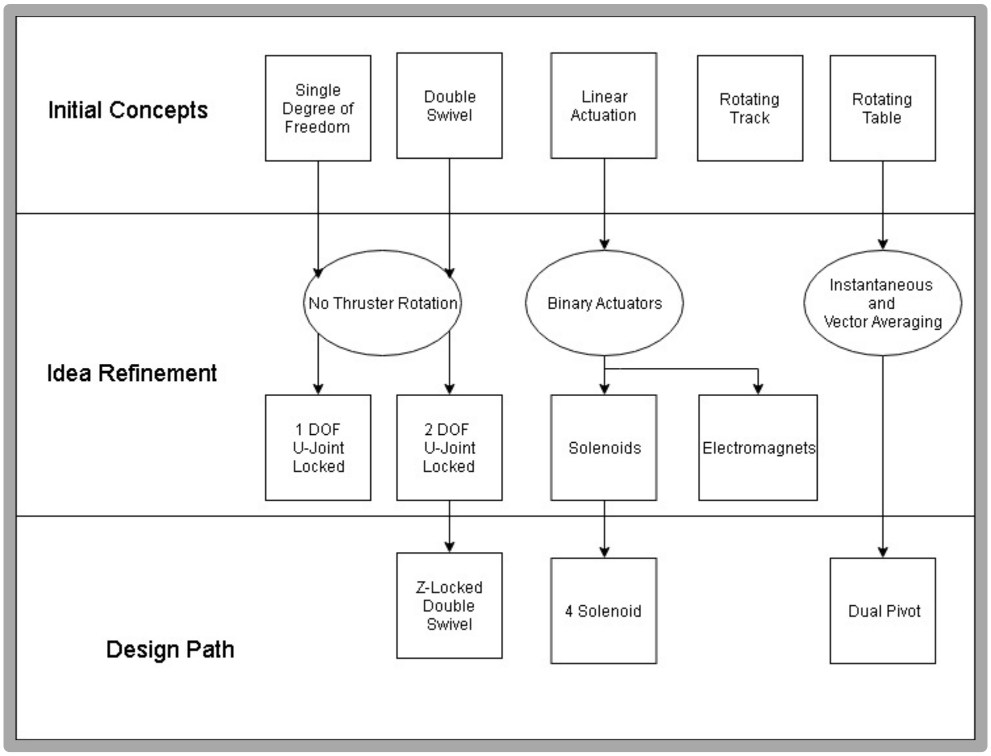


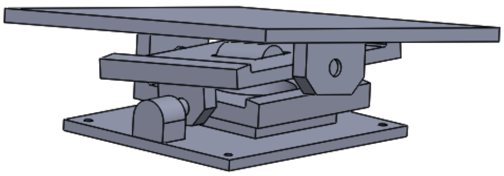
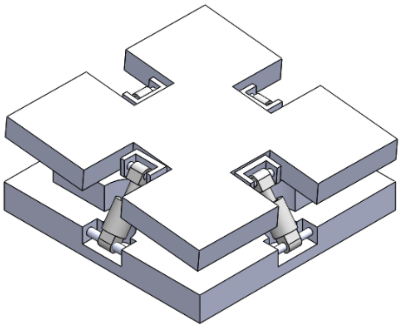
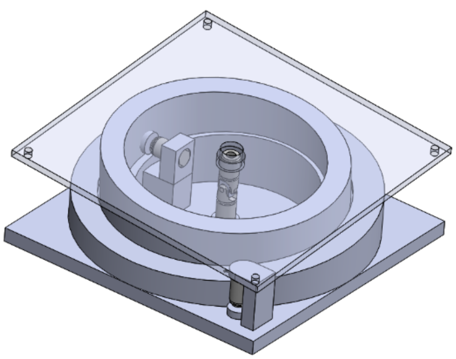
Figure 7: Overview of the initial down-selection and idea refinement process.

The conceptual design is very important to the success of our project and likely will represent the most value added to Astranis as they pursue a launch-ready version of the gimbal. Therefore, we decided to continue investigating multiple concepts in parallel. We selected three top concepts for further development and used a decision matrix to evaluate these concepts with complexity, reliability, and vector repeatability as the highest weighted factors. This chart is attached in Appendix C. Of these designs, our primary design path is a concept called the Dual Pivot. This gimbal has two rotational degrees of freedom along with hard-stops to define four angular positions. We are also considering two other options: an evolution of the Double Swivel concept, and a Linear Actuator concept. Appendix D lists alternative designs that we are not pursuing but came out of a result of idea refinement.

4.3 Design Refinement

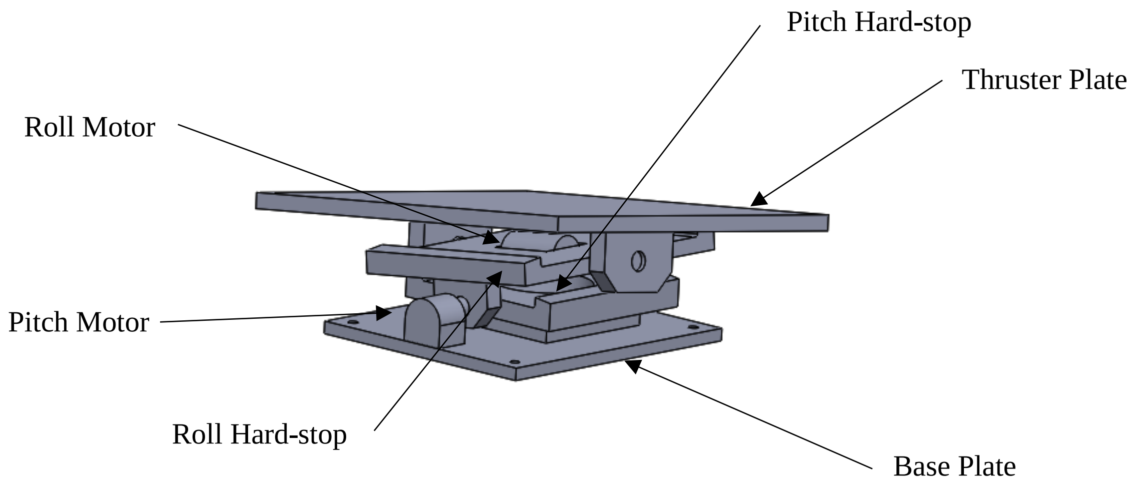
The next step in our concept design process was to explore the selected designs to greater depth. Table 5 introduces the more refined versions of the concepts generated through our preliminary ideation that we decided to move forward with. In this section, we will describe how each of these designs would operate, some advantages of each, as well as their limitations.

Table 5: Summary of Major Design Concepts

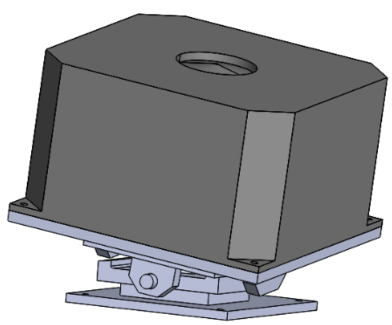
Concept	Description
Dual Pivot 	This concept uses two pivoting plates and hard stops to position the thruster in four discrete positions. This concept utilizes vector averaging. This design uses two pivoting platforms stacked on top of each other. The platforms are rotated 90° from each other and utilize two motors to control motion in pitch and roll. Rigid hard stops are located beneath each platform to clock the thruster in one of four positions.
Four Position Linear Actuator 	This concept uses four solenoids to position the thruster in four discrete positions. This concept utilizes vector averaging. Each solenoid connects to a double pivot on a plate attached to the thruster. The solenoids extend and retract to move the thruster plate four positions. A pyramidal plate with four surfaces is used to keep the thruster clocked in one of four discrete positions.
Double Swivel 	This concept uses two offset planes to produce two independent vectors. These vectors can be linearly combined to produce an instantaneous vector. This design consists of two concentric rings, each with one surface that is 2.5° offset from horizontal, and a third flat plate that the thruster rests on. The rings rotate concentrically, and through the addition of a passive stage above the rings, the thruster can remain yaw-locked.

4.3.1 Primary Design: Dual Pivot Mechanism

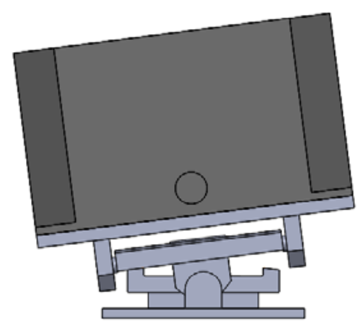
The Dual Pivot concept (Figure 8) consists of two motors controlling the pitch and roll axis. The roll motor is mounted on a plate which is rotated by the pitch motor mounted to ground. On the edges of the internal plates there are hard stops at 5° angles which restrict the angular motion. The gimbal can be positioned to rest on hard stops in four discrete positions without relying on the positioning of the motor. This design could utilize stepper motors or DC servo motors with gear reductions. It could obtain instantaneous or average pointing depending on the accuracy and holding torque of the selected actuators.



(a) Diagram of Dual Pivot concept



(b) Isometric view in corner position



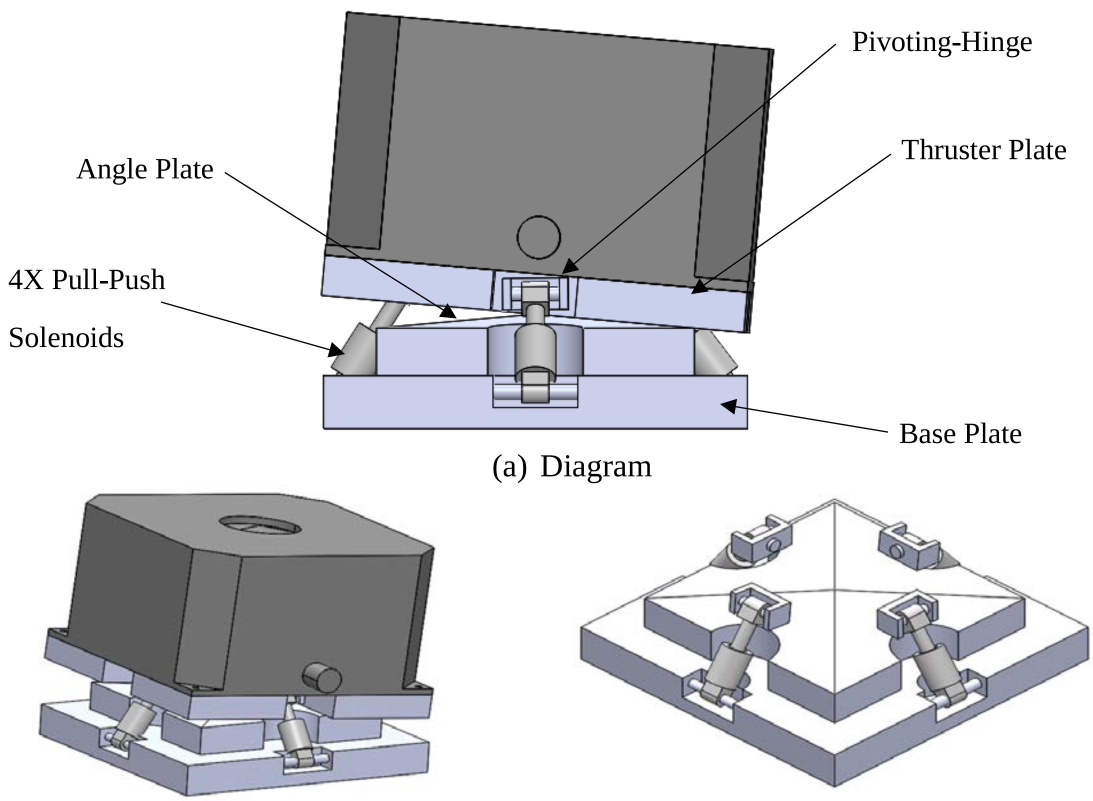
(c) Side view in pitch hard stop position

Figure 8: Dual Pivot concept

This concept has low relative complexity with two actuators and four bearing surfaces. A major benefit is we would not have to rely on precise actuators to achieve a vector as the hard-stops could define a precise angle. This could allow for lightweight and simple actuators. Also, the system can be very compact, with the vertical height only constrained by the height of the roll motor. One concern with this design is that in the event of motor failure, the system could not return to center. In addition, there is some potential complexity in the mounting and gearing of the roll motor.

4.3.2 Alternate Design 1: Four Linear Actuator Gimbal

A secondary concept we investigated further was the Four Position Linear Actuator model (Figure 9). This concept uses four solenoids connected via double pivot linkages to the thruster. The solenoids extend and retract to move the thruster between four positions. A pyramidal plate with four surfaces keeps the thruster clocked in one of four discrete positions. This design utilizes vector averaging over four discrete positions to achieve a single vector over time.



(a) Diagram

(b) Isometric view

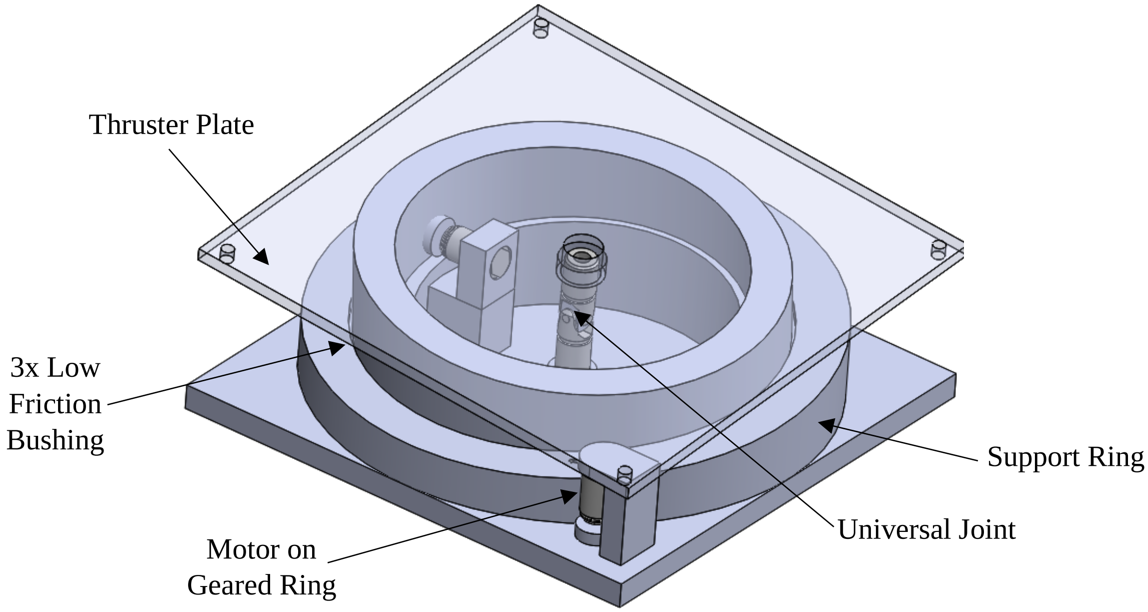
(c) View with thruster plate removed

Figure 9: Four Linear Actuator initial concept

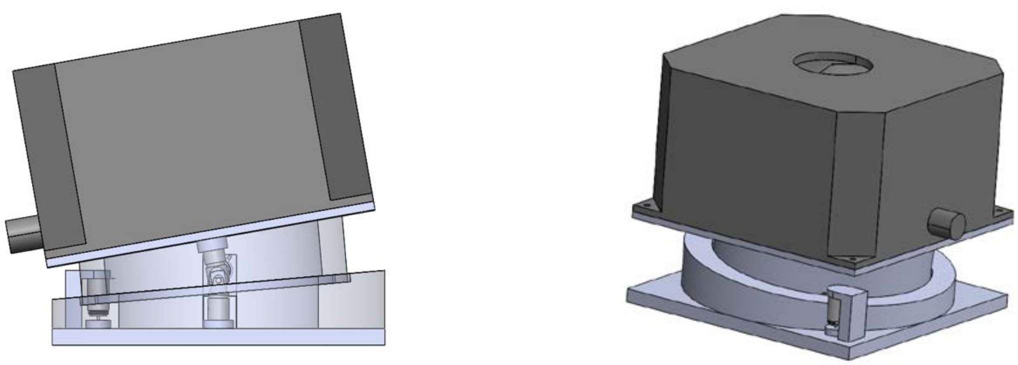
The main benefit of this design is the simplicity of the actuators. Since the actuators only exist in extended or retracted states, they do not have to be precise along their actuation path. The surface beneath the thruster defines the angle. This design also has the potential to be redundant as a single actuator on a side could actuate the full tilt. Utilizing a system to hold the thruster in place after an actuation such as locking solenoids, magnets, or a latching mechanism, this system could have very low power draw. To achieve a given vector the gimbal would only have to activate three times in the thrust window. The potential downsides of this design are the complexity of the pivoting joints. With four actuators, eight hinges and four joints there are many potential failure modes.

Although the actuators are reliable, there would be many bearing surfaces and joints that could be problematic.

4.3.3 Alternate Design 2: Z-Locked Double Swivel



(a) Double Swivel diagram



(b) Side view at maximum angle

(a) Isometric view at neutral position

Figure 10: Z-Locked Double Swivel design

The third design is a redesign of the preliminary double swivel concept with the addition of a passive stage to remove rotation in the thruster. This design consists of two concentric rings, each with one surface that is 2.5° offset from horizontal and a third flat plate that the satellite rests on. Each ring rotates concentrically on a large bushing while the upper plate is grounded to the thruster using a U-joint to prevent yaw rotation. Figure 10 shows the Z-Locked Double Swivel in both the neutral and maximum angle positions.

This design provides instantaneous pointing at a low power. Using a single motion to achieve a vector reduces the energy required per thrust period and may increase the gimbal's life. In the case of one motor or ring seizing, the thruster can be repositioned to the neutral position or actuated as a single degree of freedom model, like the concept listed in our preliminary concepts.

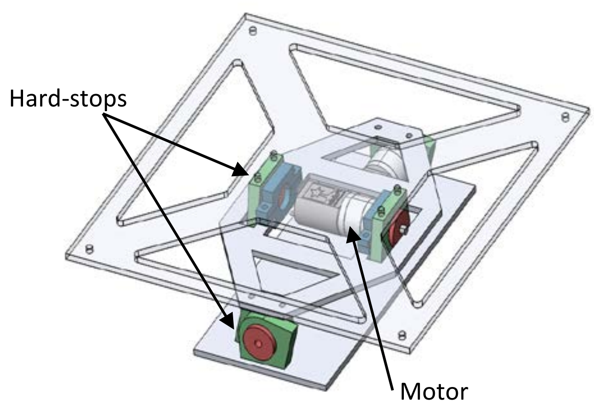
The largest immediate design challenges are the U-joint and the bushing surfaces, both of which have the potential to seize. Cable routing will also be a challenge for the motor on the inner ring, which rotates as of this design iteration. This design also may have a higher mass than the other concepts due to the gears and the rings and will be more difficult to manufacture. Like with the other concepts, both the motors and the bushings are failure points with the U-joint being the primary concern.

4.4 Post-PDR Design Iterations and Development

After our Preliminary Design Review, we decided to move forward with two concepts in tandem: the Dual Pivot and the Four Linear Actuators, with a plan to down select to a single idea before the Critical Design Review. Our first goal was to create higher resolution versions of both design ideas and select the best path forward.

4.4.1 Dual Pivot Design Development

For the Dual Pivot design, we iterated through several ideas focusing on condensing the design to reduce the overall weight. This was done by reducing the size of the plates and the hard stops and placing the motors in the plane of the middle plate as shown in Figure 11. We realized that we could integrate the hard stops into the hinge and use a pin to take the load so that the load was not directly transmitted to the motor shaft, also shown in Figure 11. This final design was one of the two structural prototypes that we built.



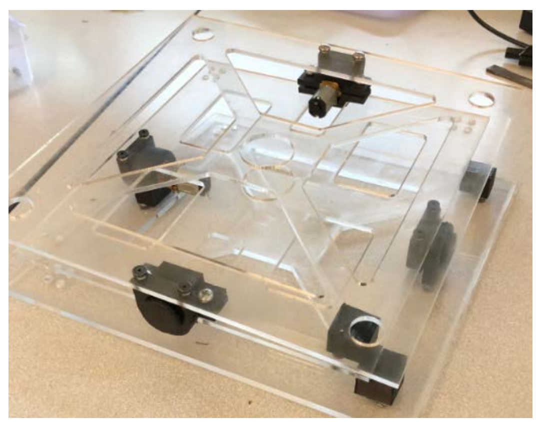


Figure 11: Dual Pivot early design and initial prototype

After this build, we made several improvements to reduce the overall weight and size. Our original concept used brushed DC motors with a gear set. However, there were concerns regarding the multiple possible failure modes from the gearboxes. We selected brushless DC motors with appropriate torque to drive the hinge and integrated the motors directly into the hinge mechanism at the center to reduce the overall mass. Figure 12 is the final design of the dual pivot concept.

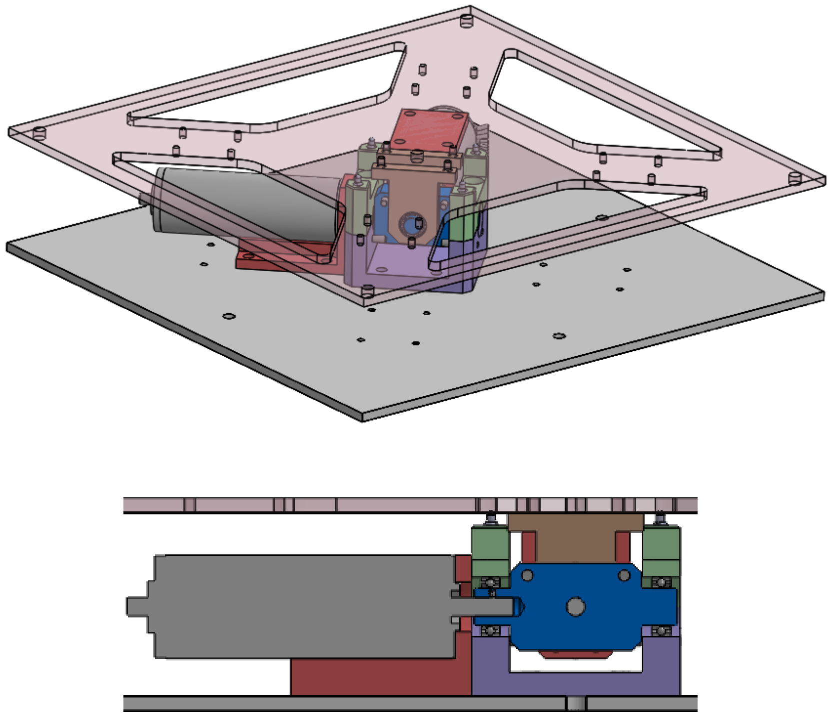


Figure 12: Isometric and cross-sectional views of Dual Pivot final design

Our major concerns with this design were that the motors would have to operate at stall with no gear reduction causing a significant decrease in life. After discussions with Astranis, we decided to pursue our linear actuator concept.

4.4.2 Linear Actuation Design Development

During the conceptualization phase with the dual pivot, we also moved forward with the linear actuator concept. We were concerned about the complexity of the attached solenoids from our PDR design, so we decided to attach the thruster to the base via a center pivot. We designed a two-axis hinge that would function like a universal joint. We decided to decouple the solenoids from the thruster plate to reduce joint complexity. One of the earliest design changes that we made after PDR for the Four Linear Actuator idea was replacing the pyramidal hard stop with a set of hard stops that also held the linear actuators. We selected four 0.5 in tubular push solenoids and positioned them vertically inside of the hard stop brackets. When they actuate, they contact the thruster plate and push it to the other side. We had many concepts for holding the position, such as: magnetically locking solenoids, a mechanical latch, a high friction hinge, and actively powering the actuator to hold the position. Figure 13 shows the structural prototype for the solenoid design.

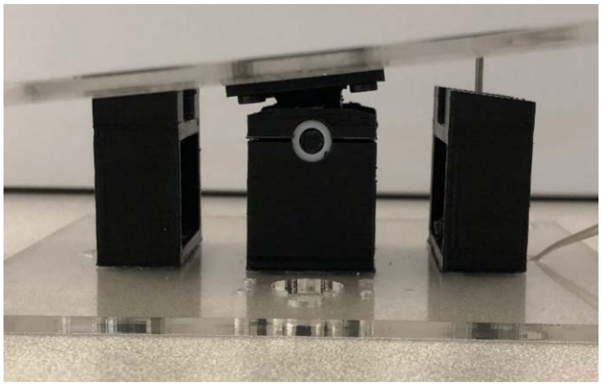
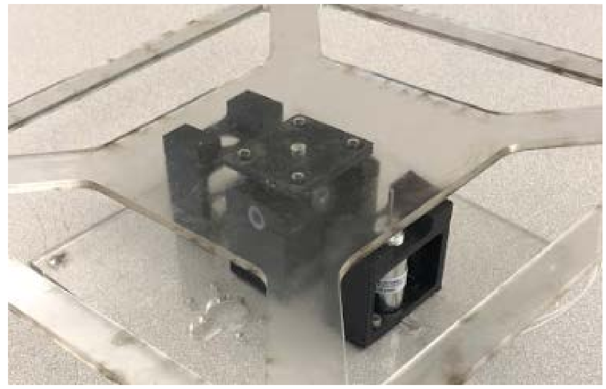
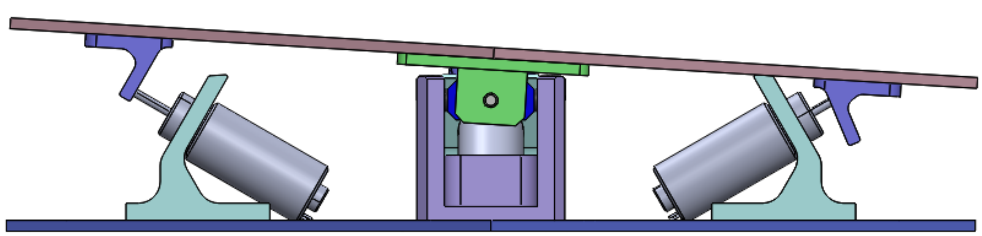



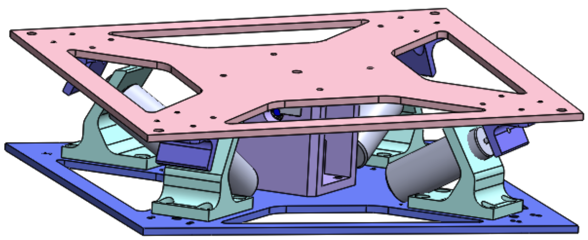
Figure 13: Prototype of vertical solenoid design.

During the testing of the structural prototypes, we learned some important lessons. For the Four Linear Actuators design, we found that the push solenoids had a plunger that protrudes from the bottom of the solenoid making it quite tall and preventing us from using a vertical orientation. We also noticed that assembly was extremely difficult for certain components, so we chose to implement a slot to assist in installing the shoulder bolt in the hinge for future designs. Finally, we found we required much more force than the solenoids were able to provide.

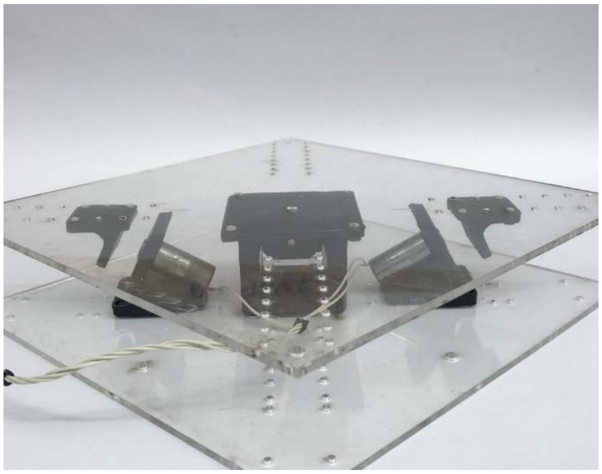
At this point, Astranis informed us they would prefer a passive return to center over a locking mechanism. That way, if there is a failure the thruster can still be used from the neutral position; however, this means the gimbal will have to constantly draw power during operation. We began designing to increase the force and reduce the height. We rotated the hinge 45° into the diagonal of the square base plate and angled the solenoids upwards to give us the largest possible moment arm. The additional horizontal area allowed us to pick solenoids with high enough force that were small enough to fit in this configuration. We added angled strike plates for the arm of the solenoid to contact. Figure 14 shows the final angled design as well as a prototype we built to validate the design.



(a) Side view of angled solenoid design with front solenoid and bracket hidden



(b) Isometric view



(c) Early prototype

Figure 14: Angled solenoid designs and prototypes

With this design, we were concerned about the impact and sliding behavior of the solenoid rod on the angle plate, as well as the cost to manufacture the angled parts. To mitigate these sources of uncertainty, we developed a linkage to attach the solenoid to the thruster plate and swapped the push solenoids for pull solenoids, which allowed for more constrained joints. We presented both the Angled Solenoid and the Linked Solenoid designs to Astranis. They encouraged us to pursue the linkage design. Taking this feedback into consideration, we created a decision matrix (Appendix C) to enumerate the advantages and disadvantages of these two designs. From this we determined that although a linkage is more complicated and requires more parts, it is more predictable because it eliminates the uncertainties associated with impact, and so could be more confidently designed for longer life.

4.5 Preliminary Analysis

In order to validate our concepts, we completed some preliminary analysis into vector pointing. Specifically, we investigated average pointing versus instantaneous pointing. Since the thruster is low force and has a long burn time, we can move the thruster during the actuation window and average all the positions over time. Using MATLAB for verification, we developed two potential averaging schemes as demonstrated in Figure 15. In this plot, the green vectors represent the multiple vectors produced and the purple vector represents their net effect. One option holds the thruster at a fixed angle and then rotates the vector along the surface of a cone. To achieve a given vector in the cone we can sum the magnitudes of two achievable vectors over time. For the other option we can actuate between four possible positions that are 90° apart. The gimbal toggles between these positions to achieve a final vector, such that the sum of the vectors over time is the desired resultant.

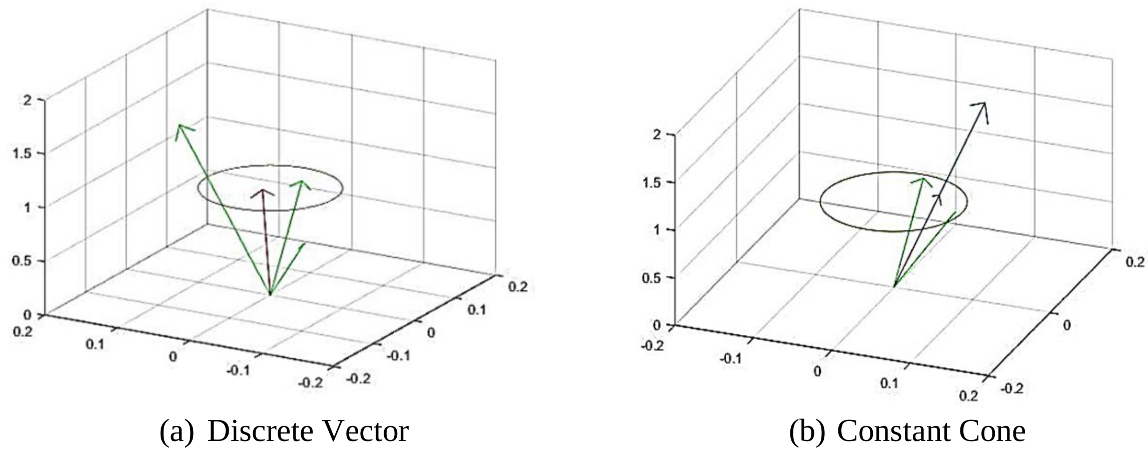


Figure 15: 3D plots of vector averaging concepts

5.0 Final Design

Refinement of our preliminary design resulted in a mechanism that utilizes four linear pull solenoids positioned around a two-axis hinge. The solenoids connect to the thruster plate by a linkage, so that the thruster plate tilts about the hinge when the solenoids actuate. Incorporated into the hinge are four spring plungers that will allow the thruster to passively return to center. In this section we detail the specifics of the design and discuss how we have engineered it to meet our design specifications. Drawings and specific dimensions can be found in Appendix E. The safety considerations and an overview of the cost of this design are also included.

The design described in this section is what we built for our Confirmation Prototype. We first built a 3D printed kinematic prototype and then outsourced parts to create the final prototype. To reduce the overall cost and lead time, components of this design are not aerospace grade. Details of our confirmation prototype test and build plans are described in the next two chapters.

5.1 Design Overview

Our final design is composed of a thruster plate mounted to a base plate via a two-axis hinge. Four solenoids tilt the plate through a linkage. Integrated into the solenoid brackets are raised features that will act as hard-stops to limit the actuation of the thruster plate and ensure its stability while in the actuated position. Figure 16 shows the fully assembled design with and without the thruster.

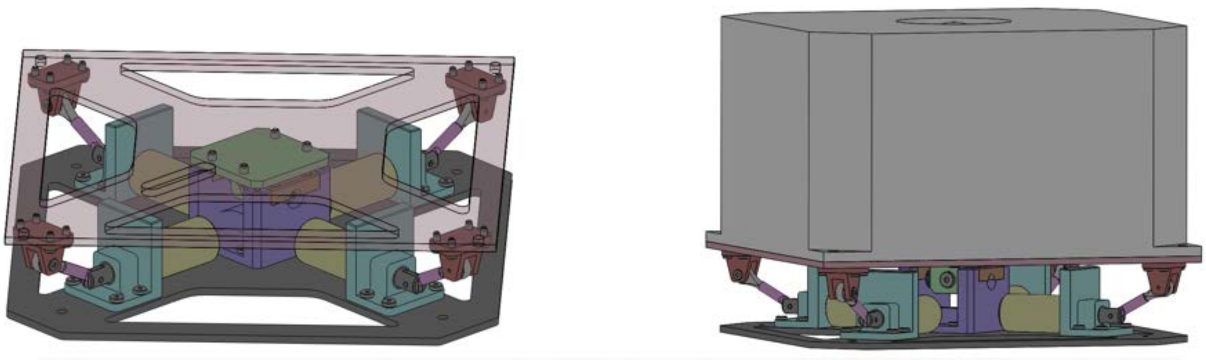


Figure 16: Final Design

Our final design has a footprint of 200x200 mm and is 44.5 mm tall, approximately half of our specified maximum height. The approximated mass of the mechanism, without the thruster, is 1.1 kg which is also below our 1.5 kg maximum. As shown in Figure 17, when a solenoid is powered on, it pulls on the linkage and rotates its side of the thruster plate down from the neutral position. The thruster plate tilts until it reaches the hard-stop integrated with the solenoid bracket. When the solenoid is powered off, the spring plungers' restoring force re-centers the thruster plate.

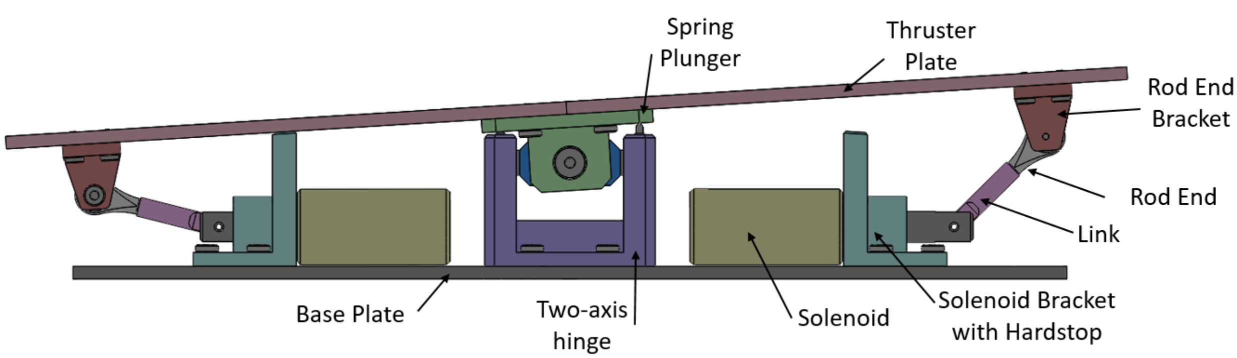


Figure 17: Main components of final design labeled.

Details of the hinge, plates, and solenoid and linkage sub-assembly are provided in the following sections.

