To: Dr. David Willy and John Veden

From: Travis Harrison, Connor Hoffmann, Sean McGee, and Scott Mesoyedz

Date: 07 October 2021

Subject: Implementation Memo

General Atomics, a company that manufactures a diverse array of technologies including satellites, has tasked this team to develop a test fixture for their 12U satellite model. The purpose of this project is to design a test fixture that allows for the implementation of a spherical air bearing. This air bearing will allow General Atomics to test their 12U satellite in a simulated space environment. The spherical air bearing is almost frictionless which provides a center of rotation for an object to rotate about freely. For the best effect of simulated space, the center of gravity of the assembly must be collocated with the center of rotation of the bearing. Our task is to create a mounting platform that meshes the bearing and the satellite creating a center of mass directly coincident with the center of rotation of the bearing. Our goal as a team is to provide General Atomics with an effective and efficient test fixture that meets all their requirements.

After a semester and a half this team has made great strides toward this goal. We are proud of the milestones we have accomplished and are motivated to keep up this rate and have the product complete and finalized by the end of the semester.

Milestones worth noting:

- Finalized Computer Model
- Acquisition of parts
- Motor Control
- Manufacturing
- Test equipment

Finalized Computer Model

After months of iterations, we have come to a design that meets all requirements while staying in budget. There were a few areas of concern regarding compliance with the customer requirements including magnetic reduction, and 35 degrees of tilt. After evaluating our options, we were able to move past these barriers and complete a detailed computer model.

Acquisition of Parts

This semester has been the beginning of ordering and acquiring parts. It has been reassuring for the entire team to hold in our hand's physical pieces to an assembly that we have only seen on a computer. After receiving shipments of parts, the project has moved into the next stages, Motor Control, Manufacturing, and Testing Equipment.

Motor Control

With parts arriving we have begun the process of creating a motor control system to operate the fixture. This aspect of the project is especially important to the success of the device. Our main sensor, an IMU, has been connected and is operating returning data of its orientation and movement.

Manufacturing

Our design has many complex parts that require precise machining. As parts arrive the process of machining these parts has begun. Currently the satellite mounts, and base plate are done with many more on the way.

Test Equipment

As the fixture's purpose is to mesh a spherical air bearing with a 12U CubeSat we require to have these components to test the fixture. As these components are expensive the team has designed a replica CubeSat, and a replica bearing to allow for testing. These components are finished and look very professional.

1 Customer Requirements (CRs)

The customer, General Atomics, has provided many requirements for this project that dictate the design process. These requirements ensure that the client and the design team both agree on what the fixture must accomplish.

Within a document provided by the customer General Atomics the requirements for this project were clearly stated. Below is a list of the requirements and their descriptions.

All requirements have remained the same since the first semester session excluding the requirement to have all components be nonmagnetic. This change occurred after the team expressed their concerns with the acquisition of electric motors without permanent magnets. The client then explained how their CubeSat will no longer be affected by magnetic fields eliminating the requirement.

1. Fixture should securely mate with CubeSat’s two clamping tabs per drawing provided at project kickoff.
    a. Ensures the satellite is held securely onto the fixture. Any movement of the satellite would cause issues during testing.
2. CubeSat weight will be 24 kg +/- 2.0 kg.
    a. Weight of the satellite will be within the provided value.
3. Fixture needs to be adjustable in all 3 axes to move the CubeSat to match the center of gravity of the combined fixture and CubeSat with the center of rotation for the spherical bearing.
    a. The main purpose of this project is to collocate the center of gravity of the satellite with the center of rotation of the spherical air bearing. This collocation will allow the system to maintain its orientation during the testing of the satellite.
    b. 3 axes of movement will allow maximum customization.
4. The fixture weight should be minimized.
    a. A lightweight fixture will minimize the effect of momentum. This will help the customer get accurate test results.
5. The center of gravity of the fixture, without the CubeSat but with the fixture mounting features in the approximate location where the CubeSat matches the center of gravity position, to match the center of rotation for the spherical bearing to minimize the effect of the fixture upon the third (3.) requirement.
    a. This requirement is interpreted as a precaution which prevents the fixture from falling over as the center of gravity would not cause the system to be top heavy without the

satellite.