5.1.1 Two-Axis Hinge

We designed a center joint in order to attach the thruster plate to the satellite plate, allow two axes of rotation, and integrate the centering force, shown in Figure 18. A two-axis joint was selected over a ball or swivel joint in order to ensure the thruster plate cannot twist normal to the satellite since our linkage does not constrain this. The hinge has three main components: the base, shaft and top. The hinge base attaches to the thruster plate and integrates four spring plungers to provide restoring force. The hinge shaft rotates relative to the base through two ball bearings. The hinge top connects to the thruster and rotates relative to the shaft. A shoulder bolt secures the hinge top to the shaft and allows rotation via two bearings. The base bearings are held in place by bearing holders screwed in from above with #4-40 screws. This method was necessary in order to assemble the shaft into the hinge base. We utilized shim washers to center the shaft and top and to provide low friction motion. The hinge will be machined from AL6061. Its footprint is 43mm square and it is 38mm tall.

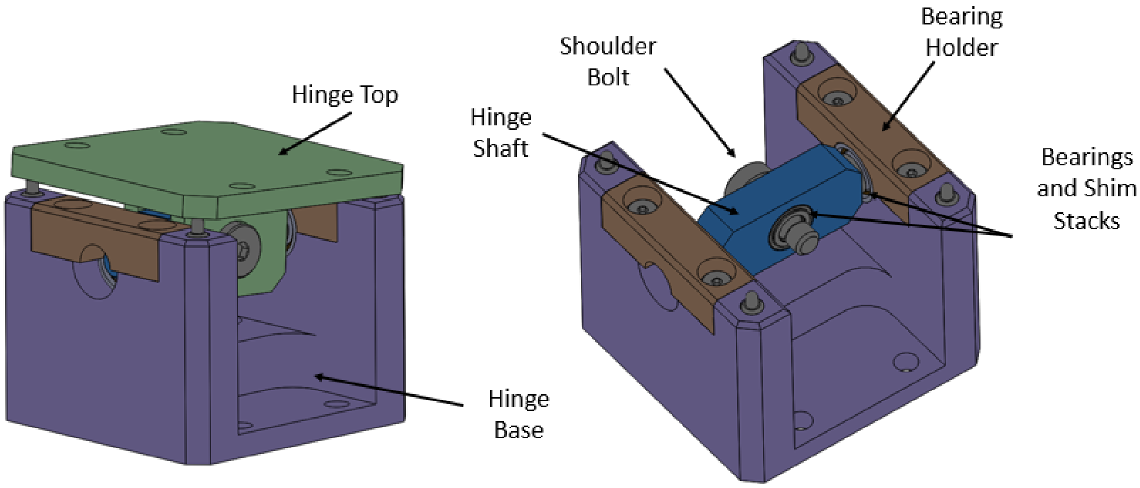


Figure 18: Two-axis hinge assembly

In the event of power loss, the thruster plate must passively return to a position parallel to the satellite. This restoring force is provided by four spring plungers integrated into the hinge base (shown in Figure 19). Spring plungers have internal compression springs and a thread used to screw them into the hinge base. They also have space flight heritage on CubeSat satellites at Cal Poly. These plungers are threaded into the four corners of the hinge base from underneath the baseplate. Once the thruster is attached, we can apply Loctite to the threads and then fine tune their height in order to pre-level the neutral position and create an appropriate holding force at neutral.

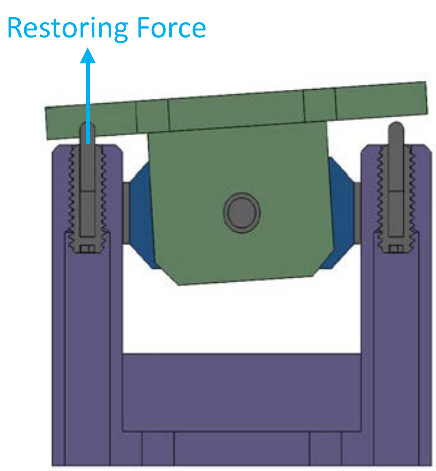


Figure 19: Spring-plunger provide the restoring force after actuation

5.1.2 Linkage and Solenoid Subassembly

The linkage and solenoid subassembly transfers the linear force from a pull solenoid into a rotational torque on the thruster plate. The final design requires four linkage and solenoid subassemblies. The major components for this subassembly can be seen in Figure 20, and include a pull solenoid, a link, a rod end bearing, a solenoid bracket, and a rod end bracket. The link, solenoid bracket, and rod end bracket components will be machined from Aluminum 6061.

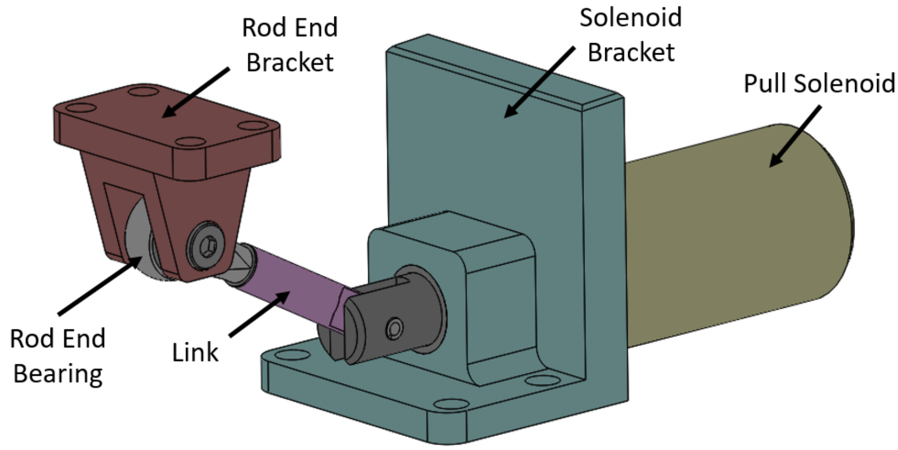


Figure 20: Linkage and solenoid subassembly.

The actuator selected for this design is a Ledex linear DC pull solenoid, Model Number 195204-230. These solenoids were selected for their continuous holding force that met our torque requirements. Detailed information about these solenoids can be seen in the datasheet attached in Appendix F. The solenoid threads into the solenoid bracket. A brass bushing is used to mitigate a portion of the radial loading that the solenoid plunger will experience during actuation and reduce the friction between the bracket and the solenoid rod.

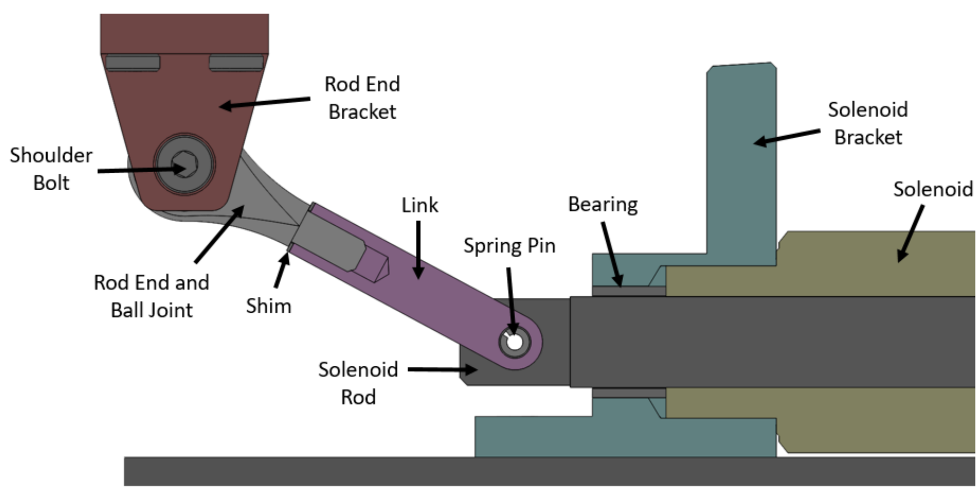


Figure 21: Cross-sectional view of solenoid and linkage system.

The upper surface of the solenoid bracket serves as a hard-stop for the thruster plate. This surface mechanically defines the angular position of the thruster plate when the solenoid is actuated. #6-32 screws are used to mount the solenoid bracket to the base plate.

The force of the solenoid is transferred to the thruster plate through a linkage consisting of the link, a rod end bearing, and the rod end bracket as shown in Figure 21. A spring pin on the solenoid plunger and a clearance hole on the link and are used to create a pin connection. The rod end threads into the opposite side of this link. The rod end bearing is mounted to the rod end bracket with an M3 shoulder bolt, producing the second joint of the link. This joint has two degrees of rotational freedom, which is required since the thruster plate rotates about two axes. Figure 22 shows the amount of swivel the ball joint needs to travel within the rod end bearing.

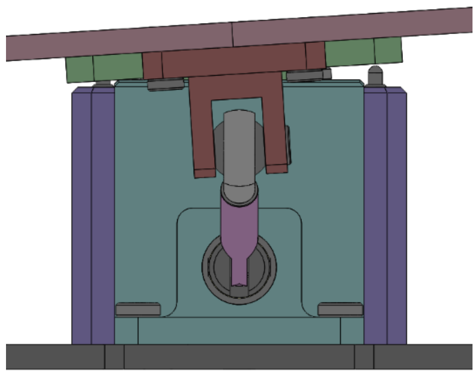


Figure 22: Swivel of ball joint rod end in actuated position.

The rod end bracket contains a U-channel for the rod end bearing to assembly into. The rod end bracket is fastened to the thruster plate using #4-40 screws.

5.1.3 Plates

The base plate and thruster plate will be manufactured from aluminum plate. Some material has been removed to reduce mass, as shown in Figure 24. A slot was added to the thruster plate so that one of the screws of the hinge would be accessible through the top during assembly. The plates are 1/8 in thick because this meets the required minimum thread depth for our chosen fasteners. The base plate and thruster plate will be secured to the satellite and the thruster respectively, so their rigidity (and therefore thickness) is not critical except for attaching components.

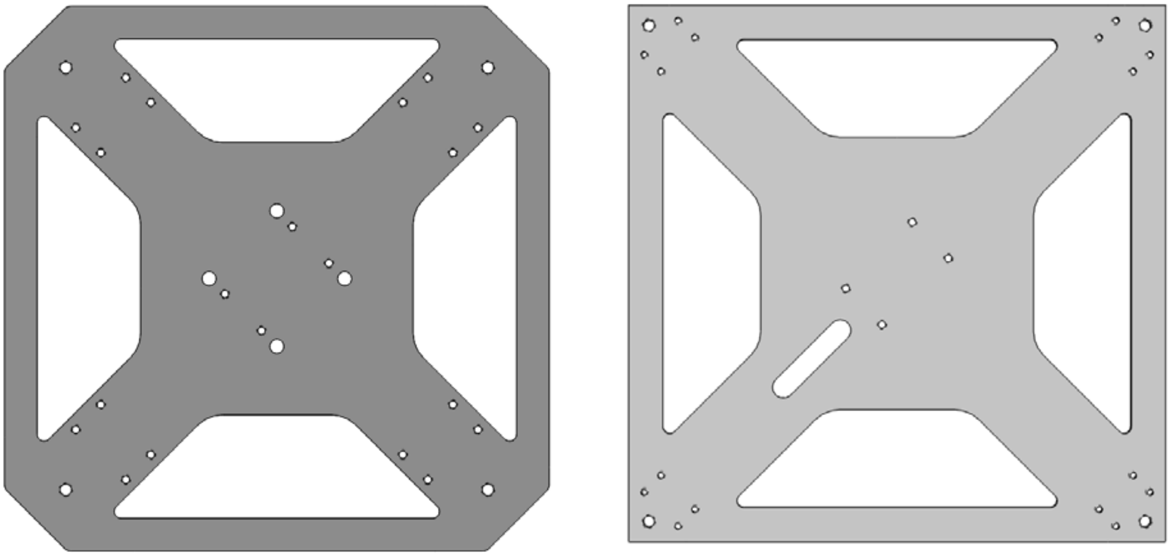


Figure 23: Base plate (left) and thruster plate (right).

5.2 Electrical and Software Design

We will not be designing any integrated electronics; however, we will build a circuit to simulate the satellite power and control system. A power supply will be used to provide the 28V available to us from the satellite. An Arduino UNO will be implemented to control the timing and to modulate the voltage levels. The Arduino will send PWM signals to MOSFETs for each solenoid through a circuit on a breadboard. A schematic of our circuit is shown in Figure 24.

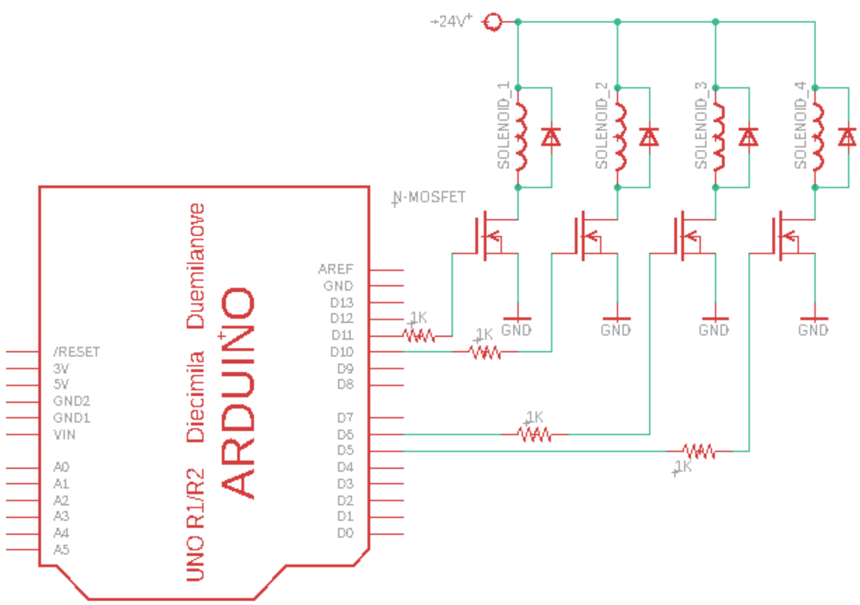


Figure 24: Electrical schematic

We created a MATLAB program to determine the percentage of time spent in each corner to achieve a given vector. For a given vector the thruster will travel to three of the four corners (A,B,C,D in Figure 25) depending on the location of the vector. It will repeatedly switch between these three vectors during the 30-minute window to reduce the continuous on time of the solenoids. For demonstration and testing purposes we will split up the actuation over 1 minute rather than the full 30-minute window and hardcode this sequence into the Arduino.

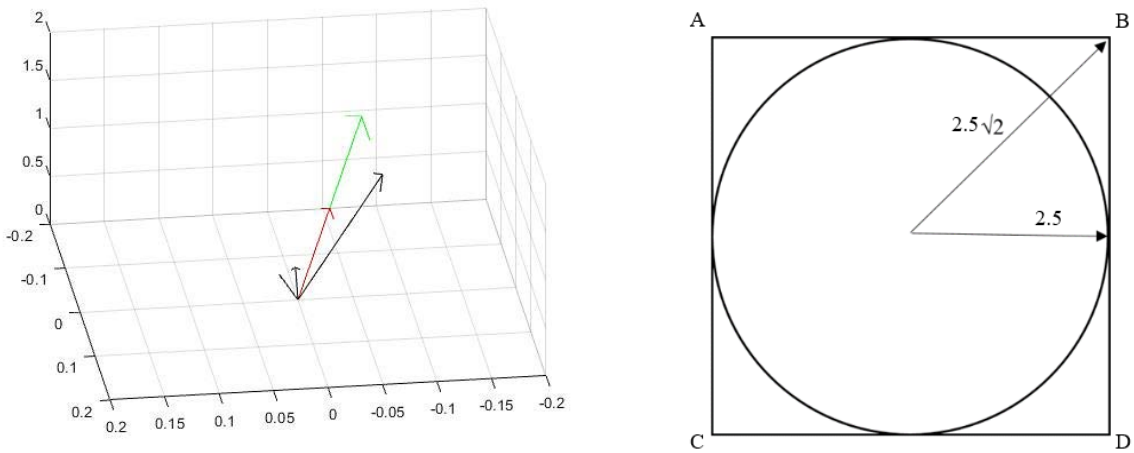


Figure 25: 2D and 3D representation of our corner vectors

5.3 Design Analysis

Analysis was performed to determine the torque requirements, vector angles, and forces transmitted through our linkage. Due to the low magnitude of the forces acting on the mechanism, we will not be presenting detailed stress analysis on any of our components at this time, but our confirmation prototype is designed to withstand the loads inherent to operating in 1g in the horizontal orientation.

To determine the required torque to rotate the thruster, we calculated the torque required to rotate the inertia of the thruster in a 3-second window with constant acceleration. This force does not include any friction from the mechanism or any cables holding the thruster in place. Since this force is difficult to quantify, Astranis proposed the torque should be enough to actuate in a 1g environment. We calculated the required torque for this and settled on a spec of 0.2N.m. Our calculations can be found in Appendix G.

As depicted in Figure 26, the actuation force generated by the solenoids acts along the linkage to create a torque on the thruster plate about the hinge in the center. The link arm transfers the load along its axis. The distance from this line of action to the center pivot is the moment arm of the actuation torque. Utilizing a calculation spreadsheet, we varied the linkage until this torque met our specifications. We also varied the geometry to reduce both height and radial loading on the solenoid. This resulted in a 0.24Nm holding torque and a 0.50Nm actuation torque. Figure 27b shows a plot of the linkage torque throughout the travel of the actuation.

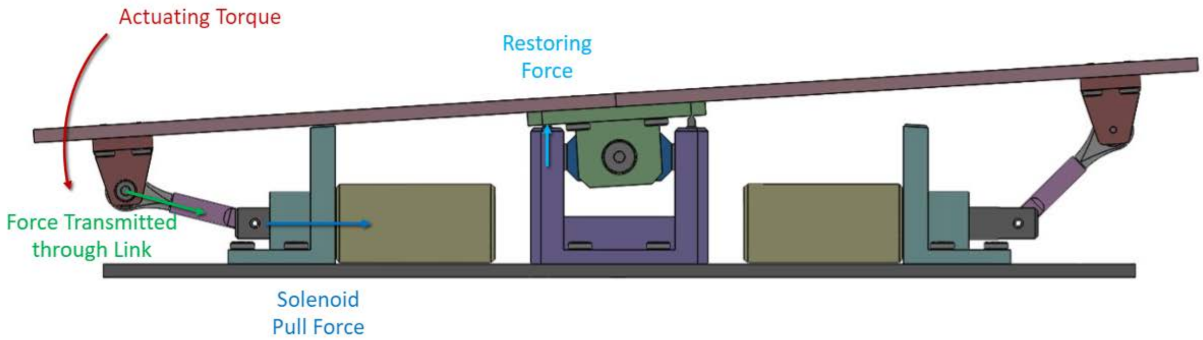
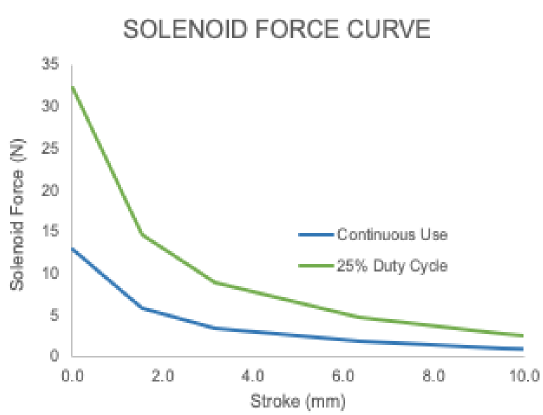


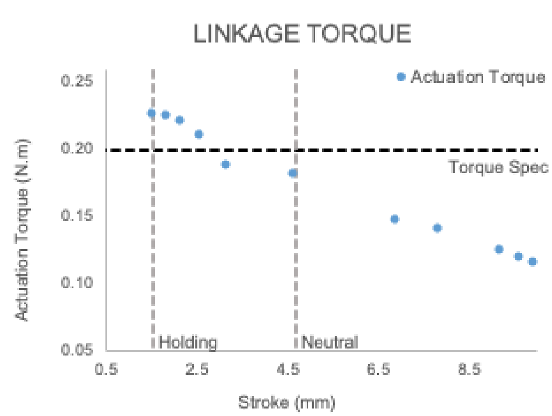
Figure 26: Diagram of forces experienced during actuation.

The spring plungers integrated in the hinge, also shown in Figure 26, provide a torque of 0.05 Nm on the thruster plate opposite the actuation torque so that when the solenoid is powered off, the thruster will passively return to a centered position. The spring plungers will provide a restoring force from the actuation position. Nominally, the plungers are partially compressed at neutral and then provide a restoring torque of 0.05 Nm once actuated.

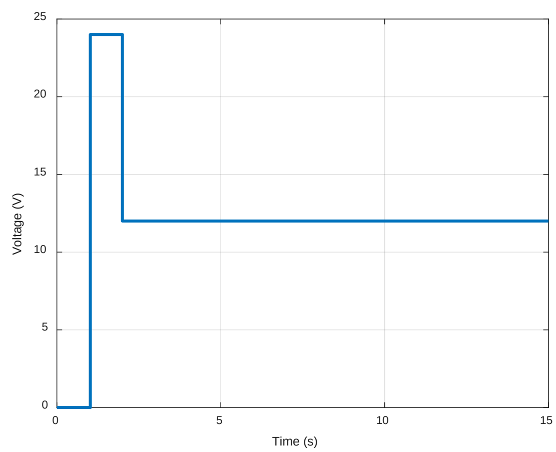
Although our linkage is designed to have enough mechanical advantage, we can operate the solenoids at higher power for increased force if necessary. To linearize the solenoid force curve, we plan to operate the solenoids at a 100% duty cycle initially for a short duration of time, to move the thruster plate from horizontal, and then switch it to a 25% duty cycle once it is in the actuated position. With this configuration we will have a resulting actuation torque of 0.5 Nm (100% duty cycle), and a holding torque of 0.24 Nm (in the actuated position). The solenoid force at different duty cycles and the proposed duty cycle are shown in Figure 27.



(a) Solenoid force curves



(b) Torque transferred through linkage



(c) Proposed power cycle for actuation

Figure 27: Force curves for the selected solenoid (a), actuation torque for the design (b), and proposed actuation cycle (c)

5.4 Post CDR Design Changes

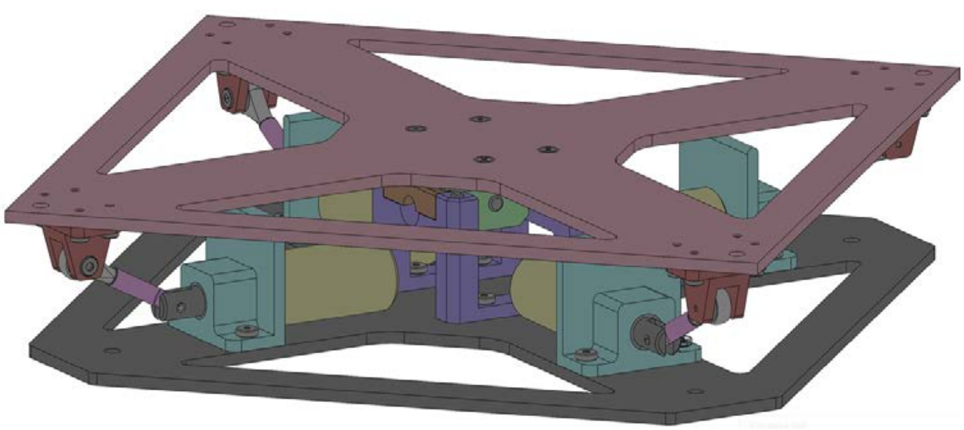


Figure 28. Post-CDR Final Gimbal Design

After building a 3D-printed prototype of the design proposed in CDR, we found a few areas for improvement in our design. Figure 28 shows our complete updated design. First, to improve ease of assembly, we flipped the direction of the screws that fastened the thruster plate to the hinge top. This change allows us to assemble the hinge top to the hinge base before fastening the thruster plate to rest of the assembly. Figure 29 shows the assembly change.

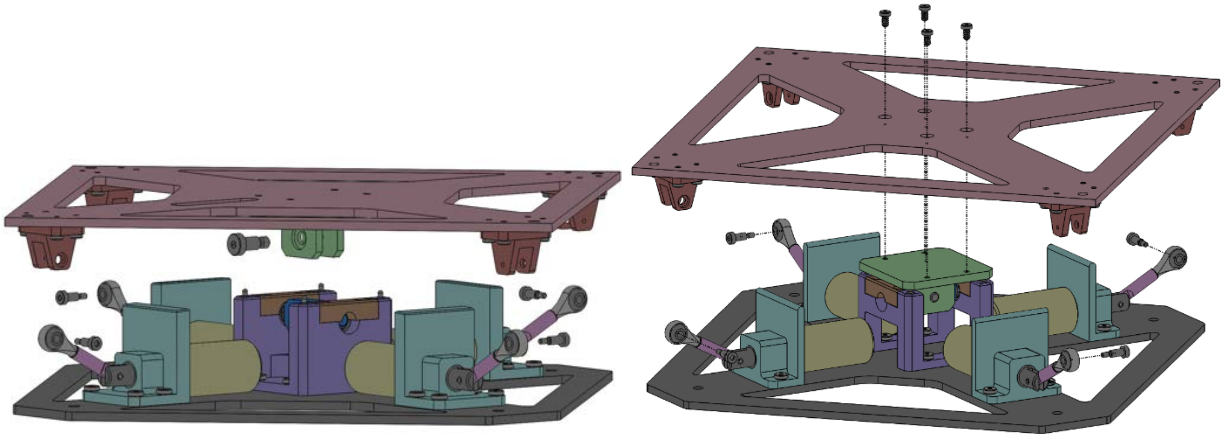


Figure 29. Pre-CDR assembly story (left) and post-CDR assembly story (right).

For the post-CDR assembly, counterbores were added to the thruster plate. Additionally, the slot on the thruster plate was removed because the post-CDR assembly does not require this feature. Figure 30 shows the thruster plate design changes.

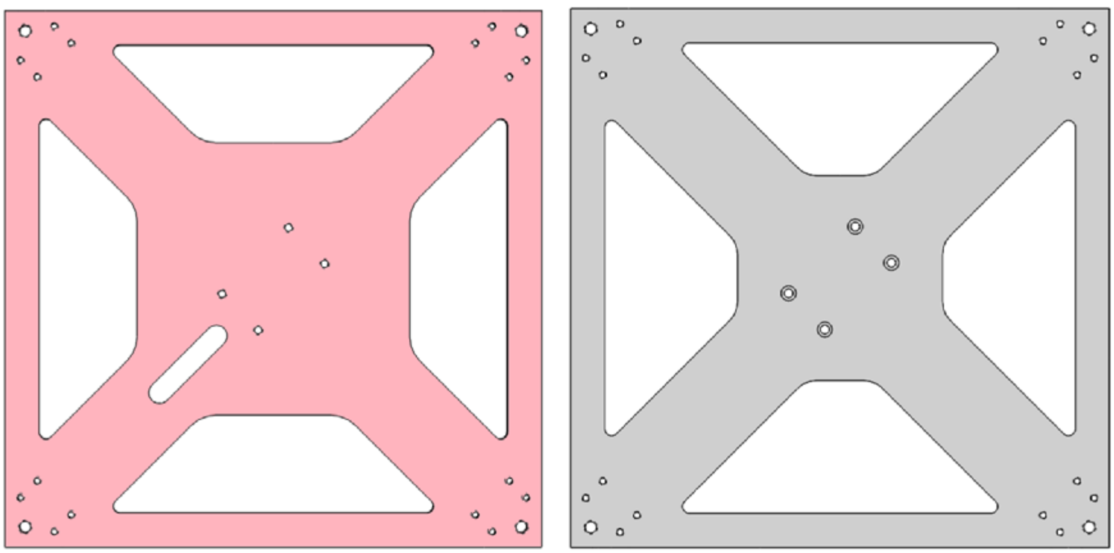


Figure 30. Pre-CDR thruster plate (left) and post-CDR thruster plate (right).

In addition to changing the assembly story, we incorporated a few design changes to the hinge base and the solenoid bracket. For the hinge, we removed excess material from the base of the part to reduce mass. Figure 31 shows this design change.

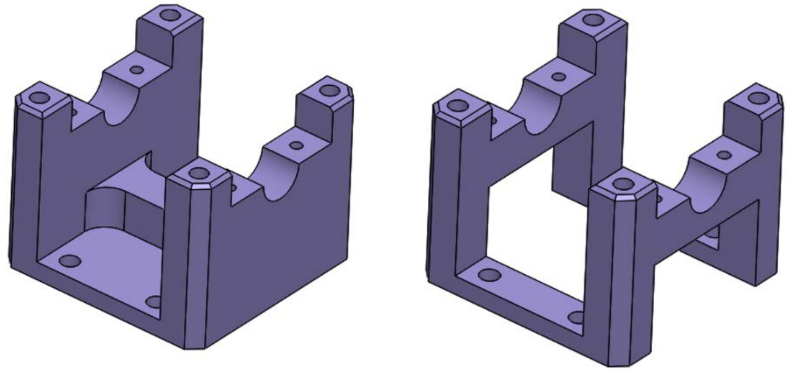


Figure 31. Pre-CDR hinge base (left) and post-CDR hinge base (right).

For the solenoid bracket, we changed the bolt pattern that mounts to the base plate by reducing the number of clearance holes from four to two, reducing the total part count. Additionally, we changed the hard stop from an angled flat surface to a rounded edge. This allows the hard stop to interface with the thruster plate by means of a line contact, instead of relying on an angled machine surface where full contact is not guaranteed. We also reduced the hard stop wall thickness and removed material from the base of the solenoid bracket to reduce mass. Figure 32 shows these design changes.

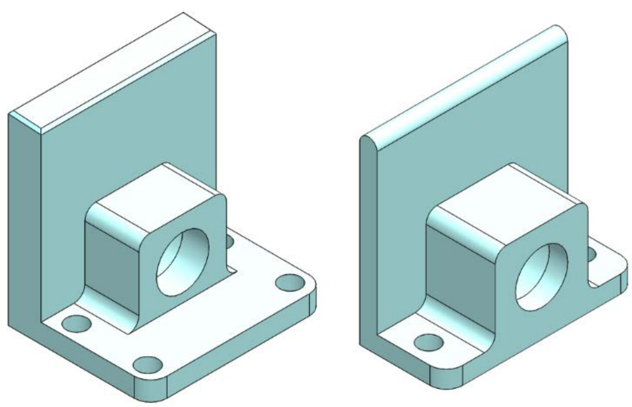


Figure 32. Pre-CDR solenoid bracket (left) and post-CDR solenoid bracket (right).

In order to facilitate our testing, we designed two acrylic boxes, a mock thruster and an electronics housing. The mock thruster was designed to simulate the volume and mass properties of an ion thruster. The electronics housing was designed to hold our Arduino and testing board. Both boxes were laser cut out of black acrylic and the internal seams were fixed using hot glue. These designs are shown in Figure 33.

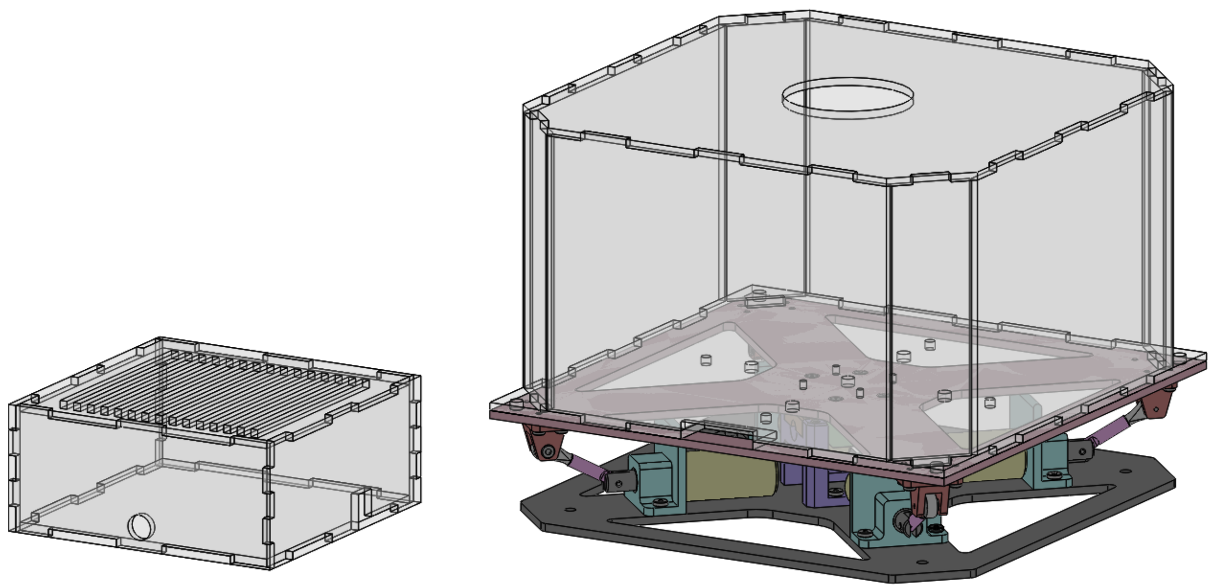


Figure 33. Final Gimbal Design with Mock Thruster and Electronics Box

To simulate the mass properties of an ion thruster, 5 kg of mass was added to the mock thruster. The center of mass location was determined in CAD, and foam was be used to raise the weights to the appropriate height. Figure 34 shows the mock thruster with the modeled weights from Cal Poly Mechatronics lab that correctly imitate the center of mass.

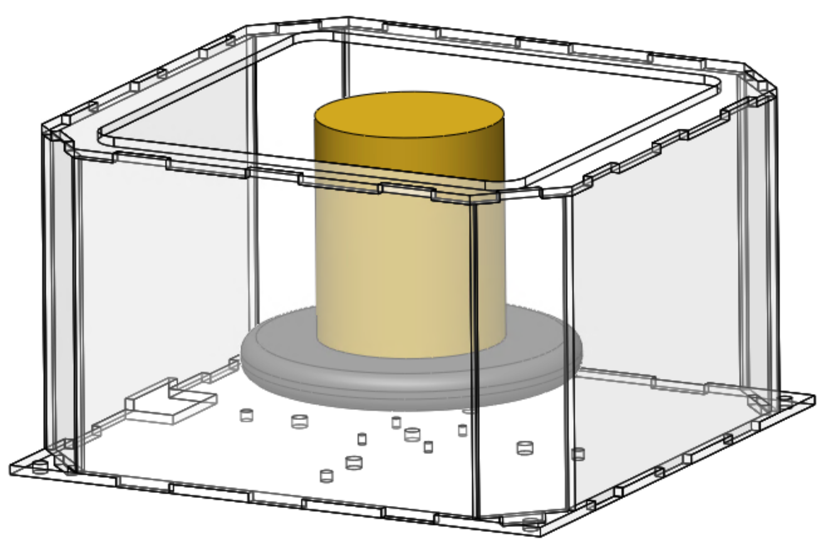


Figure 34. Acrylic Mock Thruster with Test Masses for a Similar Center of Gravity

The acrylic base plate of the mock thruster includes bolt patterns for mounting testing equipment. A 3D printed bracket was designed to hold a laser pointer during vector precision testing. These designs are shown in Figure 35 and the assembly of the vector precision test is shown in Figure 36.

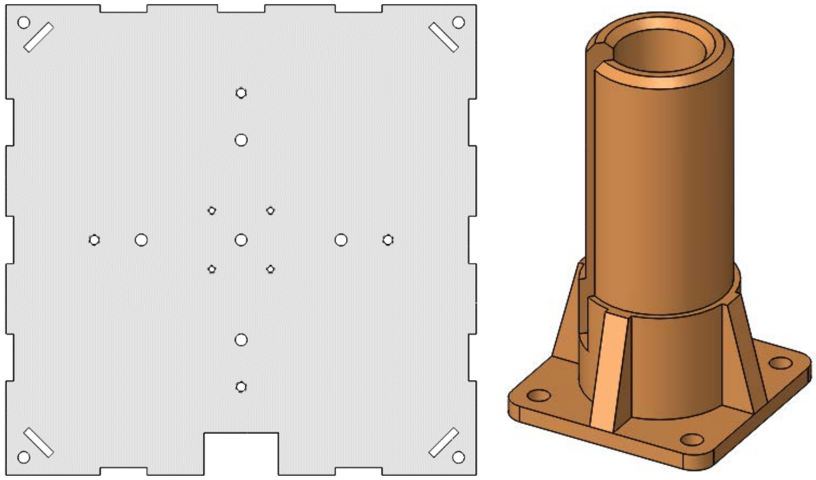


Figure 35. Mock thruster base plate (left) and laser pointer bracket (right).