6. The fixture will mate with the spherical air bearing per drawing provided at project kickoff.
    a. The inner bearing of the spherical air bearing has specific mounting dimensions which must be utilized within the design.
7. Fixture will need to provide a minimum of 50 mm of travel in all three directions about the center of rotation for the spherical bearing.
    a. This ensures that the fixture allows movement.
8. The CubeSat should be easily installed and removed.
    a. The quicker General Atomics can install and remove the satellite from the fixture the better.
9. Once positioned within the fixture, the CubeSat should be rigidly secured from movement within the fixture.
    a. This ensures that the satellite is secure and rigid to allow for precise testing.
10. The fixture will be limited to 35 degrees of tilt for 360 degrees of rotation from the normal axis.
    a. The fixture must allow the air bearing to have a full range of motion.
11. (Stretch Goal) Design should be adaptable to 3U and 6U Configurations.

These requirements have been simplified into categories with their weights and are listed below in Table 1.

Table 1: Customer Requirement Weight

Customer Requirements	Weight
1. Reliable	3
2. Durable	3
3. Securely mate with CubeSat rails	5
4. CubeSat position adjustable	4
5. Fixture remains securely on stand	4
6. As lightweight as possible	3
7. Easy install and removal	2
8. Retains CubeSat securely	5
9. Allows rotation, and tilt of CubeSat	3
10. Securely mates with bearing	5
11. Minimize effects on CubeSat dynamics	4
12. (Stretch Goal) Adaptable to 3U, and 6U	1

2 Engineering Requirements (ERs)

The original engineering requirements developed last semester were formed in the initial stages of the design before the team had formed a deep understanding of the problem at hand. It was expected that many of these ERs would require adjustments to better reflect the capabilities and function of the device. Indeed, most ERs have been modified, one has been removed, and two have been added since the Spring semester. These changes allow the ERs to better guide the design and assessment of prototypes as we approach a final product.

2.1 ER#1–3: Minimize COM X/Y/Z Location Error

2.1.1 ER#1–3: COM X/Y/Z Location Error, Target = 0 (±1) mm

The bearing fixture must allow the combined center of mass (COM) of the fixture, the inner bearing, and the satellite to be collocated with the bearing's center of rotation (COR). This allows the assembly to rotate freely atop the outer bearing with no applied torque from the force of gravity. As such, the precision with which the COM can be moved to a required location is of critical importance—even small deviations from the target location may allow the force of gravity to significantly affect the assembly's attitude. The reliability of the device and the results from testing using it depend on minimizing these errors. Some difficulty has been had in trying to work out acceptable tolerances for these errors, and the client is currently in the process of identifying an appropriate value. In the meantime, this project will continue under the assumption that repositioning the COM within ±1 mm of the COR will be sufficient.

2.2 ER#4: Endures Typical Wear *[Value changed from Spring]*

2.2.1 ER#4: Lifetime of consumable parts, Target ≥ 1,000 uses

Because of the significant cost of designing and constructing the bearing fixture, it must be durable enough to deliver reliable operation for many uses. Parts which undergo wear (e.g., bronze/plastic bushings) should be replaceable as easily and inexpensively as possible but doing so frequently can still pose an inconvenience to operation of the device. As such, all parts should be designed to withstand a minimum of 1,000 uses of the device under typical conditions. It is important to note that testing a satellite on the device a single time may involve tens or hundreds of loading cycles on some parts depending on their function. It is expected that 1,000 uses constitute a sufficiently long lifetime for any consumable parts to minimize the inconvenience of periodically replacing them.

The value given for this requirement in Fall was 10,000 ± 1,000 uses. This was chosen as an acceptable lifetime for the entire device without considering the presence of consumable parts. Changing this value to reflect the lifetime of these parts is more relevant to the goals of the project.

2.3 ER#5: Satellite Mount Dimensions Compatible with Rails

2.3.1 ER#5: Mount dimensions, Target = Per drawing

Attaching the satellite to the fixture requires appropriate mounting clamps which can mate with the satellite's existing rails. The dimensions of these rails are standardized according to *Payload Specification for 3U, 6U and 12U* [1]. The mounting hardware used on the bearing fixture must be compatible with these dimensions, shown in Figure 21.

2.4 ER#6: Adjustable in 3 Axes *[Value changed from Spring]*

2.4.1 ER#6: Satellite translation, Target ≥ 80mm (X), 70mm (Y), 100mm (Z)

The fixture must permit colocation of its COM and the bearing's COR, as stated previously. However, different satellites may have different COM positions which the fixture must be able to accommodate. Each CubeSat form factor has a standardized COM envelope, and any such satellite must feature a COM position which is within this envelope. As such, the fixture must allow satellite translation of at least this amount along each axis direction to be compatible with any such satellite. COM envelopes for 6U and 3U satellites lie within this 12U envelope, so a device which can accommodate the full volume of the 12U COM envelope can similarly accommodate the full volume of 6U and 3U COM envelopes.

The value set for this requirement in Spring was 50 + 5 mm, which failed to clearly communicate that this is the translation needed in both positive *and* negative directions *from the center position* of each axis. The value has been updated to describe the minimum *total* translation needed for each axis.

2.5 ER#7: Fixture COM below COR *[Value changed from Spring]*

2.5.1 ER#7: COM Y-Distance from COR, Target = –150 (±100) mm

During operation, the fixture is designed to induce an equilibrium state in which the assembly has no preferred orientation. However, if the satellite is removed from the fixture (e.g., during setup or teardown of the setup), the fixture and inner bearing must remain stable atop the outer bearing. If the COM of the assembly sans-satellite is located above the COR, removal of the satellite will put the system into an unstable state potentially causing the fixture to fall from the outer bearing. As such, the COM of the assembly with the satellite *removed from the fixture* must lie directly under the COR to prevent the satellite from falling from the outer bearing of its own accord. However, while a COM position which is below but still *near* the COR may be stable on its own, small amounts of force may still be enough to topple the fixture. As such, positioning the COM not just below, but 50–250mm below the COR should provide sufficient stability to resist small bumps during the process of removing the satellite.

The original value for this requirement of 0 –0/+10 mm used an unclear tolerance and failed to consider the instability of the assembly with a COM so close to the COR. Additionally, having the COM so high *without* a satellite installed would certainly cause the COM to move above the COR after the satellite is installed which poses additional problems.

2.6 ER#8: Minimize Weight of Fixture *[Value changed from Spring]*

2.6.1 ER#8: Mass of fixture, Target ≤ 25 kg

Minimizing the mass of the fixture serves multiple purposes. Operation of the fixture may already be cumbersome given the extremely low-friction air bearing and balancing required, which heavy equipment will only exacerbate. The air bearing itself is only rated to support loads up to 60 kg, beyond which the supplied air pressure is insufficient to maintain the needed cushion of air. Reserving about 10 kg of this capacity for margin of error, 24 kg for the maximum allowable 12U CubeSat mass, and about 1kg for the inner bearing, the fixture itself may not exceed 25 kg.

The target for this requirement was set as 500 –0/+10 N last semester. This included the weight of the inner bearing and the satellite, which are both known and cannot be altered. Additionally, an assembly with lower mass (which is not only acceptable, but in fact *desirable*) would fail to meet the requirement with the stated tolerance.

2.7 ER#9-10: Simplify Sat. Installation *[Values changed from Spring]*

2.7.1 ER#9: Time needed for sat. installation, Target = 3 (±3) min.

Operation of the fixture device should be made as convenient as possible to allow operators to instead focus on testing the satellite. As such, installation and removal of the satellite should be made as simple as possible while still ensuring a secure connection between satellite and fixture. Keeping the time required to reliably form this connection should be minimized. While it is expected that mounting the satellite would take 1–2 min. with the simplest possible mounting hardware, it is expected that around 5–6 min. should not pose excessive inconvenience during operation.

This value has been changed from the original 3 (–0/+1) min. stated in Spring. This tolerance had the unintended consequence of requiring satellite installation to take *at least* 2 minutes. While installation is indeed expected to take at least this long, a design which allows reliable installation to take less than this amount of time should certainly not fail to meet the requirement.