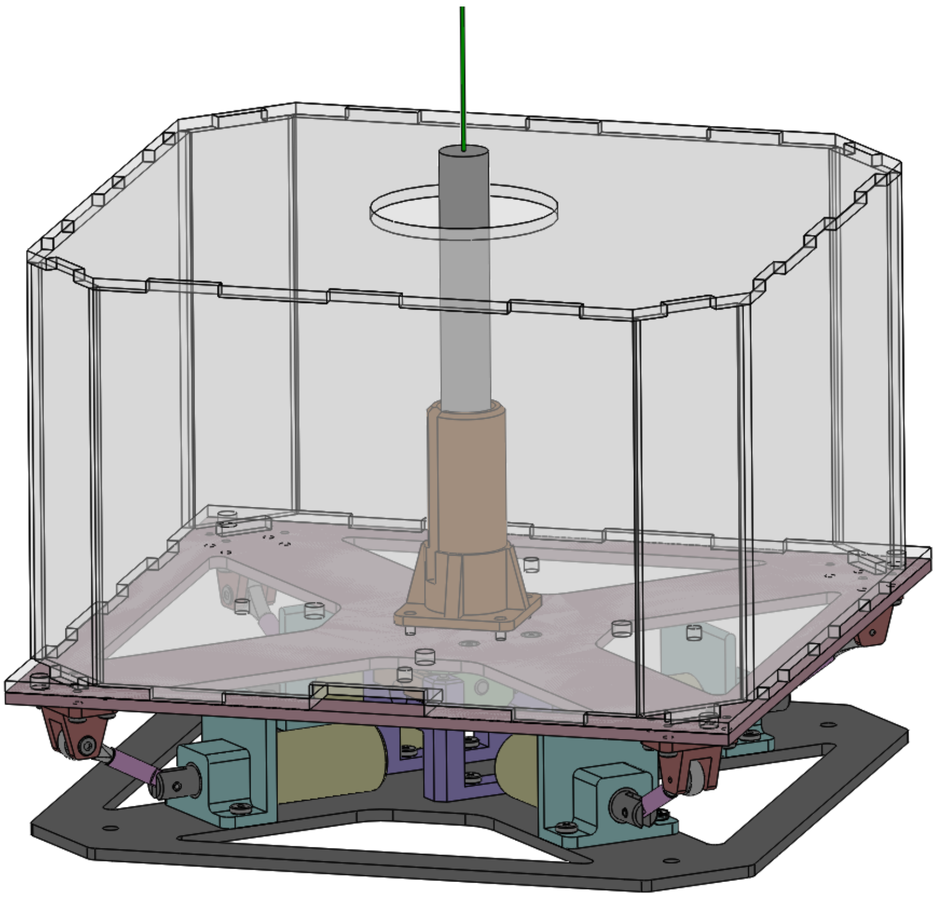


Figure 36. Assembly of vector precision test with the active laser pointer.

5.5 Safety, Maintenance, and Repairs

After completing our safety hazard analysis, shown in Appendix H, we found no major safety concerns for our design. Since this gimbal is designed to operate in space, there will be no people to injure in the event of a failure. Additionally, we performed a failure mode analysis and a risk assessment, shown in Appendix I and J respectively, and found no major risks associated with our final design.

On the ground, there are some minor concerns during assembly and testing. Those involved should be aware to avoid touching any live wires, since the solenoid will draw current when actuating, particularly at the initial pulse. While the forces are low, the hinge mechanism and the hard stops are pinch points and users should keep their hands clear while actuation is occurring.

The gimbal has been designed so that each component can be removed and replaced after testing if necessary. However, it is intended for a satellite and will not receive maintenance over its life cycle, so the gimbal has not been designed to accommodate repairs.

5.6 Cost Analysis

The costs for all components used over the course of this project total to $3,141.56, which is $359.44 below our target budget of $3,500. The full budget for all components purchased over the course of the senior project is included in Appendix K. Table 6 breaks down the cost of all off the shelf components by subsystem, which totals to $405.

Table 6: Off the Shelf Components

Subsystem	**Cost**
Hinge	$110
Solenoid and Linkage	$168
Plates	$55
Mock Thruster	$72
Total	$405

After verifying the kinematics of our design through a kinematic prototype built from off the shelf components and 3D printed parts, we ordered the remaining components which were machined by Protolabs. The costs of these components are broken down by subsystem in Table 7.

Table 7: Protolabs CNC Machined Components

Subsystem	**Cost**
Hinge	$867
Solenoid and Linkage	$1063
Total	$1930

The total cost of our confirmation prototype is the sum of the off the shelf and the Protolabs machined components, or about $2,335. The remainder of the spent budget was used for creating our initial and kinematic prototypes.

6.0 Manufacturing Plan

Our manufacturing occurred in two major steps. First, we manufactured a 3D printed kinematic prototype, using off the shelf components, as a way of verifying our design. Custom parts for this prototype were 3D printed in PLA plastic. After this build was complete and the design finalized, we sent the custom part drawings for our confirmation prototype to Protolabs Inc. to be CNC machined out of aluminum. We manufactured the plates using the water jet in the Cal Poly shops.

6.1 Procurement

We sourced the components for the gimbal from McMaster-Carr and DigiKey. The parts list with sources is attached in Appendix K. For the CNC parts, Protolabs supplied the raw stock of 6061 aluminum.

6.2 Manufacturing

For our 3D printed design, we utilized a Monoprice MakerSelect V2 3D printer. Each print used black PLA due to its low cost and availability and a 0.1mm layer height. Some features were modified to allow for 3D printing tolerances. We used the laser cutter to cut the plates from clear acrylic. The spring plungers, rod ends, and solenoids were self-threaded into the plastic. Figure 37 shows the final assembled plastic prototype.

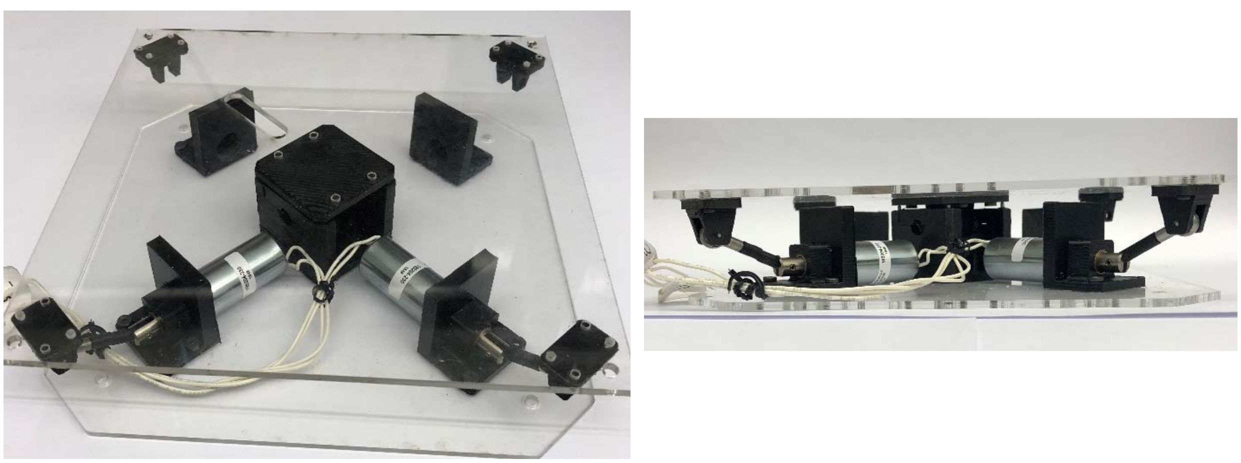


Figure 37. Complete 3D-printed prototype

After building and testing the plastic model, we began designing and manufacturing of the metal version. First, we used the IT department water jet to cut-to-cut the plates out of 1/8” 6061 aluminum plate. We created a 2D drawing file to program the path of the jet. The size of each hole was reduced in order to account for the ~1mm width of cut on the water jet. After the plates were cut, they were deburred, and the holes were brought to final size with a drill press. Finally, we used an end mill to create four counter bores and tapped the threated holes with a hand tap. Figure 38 is a photo of the completed plates.

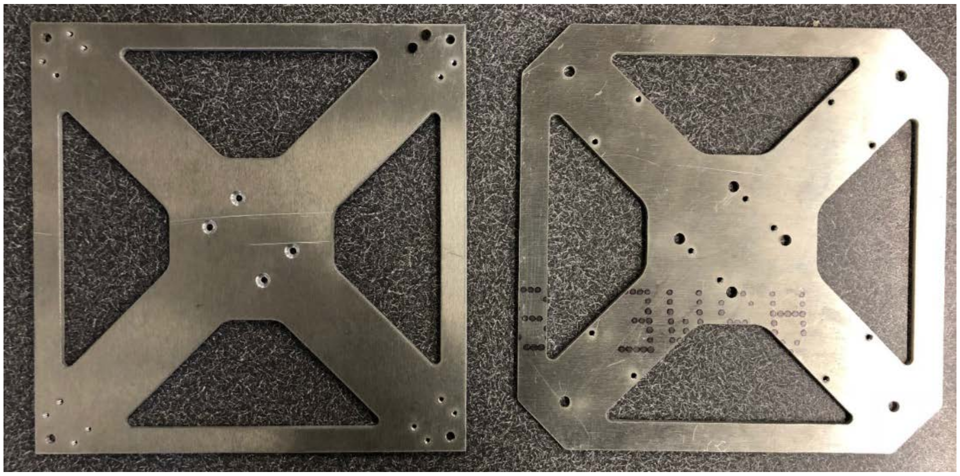
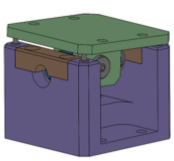
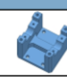
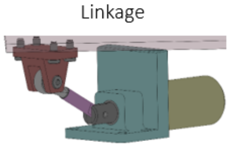
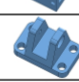


Figure 38. Completed thruster plate (left) and base plate (right).

The remaining metal parts were CNC machined by Protolabs Inc, a contract manufacturer. We submitted our designs and were provided DFM and quotes for the parts. Each part was specified to be aluminum 6061-T6 with an as machined finish. Table 8 is a summary of their quotes for our CNC parts. Detail drawings for each part can be found in Appendix E.

Table 8: Protolabs CNC Machining Quotes

Subassembly	Part	Material	Image	Cost	Quantity	Total
Universal Joint 	Base	Al 6061		334.48	1	$334
	Shaft	Al 6061		139.79	1	$140
	Top	Al 6061		168.56	1	$169
	Bearing Holders	Al 6061		112.57	2	$225
Linkage 	Solenoid Bracket	Al 6061		95.69	4	$383
	Rod End Bracket	Al 6061		101.55	4	$406
	Link	Al 6061		68.59	4	$274

The parts were received from Protolabs within two weeks. We then tapped the required threads in the Cal Poly machine shop by hand. In order to achieve concentricity, the solenoid thread was tapped on the manual mill (Figure 39). Figure 40 shows the hinge and linkage parts completed after CNC machining.

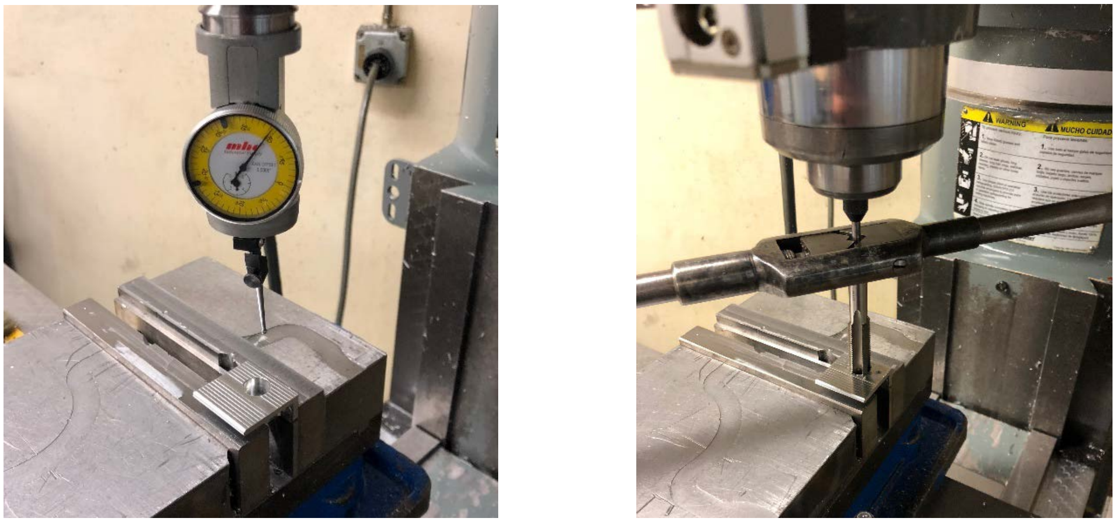


Figure 39. Tapping solenoid threads into solenoid bracket

Figure 40: Completed hinge (left) and linkage (right).

Finally, we created a mock thruster and electronics box. We designed an interlocking flat pattern for each box and laser cut it from black acrylic. Each side was glued together internally with hot glue. Figure 41 shows the completed boxes.

Figure 41: Laser cut sides (left), electronics box (center), mock thruster (right)

6.3 Assembly

We assembled our confirmation prototype manually with a set of English and Metric ball-end hex keys. The gimbal consists of two main subassemblies and one final assembly step. The first main subassembly is the two-axis hinge, depicted in Figure 42. Appendix E lists the parts and specific hardware used. One problem that occurred during assembly of the hinge was the top shims (item #8) would not stay in place during insertion of the hinge top. To fix this problem, we applied superglue to the shim and carefully located it with tweezers before assembling the rest of the parts.

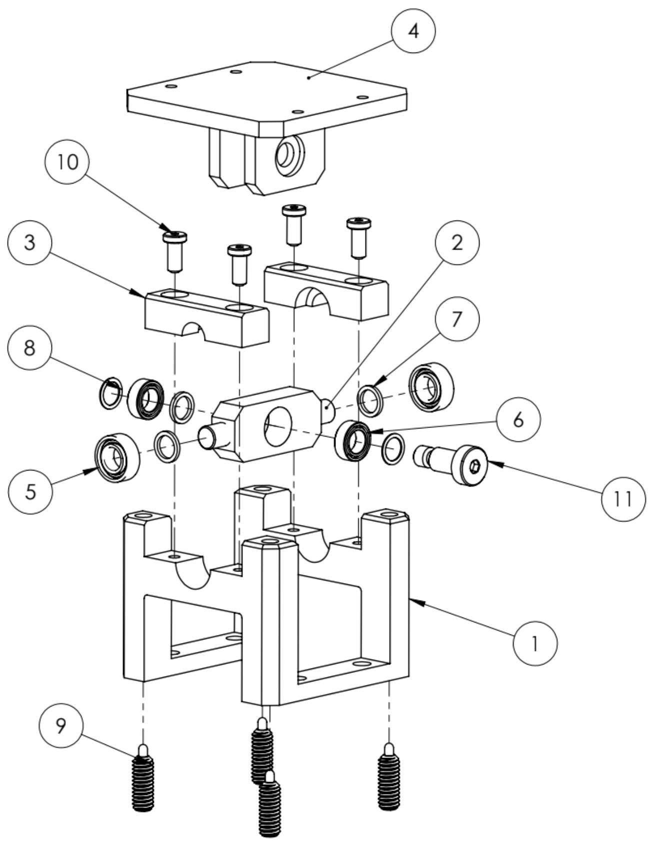


Figure 42. Two-axis hinge assembly

The linkage and solenoid assembly is the second major subassembly, depicted in Figure 43. Appendix E lists the parts and specific hardware used. The spring pin (item #6) and radial bearing (item #8) were press-fit in with a vice. To ensure the correct orientation of the rod end (item #5), we added shims (item #7) until the rod end clocked correctly with the rod end bracket (shown in Figure 43 of the final assembly). We built four linkage and solenoid assemblies before moving on to the final assembly.

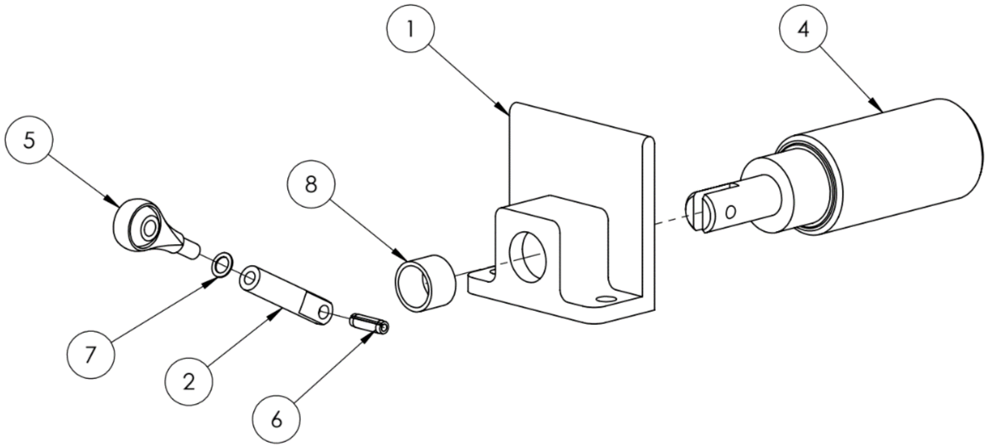


Figure 43. Linkage and solenoid assembly

Figure 44 depicts the final assembly. We first fastened the two-axis hinge (item #4) and the linkage and solenoid assemblies (item #5) to the base plate (item #1). Then, we fastened the four rod end brackets (item #3) to the thruster plate (item #2) and assembled the thruster plate to the two-axis hinge. Finally, we used shoulder bolts (item #9) to connect the rod end brackets with the linkage and solenoid assemblies. Figures 45 and 46 depicts the completed gimbal assembly.

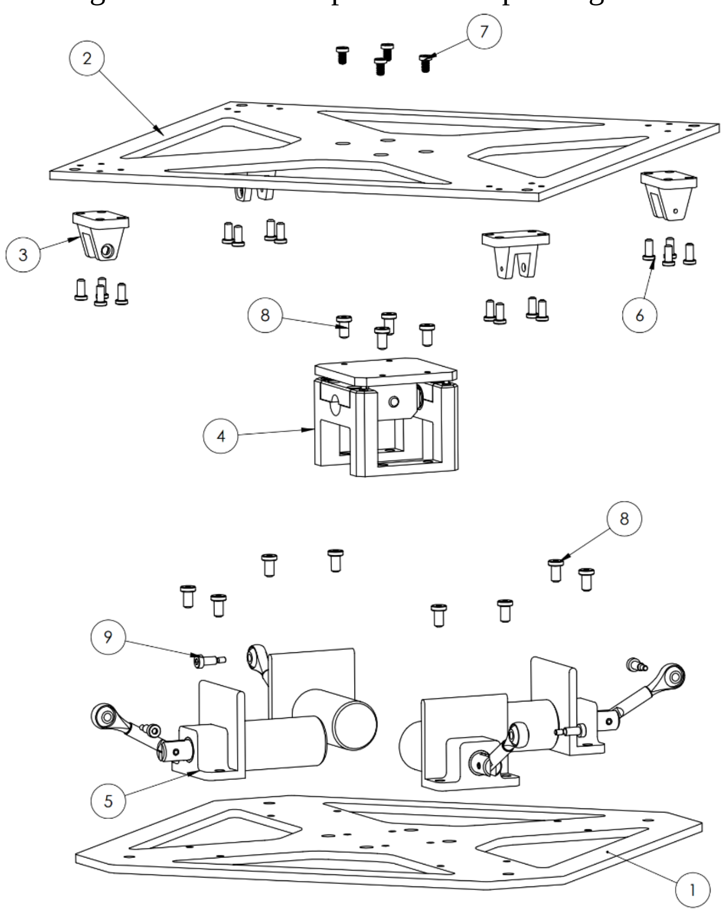


Figure 44. Final assembly

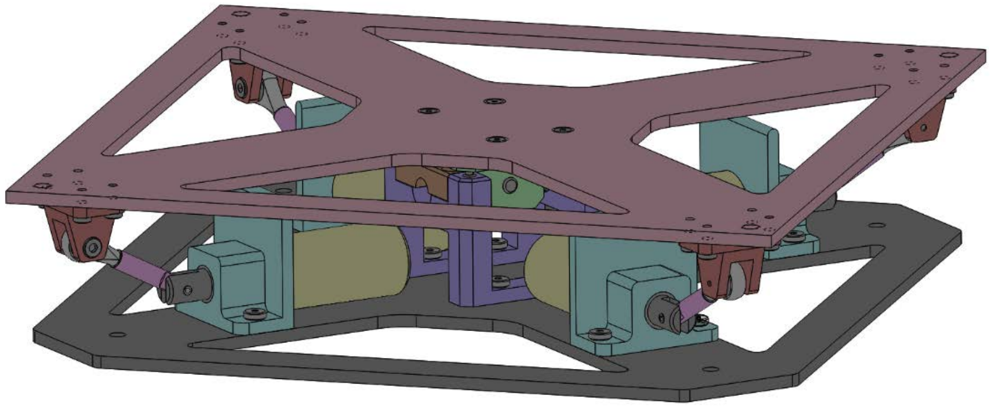


Figure 45. Completed gimbal

Figure 46. Assembled gimbal with the mock thruster

7.0 Design Verification

To validate the performance of our gimbal design, we developed a set of tests and design inspections. The results for each specification are included in Table 9. Descriptions of the original specifications can be found in Table 3. These tests were developed using our Design Verification and Testing Plan, found in Appendix L. The thermal-vacuum and life cycle tests were not performed due to logistical issues and non-space grade components used. Our testing scheme focuses on verifying two important aspects of our design. The first set of tests focuses on testing the accuracy and precision of the gimbal. The second set of tests validates the ability of the gimbal to meet the load requirement of positioning an ion thruster. In addition to these tests, we performed design inspections to measure the overall mass and product envelope of the gimbal.

Table 9: Completed Specification Table

Spec. #	Parameter	Requirement or Target	Tolerance	Value	Result
1	Mass	1.5kg	Max	0.926kg	Pass
2	Product Size	200x200x80mm	Max	199x199x44mm	Pass
3	Vector Precision	±0.5°	Max	±0.01°	Pass
4	Cost	$3500	Max	$2,264	Pass
5	Operational Temperature	-40°C to 100°C	Min	Not Tested	-
6	Survival Temperature	-100°C to 200°C	Min	Not Tested	-
7	Operational in Vacuum	10^{-8} Pa	Min	Not Tested	-
8	Cycle life	10 Years	Min	Not Tested	-
9	Vector Cone	2.5°	Min	2.455°	Fail
10	On- Axis Holding Torque	0.2Nm	Min	0.25N-m	Pass
11	Off-Axis Holding Torque	0.2Nm	Min	0.1N-m	Fail
12	Actuation in 1G	Go/No-go	-	Pass	Pass

7.1 Test #1: Vector Precision by Laser Pointer

For this test, we attached a laser pointer with a bracket to the center of our mock thruster. We then fixed the gimbal base plate to the ground so that the laser pointed vertically towards a sheet of paper attached on the ceiling. The setup used for testing is shown in Figure 47. We ran the gimbal through its actuation range and recorded the position of the laser at each position with a pen. This allowed us to measure the spread of the data around a position after repeated tests. We found that the laser center varied by 2mm maximum over a 2.974m distance. This corresponds to a change in corner angle of 0.001° each actuation. We conducted an uncertainty analysis on this measurement, and after factoring in the resolution of the measurement of the height of the ceiling, distance between the projected corners, and the spread of each data set. This resulted in an uncertainty of 0.004°, so we conservatively set the rated uncertainty to 0.01°. One problem with this test is the resolution of the laser pointer. We found that the laser pointer we used had a size of 4mm over this same distance. We plotted the center of the laser pointer beam on the paper to obtain the results, but the fact that the data was completely enclosed by the laser beam is strong evidence for the repeatability of the angle produced by the solenoids.

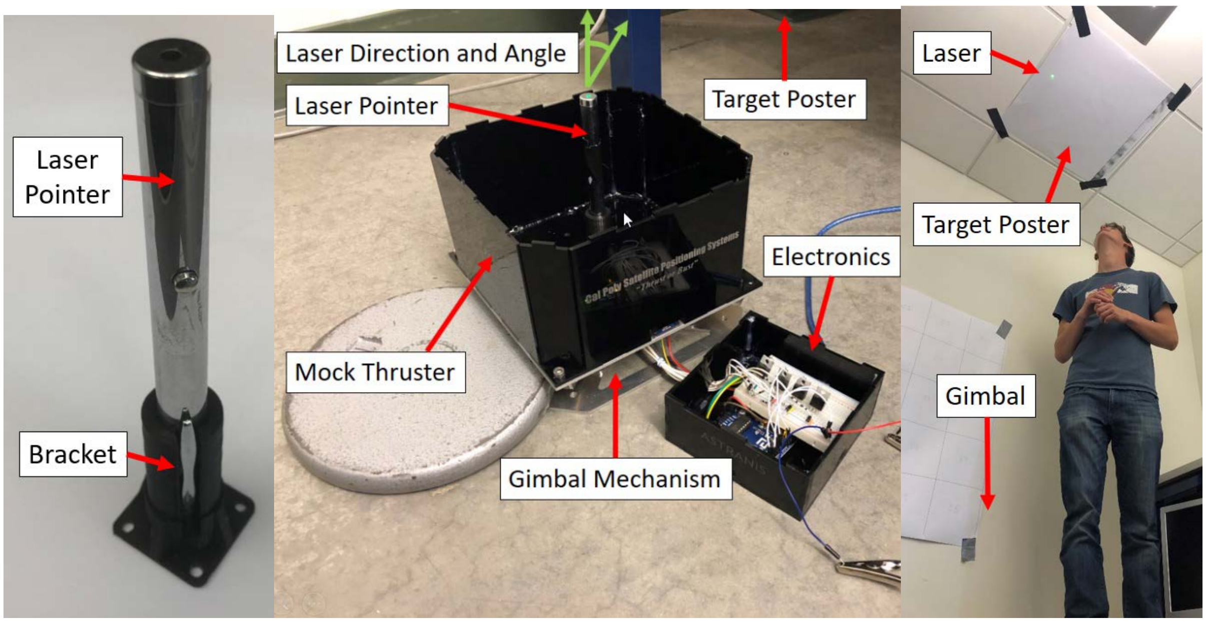


Figure 47. Laser pointer vector precision testing setup

7.2 Test #2: Vector Precision by Inertial Measurement Unit

The second test for verifying vector precision utilized the MPU9250 inertial measurement unit (IMU). We used a script to test each of the four positions and record the position of the IMU after each actuation. Table 10 shows the results of this test.

This test did not prove to be useful. The purpose was to determine the repeatability of the actuation angles, but there was a lot of noise affecting the measurement by approximately ±0.3°. Since the IMU noise is larger than our anticipated measurement range, it gives a poor indication of our repeatability. A graph of some of the data is shown in Figure 49 with each horizontal segment is a corner vector. Additionally, the calibration of the IMU proved to be challenging. To calibrate the system with respect to the angle of the table, we removed the thruster plate from the gimbal and placed it on a block of machined aluminum to raise it off the table, aligning it with the edge of the table. We then began the calibration and once the system reached steady state, we zeroed the position. Next, we re-attached the thruster plate to the gimbal and re-aligned the thruster plate with the edge of the table. The program then began actuating and collecting position data.

Table 10: Vector Precision IMU Test Results

Average Angle (degrees)			
Corner	Trial 1	Trial 2	% Difference
A	3.333	3.348	0.438
B	3.478	3.565	2.465
C	3.501	3.530	0.817
D	3.252	3.241	0.359

Figure 48. IMU Test variance

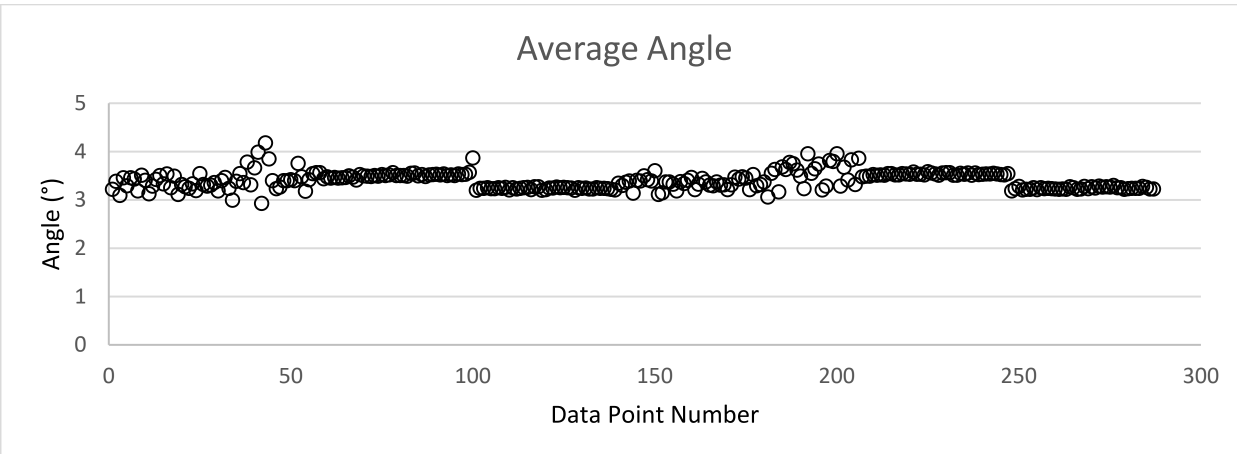


Figure 49. IMU angle data for a series of eight actuations

7.3 Test #3: Vector Accuracy by Mechanical Measurement

We used the vector accuracy test to determine the actuation range and accuracy of the angles produced by the gimbal and the hard stops. Our goal was to verify whether our gimbal can output a vector 2.5° from a neutral position. For this test, we used calipers to measure the height of each corner of the thruster plate with respect to the base. We calculated the resultant thrust angle for each actuation position. These four vector angles were then used to calculate the radius of the largest cone that our gimbal can guarantee. Table 11 shows the results of this test. From these results, we selected the smallest cone produced by the gimbal, 2.445°, which is 2.2% smaller than the desired cone. We attempted hit the exact nominal value of 2.5° in our design and the accumulated error resulted in the gimbal not meeting this specification. We would advise increasing the nominal angles slightly to ensure the cone angle is always larger than the spec within tolerance.

Table 11: Calculated Vector Cone Angle with Respect to Vertical Position

Corner	Smallest Average Vector Cone (°)	Percent Error (%)
1	2.459	-1.656
2	2.457	-1.704
3	2.445	-2.192
4	2.481	-0.778

7.4 Test #4: 1G Operation Test

Astranis asked that the gimbal be operational under 1G conditions with the expected 5 kg load. The mass-correct mock thruster was mounted to the thruster plate using M5 screws. We used a combination of weights and a Styrofoam block to position the center of mass at the same location as the center of mass of the thruster (based on a 5 kg thruster of uniform density), or 55 mm above the thruster plate. This setup is shown in Figure 50. We also found that a fully loaded thruster settled to the neutral position in under 1 second.

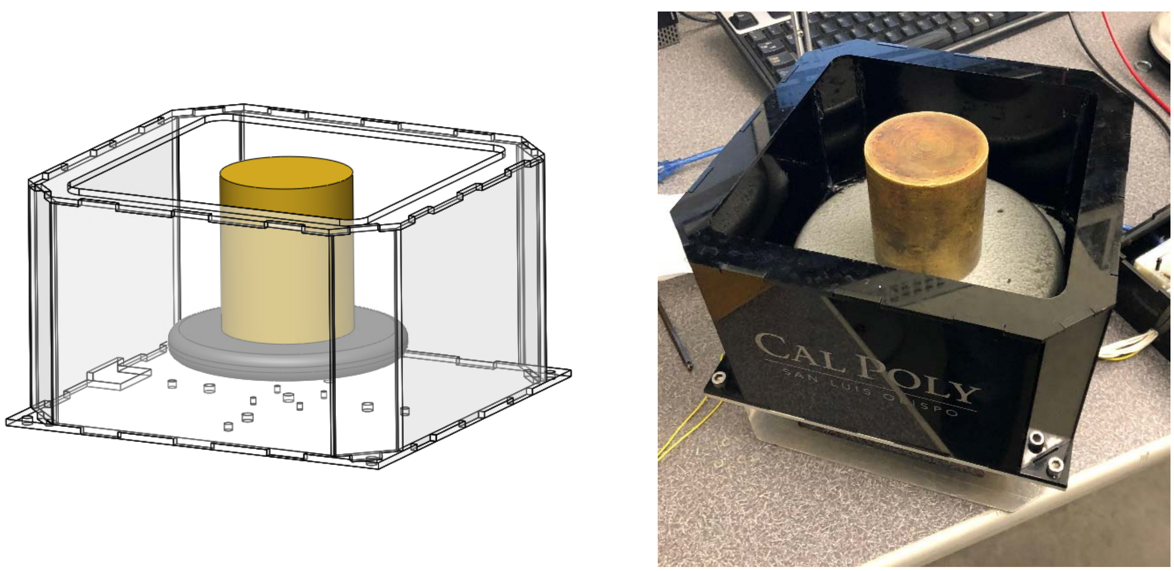


Figure 50. Mock thruster with internal space for adding weights and a slot on the side for mounting an IMU to the thruster plate

7.5 Test #5: Torque Test

To determine the maximum torque that the gimbal can produce, we mounted the gimbal in place and fixed the thruster plate so that it could not rotate past the horizontal position. A bag was hung on the opposite side of the test solenoid and weights were added incrementally. This configuration is shown in Figure 51. This test used 13.5V and 0.47A, corresponding to full power for the continuous usage setting. The solenoid opposite the weight was actuated. Once thruster plate began to lift from the hard stop, the final weight was recorded. This test was repeated on each of the sides. The lowest mass at which this failure occurred at was 200g, resulting in a maximum torque of 0.25Nm. We also tested the loading on the axis perpendicular to the actuated solenoid. The off-axis holding torque was much lower at 0.1Nm. The width of the hard stop could also be increased to increase the moment arm in the off-axis configuration.

When we did our initial test, we had no problems meeting the 0.2Nm torque requirement with one solenoid tested. However, when we returned to do a second round of testing after making some minor positional adjustments, we found that the gimbal was producing significantly less torque than it had previously. We determined that this was due to the solenoid plunger no longer seating fully in the solenoid. Once the plungers were adjusted so that they fully retracted when powered, we again were able to meet the 0.2Nm requirement.

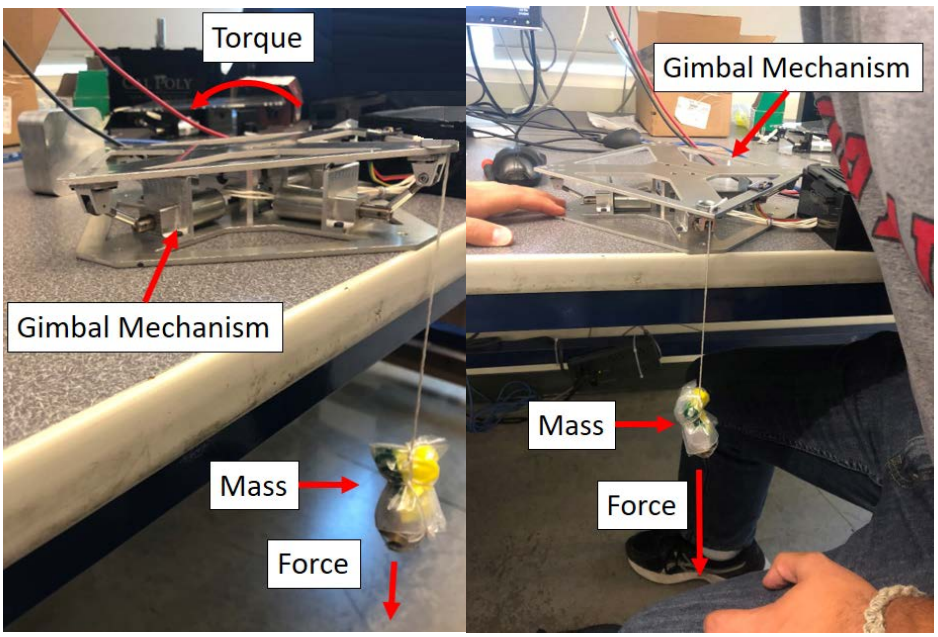


Figure 51. Torque test experimental setup for the in-axis and off axis configurations

7.6 Inspection and Analysis Results

The verification of the remainder of our parameters was done by inspection and analysis. Our mechanism has a mass 0.926 kg, well within our maximum mass parameter of 1.5 kg. The envelope of the gimbal in the neutral position is 199x199x44 mm, with the height gimbal 45% lower than the design envelope.

7.7 Future Testing

In the future, a full integration test with the other systems on the satellite would be required. The interactions with the actual ion thruster will be more complex and will need to be tested thoroughly. Basic functionality tests can be conducted using the Operator's Manual, found in Appendix M.