2.7.2 ER#10: Tools needed for CubeSat installation, Target = 1 (±1)

Reducing the number of tools required to install the satellite on the fixture should also simplify the installation and removal process by reducing time spent searching for the correct tool. Requiring multiple different tools also means that misplacing just one of them can prevent the operator from correct satellite installation. This at best requires additional time to track down or replace the tool, and at worst tempts the operator to install the satellite incorrectly. Using fewer tools requires the design to use the same style of fastener(s) in multiple locations, which may reduce the cost of the device and simplify correct assembly and disassembly of the device for maintenance.

The value assigned to this requirement in Spring was 3 (–2, +1) tools. Additional experience with the project revealed this value to be overly generous, since using four different tools to install the satellite would pass the requirement but still be quite inconvenient. Additionally, the stated tolerance does not permit a device to use *no* tools which, while difficult to design, should be considered acceptable by this requirement.

2.8 ER#11: Force to Dislodge Satellite *[Value changed from Spring]*

2.8.1 ER#11: Force needed to dislodge satellite, Target ≥ 500 N

There are significant potential consequences should the fixture's satellite mounting hardware fail to retain the satellite during operation. Beyond the obvious safety concerns associated with a 50 kg device falling from the bearing stand, there is risk of incurring significant financial losses from damage to the satellite. The satellite must then be fastened to the fixture very securely to prevent it from dislodging during operation. A force of 500 N should be enough to secure the satellite without causing damage to its mounting rails.

The force required was originally specified as 500 (–0/+10) N which is an unnecessarily tight tolerance. The value has been changed to instead specify the minimum force, since greater forces are acceptable as long as they do not damage the satellite's rails or introduce other problems.

2.9 ER#12–13: Range of motion *[Values changed from Spring]*

2.9.1 ER#12: Range of rotation about vertical axis, Target ≥ 360°

Testing of satellites will include, among other things, verifying expected operation of the satellite's torque rods used for attitude adjustments. The fixture must therefore be designed to not interfere with the satellite, outer bearing, or bearing stand for the full 360° of rotation about the vertical axis.

The original value of 360° (–0/+360) seemed to suggest that a device capable of making more than two full rotations should fail to meet this requirement. In fact, the design should be able to rotate *at least* 360°, but there is not a maximum bound on allowable range of rotation.

2.9.2 ER#13: Range of tilt from level, Target = ±35° (±1°)

In addition to the rotation about the vertical axis described above, the fixture must also permit the satellite to reach 35° of tilt along any axis parallel to the ground.

This requirement originally specified a value of 35° (–0°/+10°) which neglects the fact that the air bearing is itself only capable of achieving a maximum tilt of about 35°, effectively eliminating the entire stated tolerance.

2.10 ER#14: Bearing Mount Compatible with Bearing Dimensions

2.10.1 ER#14: Bearing mount compatible with bearing, Target = Per drawing

While a custom inner bearing is being manufactured for testing prototypes, the product delivered to the client must have mounting features which are compatible with the client's inner bearing to ensure reliable operation of the device. The associated dimensions and tolerances have been provided by the client and will be used to ensure appropriate mounting features are included in our design where appropriate.

2.11 ER#15: Minimize moment of inertia *[Value changed from Spring]*

2.11.1 ER#15: Fixture moment of inertia, Target = 300,000 (±200,000) kg· mm^2

The effectiveness of a satellite's internal torque rods depends on the moment of inertia of the torque rods themselves compared to the moment of inertia of the satellite. Performing torque rods testing should therefore be performed in a manner which produces as insignificant impact on the satellite's moment of inertia as possible. While the moment of inertia of the fixture cannot be reduced to the point of being negligible, it should be kept as low as possible to minimize its impact on the satellite's dynamics.

As shown in Figure 22, the dimensions of the satellite, COM envelope, and inner bearing prevent translation of the satellite along the vertical axis to collocate the COM with the bearing's COR. As such, any suitable fixture design must instead use vertically translating weights to counteract the torque of gravity. Under the best possible circumstances, the fixture must be able to accommodate a satellite with the maximum possible 24 kg mass concentrated entirely at the COM in the highest possible position, 72 mm above the bearing COR. This configuration results in a satellite moment of inertia of:

$$I_{sat} = m_{\mathrm{sat}} {r_{\mathrm{sat}}}^2 = 24\mathrm{kg} \cdot (72\mathrm{mm})^2 = 124{,}416\mathrm{kg} \cdot \mathrm{mm}^2 \tag{1}$$

This configuration corresponds to a maximum restoring torque of:

$$T_{sat} = r_{\mathrm{sat}} \cdot (m_{\mathrm{sat}} g) = 72\mathrm{mm} \cdot \left(24\mathrm{kg} \cdot 9.81 \frac{\mathrm{m}}{\mathrm{s}^2}\right) \approx 17\ \mathrm{N} \cdot \mathrm{m} \tag{2}$$

The maximum torque supplied by the weights must be at least equal to this to achieve colocation of the COM and COR. Using the maximum possible 25 kg mass of the fixture (as stated in ER#8) for weights[1]counteracting the torque of the satellite requires the COM of the weights to be below the COR by:

$$\mathrm{T_{fix}} = \mathrm{r_{fix}} \cdot (\mathrm{m_{fix}g}) = \mathrm{T_{sat}} \approx 17\ \mathrm{N} \cdot \mathrm{m} \tag{3}$$

$$\mathrm{r_{fix}} = \frac{17\ \mathrm{N{\cdot}m}}{25\mathrm{kg}{\cdot}9.81\frac{\mathrm{m}}{\mathrm{s}^2}} = 69.3\ \mathrm{mm} \tag{4}$$

The minimum possible moment of inertia of the fixture is then:

$$\mathrm{I_{fix}} = 25\mathrm{kg} \cdot (69.3\mathrm{mm})^2 \approx 120{,}000\ \mathrm{kg} \cdot \mathrm{mm}^2 \tag{5}$$

The satellite cannot realistically be placed directly against the inner bearing, nor can the fixture be entirely massless except for the weights. As such, the minimum *practical* moment of inertia is 2 to 3 times this value. The client agreed with our conclusions and explained that while the moment of inertia of the fixture should be minimized, it should not have a significant impact on their testing. A fixture moment of inertia of 400,000 kg· mm^2 is therefore an acceptable target.

The moment of inertia requirement target from Spring was given a value of 40,000 (±1,000) kg· mm^2, one-third of the minimum possible value identified above. This was certainly a miscalculation or a typo, but the tolerance range provided is also too restrictive. The updated value is attainable while preserving the necessary functionality, and the tolerance range is broader without permitting excessively large values.

2.12 ER#16: Satellite mount compatible with 3U, 6U CubeSats

2.12.1 ER#16: Mount dimensions, Target = Per drawing

While the fixture is required to be compatible with 12U CubeSats, the project description also stated that compatibility with 3U and 6U CubeSats is a stretch goal of the project. While given lower priority compared to other critical project requirements, the mounting rails of all three CubeSat form factors are identical (see Figure 21). Additionally, the 6U form factor has the same rail-to-rail width as the 12U form factor, making any 12U-compatible device also 6U-compatible with few to no modifications. 3U satellites are about half as wide as 6U and 12U satellites, introducing several design considerations for compatibility.

2.13 ER#17–18: Simplify COM Adjustment *[Added from Spring]*

2.13.1 ER#17: Time for max. COM adjustment, Target = 3 (±3) min.

COM adjustments involve precisely moving the satellite and attached fixture components, totaling 30 kg. In order to do this while also minimizing the total mass of the fixture according to ER#8, the devices (e.g., electric motors) which drive these adjustments should be as lightweight as possible. Generating the force required can be accomplished through speed reduction, but this comes at the cost of prolonging the process of setting the device up for operation. In the same way that satellite installation should be made as simple as possible (ER#9), making the required COM adjustments should not be burdensome to operation of the device. Also, like ER#9, it is expected that even a fast adjustment process would take at least 1–2

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[1] Note that because moment of inertia is *linearly* proportional to mass but proportional to the *square* of distance from the axis of rotation, using the greatest possible mass minimizes moment of inertia by permitting the smallest possible distance from the axis of rotation.

minutes, so a duration of no more than 6 minutes is a reasonable target.