Additionally, environmental tests with aerospace grade components would be required to test the operational and survival temperature ranges. The solenoids that we utilized are not aerospace grade and would need to be replaced. For these tests, the gimbal should be tested in a thermo-vacuum chamber. After the test, the gimbal should be inspected for deformation, mass change, and functionality.

8.0 Project Management

For this project, we used a Gantt chart to track major milestones, create tasks, and allocate responsibility for those tasks to ensure that we met the major milestones. This allowed each team member to know which tasks were most critical and effectively decide which tasks to work on next. For the third quarter, we used the Gantt chart more heavily than in the previous two quarters due to the focus on manufacturing and testing rather than concept development. A copy of the Gantt chart used for this project can be found in Appendix N.

Almost all of our major tasks took place during group meetings with the entire team present. During the ideation and design phases when we were developing multiple designs in parallel, we often worked on our own designs individually before bringing them back to the group for evaluation. When writing reports, performing analysis-based tasks, manufacturing, and testing however, we worked together as a group. As such, it was often not necessary to break down tasks like the testing procedures into individual components when all team members were expected to work on the same task. We made all planning decisions by order of next importance, and the Gantt chart served as a record for the tasks that were completed. Overall, we found that although a Gantt chart may be very useful on larger, more disjointed projects with more intermediate goals and milestone, the use of it did not prove critical for this project.

9.0 Conclusions and Recommendations

Over the course of this senior design project, we designed and built a gimbal prototype to orient an ion thruster on one of Astranis' future satellites. This section provides the results of our project in relation to our original specifications and includes our recommendations for future work.

9.1 Results

Our gimbal can produce an average vector within a 2.45° by using a combination of 4 angular positions, each with an accuracy of 0.01°. The cone produced by our gimbal is 2.4% below the 2.5° cone that we aimed to produce. On all other parameters, including total mass, cost, and precision, we either met or exceeded the requirements. The gimbal's holding torque closely matched our calculations at 0.25Nm, but was lower than our specification for an off-axis load. The environment and life targets were out of the scope of the project.

With some minor design changes to either the location or height of the hard stops, it is possible to increase the size of the cone. An option would be to slightly reduce the height of the hard stops. In our design, we relied on many shims and clearance fits to tune component positions. In future designs, we recommend that positions are more tightly controlled and permanently fixed.

As for working with Astranis, the biggest challenge that we encountered was the initial lack of definition for the project. The project had a considerable amount of design freedom, which both helped and hindered our progress early on. The freedom allowed us to create and test a wide variety of designs. Pursuing multiple parallel paths allowed us to take the insights from one path and apply it to another. However, this open-endedness made it difficult to determine which paths should be cut, which slowed our progress as we approached the Critical Design Review. After that point, we were able to focus on optimizing and improving upon a single design.

Another issue that we encountered was that certain requirements for the design, such as the holding torque specification or the inability to spin the thruster, were added several months into the project. While we were able to redesign to meet these new specifications as soon as we received them, a complete set of requirements at the beginning would have been beneficial.

We found that the more we communicated with Jay, the better our designs became because of the quick turnaround time for feedback. Before our Preliminary Design Review, we sent a preview of the concepts that we intended to present. Jay informed us of several places where communication had been previously unclear, prompting major improvements before PDR. This feedback also played into our later design decisions. During the CDR design phase, we began creating short PowerPoints for our weekly meetings with Jay. These presentations were brief but allowed us to better communicate recent developments. Additionally, it allowed Jay to provide continuous feedback, so when we presented our CDR, it contained no surprises. We continued this process into the manufacturing and testing phase, although less frequently once the design was locked-in.

Another benefit of working with Jay was the quick turnaround time for ordering parts. We used 3D-printed materials and McMaster-Carr parts to construct our structural and kinematic prototypes. The ability to send Jay a McMaster cart and have all the materials available within two days for constructing the prototypes helped us stay on timeline immensely. Jay was fantastic as a mentor and knowledgeable resource for this project. We would also like to thank professor Schuster for coordinating senior project and for his valuable guidance throughout the year.

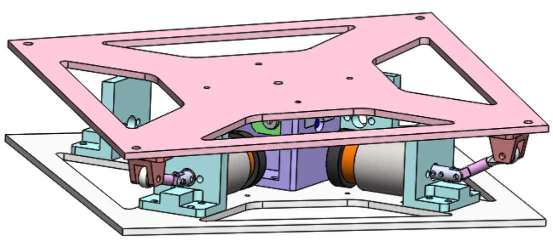
9.2 Next Steps

As discussed in Section 7.7, the primary next step would be to perform additional environment and life tests to verify that the gimbal will withstand the space environment for the life cycle of the satellite.

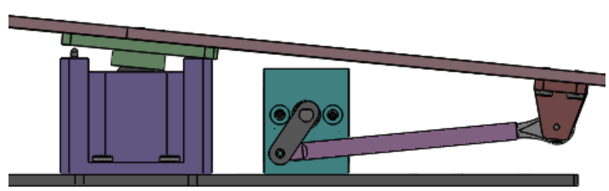
In terms of our design, there are many improvements we would suggest. First, we would optimize the thruster plate and the base plate. These components contribute to about half of the weight of the gimbal so present an opportunity for light-weighting. All components could be optimized for mass through stress analysis. We also recommend integrating the hard stops into the hinge. This would allow the gimbal to rest against a hard stop for each axis of rotation, improving stability.

This prototype was designed with easily procurable parts so there are several changes that would have to be made for this design to be launch ready. All components, such as bearings, fasteners, and joints, would need to be replaced with aerospace grade components rated for our life and temperature requirements. Also, the aluminum parts should be hard anodized to mitigate damage at contact surfaces. It would be advantageous to work with a vendor to create solenoids optimized for the gimbal. In our design, we relied on many shims and clearance fits to tune component positions. For future designs, we recommend that the positions are more tightly controlled and permanently fixed.

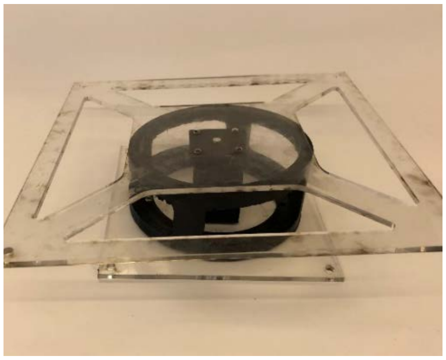
Over the course of our critical design and testing, we thought of several concepts for future design exploration. One area for improvement would be actuator selection. Solenoids are simple, reliable, and non-locking, however, they have nonlinear force curves, short actuation distances, and are quite heavy. We suggest an investigation of using two voice coils to replace the four solenoids. Voice coils can be position controlled, they are bidirectional, and they do not hold position when unpowered. We found one feasible voice coil, Moticont model #GVCM-025-029-01. It has similar stroke, force, and power draw, but it is much larger than the solenoids we used. Another possibility is to replace the solenoids with two rotary motors creating a four-bar linkage. In this case the center joint could be replaced with a ball joint. However, to avoid using geared motors, we would need a strong motor operating at stall. We also recommend exploration of the single degree of freedom concept. This design was eliminated due to complicated manufacturing and no passive return, but it has the potential to be a feasible solution. These concepts are depicted in Figure 53.



(a) Voice Coil Actuators



(b) Rotary linkage

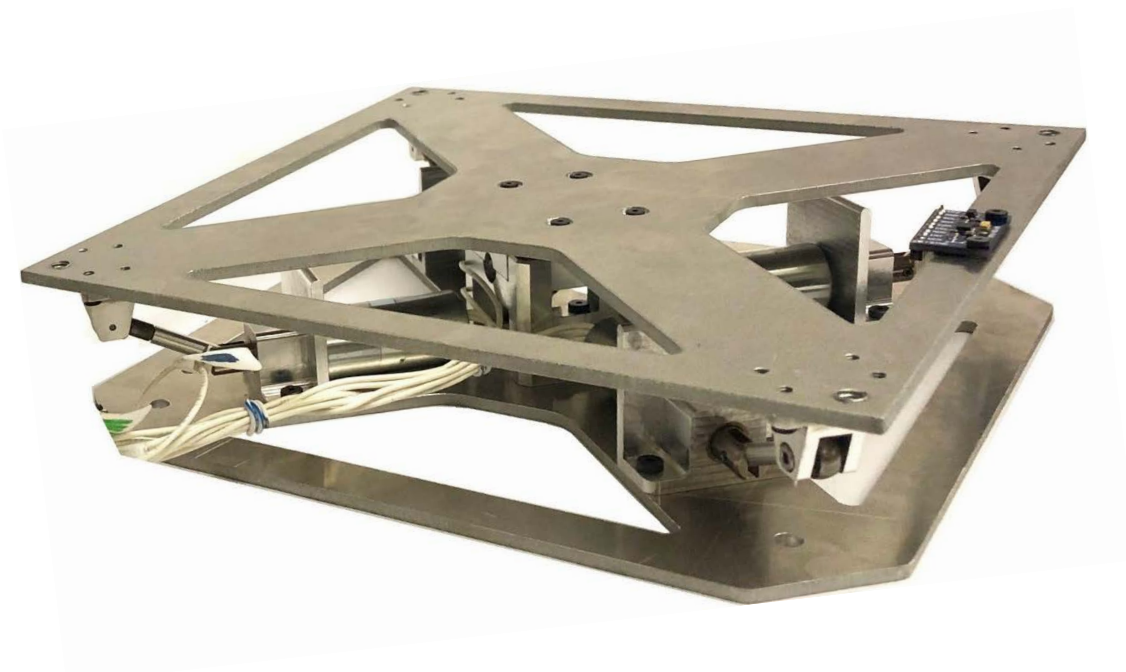


(c) Single Degree Of Freedom

Figure 53. Proposed Future Iterations

9.3 Final Thoughts

The Thruster Gimbal project proved to be an extremely interesting and nuanced problem to solve. We were able to pursue multiple designs in parallel and we enjoyed the freedom and flexibility that this provided. Although we recognize that our design is not launch ready, we are hopeful our discoveries will help motivate the design that is ultimately launched into space. The gimbal prototype that we created using solenoids and vector averaging is a unique solution to orient an ion thruster and we are eager to see how this concept develops in the future.



Appendices:

[A] Quality Function Deployment Chart
[B] Pugh Matrix
[C] Design Refinement Decision Matrix
[D] Alternative Designs
[E] Drawing Package
[F] Product Literature
[G] Design Analysis
[H] Design Hazard Checklist
[I] Failure Modes and Effects Analysis
[J] Risk Assessment
[K] Project Budget
[L] Design Verification Plan and Report
[M] Operator's Manual
[N] Gantt Chart

References

[1] "AMG-LP Low-Profile Direct-Drive Gimbals." *Aerotech*, www.aerotech.com/product-catalog/gimbals-and-optical-mounts/amg-lp.aspx?p=/product-catalog/gimbals-and-optical-mounts.aspx.

[2] *COBRA Gimbal 3DOF, High Accuracy, High Reliability Carpal-Wrist Gimbal*. *COBRA Gimbal 3DOF, High Accuracy, High Reliability Carpal-Wrist Gimbal*, www.tethers.com/SpecSheets/Brochure_Gimbal.pdf.

[3] "Interactive G35 Gimbal Model." *NEA Electronics*, www.neaelectronics.com/products/gimbals-and-pointing-mechanisms/.

[4] *Ion Thruster Gimbal*. *Ion Thruster Gimbal*, www.moog.com/content/dam/moog/literature/Space_Defense/Spacecraft/Spacecraft_Mechanisms/500-764_Ion_Thruster_Gimbal_0414.pdf.

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[6] Haag, Thomas W. *Ion Thruster Support and Positioning System*. 14 Apr. 1998.

[7] Tilley, Scott W, et al. *Spacecraft Attitude Control and Momentum Unloading Using Gimballed and Throttled Thrusters*. 20 Sept. 1994.

[8] Goodzeit, Neil Evan, and Santosh Ratan. *Gimbaled Thruster Control System*. 19 Nov. 2002.

[9] Voigt, Che-Ram S. Mechanism for Thrust Vector Control Using Multiple Nozzles. 2 Sept. 1997.

[10] Charles, Che-Hang, et al. Attitude Slew Methodology for Space Vehicles Using Gimbaled Low-Thrust Propulsion Subsystem. 20 Dec. 2016.

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[12]"Space and Missile Systems Center Standard, Test Requirements for Launch, Upper-Stage and Apace Vehicles." United States Air Force Space Command, 5 Sept. 2014.

[13] "General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects." NASA Goddard Space Flight Center, 22 Apr. 2013.

[14] "Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment." American Society for Testing and Materials

Appendix A: Quality Function Development

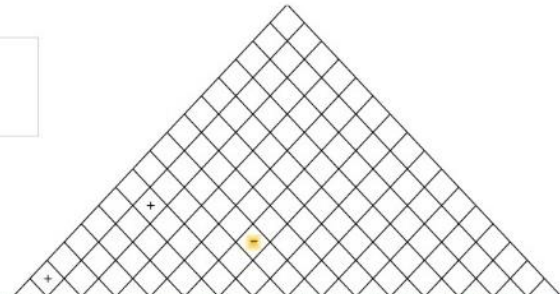
Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Astranis Satellite Thruster Gimbal
Revision Date: 10/11/2018

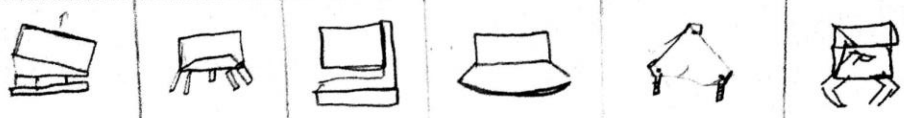


Row #	Weight Chart	Relative Weight	Astranis	Other Satellite Manufacturers	Satellite Technicians	Telecom Companies	Maximum Relationship	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Moog Ion Thruster Gimbal	3-Axis Fixed Thruster	Reaction Wheel	Tethers Cobra	RUAG EPMAC	Row #
	WHO: Customers							Direction of Improvement	▲	▼	◇	◇	◇	▲	▼	▼	▲	▲	▼	▼					NOW: Curr. Products					
								WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (Tests)	Cost	Mass	Temperature Resistance	Vector Precision	Vaccum Chamber Resistance	Actuation speed	Volume Envelope	Max Deflection Under Load	Vector Accuracy	Hours of Operation	Time to Assemble	Power Consumption										
1		10%	7	7	8	1	9	Dimensional Requirements	▽	○					●										1	4	1	5	5	1
2		9%	9	9	2	4	9	Lightweight		●					▽										4	5	1	5	5	2
3		13%	10	8	4	10	9	Precise/High Resolution			○	●	▽	○		○	●								4	3	4	3	4	3
4		15%	10	10	7	10	9	Reliable			●	▽	○			●	●	●		○					3	4	4	4	4	4
5		11%	10	10	1	10	9	Operable in space			●		●												5	5	5	5	5	5
6		12%	4	8	6	10	9	Cheap	●	●									○						1	4	1	2	2	6
7		8%	6	2	8	1	9	Manufacturability	○										●						2	4	2	4	4	7
8		6%	8	8	1	1	9	Low Power Consumption												●					3	4	2	5	3	8
9		11%	9	9	1	10	9	Long Lifespan			○		○			▽		●		○					3	2	4	4	3	9
10		4%	4	6	1	1	9	Quick Actuation				▽		●			▽								4	5	3	5	4	10
11		0%																												11
12		0%																												12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	$5,000	1.5kg	Go/No-go	0.5°	Go/No-go	0.2°/s	3200cm^3	TBD	0.5°	100	1 day	10W				
	Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9				
	Technical Importance Rating	143	218.4	311.2	134.1	194	77.03	99.79	186.6	256.4	234.8	109.6	134.7				
	Relative Weight	7%	10%	15%	6%	9%	4%	5%	9%	12%	11%	5%	6%				
Curr. Products	Moog Ion Thruster Gimbal	1	2	5	5	5	3	2	4	5	5	2	4				
	3-Axis Fixed Thruster	1	2	5	5	5	4	1	4	5	5	3	3				
	Reaction Wheel	1	1	5	5	5	1	1	4	5	5	1	2				
	Tethers Cobra	1	5	5	5	5	4	4	2	5	5	2	5				
	RUAG EPMAC	1	3	5	5	5	4	3	4	5	5	2	3				
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B: Pugh Matrix

PUGH MATRIX

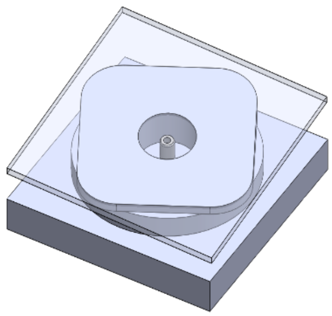
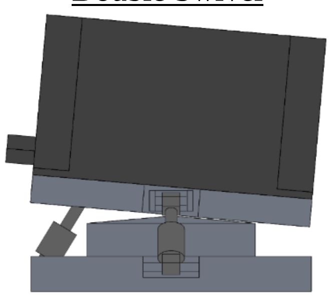
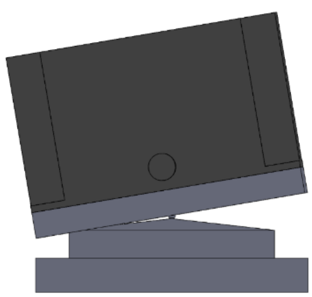


CRITERIA \ CONCEPT	1 DOF	LEAD SCREW	2 DOF	SURFACE	3 LINEAR	BENT LINKS
COMPLEXITY	+	-	S	-	-	-
ACCURACY	S	-	S	-	-	S
COST	+	-	+	-	S	-
WEIGHT	+	S	S	-	+	+
TEMP	S	S	S	S	S	S
VACUMM	S	S	S	S	S	S
AVERAGING	+	-	S	-	-	-

Appendix C: Design Refinement Decision Matrix

Decision Matrix							
Concept		Four Linear Actuators		Dual Pivot		Double Swivel	
Attribute	Weight						
Complexity	9	5	45	7	63	3	27
Temperature Resistance	7	5	35	5	35	5	35
Mass	8	4	32	7	56	3	24
Cost	4	4	16	6	24	5	20
Vacuum Resistance	6	5	30	5	30	5	30
Redundancy	6	6	36	6	36	7	42
Reliability	10	4	40	6	60	5	50
Time to Manufacture	3	2	6	5	15	2	6
Volume	5	3	15	5	25	3	15
Vector Repeatability	9	7	63	6	54	8	72
Actuation Time	3	8	24	7	21	6	18
Stiffness	4	5	20	4	16	9	36
Power Consumption	8	5	40	8	64	8	64
Cable Management	5	9	45	8	40	1	5
Sum:			447		539		444

Appendix D: Alternative Designs

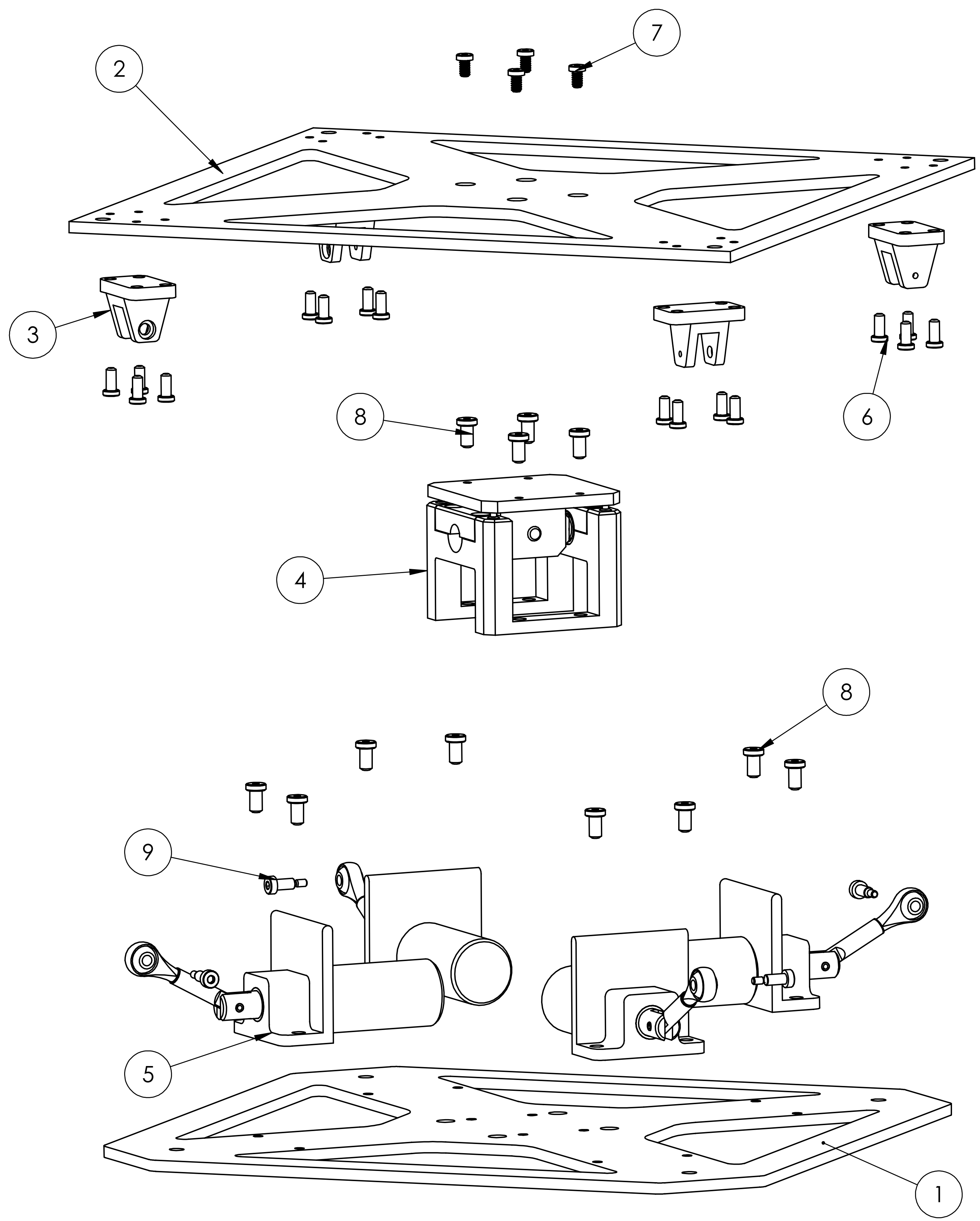
Concept	Description
Single DOF No Rotation 	Further development of the preliminary single DOF idea. This design uses a tilted surface beneath the thruster that rotates independently. This tilted surface makes sliding contact with a plate attached to the thruster. The thruster includes a passive rotary stage made up of a U-joint to prevent it from rotating about the z-axis.
Double Swivel 	This design is an iteration of the four-position linear actuator concept and utilizes vector averaging to achieve a single vector over time. This concept uses two solenoids and a ball joint to position the thruster in four discrete positions. A pyramidal plate with four surfaces is used to keep the thruster clocked in one of four positions.
Electromagnetic Locking Positions 	This design is another iteration of the four-position linear actuator concept and utilizes vector averaging to achieve a single vector over time. This concept uses four electromagnets and a ball joint to position the thruster in four discrete positions. For this design an electromagnet is located underneath each face of a pyramidal plate. The electromagnets are independently activated to clock the thruster to one face of the pyramidal surface.

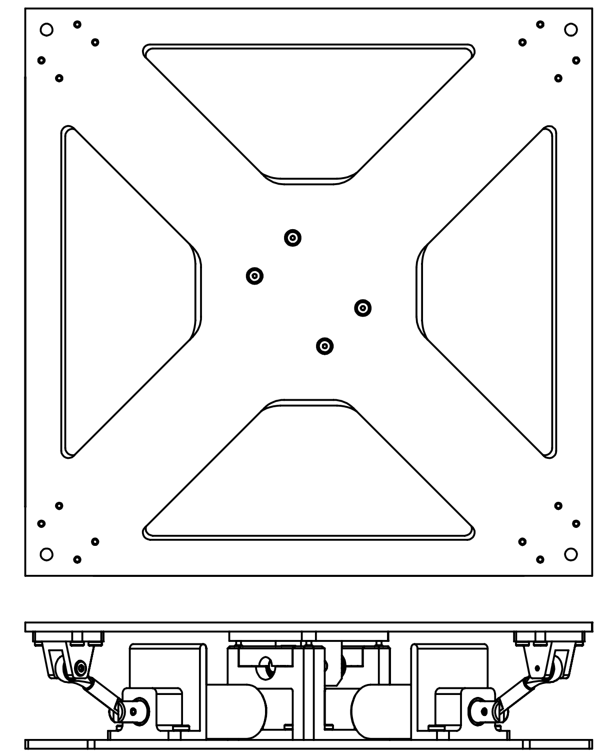
Appendix E: Drawing Package

BOM
Assembly Drawing
Part Drawings

Indented Bill of Material (BOM)
Gimbal Mechanism

Assembly	Part Number	Description Lvl0	Lvl1	Lvl2	Matl	Vendor	Qty	Cost	Ttl Cost	Status
0	1000	Final Assembly								
1	0100		Base Plate			------	1			Manuf'd
2	89015K18			12"X12" Alum. Plate	Al 6061	McMaster	1	27.71	27.71	Received
1	0200		Thruster Plate			------	1			Manuf'd
2	89015K18			12"X12" Alum. Plate	Al 6061	McMaster	1	27.71	27.71	Received
2	0201			Rod End Bracket	Al 6061	Protolabs	4	101.55	406.20	Received
1	0300		Two-Axis Hinge			------				
2	0301			Base	Al 6061	Protolabs	1	334.48	334.48	Received
2	0302			Shaft	Al 6061	Protolabs	1	139.79	139.79	Received
2	0303			Bearing Holder	Al 6061	Protolabs	2	112.57	225.14	Received
2	0304			Hinge Top	Al 6061	Protolabs	1	168.56	168.56	Received
2	57155K352			R156 Ball Bearing	Stl Steel	McMaster	2	6.32	12.64	Received
2	57155K353			R166 Ball Bearing	Stl Steel	McMaster	2	5.55	11.10	Received
2	97022A887			3/16" Shim	Stl Steel	McMaster	1 Pack	10.04	10.04	Received
2	97022A876			3/16" Shim	Stl Steel	McMaster	1 Pack	7.15	7.15	Received
2	N/A			8-36 Spring Plunger	Stl Steel	CubeSat	4	11.00	44.00	Received
2	93615A110			4-40 Socket Head Screw	Stl Steel	McMaster	1 Pack	5.65	5.65	Received
2	90337A184			3/16" Shoulder Screw	Stl Steel	McMaster	1	7.74	7.74	Received
1	0400		Linkage and Solenoid			------				
2	0401			Solenoid Bracket	Al 6061	Protolabs	4	95.69	382.76	Received
2	0402			Link	Al 6061	Protolabs	4	68.59	274.36	Received
2	2024-1074-ND			3/4" Pull Solenoid	Stl Steel	DigiKey	4	26.50	106.00	Received
2	59935K110			Ball Joint Rod End	Alloy Steel	McMaster	4	7.50	30.00	Received
2	92373A140			3/32" Spring Pin	Stl Steel	McMaster	1 Pack	3.19	3.19	Received
2	97022A868			1/8" Shim	Stl Steel	McMaster	1 Pack	8.42	8.42	Received
2	9368T450			5/16" Brass Bearing	Bronze	McMaster	4	0.59	2.36	Received
1	500		Mock Thruster			------				
2	501			Thruster Base		------	1			Manuf'd
2	502			Thruster Top		------	1			Manuf'd
2	503			Thruster Side		------	3			Manuf'd
2	504			Thruster Side IMU		------	1			Manuf'd
2	505			Thruster Chamfer		------	4			Manuf'd
2	8505K741			12"x12" Acrylic Sheet	Acrylic	McMaster	3	7.14	21.42	Received
1	92220A313		4-40 Socket Head Screw		Stl Steel	McMaster	1 Pack	9.38	9.38	Received
1	93615A210		6-32 Socket Head Screw		Stl Steel	McMaster	1 Pack	8.57	8.57	Received
1	90265A113		3mm Shoulder Screw		Stl Steel	McMaster	4	3.08	12.32	Received
								Total:	**2286.69**	





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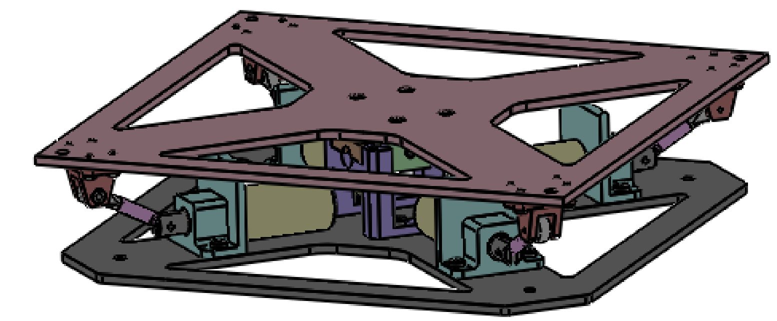

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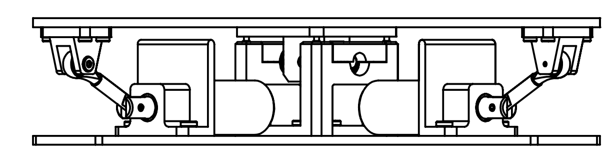


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	0100	BASE PLATE	1
2	0200	THRUSTER PLATE	1
3	0201	ROD END BRACKET	4
4	0300	TWO-AXIS HINGE SUBASSEMBLY	1
5	0400	LINKAGE AND SOLENOID SUBASSEMBLY	4
6	93615A110	4-40 SOCKET HEAD SCREW	16
7	92220A313	4-40 SOCKET HEAD SCREW	4
8	93615A210	6-32 SOCKET HEAD SCREW	12
9	90265A113	3MM SHOULDER SCREW	4

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.050
X.X° ± 0.5°

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5

MATERIAL: AL6061-T6

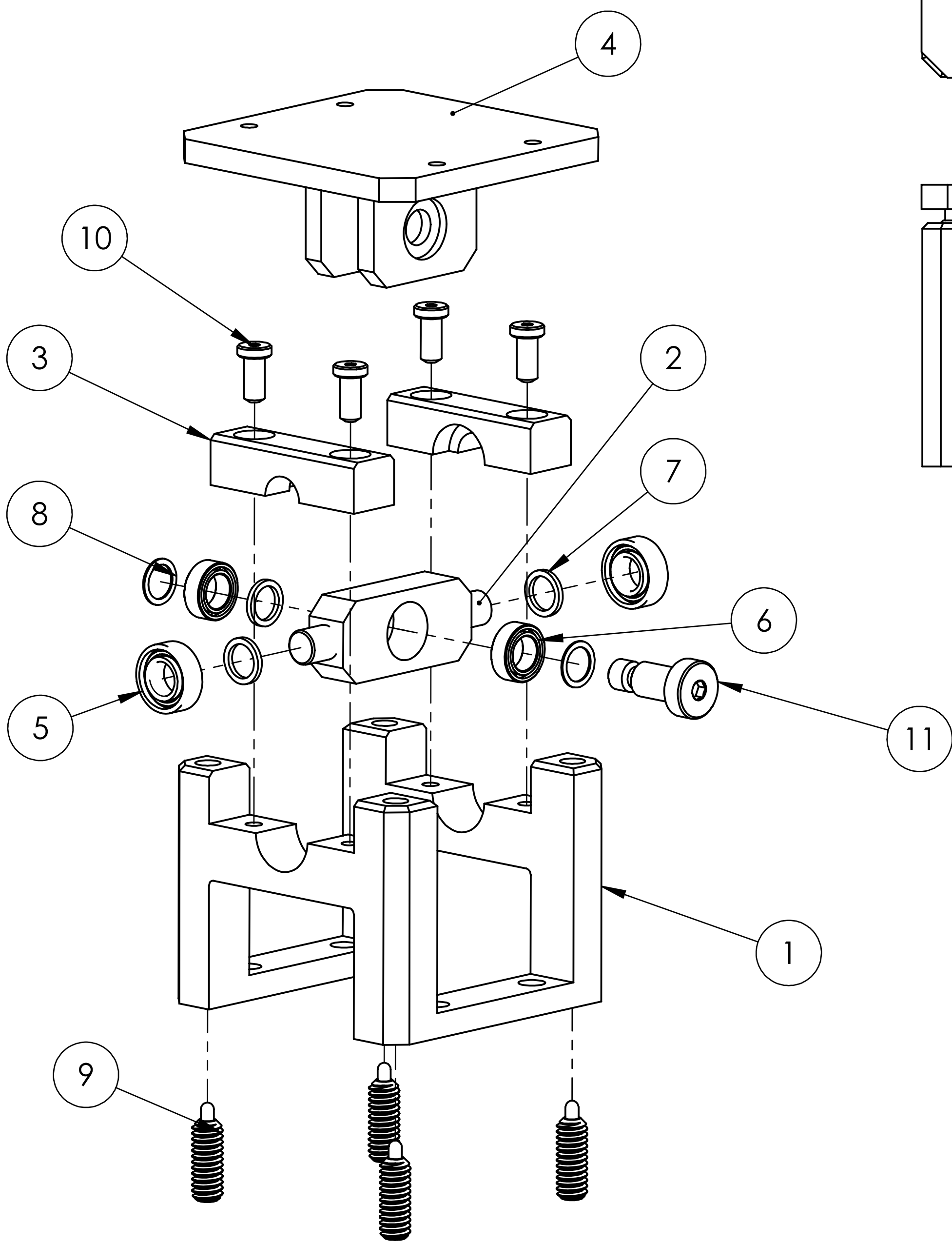
FINISH: AS MACHINED BREAK EDGES

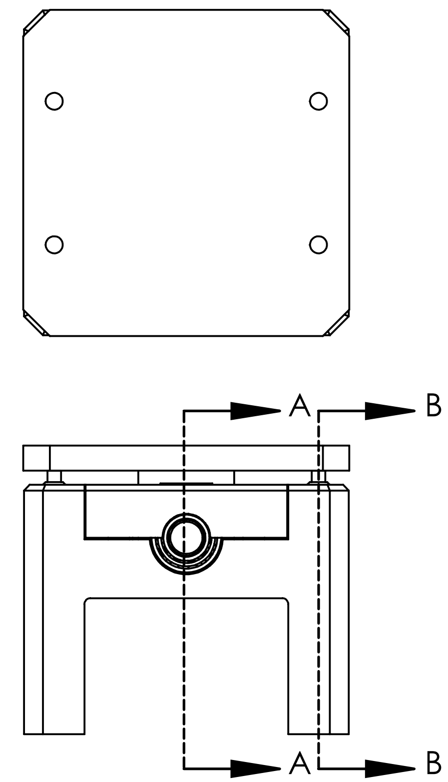
	NAME	DATE
DRAWN	G. RAMIREZ	5/22/19
CHECKED	J. TRAN	

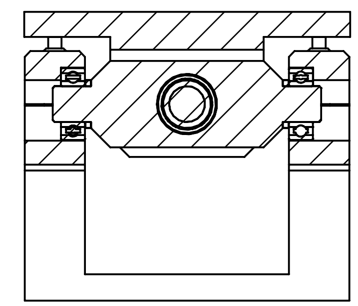
TITLE:
FINAL ASSEMBLY

SIZE: **B** | DWG. NO. 1000 | REV

SCALE: 2:3 | WEIGHT: | SHEET 1 OF 1







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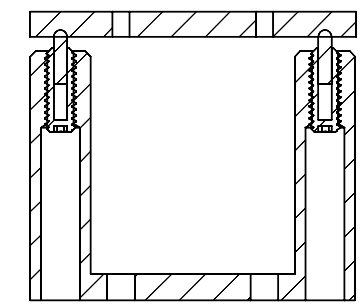

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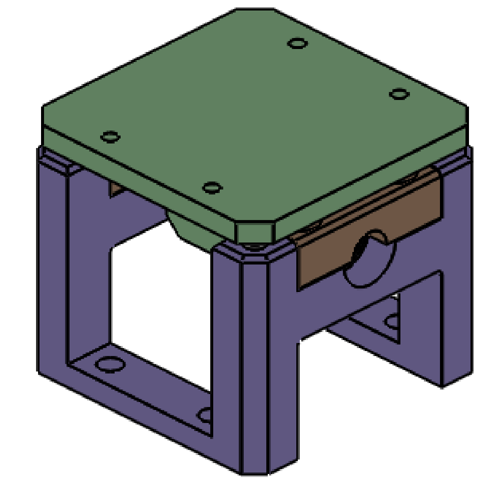