2.13.2 ER#18: Steps requiring user input, Target = 2 (±2) inputs

Colocation of the COM with the COR is expected to require a system for identifying the current COM location, calculating the amount of translation needed along each axis, controlling the drive devices to make those adjustments, and verifying that the new location is correct. All of these tasks are possible to perform manually but conveying *what* needs to be performed and *how* to perform it to the device operator is expected to be difficult and following those directions precisely may be confusing. Instead, having a system which can automate as many of these steps as possible is expected to simplify operation, reduce opportunities for user error, and deliver faster and more reliable results. It is important to note that this system should allow the operator the option of manually performing as many of these actions as possible as a backup to the automated system.

2.14 ~~ER#16:~~ Minimize Magnetic Field Strength *[Removed from Spring]*

The project description originally required that the fixture be entirely non-magnetic due to the use of sensitive magnetic-field sensing devices onboard the satellite. This posed a design challenge as repositioning the COM could not be accomplished simply though use of electric motors. However, this September the client revealed that the magnetic field requirement was no longer needed due to changes in the experimental setup at their facility.

3 Design Changes

It is important for a design to be reevaluated. It is part of the job of an engineer to improve ideas to make devices and inventions better. The design for this project has been changed repeatedly this semester for a variety of reasons. In some cases, better ideas were thought of. In others, some parts needed to be changed because the shop did not have the right size to machine it, or it needed to be altered to make it possible to create at all. As of now, every part has experienced this treatment. These are the reasons, rationales, and justifications as to why these changes were made.

3.1 Design Iteration 1: Change in Base Plate discussion

The base plate is the primary interface between all parts. It connects the bearing on the bottom and attaches to the worm gear and z-carriage. The original design was three quarters of an inch and made of Garolite. It also had a complex skeletonized underbelly that would reduce the weight. This iteration is shown in Figure 1.

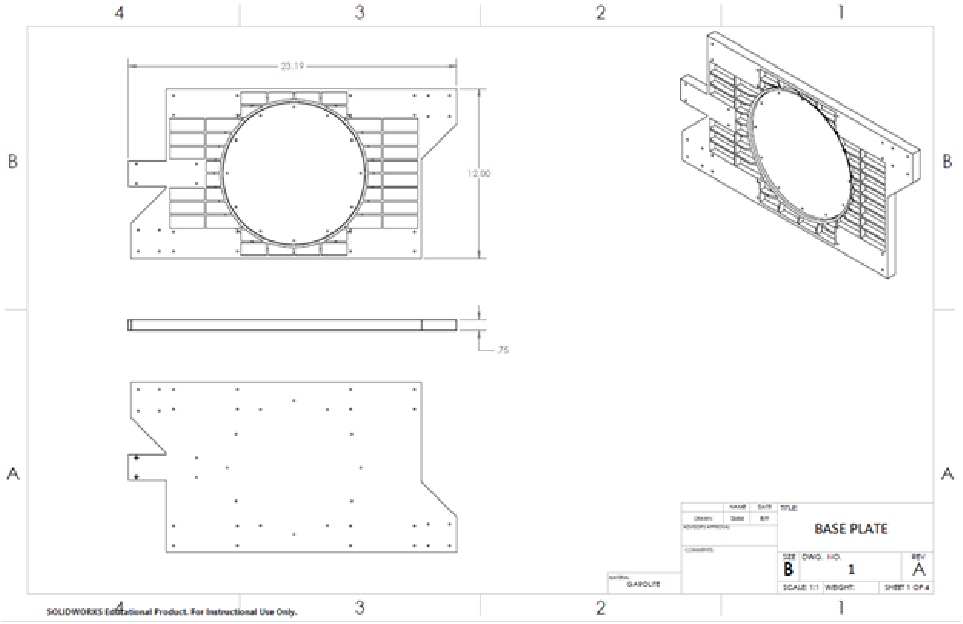


Figure 1: Garolite Base Plate

When speaking to Dr. Perry Wood about the feasibility of this design he told the team that the dust particles from the fiberglass epoxy would be dangerous for humans. The alternative was to order it. However, it would take a substantial amount of the budget. The team shifted to a half inch aluminum design, as aluminum is possible to machine. The skeletonization was simplified because the team was under the impression it would have to be made on the manual mill. The second version of this is shown in Figure 2.