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	0301	HINGE BASE	1
2	0302	HINGE SHAFT	1
3	0303	BEARING HOLDER	2
4	0304	HINGE TOP	1
5	SR166	3/8" BALL BEARING	2
6	57155K352	5/16" BALL BEARING	2
7	97022A887	3/16" SHIM	3
8	97022A876	3/16" SHIM	2
9	8495A6	8-36 SPRING PLUNGER	4
10	93615A110	4-40 SOCKET HEAD SCREW	4
11	90337A184	SHOULDER BOLT	1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.050
X.X° ± 0.5°

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5

MATERIAL: AL6061-T6

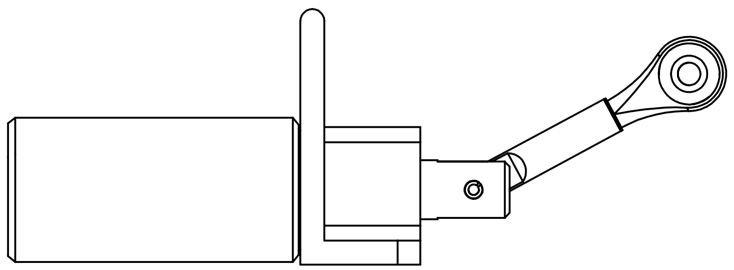
FINISH: AS MACHINED, BREAK EDGES

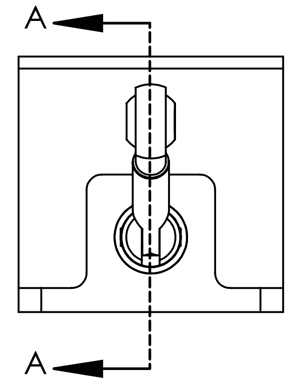
	NAME	DATE
DRAWN	G.RAMIREZ	5/27/19
CHECKED	J.NEIMAN	5/27/19

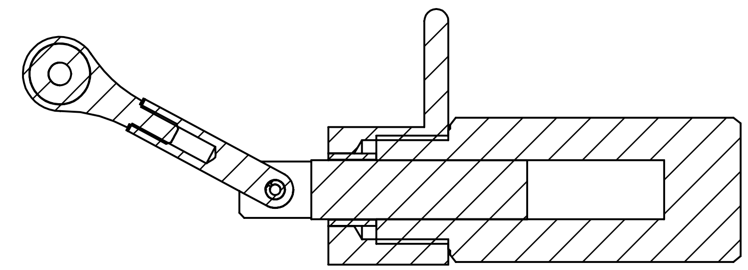
TITLE:
TWO-AXIS HINGE

SIZE: **B** | DWG. NO. 0300 | REV

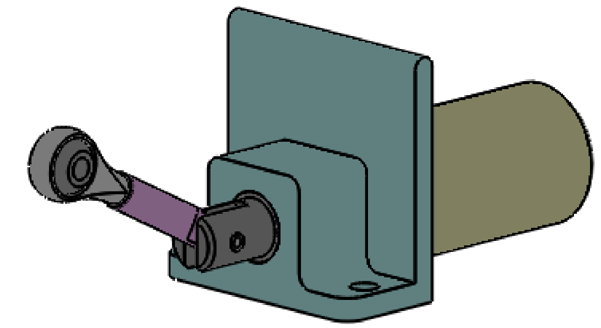
SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1

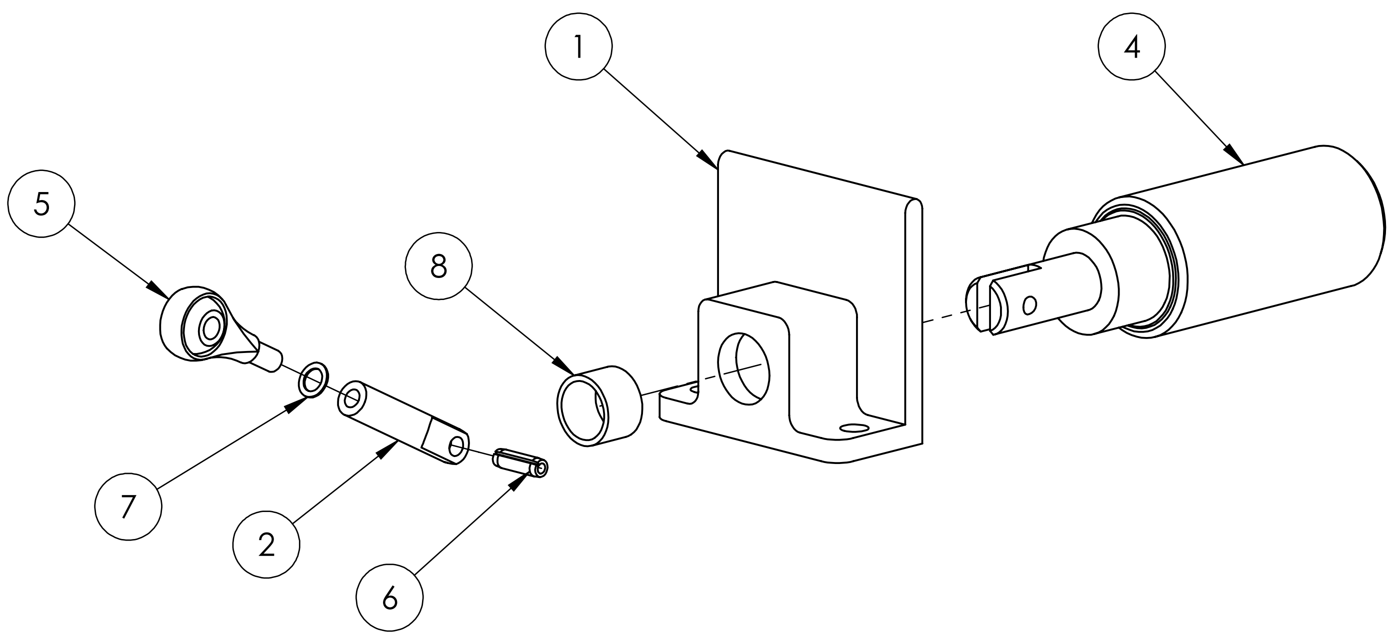






SECTION A-A





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	0401	SOLENOID BRACKET	1
2	0402	LINK	1
4	195204-230	PULL SOLENOID	1
5	59935K11	BALL JOINT ROD END	1
6	92373A140	3/32" SPRING PIN	1
7	97022A868	1/8" SHIM	AS REQ.
8	9368T45	5/16" BRASS BEARING	1

NOTES

1. ADJUST QTY. OF SHIMS (ITEM NO. 6) UNTIL ROD END IS PERPENDICULAR TO BASE OF SOLENOID BRACKET

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.050
X.X° ± 0.5°

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5

MATERIAL: AL6061-T6

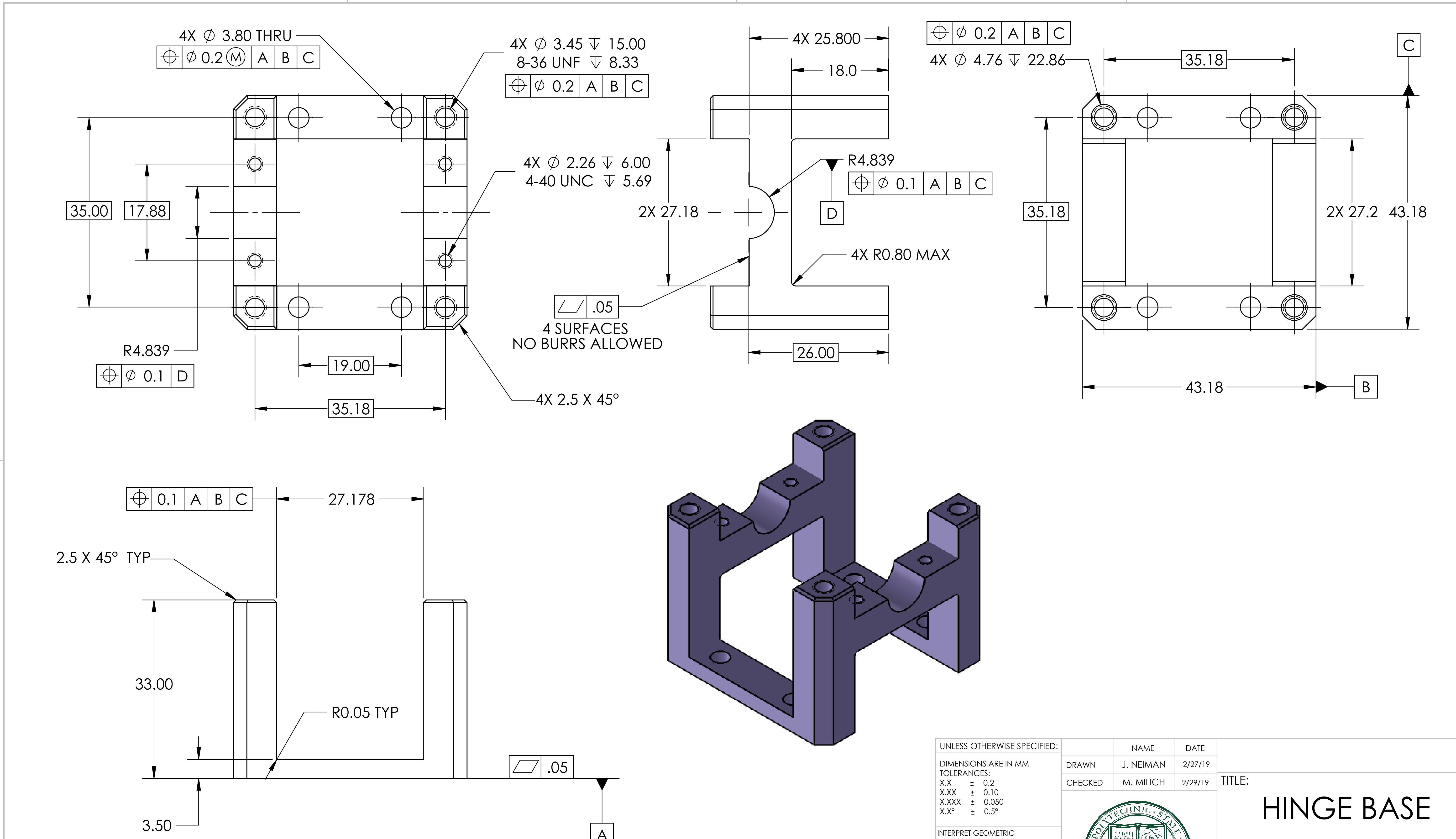
FINISH: AS MACHINED BREAK EDGES

	NAME	DATE
DRAWN	G. RAMIREZ	5/27/19
CHECKED	J. NEIMAN	

TITLE: LINKAGE AND SOLENOID

SIZE: B | DWG. NO.: 0400 | REV:

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

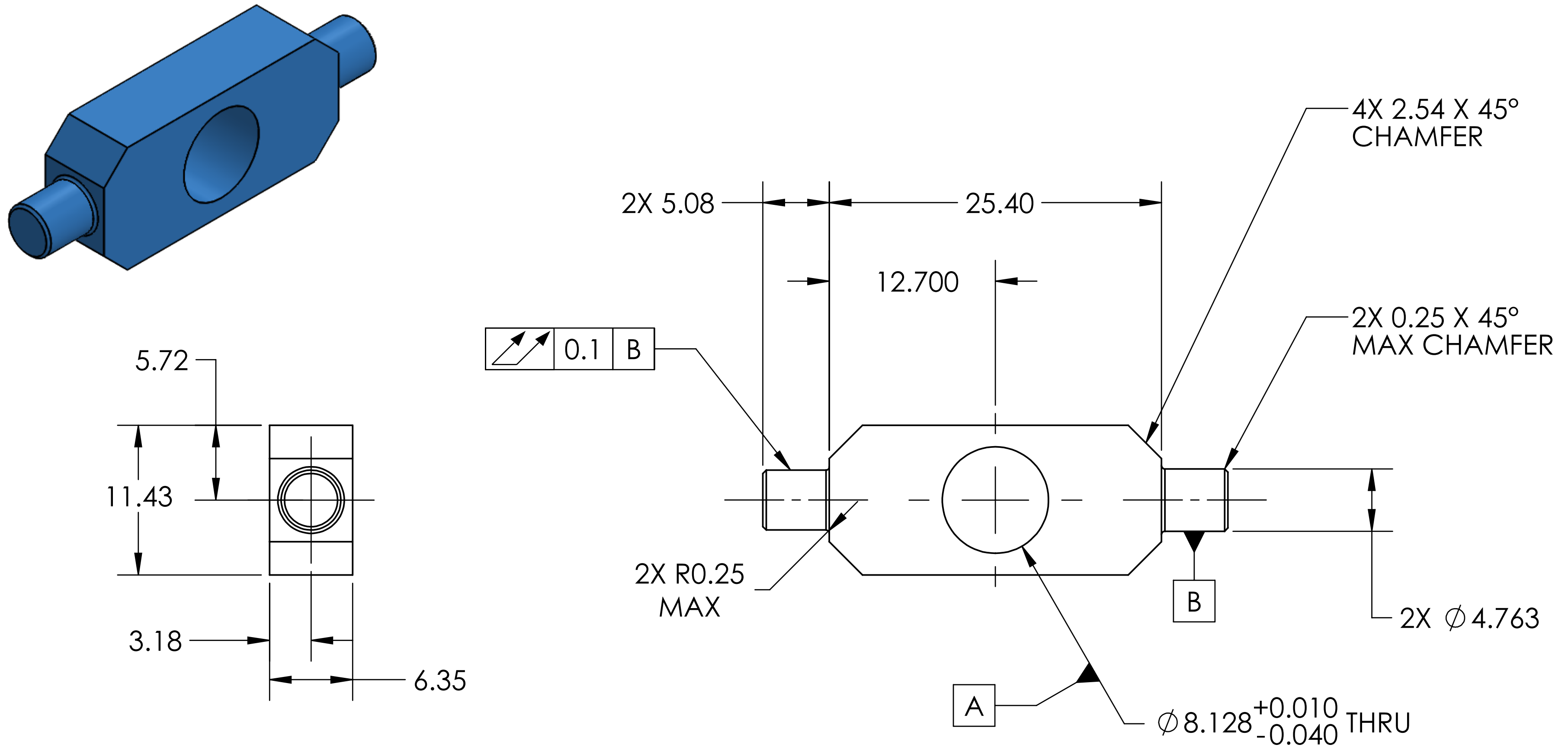


UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MM TOLERANCES: X.X ± 0.2 X.XX ± 0.10 X.XXX ± 0.050 X.X° ± 0.5°	DRAWN	J. NEIMAN	2/27/19
	CHECKED	M. MILICH	2/29/19
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5			
MATERIAL: AL6061-T6			
FINISH: AS MACHINED BREAK EDGES			

TITLE:

HINGE BASE

SIZE	DWG. NO.	REV
B	0301	04
SCALE: 2:3	WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.050
X.X° ± 0.5°

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5

MATERIAL
AL6061-T6

FINISH
AS MACHINED
BREAK EDGES

	NAME	DATE
DRAWN	J. NEIMAN	3/3/19
CHECKED	J. NEIMAN	

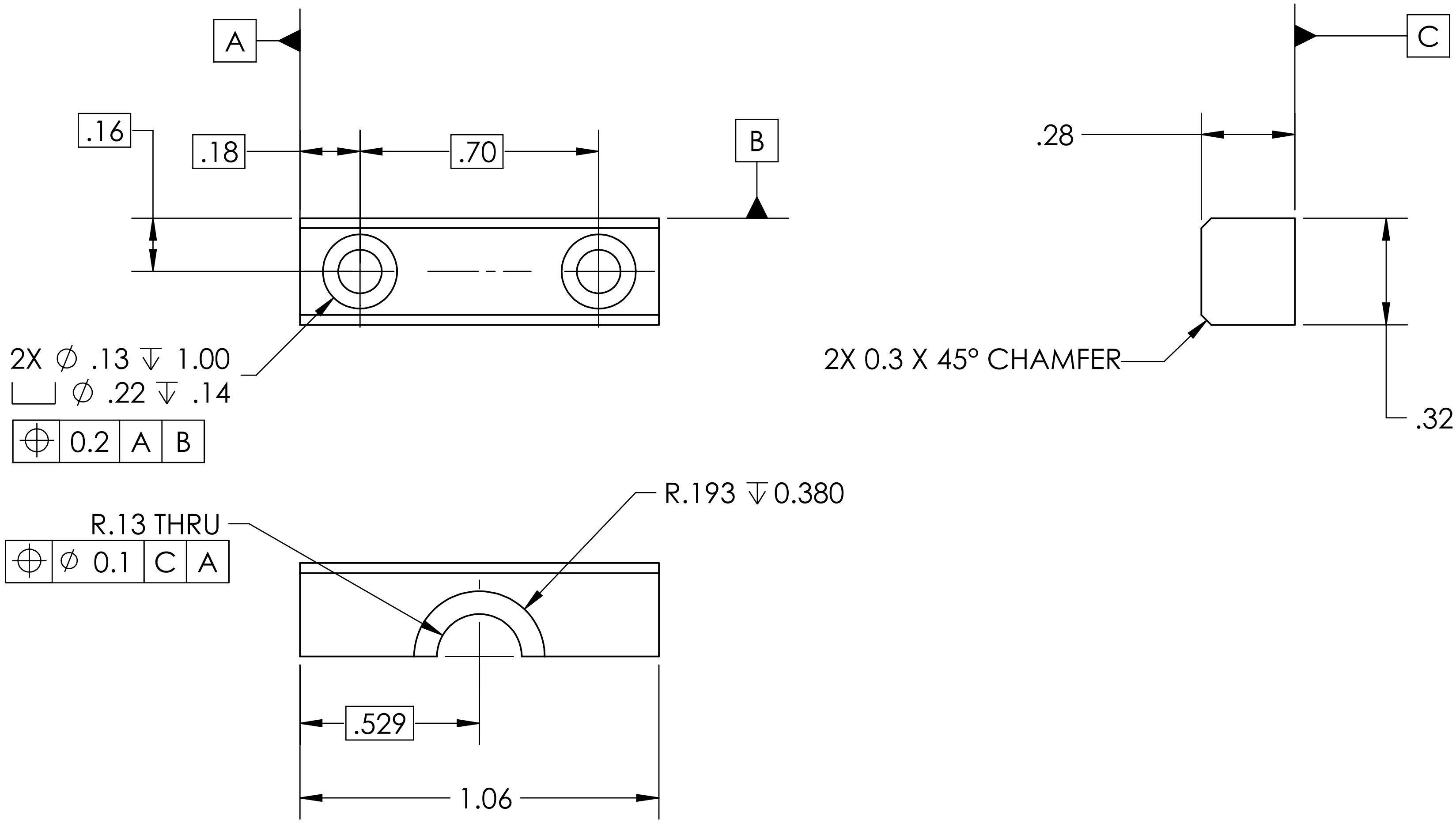
TITLE:

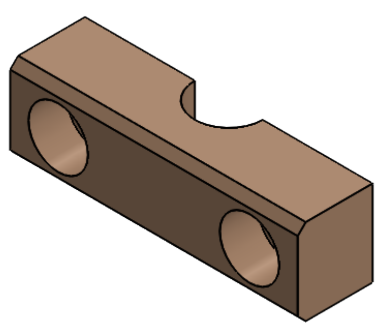
HINGE SHAFT

SIZE	DWG. NO.	REV
A	0302	01

SCALE: 2:1

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.050
X.X° ± 0.5°

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5

MATERIAL: AL6061-T6

FINISH: AS MACHINED, BREAK EDGES

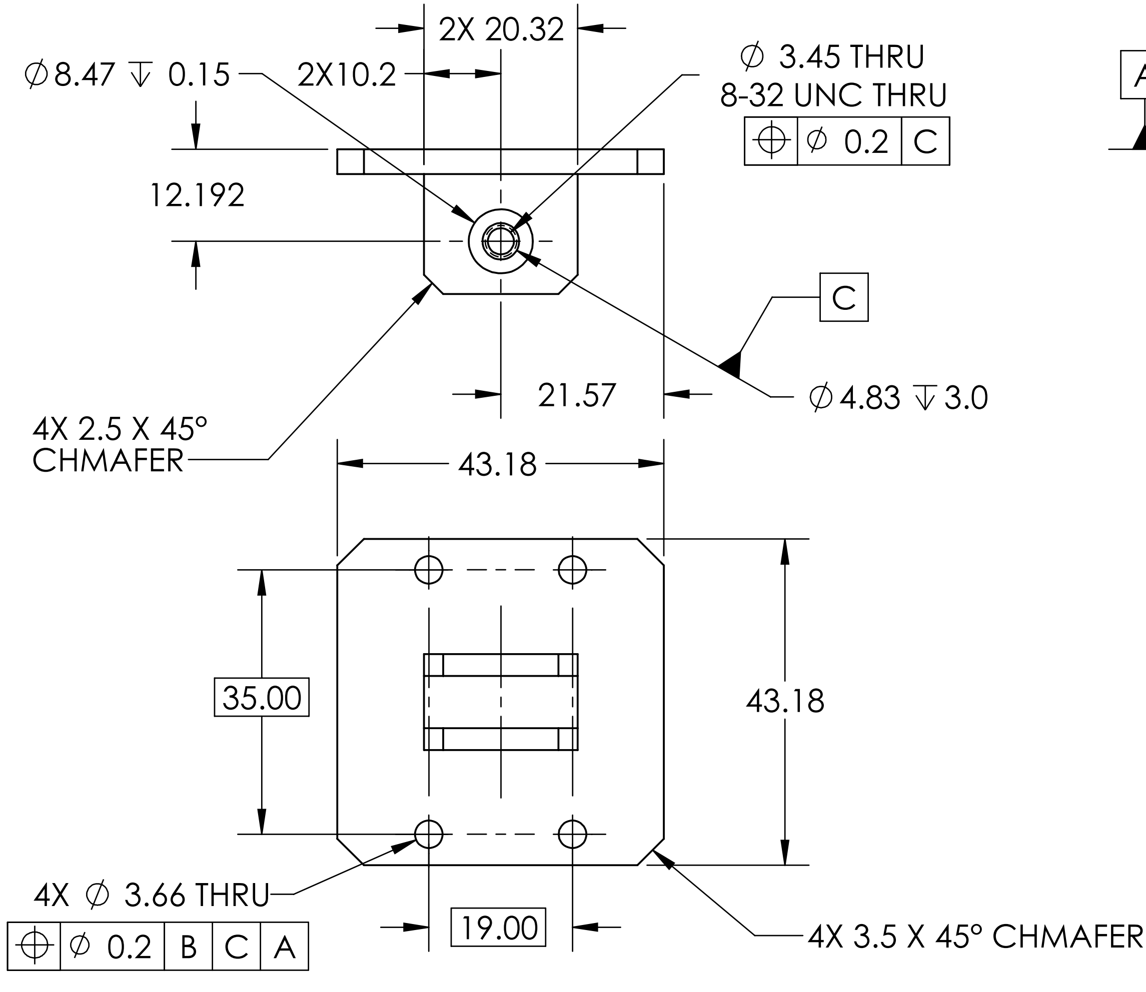
	NAME	DATE
DRAWN	J. NEIMAN	3/07/19
CHECKED	J. NEIMAN	

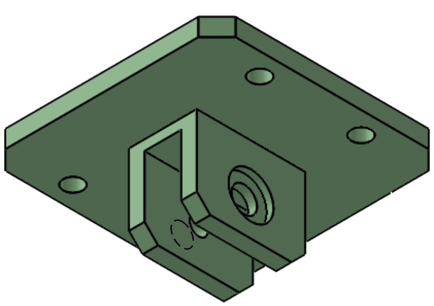
TITLE:

BEARING HOLDER

SIZE	DWG. NO.	REV
A	0303	02

SCALE: 2:1 SHEET 1 OF 1



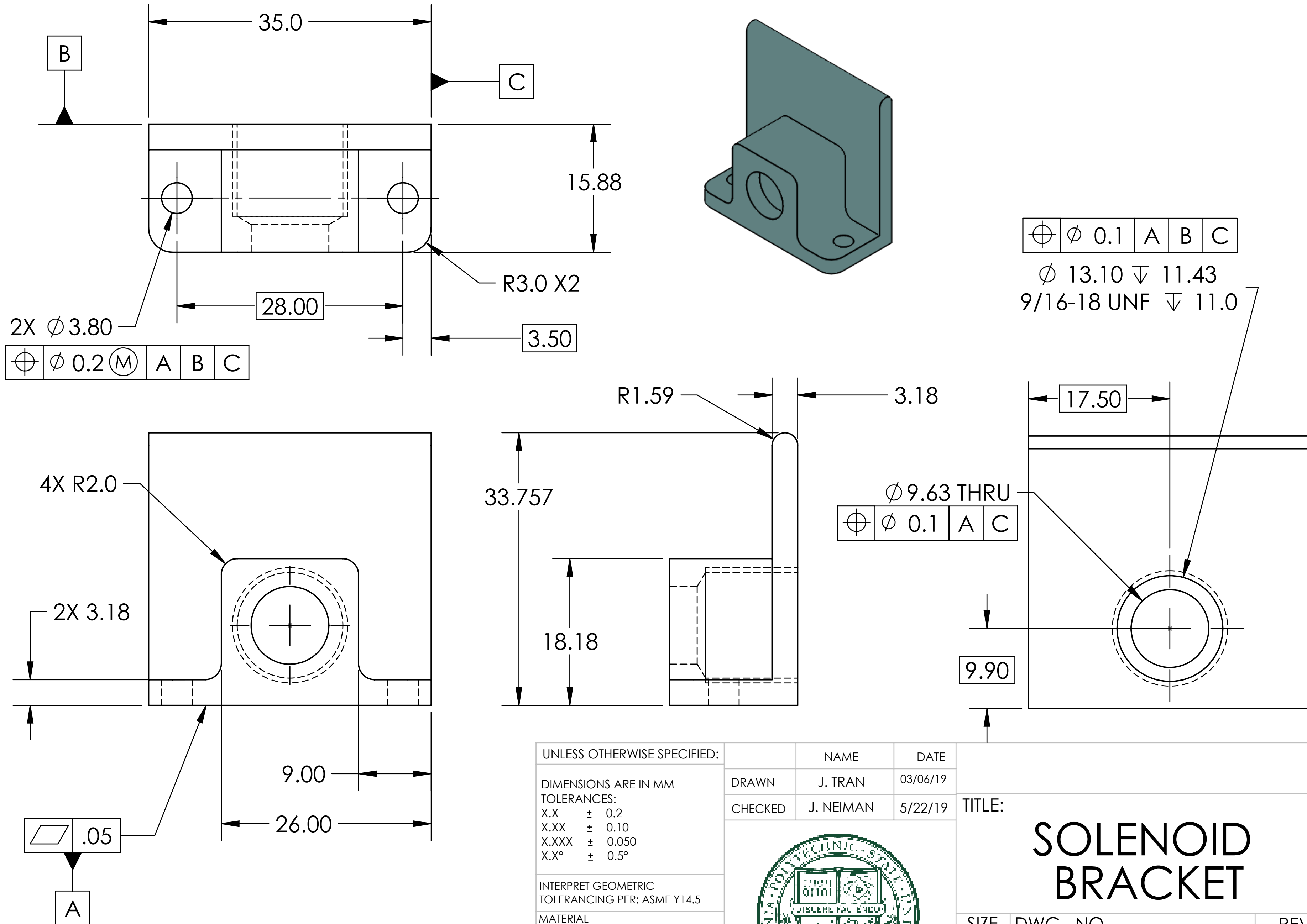


UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MM TOLERANCES: X.X ± 0.2 X.XX ± 0.10 X.XXX ± 0.050 X.X° ± 0.5°	DRAWN	J. NEIMAN	3/07/19
	CHECKED	J. NEIMAN	
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5			
MATERIAL AL6061-T6			
FINISH AS MACHINED BREAK EDGES			

TITLE:

HINGE TOP

SIZE	DWG. NO.	REV
A	0304	02
SCALE: 1:1		SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	NAME	DATE
DRAWN	J. TRAN	03/06/19
CHECKED	J. NEIMAN	5/22/19

DIMENSIONS ARE IN MM
TOLERANCES:
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.050
X.X° ± 0.5°

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5

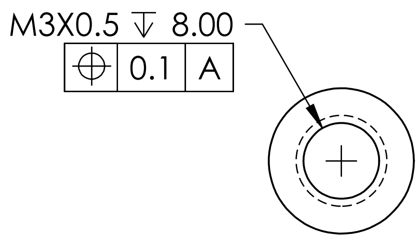
MATERIAL
AL6061-T6

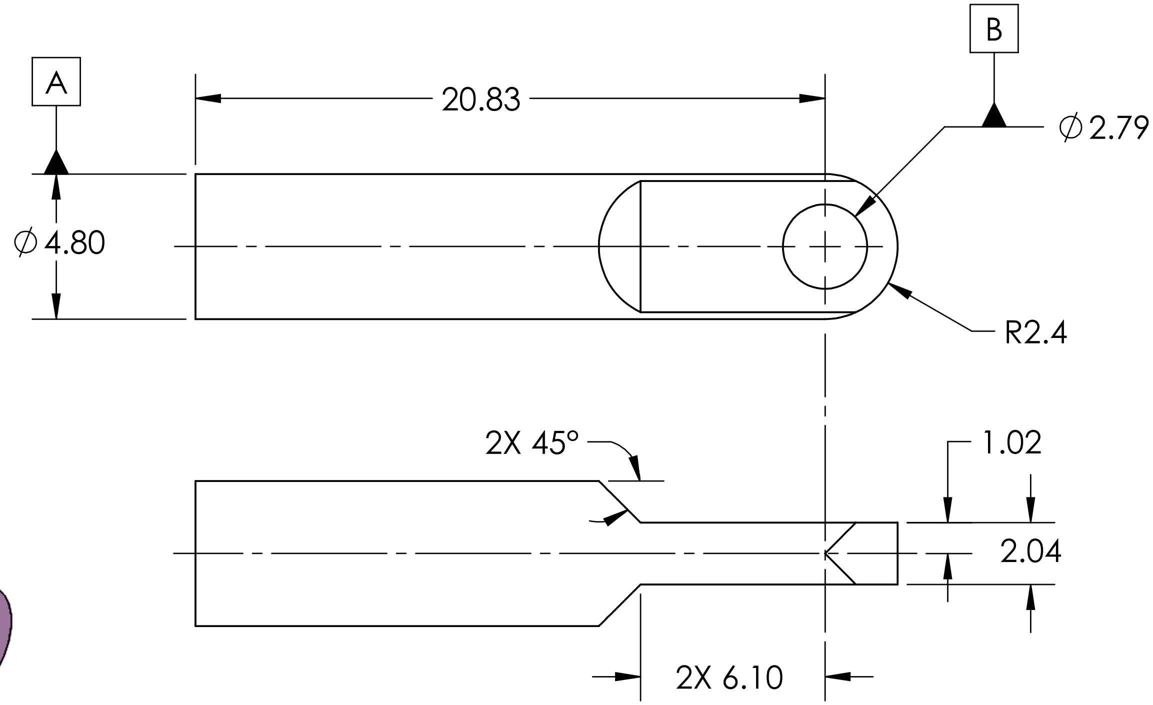
FINISH
AS MACHINED
BREAK EDGES

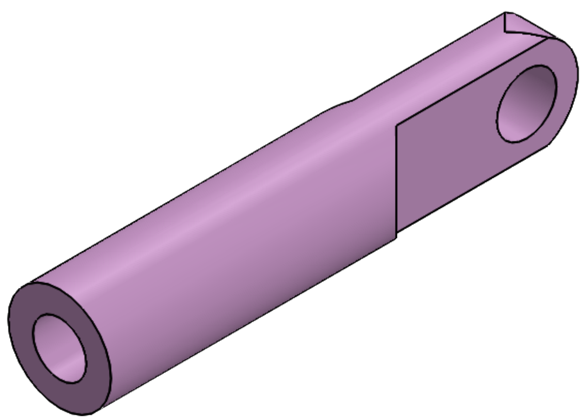
TITLE:

SOLENOID BRACKET

SIZE	DWG. NO.	REV
A	0401	01
SCALE: 3:2		SHEET 1 OF 1

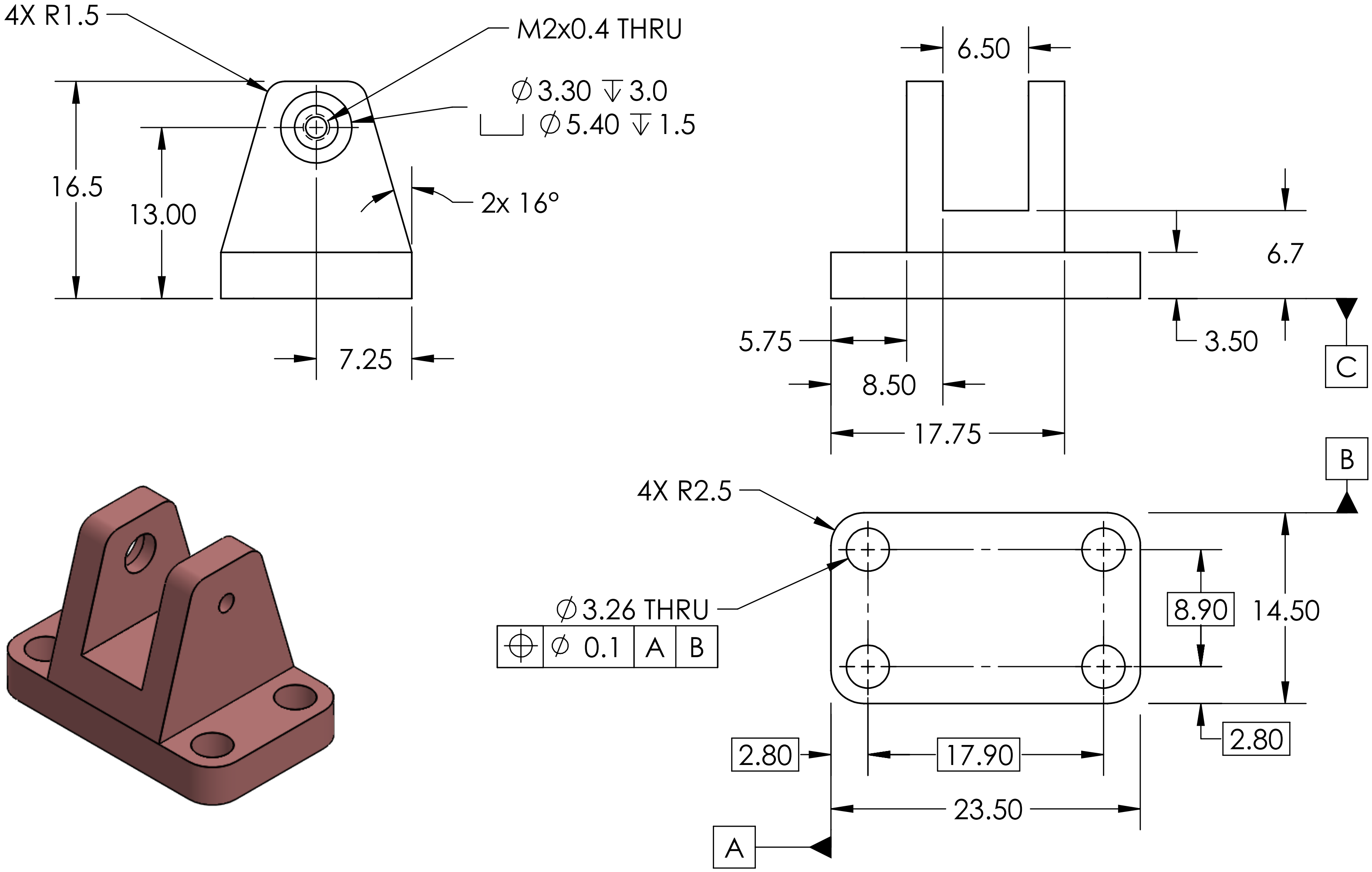






UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MM TOLERANCES: X.X ± 0.2 X.XX ± 0.10 X.XXX ± 0.050 X.X° ± 0.5°	DRAWN	G. RAMIREZ	3/7/19	
	CHECKED	G. RAMIREZ		TITLE: LINK
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5				SIZE A · DWG. NO. 0402 · REV 3
MATERIAL AL6061-T6				
FINISH AS MACHINED BREAK EDGES				SCALE: 4:1 · SHEET 1 OF 1