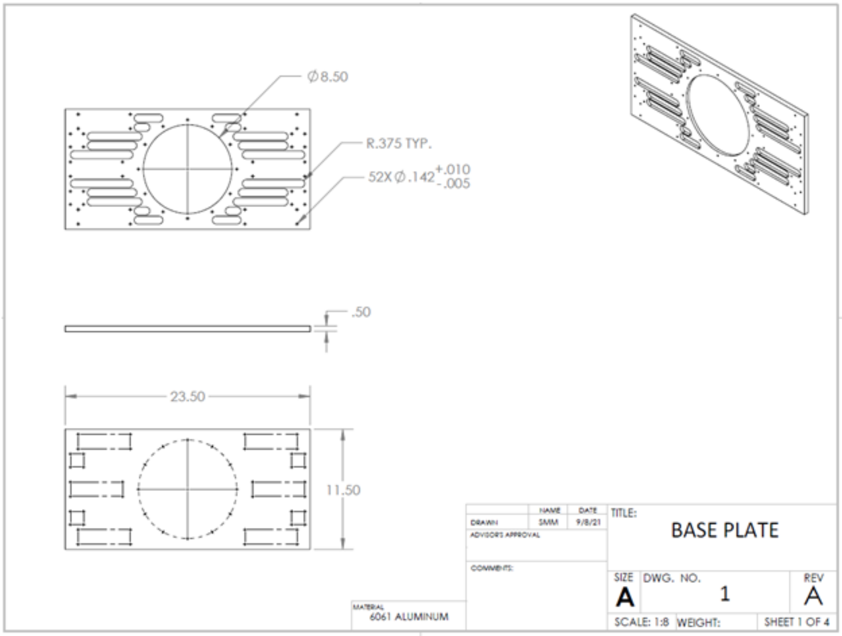


Figure 2: First Aluminum Base Plate

Dr. Wood told the group it would be possible to use the hawse, a large CNC mill at the machine shop that runs on G Code. The current design is depicted in Figure 3.

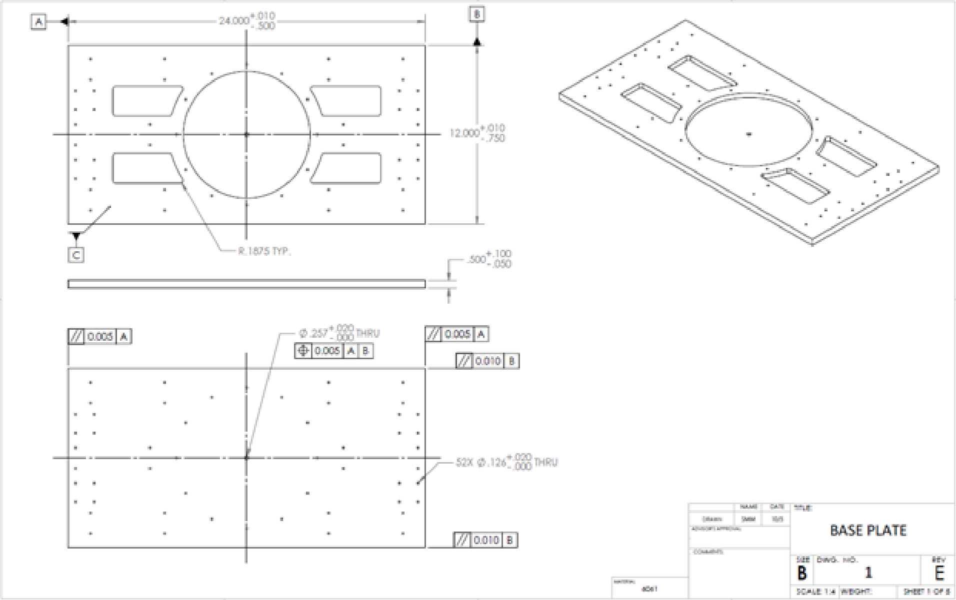


Figure 3: Current Model

This version had another simplification of the bottom. The shop members asked the team to make that change to decrease the amount of machining time. Instead of strips being cut out, polygons were cut out to maximize weight loss while making it easier to achieve.