2 | 1



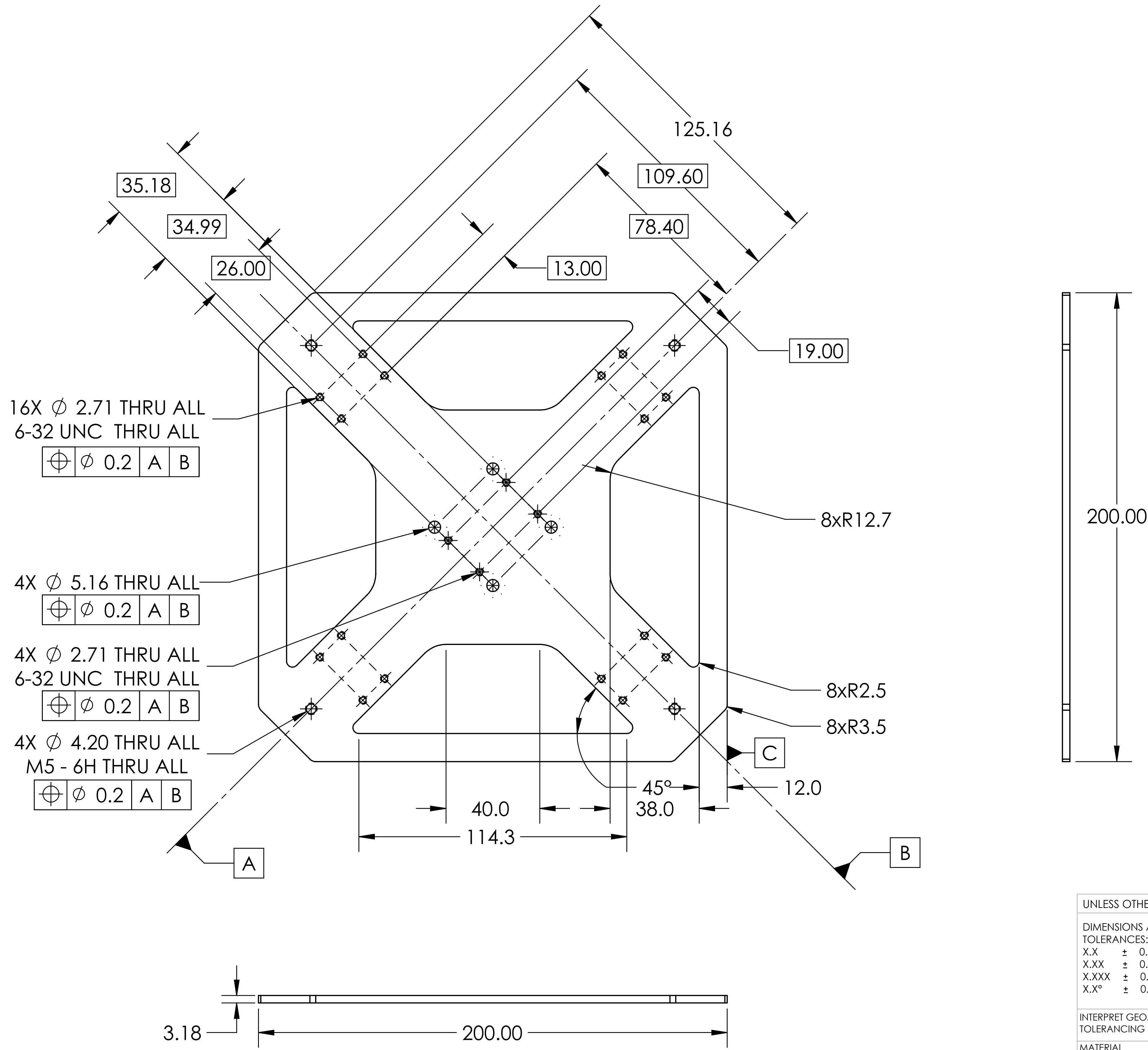
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MM TOLERANCES: X.X ± 0.2 X.XX ± 0.10 X.XXX ± 0.050 X.X° ± 0.5°	DRAWN	G. RAMIREZ	3/3/2019
	CHECKED	G. RAMIREZ	
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5			
MATERIAL AL6061-T6			
FINISH AS MACHINED BREAK EDGES			

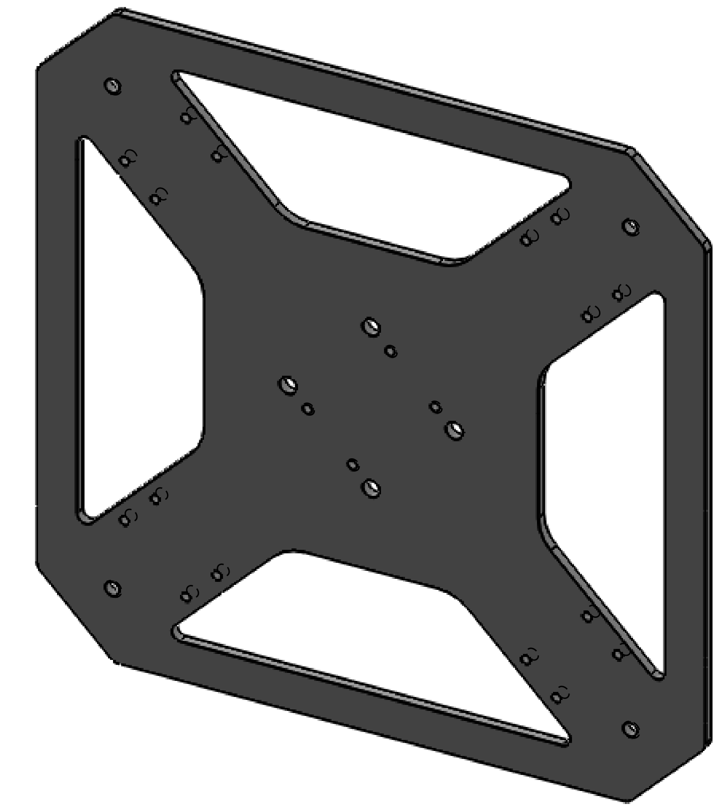
TITLE:

ROD END BRACKET

SIZE	DWG. NO.	REV
A	0201	3
SCALE: 2:1		SHEET 1 OF 1

2 | 1





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.050
X.X° ± 0.5°

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5

MATERIAL
AL6061-T6

FINISH
AS MACHINED
BREAK EDGES

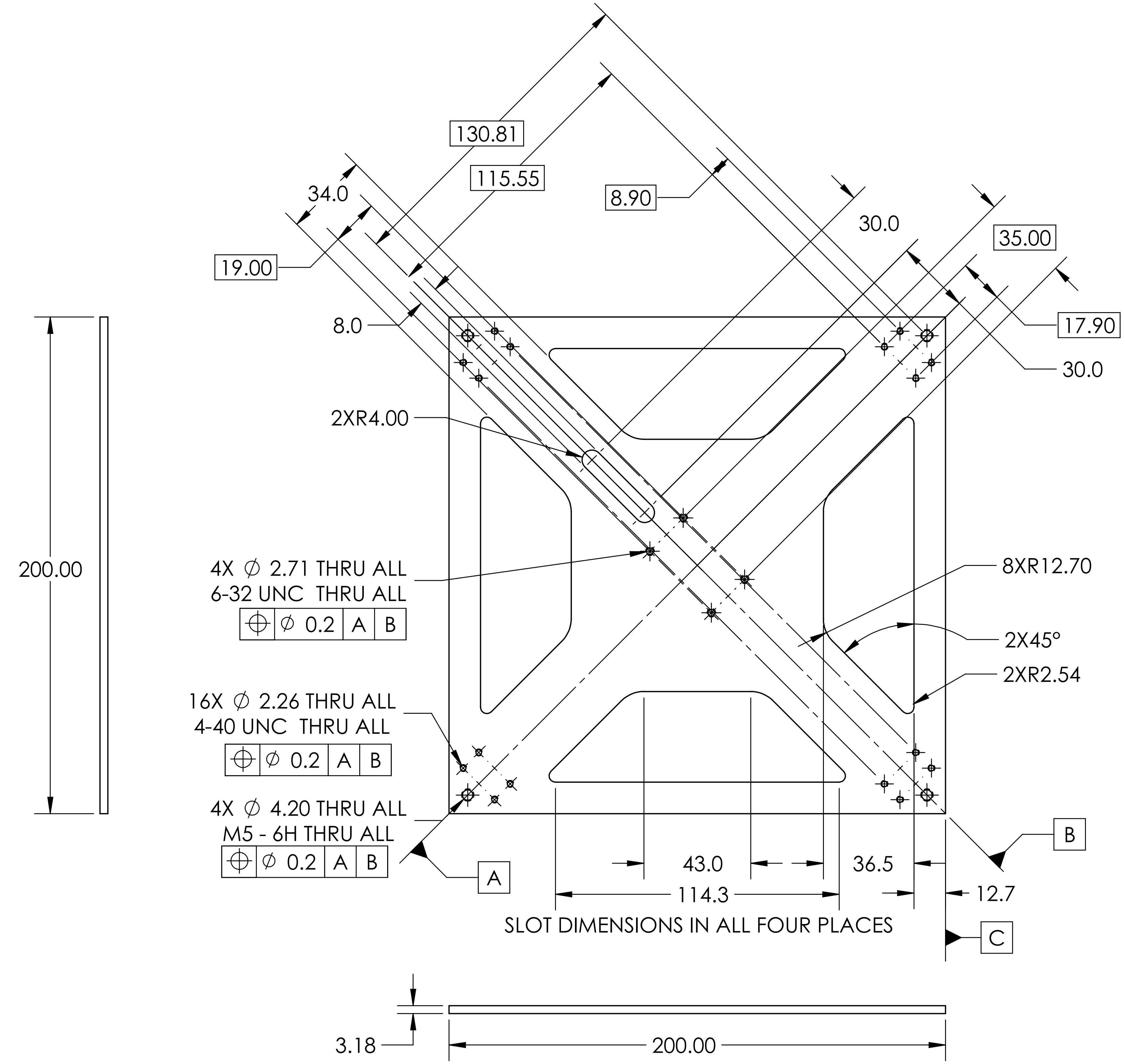
	NAME	DATE
DRAWN	M. MILICH	2/27/19
CHECKED	M. MILICH	

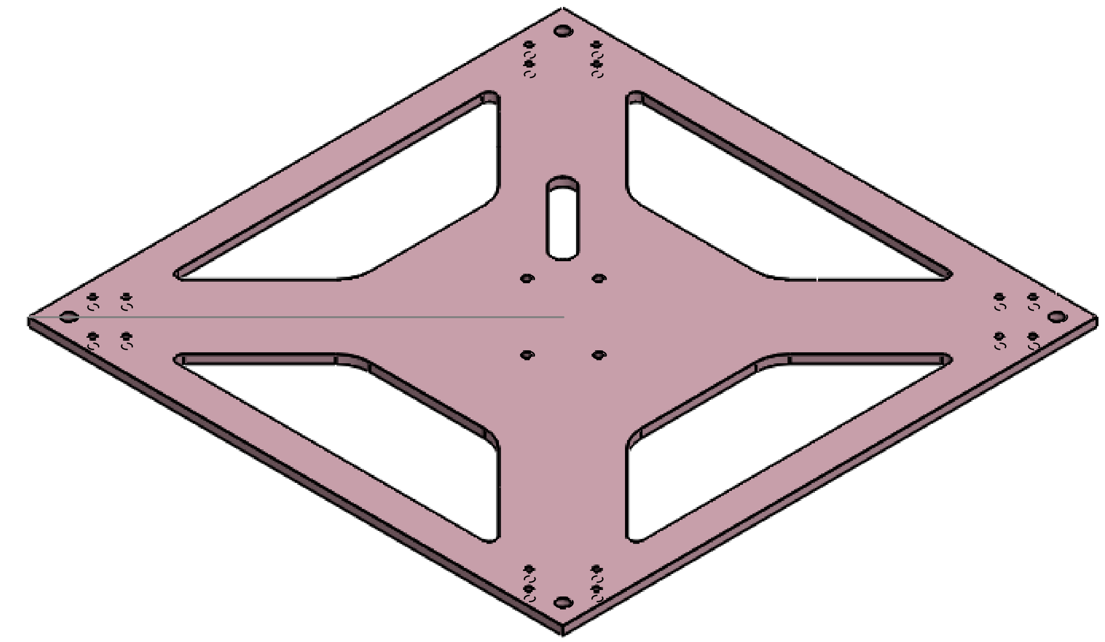
TITLE:

BASE PLATE

SIZE **B** DWG. NO. 0100 REV 01

SCALE: 1:2 WEIGHT: SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.050
X.X° ± 0.5°

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5

MATERIAL: AL6061-T6

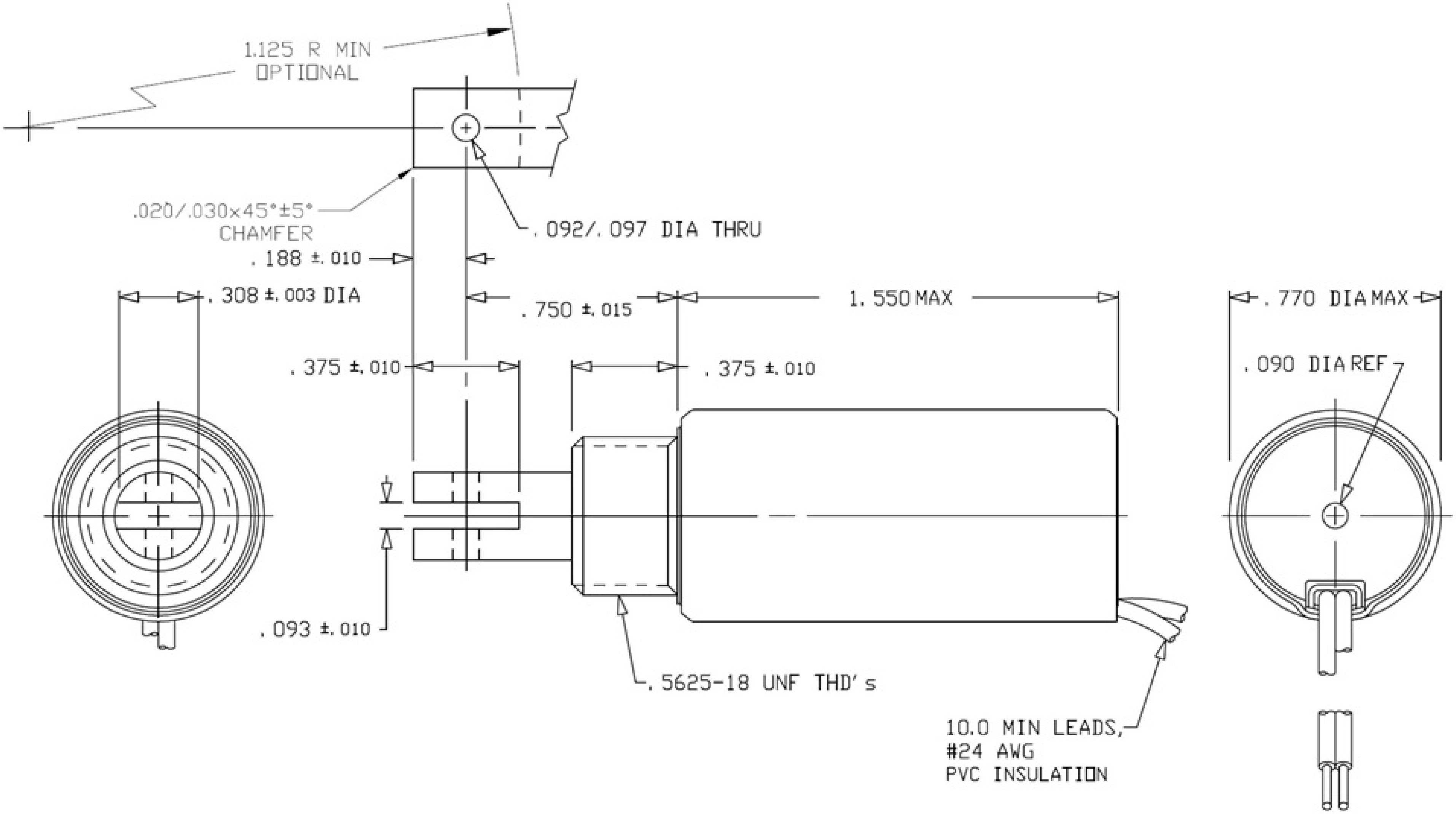
FINISH: AS MACHINED BREAK EDGES

	NAME	DATE
DRAWN	M. MILICH	3/7/19
CHECKED	M. MILICH	

TITLE:
THRUSTER PLATE

SIZE: B | DWG. NO.: 0200 | REV: 01

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS IN:
☐ METRIC (mm) ☒ INCHES ☐ mm/INCHES

METRIC	DECIMAL
X.X ± 0.3 mm	.XX ± .010 IN
X.XX ± 0.13 mm	.XXX ± .005 IN

ANGLES: ±
ES-612 & ES-613 APPLIES
THIRD ANGLE PROJECTION

Saia Burgess LLC
801 Scholz Dr.
Vandalia, OH 45377

TITLE: SOLENOID - TUBULAR

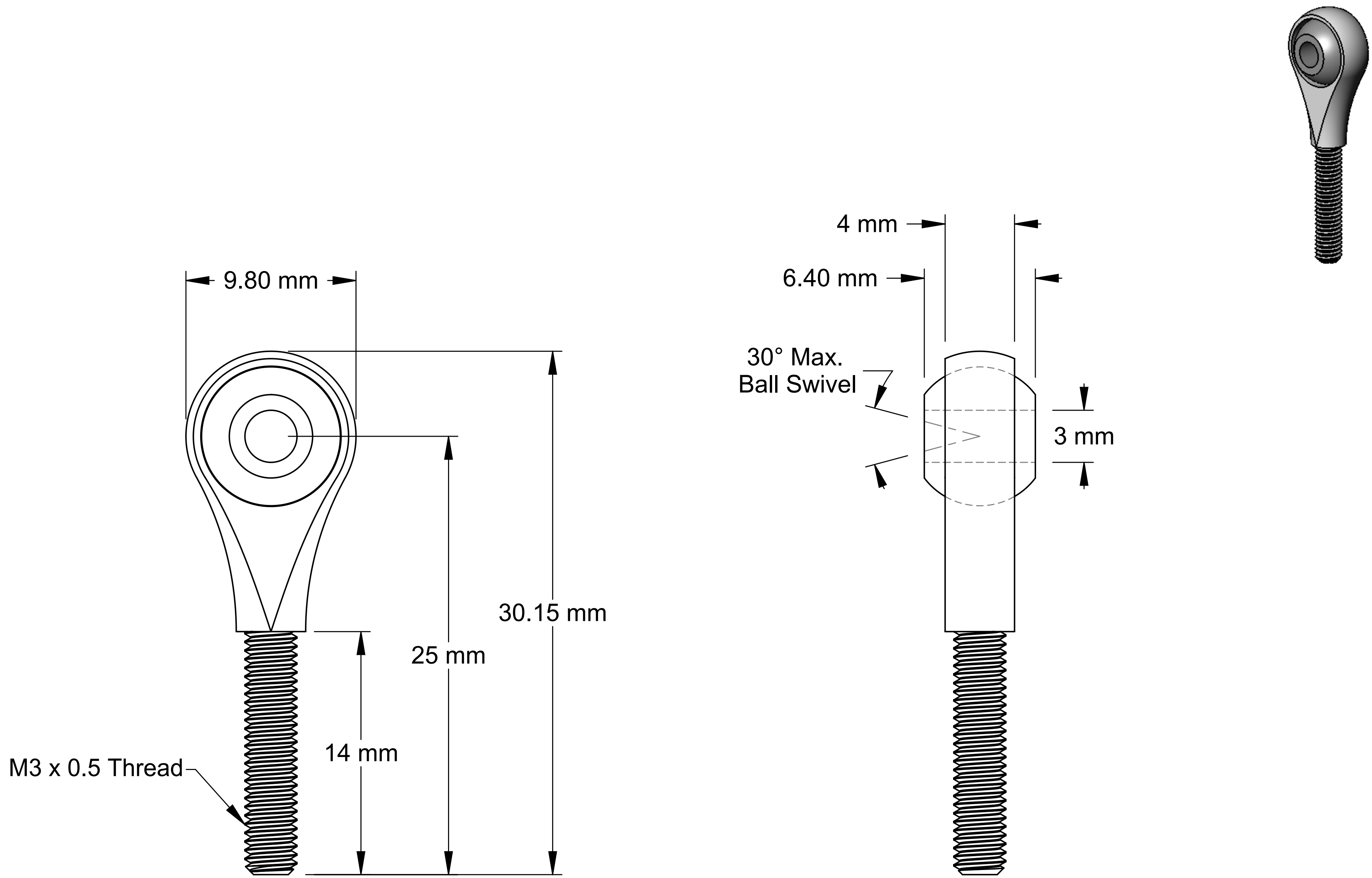
CODE IDENT: 81840

DRWG. NO.: 195204-XXX

A

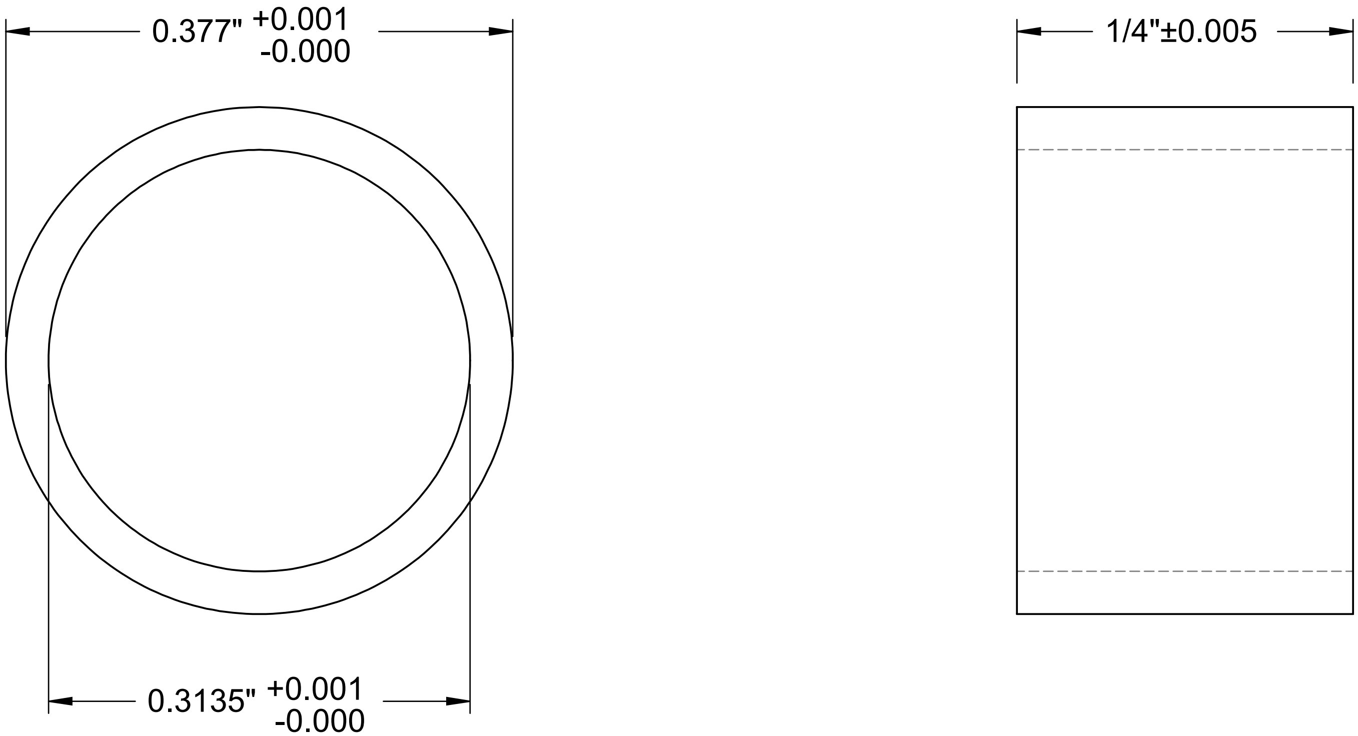
SCALE: NONE

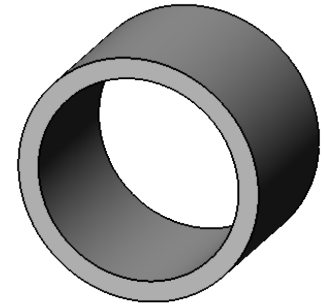
SHEET 1 OF 1



Note:
Steel Housing and Ball

McMASTER-CARR® CAD	PART NUMBER	59935K11
http://www.mcmaster.com © 2017 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Right-Hand Thread Ball Joint Rod End	



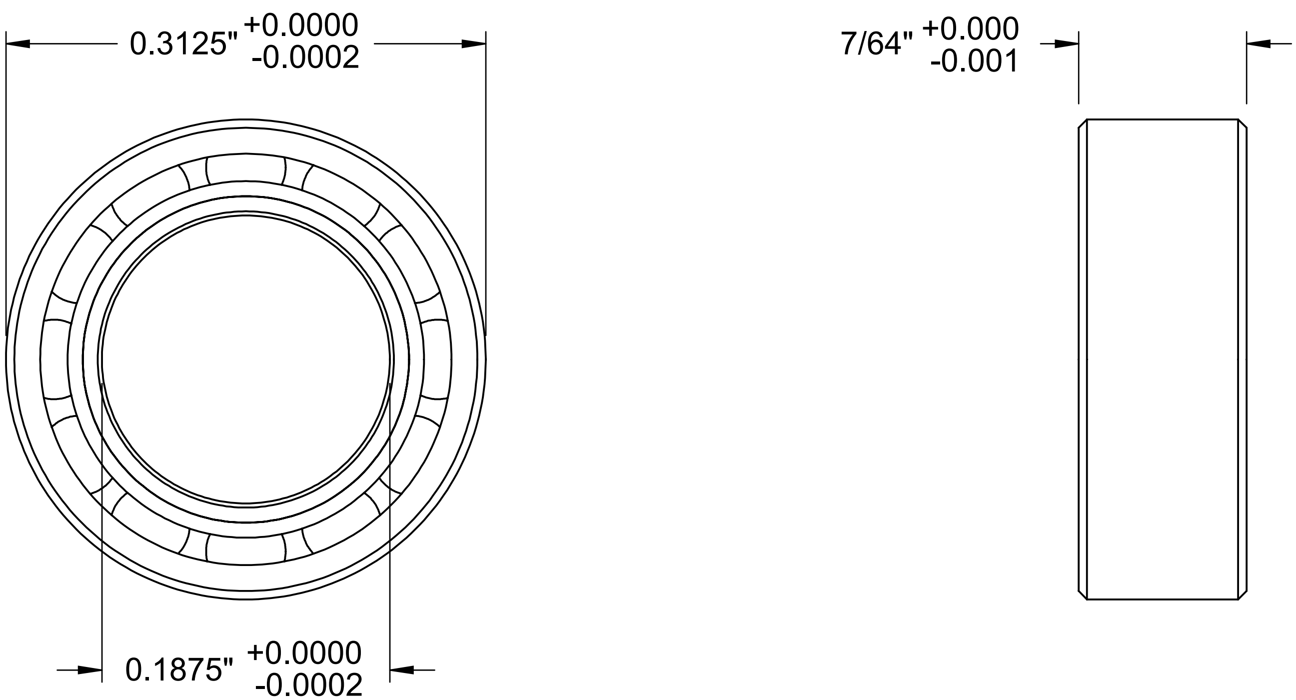


McMASTER-CARR® CAD

PART NUMBER 9368T45

http://www.mcmaster.com

High-Temperature Dry-Running Sleeve Bearing



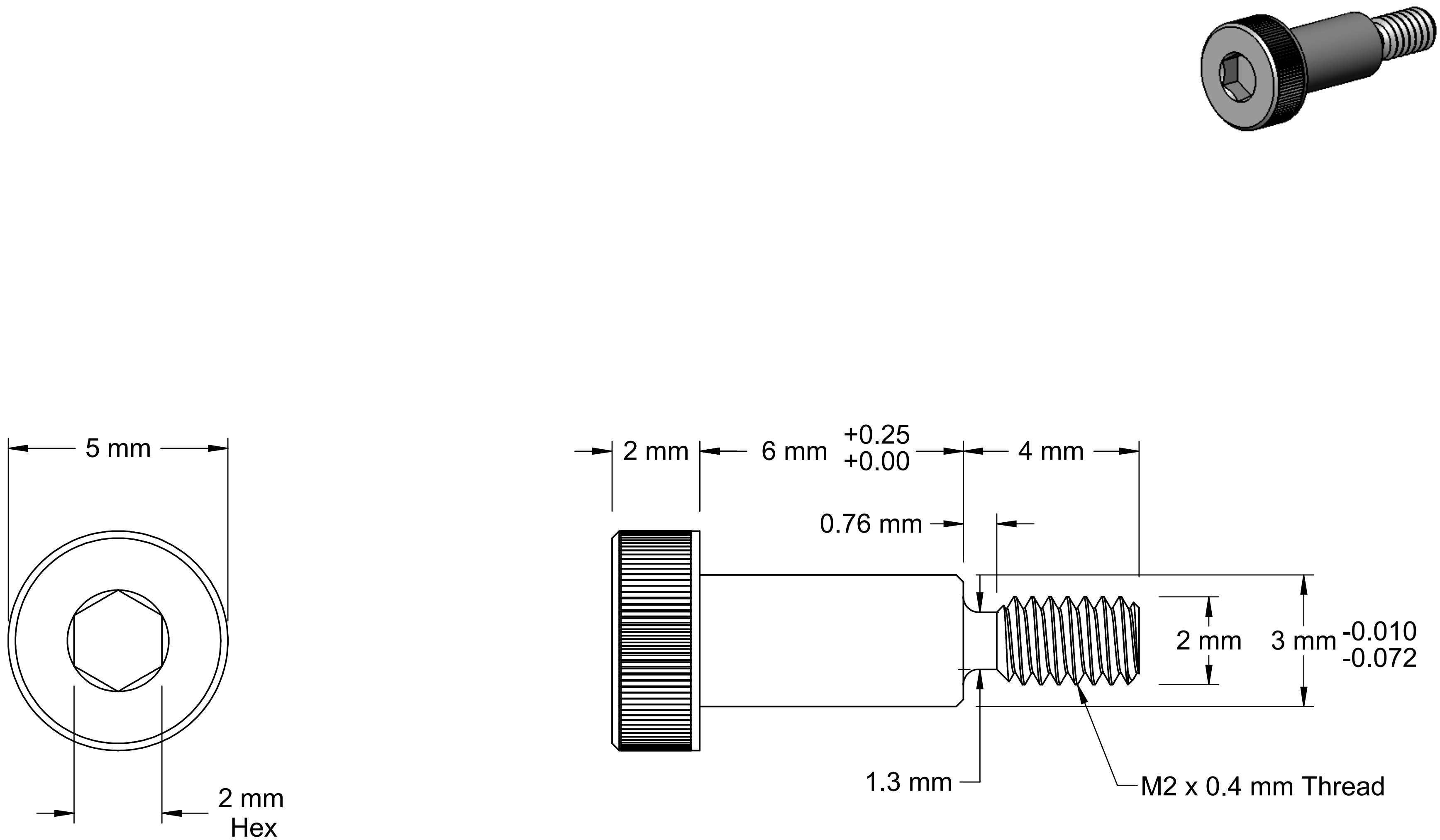
Trade Number: R156

McMASTER-CARR® CAD

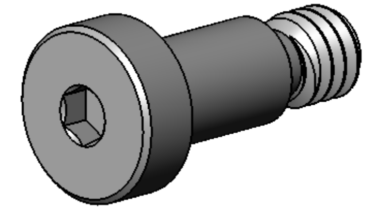
PART NUMBER 57155K352

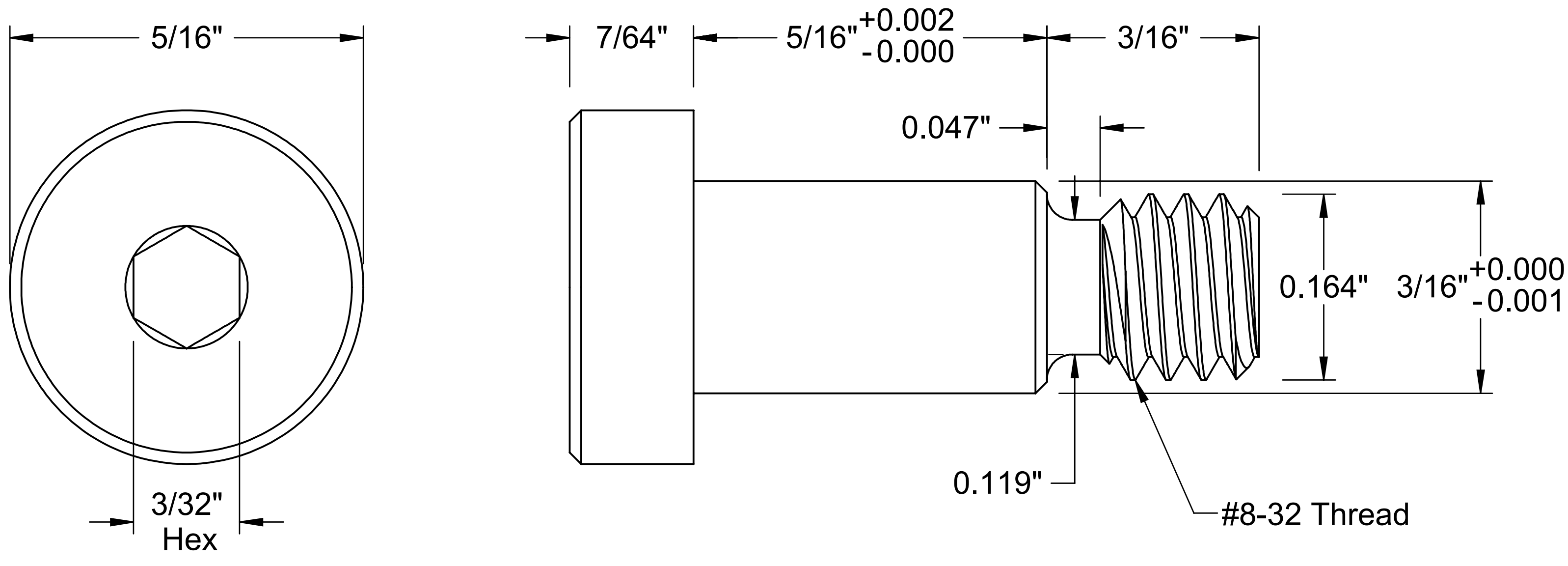
http://www.mcmaster.com

Stainless Steel Ball Bearing

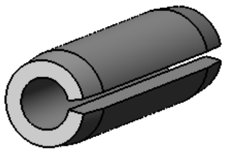


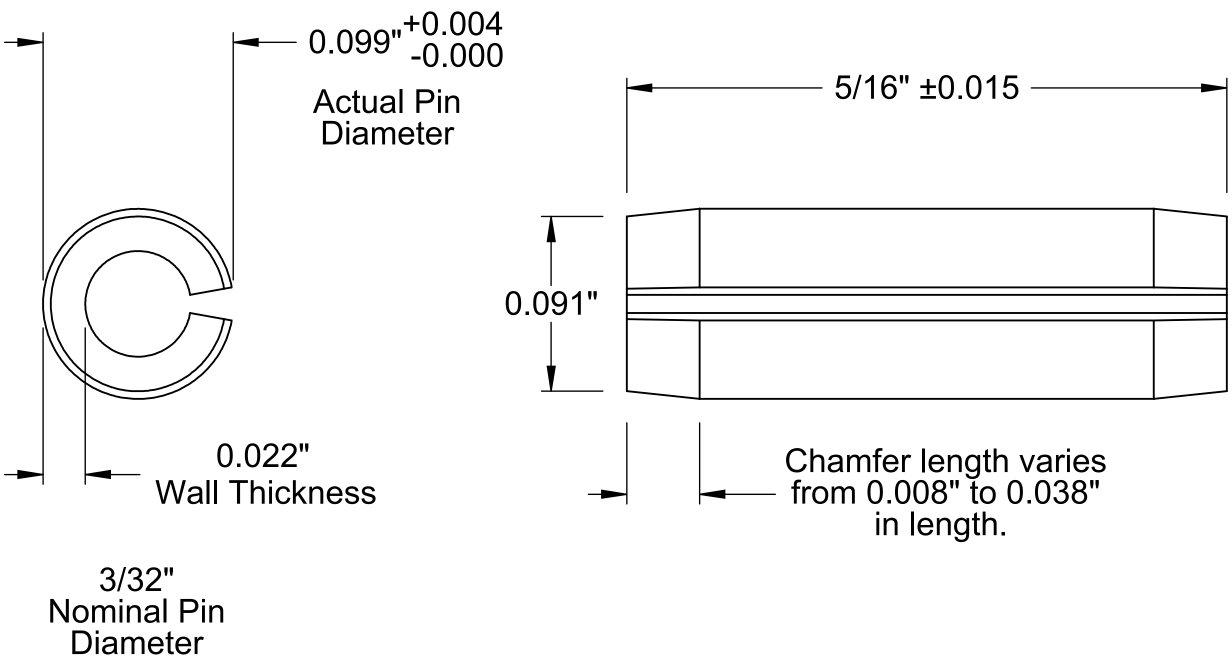
McMASTER-CARR® CAD	PART NUMBER 90265A113
http://www.mcmaster.com © 2018 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric 18-8 Stainless Steel Shoulder Screw





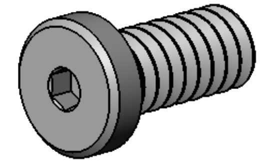
McMASTER-CARR® CAD	PART NUMBER	90337A184	
http://www.mcmaster.com	Low-Profile Precision Shoulder Screw		

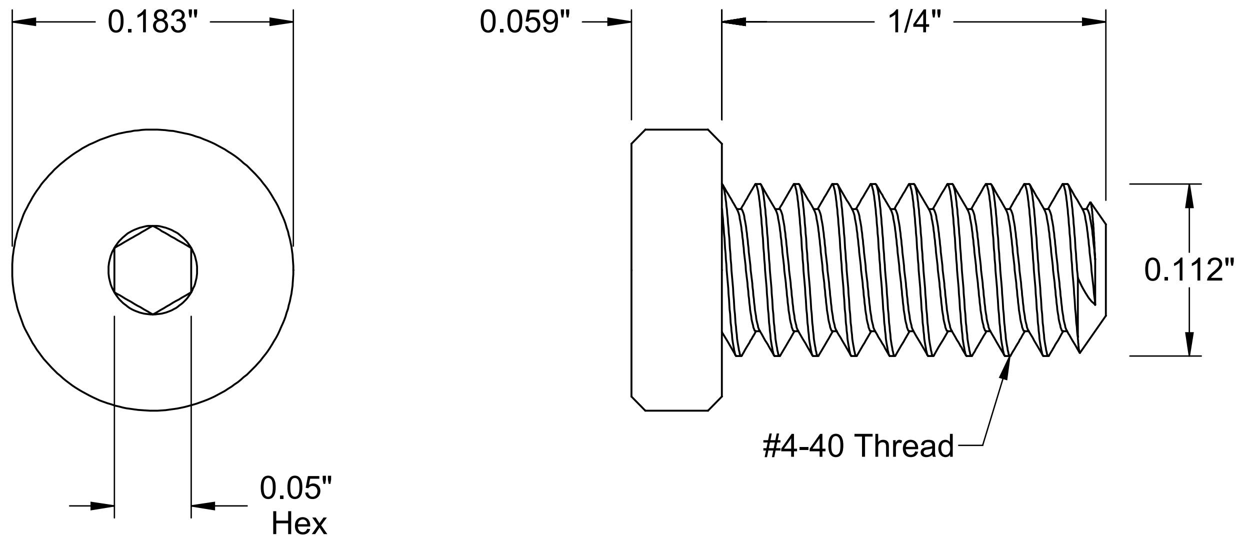




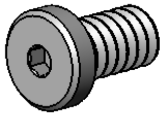
Recommended 0.094" to 0.097" Diameter Hole Size

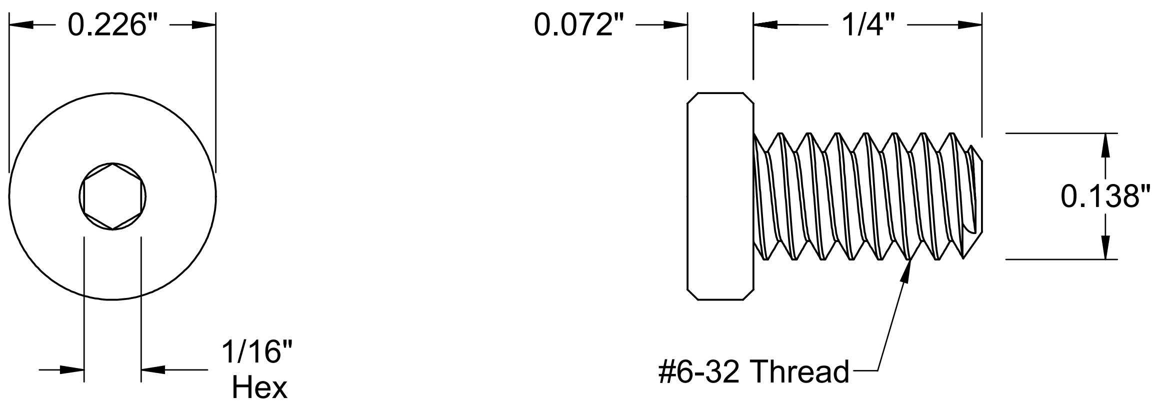
McMASTER-CARR® CAD	PART NUMBER 92373A140
http://www.mcmaster.com © 2011 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	18-8 Stainless Steel Slotted Spring Pin





McMASTER-CARR® CAD	PART NUMBER	93615A110	
http://www.mcmaster.com © 2019 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Low-Profile Stainless Steel Socket Head Cap Screw		



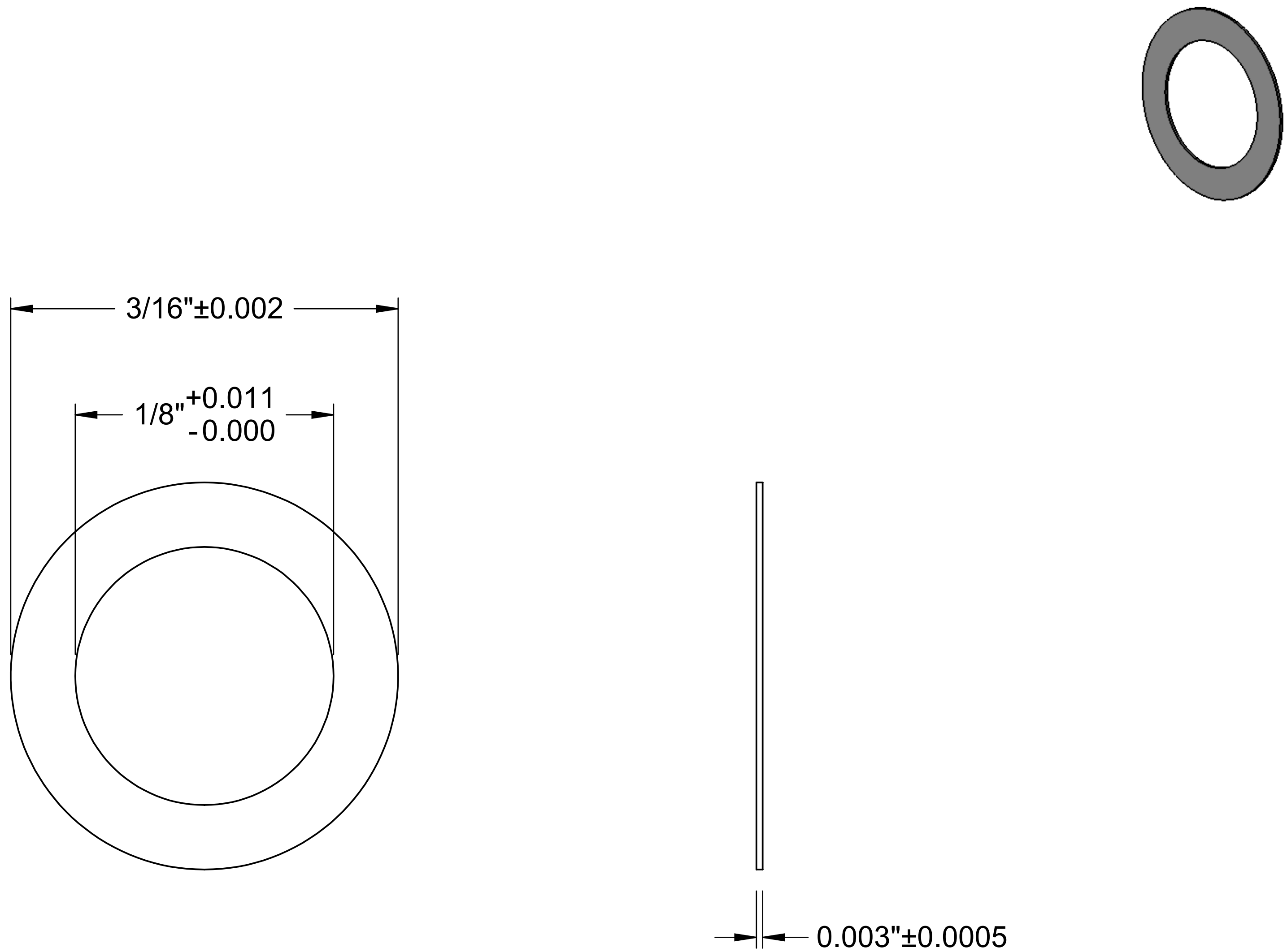


MCMASTER-CARR® CAD

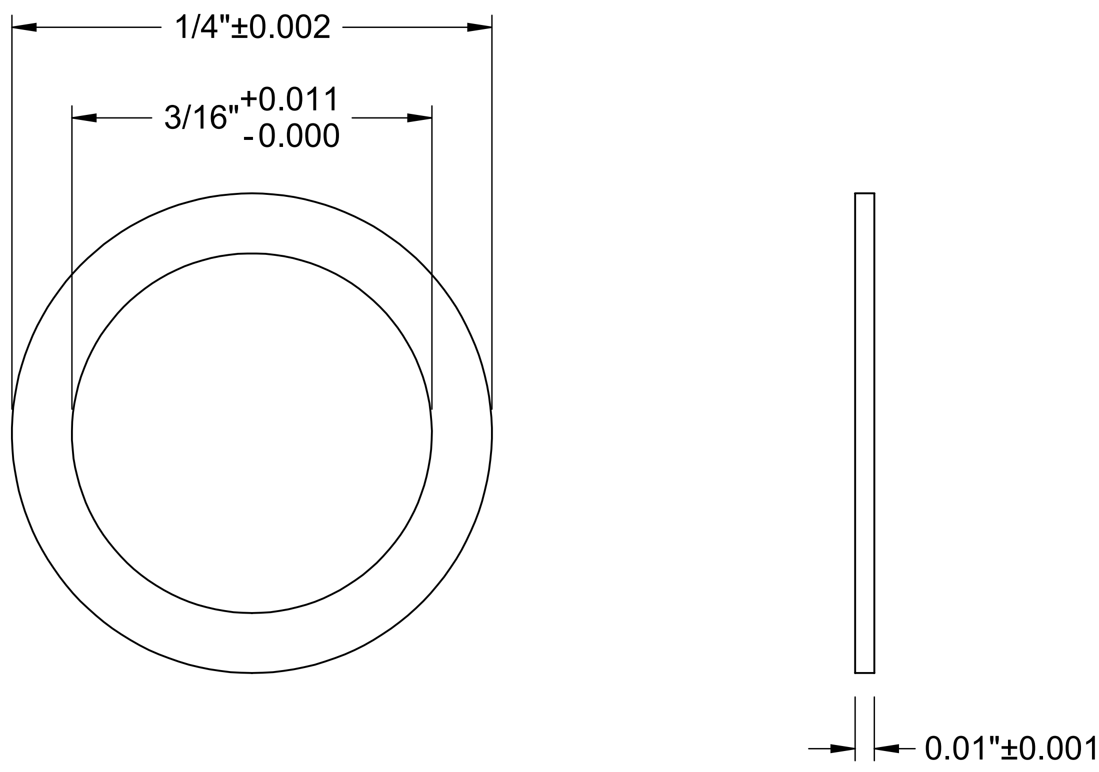
PART NUMBER 93615A210

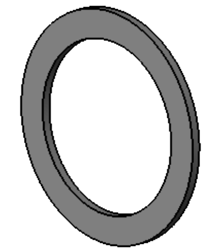
http://www.mcmaster.com

Low-Profile Stainless Steel
Socket Head Cap Screw

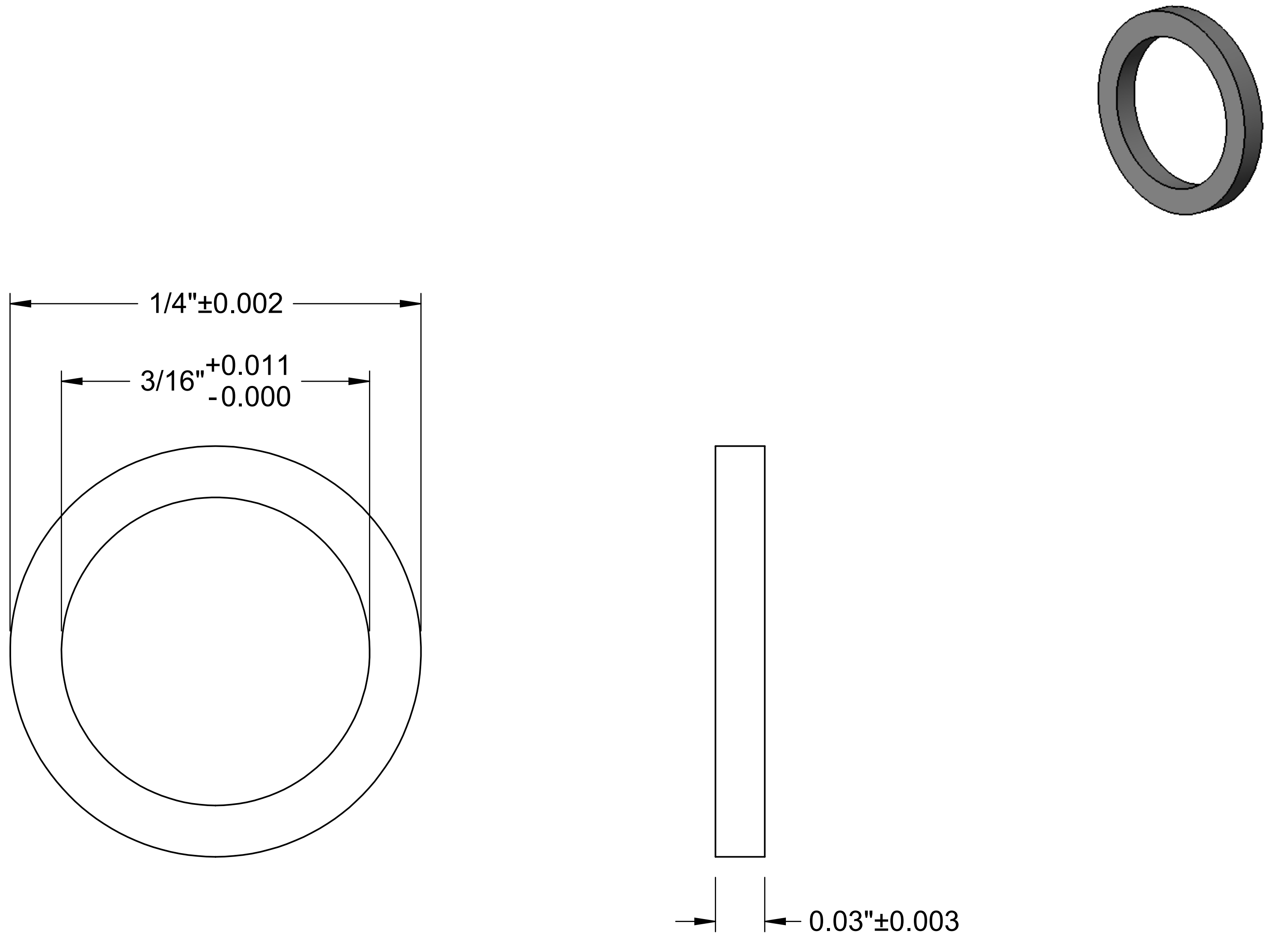


McMASTER-CARR® CAD	PART NUMBER 97022A868
http://www.mcmaster.com © 2017 McMaster-Carr Supply Company	316 Stainless Steel Round Shim
Information in this drawing is provided for reference only.	





MCMASTER-CARR® CAD	PART NUMBER 97022A876
http://www.mcmaster.com © 2017 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	316 Stainless Steel Round Shim



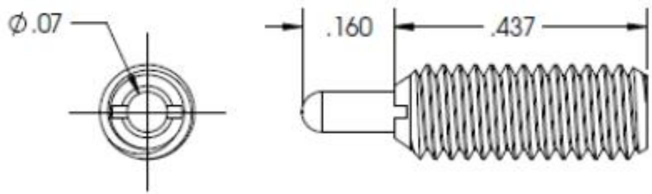
McMASTER-CARR® CAD

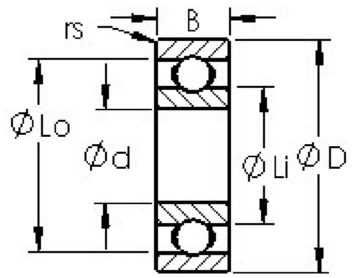
PART NUMBER **97022A887**

http://www.mcmaster.com

316 Stainless Steel
Round Shim

Characteristics	*Value*
Plunger Material	*Stainless Steel*
End Force Initial/Final	*0.14 lbs. / 0.9 lbs.*
Throw Length	*0.16 inches minimum above the standoff surface*
Thread Pitch	*8-36 UNF-2B*





Part Number: SR166 Miniature & Instrument Series, Stainless Steel Ball Bearing

Product Details

Specifications

Bearing Type	Open	
Bore Dia (d)	0.1875	in
Outer Dia (D)	0.3750	in
Width (B)	0.1250	in
Radius (min) (rs)	0.004	in
Dynamic Load Rating (Cr)	136	lbs
Static Load Rating (Cor)	49	lbs
Max Speed (Grease)	50,000	rpm
Max Speed (Oil)	60,000	rpm
Max. Shaft Shoulder Dia. Inner (Li)	0.2	in
Min. Housing Shoulder Dia., Outer (Lo)	0.3	in
Ball Qty	8	
Ball Dia (Dw)	0.0625	in
Weight (g)	0.81	grams
Precision	A1	
Standard Clearance	K25	
Material	Martensitic Stainless Steel	

* Also available in 52100 Chrome Steel

* ABEC Grades 1, 3, 5, 7, and 9 are available.

HEADQUARTERS:
222 New Road
Parsippany, NJ 07045
(800) 526-1250

WEST COAST OFFICE:
3740 Prospect Ave
Yorba Linda, CA 92886
(800) 227-8786

email:
inquiry@astbearings.com

Appendix F: Product Literature

Product Literature

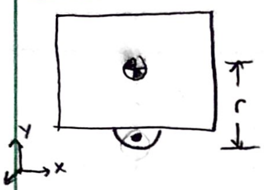
Cal Poly Thruster Gimbal

Description	Manufacturer	Part #	Component	Literature Links
Pull Solenoid	DigiKey	2024-1074-ND	Solenoid	https://www.digikey.com/products/en?keywords=2024-1074-ND
Rod End	McMaster	59935K110	Linkage	https://www.mcmaster.com/59935k11
3/32” Spring Pin	McMaster	92373A140	Solenoid	https://www.mcmaster.com/92373a140
8”X8” Aluminum Plate	McMaster	89015K239	Plates	https://www.mcmaster.com/89015k239
3/16” Shim	McMaster	97022A887	Hinge	https://www.mcmaster.com/97022a887
3/16” Shim	McMaster	97022A876	Hinge	https://www.mcmaster.com/97022a876
1/8” Shim	McMaster	97022A868	Linkage	https://www.mcmaster.com/97022a868
3/8" Bearing	AST Bearings	SR166	Hinge	https://www.astbearings.com/catalog.html?page=product&id=SR166
5/16” Ball Bearing	McMaster	57155k352	Hinge	https://www.mcmaster.com/57155k352
5/16” Bronze Bearing	McMaster	9368T450	Solenoid	https://www.mcmaster.com/9368t45
Spring Plunger	CubeSat	N/A	Hinge	https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/56e9b62337013b6c063a655a/1458157095454/cds_rev13_final2.pdf
3/16” Shoulder Screw	McMaster	90337A184	Hinge	https://www.mcmaster.com/90337a184
3mm Shoulder Screw	McMaster	90265A113	Linkage	https://www.mcmaster.com/90265a113
Socket Head Screw 6-32	McMaster	93615A210	Various	https://www.mcmaster.com/93615a210
Socket Head Screw 4-40	McMaster	93615A110	Various	https://www.mcmaster.com/93615a110

Appendix G: Design Analysis Calculations

J. NEIMAN

FIND TORQUE REQUIRED TO MOVE THRUSTER

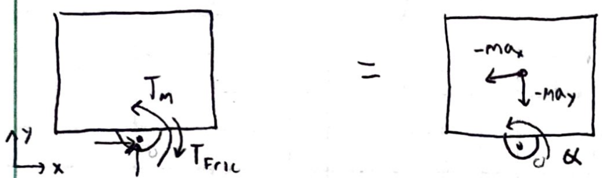


$r = 70\,mm$

$I_{zz} = 21455\ kg\ mm^2$

$m = 5\ kg$

FBD



ASSUME

$t = 3\ s$

$\theta = 10° \rightarrow \pi/18$

CONSTANT α

NEGLECT FRICTION

ANALYSIS

$$\Sigma M_o = \bar{I}\alpha$$

$$T_m = \bar{I}\alpha + (\alpha r) m r$$

$$T_m = \alpha(\bar{I} + mr^2)$$

FOR CONSTANT α,

$$\theta = \cancel{\omega_0 t}^{\,0} + \tfrac{1}{2}\alpha t^2$$

$$\alpha = \frac{2\theta}{t^2}$$

$$T_m = \frac{2\theta}{t^2}\left(\bar{I} + mr^2\right)$$

$$T_m = \frac{2\pi}{18(3\,s)^2}\left(21455\ kg\ mm^2 + 5\,kg(70\,mm)^2\right)$$

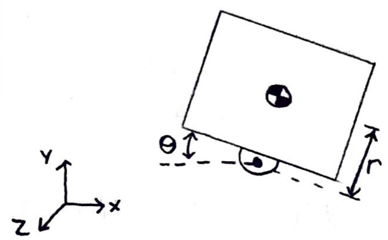
$$T_m = 1782\left(\frac{kg\ \cancel{mm^2}}{s^2}\right)\left(\frac{1\,m^2}{1000^2\,\cancel{mm^2}}\right)$$

$$\boxed{T_m = 0.00178\,N\cdot m}$$

1G ACTUATION

MILENA MILICH

FIND: TORQUE REQUIRED TO MOVE THRUSTER IN 1G



KNOW:

$r = 70\ mm$

$I_{zz} = 21455\ kg\,mm^2$

$m = 5\ kg$

$\theta_0 = -3° = -\frac{\pi}{60}$

$\theta_f = 3° = \frac{\pi}{60}$

ASSUME:

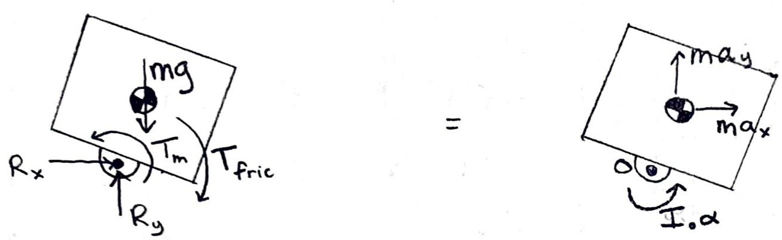
$t = 3s$

α IS CONSTANT

FRICTION IS NEGLIGIBLE

BEGINS AT REST

FBD:



ANALYSIS:

$$\Sigma M_o = I_o\alpha$$

$$T_m = \cancel{T_{fric}}^{\,0} + mg(r\sin\theta) + \alpha(I + mr^2)$$

FOR CONSTANT α:

$$\theta_f = \theta_0 + \cancel{\omega_0 t}^{\,0} + \tfrac{1}{2}\alpha t^2$$

$$\alpha = \frac{2(\theta_f - \theta_0)}{t^2}$$

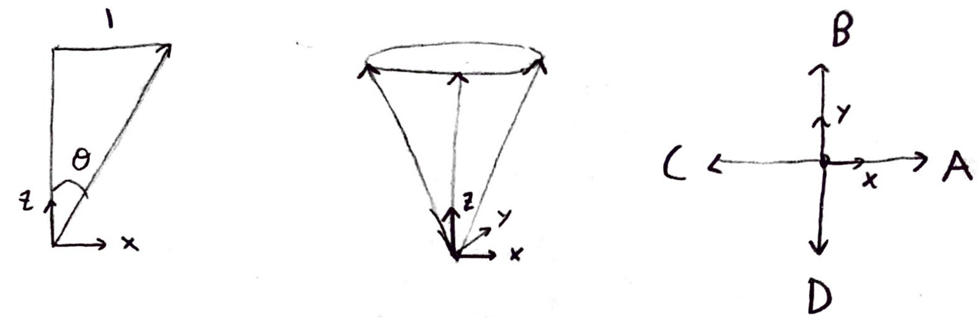
$$T_m = mgr\sin\theta + \frac{2(\theta_f - \theta_0)}{t^2}(I + mr^2)$$

$$T_m = (5kg)(9.81\ m/s^2)(0.07m)\sin\left(\frac{\pi}{60}\right) + \frac{2\left(\frac{\pi}{30}\right)}{(3s)^2}\left(0.021455\ kgm^2 + \ldots\right.$$

$$\left.(5kg)(0.07m)^2\right)$$

$$\boxed{T_m = 0.1808\ N{\cdot}m}$$

ANGLE



"BASE" VECTORS

$$A = \langle 1,\ 0,\ \frac{1}{\tan(\theta)} \rangle$$

$$\hat{A} = \frac{\langle 1,\ 0,\ \frac{1}{\tan(\theta)} \rangle}{\|A\|}$$

$\hat{a} = \langle .0617 \quad 0 \quad .9981 \rangle$ A

$\hat{b} = \langle 0 \quad .0617 \quad .9981 \rangle$ B

$\hat{c} = \langle -0.0617 \quad 0 \quad .9981 \rangle$ C

$\hat{d} = \langle 0 \quad 0.617 \quad .9981 \rangle$ D

LINEAR COMBINATION OF BASE VECTORS EQUALS ARBITRAY VECTOR $\langle x, y, z \rangle$

$$A\hat{a} + B\hat{b} + C\hat{c} + D\hat{d} = \vec{X}$$

$\hat{\imath}$: $x = A(.0617) - (0.0617)C$

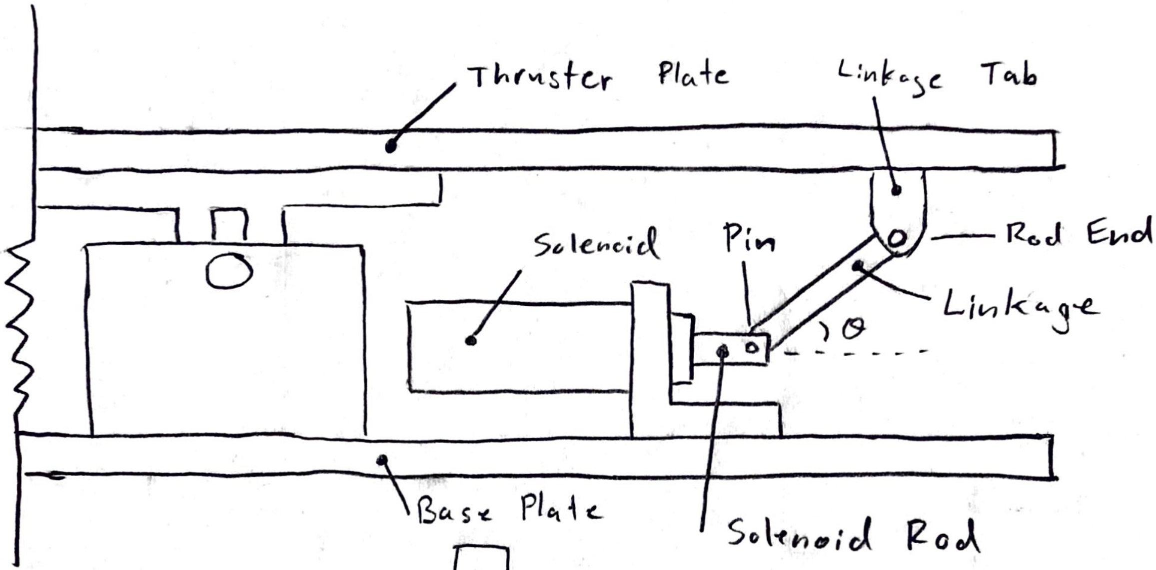
$y = B(.0617) - D(.0617)$

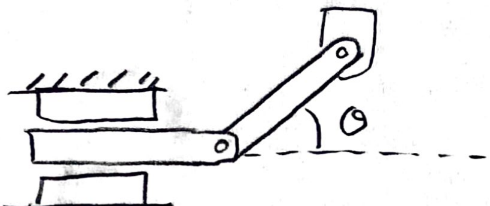
$z = .9981(A + B + C + D)$

SYSTEM UNKNOWN SO ADDITIONAL CONSTRAINT IS ADDED; D = 0 (DON'T MOVE TO POSITION d)

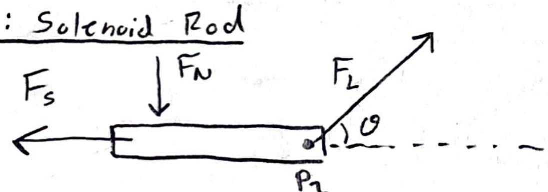
$$\begin{bmatrix} .0617 & 0 & -.0617 & 0 \\ 0 & .0617 & 0 & .0617 \\ .9981 & .9981 & .9981 & .9981 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ 0 \end{bmatrix}$$

SOLVED IN MATLAB





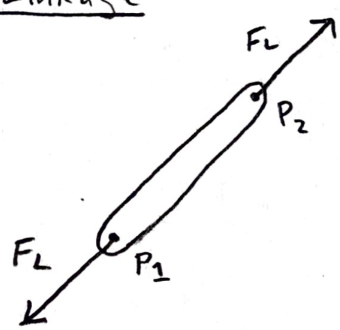
FBD: Solenoid Rod



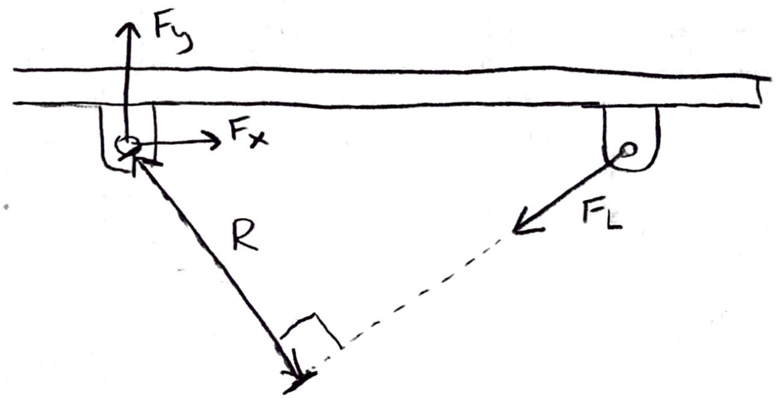
$$\Sigma F_x = 0$$

$$F_L \cos\theta = F_s \implies F_L \leq \frac{F_s}{\cos\theta}$$

FBD: Linkage



FBD: Thruster Plate and Linkage Tab



Contents


```
%Vectors 2/18
clear all
close all
```

Constants

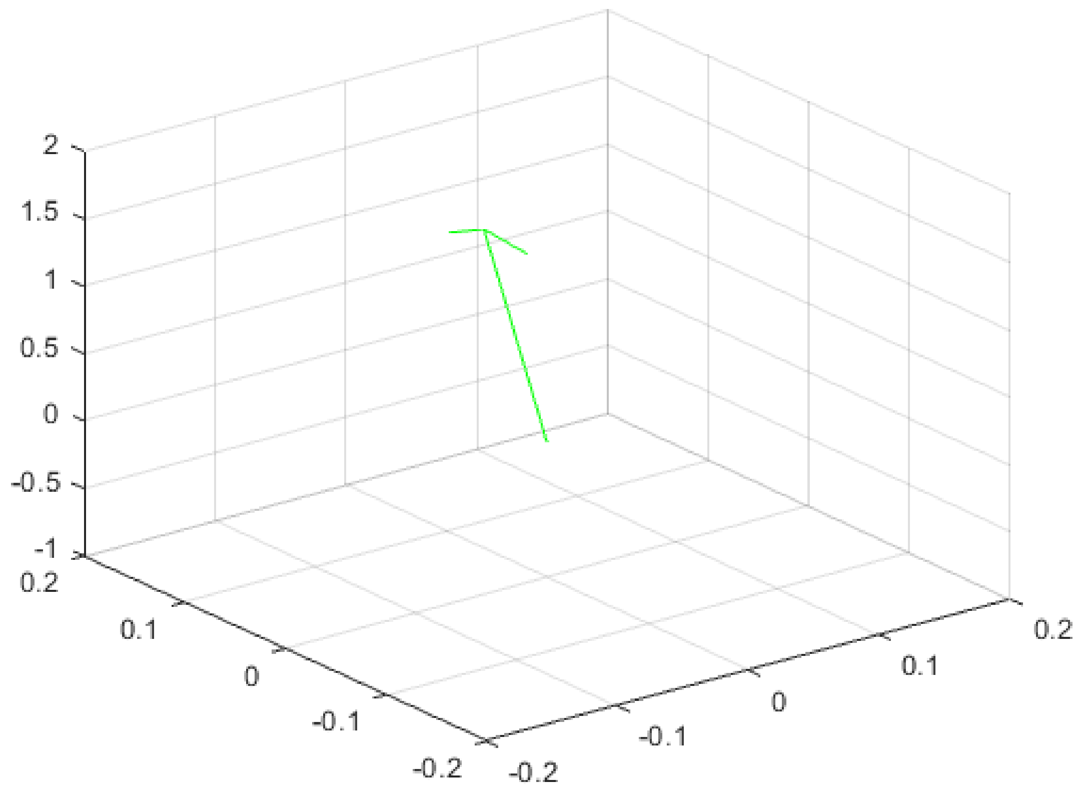
```
thetaCone = 2.5; %"fixed" gimbal angle (degrees)
theta = thetaCone*sqrt(2); %angle of each corner
time = 30; %minutes
```

Input vector

input a desired vector

```
alpha = 195; %Horizontal Angle from 0 deg around the circle (at A)
theta1 = 2; %Angle from vertical
M = 2; % magnitude

%build input vector in x,y,z from entry
x1 = M*sind(theta1)*cosd(alpha);
y1 = M*sind(theta1)*sind(alpha);
z1 = M*cosd(theta1);
X = [x1 y1 z1];
quiver3(0,0,0,X(1),X(2),X(3),'g'); %plot input vector in green
hold on
axis([-.2,.2,-.2,.2,-1,2]);
```



Determine time required in each postition

```
%base unit vectors (the four corner vectors)
a1 = [1,0,1/tand(theta)];
a = a1/rssq(a1);
b1 = [0,1,1/tand(theta)];
b = b1/rssq(b1);
c1 = [-1,0,1/tand(theta)];
c = c1/rssq(c1);
d1 = [0,-1,1/tand(theta)];
d = d1/rssq(d1);


if alpha <= 180 %if y is positive
    E = [[a 0]',[b 0]',[c 0]',[d 1]']; %Base matrix with D = 0
    E1 = inv(E); %invert
    Co = E1*[X 0]'; %solve for coefficents
elseif alpha > 180 %if y is positive
    E = [[a(1);0;a(3);a(2)],[0;1;0;0],[c(1);0;c(3);c(2)],...
        [d(1);0;d(3);d(2)]]; %Base matrix with B = 0
    E2 = inv(E);
    Co = E2*[X(1);0;X(3);X(2)];%solve for coefficents
end

%calculate required time
Coefficents = Co';
Percent = Coefficents/sum(Coefficents);
Times = Percent*time;
fprintf('\n\n\nThe time is each position [min] is: \n')
```

```
disp(Times)
```

```
The time is each position [min] is:
    4.6167         0   20.9948    4.3885
```

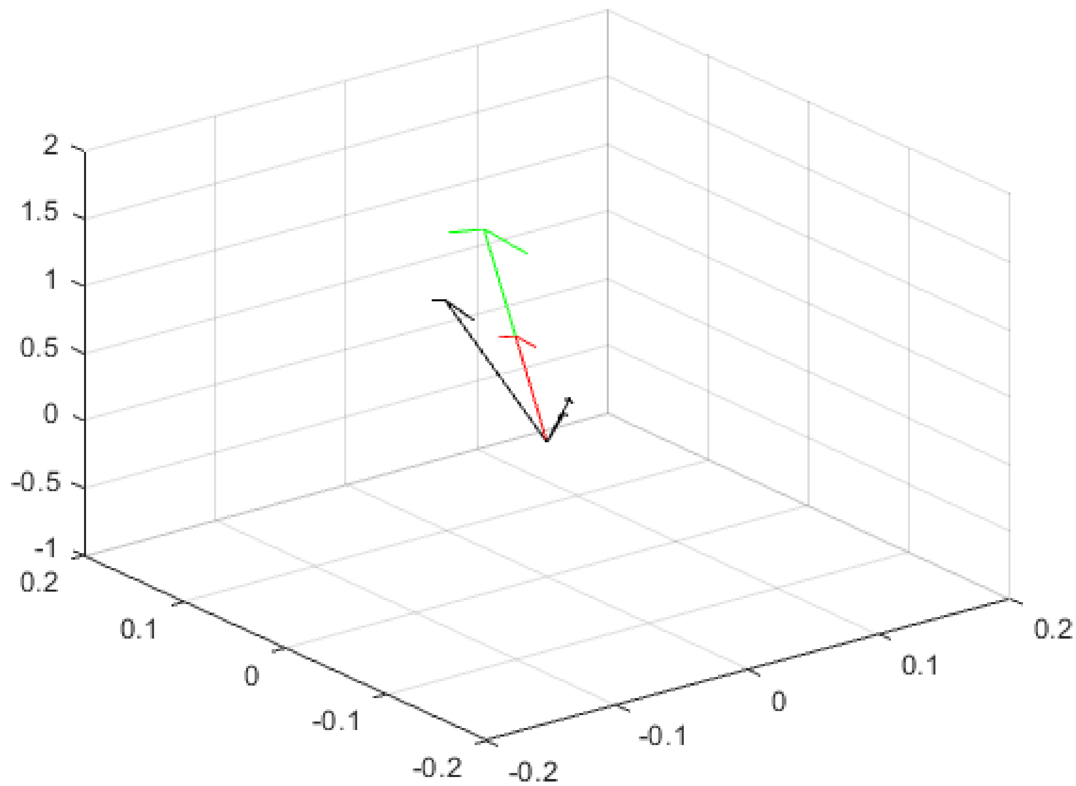
Generate thrust vector and plot net thrust

```
%generate vectors scaled by coefficents
A = Co(1)*a;
B = Co(2)*b;
C = Co(3)*c;
D = Co(4)*d;

%plot three thrust vectors
quiver3(0,0,0,A(1),A(2),A(3),'k');
quiver3(0,0,0,B(1),B(2),B(3),'k');
quiver3(0,0,0,C(1),C(2),C(3),'k');
quiver3(0,0,0,D(1),D(2),D(3),'k');

%combine vectors to get net thrust
Vx = A(1)+B(1)+C(1)+D(1);
Vy = A(2)+B(2)+C(2)+D(2);
Vz = A(3)+B(3)+C(3)+D(3);
V1 = [Vx Vy Vz];
V = [Vx Vy Vz]/rssq(V1);

quiver3(0,0,0,V(1),V(2),V(3),'r');
```



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Appendix H: Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: Thrust or Bust   Advisor: Schuster   Date: 05/30/2018

Y	N	
☐	×	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	×	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
☐	×	3. Will any part of the design undergo high accelerations/decelerations?
☐	×	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
☐	×	5. Could the system produce a projectile?
☐	×	6. Could the system fall (due to gravity), creating injury?
☐	×	7. Will a user be exposed to overhanging weights as part of the design?
×	☐	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	×	9. Will any part of the electrical systems not be grounded?
☐	×	10. Will there be any large batteries (over 30 V)?
☐	×	11. Will there be any exposed electrical connections in the system (over 40 V)?
☐	×	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☐	×	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	×	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☐	×	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
☐	×	16. Could the system generate high levels (>90 dBA) of noise?
×	☐	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
☐	×	18. Is it possible for the system to be used in an unsafe manner?
☐	×	19. For powered systems, is there an emergency stop button?
☐	×	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

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

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
May have sharp edges or pinch points.	Break edges and inform operator of potential pinch points, if any exist for the chosen design.	5/15/19	5/9/19
The mechanism will be operated in space.	No corrective action is required because the mechanism will only be exposed to extreme environments once in space.	N/A	
There is no “Emergency Stop” button.	No corrective action is required because the voltage and current will be very low, and the power supply will have a button to suppress output.	N/A	

Appendix I: Failure Modes and Effects Analysis

Design Failure Mode and Effects Analysis

Product: THRUSTER GIMBAL

Prepared by: MILENA MILICH
Date: 03/07/2019

Team: THRUST OR BUST

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Severity	Action Results: Occurence	Action Results: Criticality
Thruster plate/ hold thruster secure	thruster becomes loose	a) lose accuracy b) lose thruster	8	1) bolt failure 2) vibe backout	1) load and bolt analysis (pretorque, etc) 2) staking	2	Visual detection	4	64	1) Position sensor on the thruster 2) Satellite position feedback	1) J. Tran (5/9/19) 2) N/A	Holes added to thruster plate for mounting IMU			
Base plate/ secure mechanism to satellite	thruster and mechanism become loose	a) lose accuracy b) lose thruster	9	1) bolt failure 2) vibe backout	1) load and bolt analysis (pretorque, etc) 2) staking	2	None	4	72	1) Position sensor on the thruster 2) Satellite position feedback	1) J. Tran (5/9/19) 2) N/A	Holes added to thruster plate for mounting IMU			
Base plate/ hold cables	cable wear	a) lose power to the thruster or solenoids	7	1) cable sliding against edge of one of the plates	1) cable management 2) chamfer or break edges	4	Visual inspection	2	56	None					
Hinge top/ rotate about shaft	Joint locks	a) thruster motion limited to one plane	6	1) Uneven thermal expansion	1) use bearings	3	Visual inspection	2	36	None					
Hinge top/ hold thruster plate secure	thruster becomes loose	a) lose accuracy b) lose thruster	8	1) bolt failure 2) vibe backout	1) load and bolt analysis (pretorque, etc) 2) staking	2	Visual inspection	4	64	None					
Hinge shaft/ rotate in hinge	Joint locks	a) thruster motion limited to one plane	6	1) Uneven thermal expansion	1) use bearings	3	Visual inspection	2	36	None					
Solenoid bracket/hold solenoid	Solenoid no longer held in position	a) Lose positioing ability in half the cone	5	1) bracket deforms under high moment 2) bracket breaks under moment at extreme temperatures	1) limit solenoid force	1	Visual inspection	2	10	None					
Solenoid/pull on linkage	Lose power	a) lose thruster positioning in half of the cone	5	1) cable wear 2) out of temperature range	1) cable management	5	Visual inspection	2	50	None					
	Solenoid pin becomes stuck to solenoid	a) thruster becomes stuck at one angle	7	1) Large radial force at extreme temperatures	1) add bearing to take some of the load	4	Visual inspection	2	56	None					
Spring pin/ hold link to solenoid (allowing rotation)	Joint locks	a) Thruster becomes stuck at one angle	7	1) Uneven thermal expansion	1) None	4	Visual inspection	2	56	None					
	Pin breaks	a) Thruster becomes stuck at one angle	7	1) Large actuation forces	1) limit solenoid force	4	Visual inspection	2	56	None					
Rod end/ allow rotation	Joint locks	a) Thruster becomes stuck at one angle	7	1) Uneven thermal expansion	1) None	4	Visual inspection	2	56	None					
Linkage bracket/ hold rod end to thruster plate	Joint locks	a) Thruster becomes stuck at one angle	7	1) Uneven thermal expansion	1) None	4	Visual inspection	2	56	None					
	Linkage detatches from thruster plate	a) Lose positioing ability in half the cone	5	1) bolt failure 2) vibe backout	1) load and bolt analysis (pretorque, etc) 2) staking	2	Visual inspection	4	40	None					
Spring plungers/ return thruster to center	Lose of restoring force	a) Loss of passive return to center	5	1) loss of stiffness 2) vibe backout	1) use parts with aerospace heritage 2) Loctite	3	Testing	6	90	1) Position sensor on the thruster 2) Satellite position feedback	1) J. Tran (5/9/19) 2) N/A	Holes added to thruster plate for mounting IMU			

Appendix J: Risk Assessment

designsafe Report

Application:	Preliminary Risk Assesment	Analyst Name(s):	Thrust or Bust
Description:		Company:	Cal Poly San Luis Obispo
Product Identifier:	Thruster Gimbal Mechanism	Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			
Risk Scoring System:	ANSI AIHA Z10 2005		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity LIkelihood of Oc	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity LIkelihood of Oc	Risk Level	Status / Responsible /Comments /Reference
1-1-1	operator(s) normal operation	pinch points : between thruster plate and gimbal misuse (placing hands near mechanism during operation)	Negligible Occasional	Low		Negligible Occasional	Low	/Standard preocedures for testing and operation will be created by the team once the prototype is manufactured (TYP)
1-1-2	operator(s) normal operation	electrical / electronic : normally live parts(direct contact) loose wires	Marginal Occasional	Medium	standard procedures	Marginal Improbable	Low	In-process Team
1-1-3	operator(s) normal operation	electrical / electronic : software errors unexpected actuation	Negligible Remote	Low		Negligible Remote	Low	
1-1-4	operator(s) normal operation	heat / temperature : burns / scalds extended use of solenoids	Marginal Occasional	Medium	warning label(s)	Marginal Remote	Medium	Action Item [5/23/2019] Milena
1-2-1	operator(s) clear jams	mechanical : unexpected motion device not powered off	Negligible Remote	Low		Negligible Remote	Low	
1-2-2	operator(s) clear jams	pinch points : between thruster plate and gimbal device not powered off	Negligible Remote	Low		Negligible Remote	Low	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity LIkelihood of Oc	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity LIkelihood of Oc	Risk Level	Status / Responsible /Comments /Reference
2-1-1	technician(s) trouble-shooting / problem solving	pinch points : between thruster plate and gimbal not moving hands away during operation	Negligible Occasional	Low		Negligible Occasional	Low	
2-1-2	technician(s) trouble-shooting / problem solving	electrical / electronic : normally live parts(direct contact) loose wires	Marginal Occasional	Medium	standard procedures	Marginal Improbable	Low	In-process Team
2-1-3	technician(s) trouble-shooting / problem solving	heat / temperature : hot surfaces extended use of solenoids	Marginal Occasional	Medium	warning label(s)	Marginal Remote	Medium	Action Item [5/23/2019] Milena
2-2-1	technician(s) adjust controls / switches	mechanical : unexpected motion software or wiring errors	Negligible Probable	Medium	standard procedures	Negligible Remote	Low	In-process Team
3-1-1	engineer(s) adjust controls	mechanical : unexpected motion device not powered off	Negligible Occasional	Low		Negligible Occasional	Low	
3-1-2	engineer(s) adjust controls	pinch points : between thruster plate and gimbal misuse (placing hands near mechanism during operation)	Negligible Occasional	Low		Negligible Occasional	Low	
3-1-3	engineer(s) adjust controls	electrical / electronic : normally live parts(direct contact) loose wires	Marginal Occasional	Medium	standard procedures	Marginal Improbable	Low	In-process Team
3-1-4	engineer(s) adjust controls	heat / temperature : burns / scalds contact with solenoids before they are allowed to cool	Marginal Occasional	Medium	warning label(s)	Marginal Remote	Medium	Action Item [5/23/2019] Milena
4-1-1	passer-by / non-user walk near robot	pinch points : between thruster plate and gimbal misuse (placing hands near mechanism during operation)	Negligible Occasional	Low		Negligible Occasional	Low	

Appendix K: Project Budget

Description	Vendor	Vendor Part #	Where Used (PN)	How Purch'd	When Purch'd	Rec'd	Cost	Quantity	Total
6-32 Screws	McMaster	92220A141	Prototype	Reimbursed	1/20	Received	8.57	1	8.57
4-40 Screws	McMaster	92220A121	Prototype	Reimbursed	1/20	Received	5.65	2	11.30
Sleeve Bearings	McMaster	2639T3	Prototype	Reimbursed	1/20	Received	4.31	4	17.24
3/16" Shoulder Screw	McMaster	90337A184	Prototype	Reimbursed	1/20	Received	7.74	1	7.74
Acrylic	McMaster	8589K41	Prototype	Reimbursed	1/20	Received	6.05	7	42.35
Tax and Shipping	-	-	-	-	-	-	-	-	22.51
Push Solenoids	DigiKey	2024-1072-ND	Prototype	Reimbursed	1/21	Received	27.60	2	55.20
Tax and Shipping	-	-	-	-	-	-	-	-	12.13
Ball Bearing	McMaster	57155K352	Prototype	Reimbursed	2/21	Received	6.32	3	18.96
Slotted Spring Plunger	McMaster	3126A2	Prototype	Reimbursed	2/21	Received	4.04	4	16.16
Clear Acrylic	McMaster	8589K41	Prototype	Reimbursed	2/21	Received	6.05	2	12.10
Tax and Shipping	-	-	-	-	-	-	-	-	12.01
LEDEX Push Solenoid	Testco	195205-230	Prototype	Reimbursed	2/21	Received	20.34	1	20.34
Spring Kit	Testco	153913-001	Prototype	Reimbursed	2/21	Received	15.00	1	15.00
Tax and Shipping	-	-	-	-	-	-	-	-	2.74
Rod End	McMaster	59935K110	200	By Sponsor	3/18	Received	7.50	5	37.50
3/32” Spring Pin	McMaster	92373A140	200	By Sponsor	3/18	Received	3.19	1 Pack	3.19
12”X12” Aluminum Plate	McMaster	89015K18	100 & 200	By Sponsor	3/18	Received	27.71	2	55.42
1/8” Shim	McMaster	97022A868	200	By Sponsor	3/18	Received	8.42	2 Packs	16.84
3/16" Shim	McMaster	97022A876	300	By Sponsor	3/18	Received	7.15	2 Packs	14.30
3/16" Shim	McMaster	97022A887	300	By Sponsor	3/18	Received	10.04	1 Pack	10.04
Ball Bearing	McMaster	57155K352	300	By Sponsor	3/18	Received	6.32	1	6.32
Ball Bearing	McMaster	57155K353	300	By Sponsor	3/18	Received	5.55	4	22.20
Bronze Sleeve Bearing	McMaster	9368T450	400	By Sponsor	3/18	Received	0.59	6	3.54
3mm Shoulder Screw	McMaster	90265A113	400	By Sponsor	3/18	Received	2.62	6	15.72
4-40 Socket Head Screw	McMaster	92220A121	200	By Sponsor	3/18	Received	5.65	3 Packs	16.95
6-32 Socket Head Screw	McMaster	92220A141	1000	By Sponsor	3/18	Received	8.57	2 Packs	17.14
6061 Aluminum	McMaster	8974K21	400	By Sponsor	3/18	Received	1.41	1	1.41
Tax and Shipping	-	-	-	-	-	-	-	-	25.59
Pull Solenoid	DigiKey	2024-1074-ND	400	By Sponsor	3/18	Received	26.50	4	106.00
Transistor	Digikey	IRL540NPBF-ND	1000	By Sponsor	3/18	Received	1.59	6	9.54
Tax and Shipping	-	-	-	-	-	-	-	-	17.94
8-36 Spring Plunger	CubeSat	N/A (custom)	300	Reimbursed	4/19	Received	11.00	4	44.00
Rod End	McMaster	59935K110	200	By Sponsor	4/19	Received	7.50	3	22.50
1/8” Shim	McMaster	97022A868	200	By Sponsor	4/19	Received	8.42	1 Pack	8.42
3/16" Shim	McMaster	97022A876	300	By Sponsor	4/19	Received	7.15	1 Pack	7.15
3/16" Shim	McMaster	97022A887	300	By Sponsor	4/19	Received	10.04	1 Pack	10.04
Ball Bearing	McMaster	57155K352	300	By Sponsor	4/19	Received	6.32	2	12.64
Ball Bearing	McMaster	57155K353	300	By Sponsor	4/19	Received	5.55	2	11.10
Bronze Bearing	McMaster	9368T450	400	By Sponsor	4/19	Received	0.59	2	1.18
3mm Shoulder Screw	McMaster	90265A113	400	By Sponsor	4/19	Received	2.62	5	13.10
4-40 Socket Head Screw	McMaster	92220A121	200	By Sponsor	4/19	Received	5.65	1 Pack	5.65
6-32 Socket Head Screw	McMaster	92220A141	1000	By Sponsor	4/19	Received	8.57	1 Pack	8.57
Washer	McMaster	90945A710	400	By Sponsor	4/19	Received	14.39	1 Pack	14.39
Washer	McMaster	90945A715	400	By Sponsor	4/19	Received	4.72	1 Pack	4.72
4-40 Socket Head Screw	McMaster	92220A313	1000	By Sponsor	4/19	Received	9.38	2 Packs	18.76
Tax and Shipping	-	-	-	-	-	-	-	-	24.59
Pull Solenoid	Digikey	2024-1074-ND	400	By Sponsor	4/19	Received	26.50	2	53.00
Transistor	Digikey	IRL540NPBF-ND	1000	By Sponsor	4/19	Received	1.59	4	6.36
Tax and Shipping	-	-	-	-	-	-	-	-	4.60
Rod End Bracket	Protolabs	N/A (custom)	200	By Sponsor	4/19	Received	101.55	4	406.20
Base	Protolabs	N/A (custom)	300	By Sponsor	4/19	Received	334.48	1	334.48
Shaft	Protolabs	N/A (custom)	300	By Sponsor	4/19	Received	139.79	1	139.79
Bearing Holder	Protolabs	N/A (custom)	300	By Sponsor	4/19	Received	112.11	2	224.22
Hinge Top	Protolabs	N/A (custom)	300	By Sponsor	4/19	Received	168.56	1	168.56
Solenoid Bracket	Protolabs	N/A (custom)	400	By Sponsor	4/19	Received	95.69	4	382.76
Link	Protolabs	N/A (custom)	400	By Sponsor	4/19	Received	68.59	4	274.36
Tax and Shipping	-	-	-	-	-	-	-	-	164.08
Acrylic	McMaster	8505K741	500	Reimbursed	5/1	Received	7.14	7	49.98
Tax and Shipping	-	-	-	-	-	-	-	-	12.51
Spring Plunger 0.5-1.5 lb	McMaster	3126A81	300	Reimbursed	5/1	Received	3.97	4	15.88
Spring Plunger 1.5-4.8 lb	McMaster	3126A82	300	Reimbursed	5/1	Received	3.97	4	15.88
Tax and Shipping	-	-	-	-	-	-	-	-	12.47
8inx8in Styrofoam Cube	Beverly's	-	500	Reimbursed	5/3	Received	14.63	1	14.63
								Total:	**3140.56**

Appendix L: Design Verification Plan & Report

Senior Project DVP&R

Date: 05/30/2019	Team: Cal Poly Satelite Positioning Systems	Sponsor: Astranis Space Technologies Corp.	Description of System: Gimbal system for pointing an ion thruster	DVP&R Engineer: Joshua Tran

TEST PLAN										TEST REPORT			
Item No.	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Vector Precison by Laser Pointer	Use a laser pointer to determine the repeatability of a given angle	±0.5°	Milena M.	FP	1	Sys	5/11/2019	5/13/2019	±0.004°	1	0	
2	Vector Precision by IMU	Use IMU to determine the angle created by each position	±0.5°	Junior R.	FP	1	Sys	5/8/2019	5/11/2019	N/A	N/A	N/A	IMU produced too much noise to be useful
3	Vector Accuracy by Mechanical Measurement	Use calipers to measure the change in plate corner height during actuation	2.5° minimum	Josh T.	FP	1	Sys	5/13/2019	5/15/2019	2.445°	0	1	2% below desired angle
4	1g Actuation Test	Attach the mock thruster and weight it such that it is 5kg. Actuate the gimbal to ensure that it is still functional. Increase weight until failure	Actuation in 1g with 5kg of mass minimum	Josh T.	FP	1	Sys	5/13/2019	5/15/2019	Pass	1	0	
5	Torque Test	Fix the thruster plate to a horizontal position. Add weights to the opposite side until the gimbal fails to actuate	0.2 Nm torque minimum	Josh N.	FP	1	Sys	5/13/2019	5/15/2019	0.25Nm	1	0	Solenoids required minor tuning before testing

Appendix M: Operator’s Manual

Operators' Manual – Thrust or Bust

Introduction

The document outlines the set-up procedure to run the default test program on the Satellite Thruster Gimbal. It also includes instructions to modify the control system on the Arduino and troubleshooting tips. This manual assumes the gimbal is fully assembled; for assembly instructions see technical drawings.

Component Diagram and Required Equipment

The following equipment is required to run the demonstration test procedure:

- Gimbal Prototype
- Electronics Box
- Flat table or surface
- DC Power Supply (24V,>1A)
- 5V USB power source (wall adapter or computer)
- 2 Banana to Alligator Power Cables

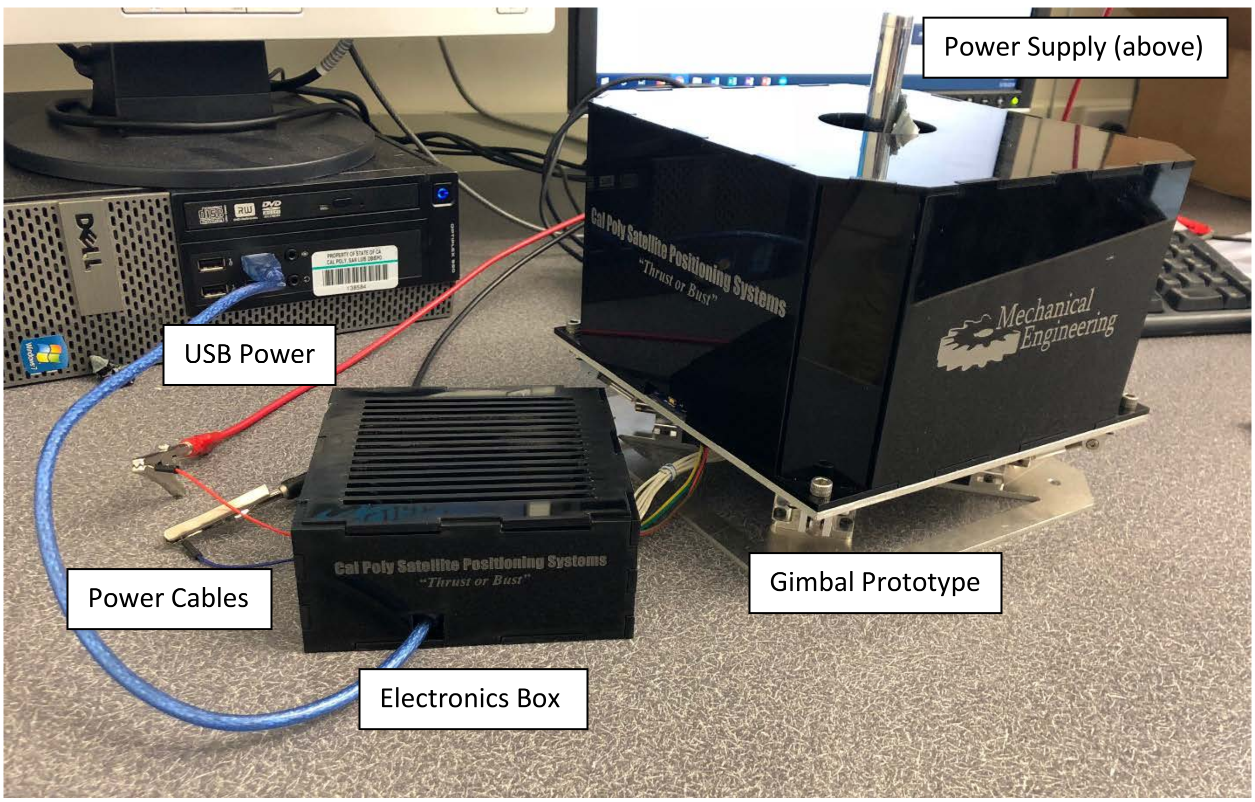


Figure 1. System Diagram

Test Cycle Instructions

The following instruction describe how to run the default demonstration mode. Once it is correctly set-up, it will run continuously without input from the user.

Step 1: Place gimbal baseplate on flat level surface. Secure the gimbal to the surface with bolts or a clamp.

Step 2: Attach banana cables to power supply with alligator clips on the opposite ends. Ensure the alligator clips do not touch at any point during operation. Plug the blue USB cable into a 5V source (computer or wall adapter).

Step 3: Set power supply to 24V DC voltage, set current limit to 1A.

Step 4: Open the electronics box and press the red restart button on the Arduino board. This will run the firmware loaded onto this microprocessor. This will cycle through each of the positions for 5 seconds each. Keep hands away from the gimbal to avoid pinch points, hot surfaces, and live wires.

Step 5: After the test is completed, turn off the power supply and disconnect the power supply cables.

Warnings:

Solenoids may become hot. Avoid touching solenoids during operation. Do not exceed 10W power for greater than 5 minutes.

Avoid pinch points. Keep hands away from mechanism during operation.

Harmless but painful shocks are possible. Keep hands away from alligator clips and electronics box during operation.

Test Modifications

The gimbal comes preprogrammed with a test routine. This program can be modified through the C-program in the Arduino IDE. To modify the program, download the code file, plug the blue USB cable into a computer, modify the code as required, and re-upload to the Arduino. The source code can be downloaded at the following link:

https://drive.google.com/open?id=1onqjaCb00ICId-91O-oUSQstvOKdRYiy

The example code bellow causes one actuation. The actuation occurs in three phases. First the solenoid is given full power for a short period of time to initiate motion. Then the solenoid is held at a lower power for the required time period. Finally, the solenoid is turned off and the system is allowed some time to recenter. The power is controlled by a PWM signal. To set the duty cycle (percent of full power) adjust the power level from 0 (0%) to 255 (100%). To change the timing adjust each delay value in milliseconds.

```
analogWrite(PIN_10,255); //Corner 2 full power on
delay(800); // Delay .8 seconds
analogWrite(PIN_10,150); //Corner 2 low power on
delay(Time_one); //Holding time (ms)
analogWrite(10,0); //Shut off solenoid
delay(3000); //Return to center delay
```

Troubleshooting

If the gimbal is not actuating the first step is to reset the program. Open the electronics box and hit the red button located on the Arduino. Next, confirm it is correctly receiving power. Check that the ground and power line are connected to the black and red wire and that the alligator leads are not shorted together. Next, verify the LEDs on the Arduino are on. Finally open the electronics box and ensure the blue and red wires are connected to the breadboard.

If a single or multiple solenoid no longer actuates it may be because of a loose connection. The circuit is contained on a breadboard so may be prone to disconnection. To fix this problem open the electronics box and identify the loose wire. Then reattach the wire in the appropriate location based on the photo in Figure 2 or the circuit diagram in Figure 3.

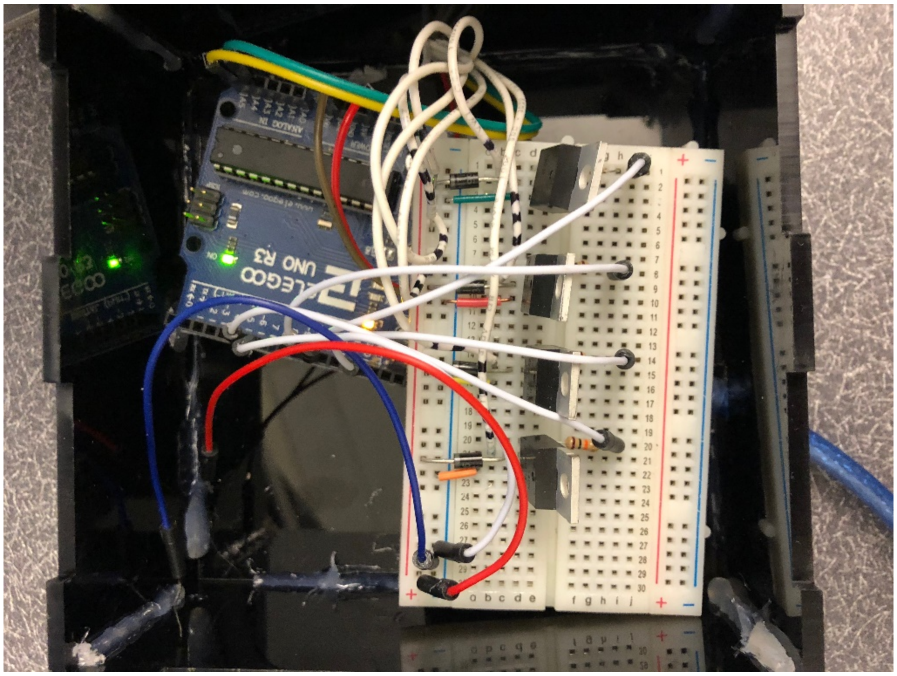


Figure 2. Breadboard circuit

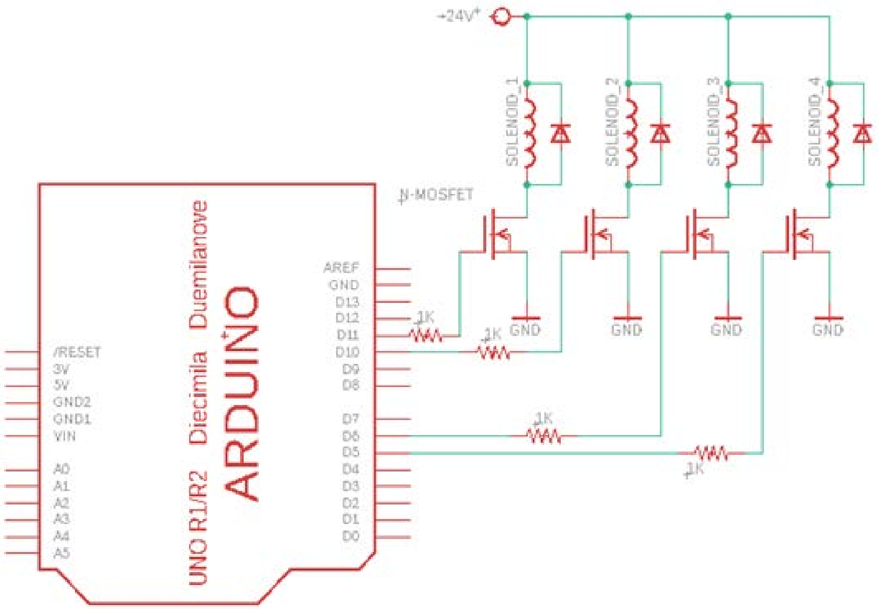
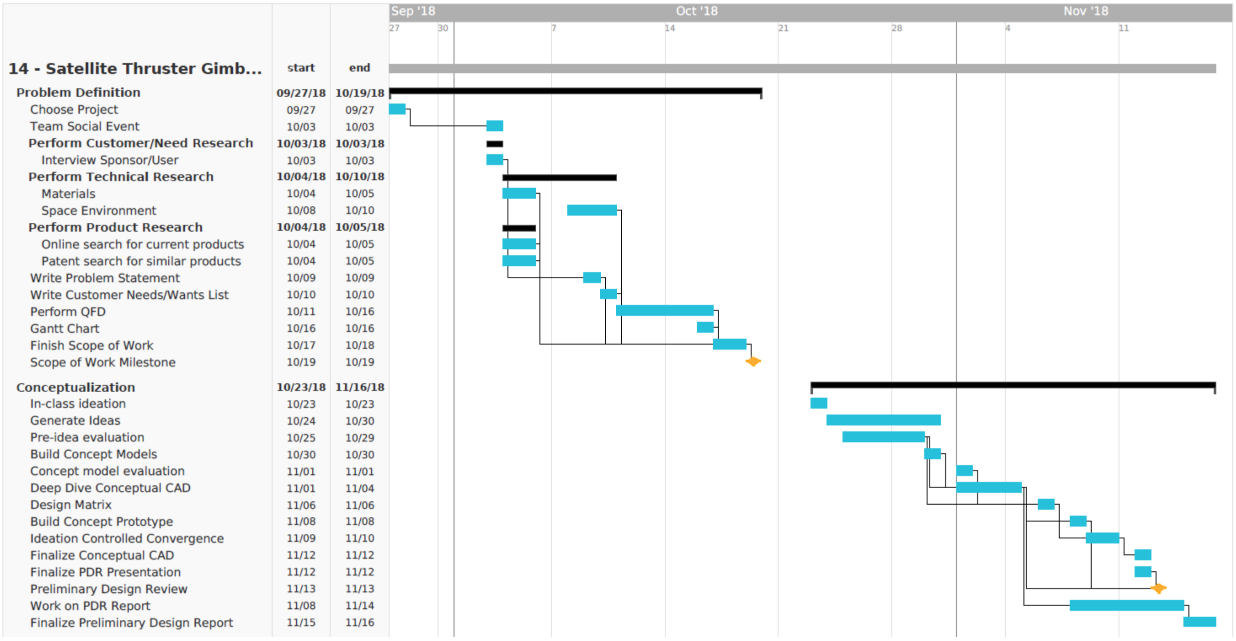
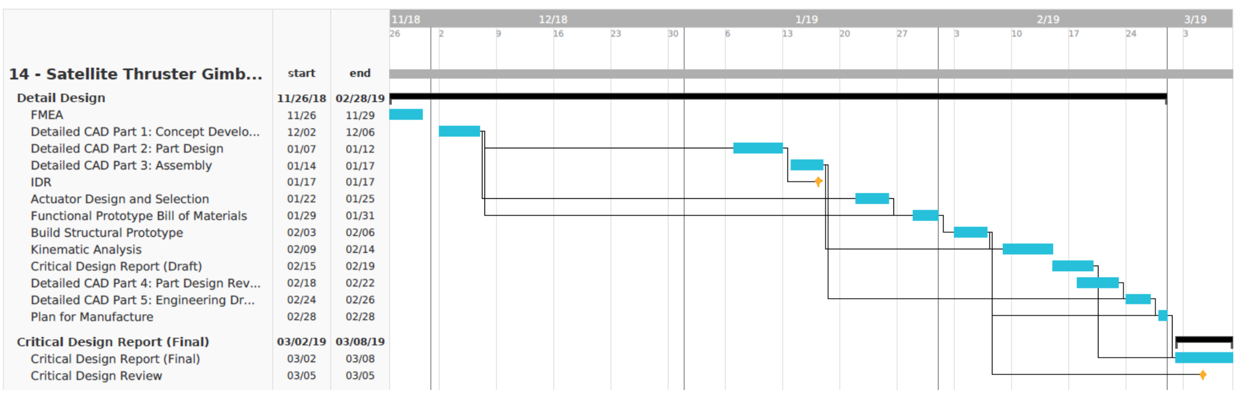


Figure 3. Electrical Schematic

Appendix N: Gantt Chart





14 - Satellite Thruster Gimb...

	start	end
Manufacturing	**03/09/19**	**05/07/19**
Determine parts to purchase	03/09	03/11
Manufacturing & Test Review	03/14	03/14
Order parts for structural prototype	04/02	04/02
Additional structural prototype	04/04	04/08
Final Design check	04/11	04/17
Prototype review presentation	04/11	04/17
Redesign solenoid holder	04/14	04/17
Create test circuit	04/11	04/17
Finalize quotes	04/14	04/18
Final fit check	04/16	04/17
Send purchase list to sponsor	04/19	04/19
Water Jet Plates	04/20	04/22
Drill and Tap Plates	04/23	04/23
Manufacture Part 2: Electronics	04/20	04/26
Manufacture Part 3: Control System	04/24	04/25
Tap Purchased Parts	05/02	05/02
Create mock thruster	05/02	05/04
Manufacture Part 4: Full Assembly	05/03	05/06
Final Electrical Assembly	05/02	05/05
Electrical/Function Test	05/04	05/06
Confirmation Prototype Review	05/07	05/07
Testing	**04/04/19**	**05/31/19**
Create Test Plan	04/04	04/08
Finalize Test Procedures	04/22	05/02
Obtain test mass and equipment	05/02	05/06
Final Inspection and Mass	05/05	05/12
IMU Vector Performance Test	05/07	05/14
Power Consumption inspection	05/09	05/09
Vector Repeatably test	05/11	05/16
Torque Test	05/11	05/16
Operator's Manual	05/16	05/20
Expo Poster	05/20	05/24
Write Final Design Report	05/23	05/29
Project Expo	05/31	05/31
Final Design Report	05/31	05/31