3.2 Design Iteration 2 Change in Y-Weights

The weights to adjust the center of mass in the vertical direction have gone through only two designs. Originally, they were attached to 2 opposing corners of the bases plate. They were square channels that housed brass weights. After doing an FEA (Finite Element Analysis) analysis of the system, the team discovered there was only one tenth of an inch between the channels and the stand at the allowed 35 degrees of tilt. **Error! Reference source not found.** is from that FEA showing how close the two parts of the system can get.

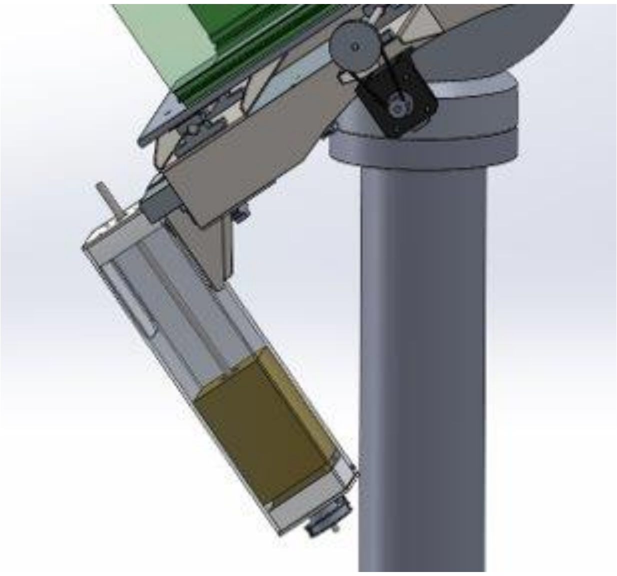


Figure 4: Y-Weights Rails at 35 Degrees of Tilt

When this was discovered, the team moved to the shorter rail system visible in Figure 20.

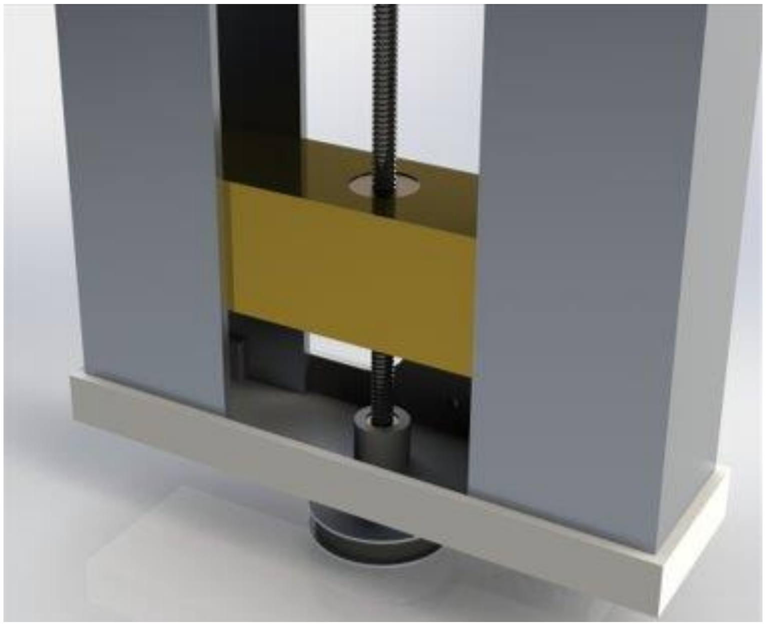


Figure 5: Horizontal Y-Weights with C channels

By rotating the weight to its side and moving it to the middle of the fixture instead of being on the corners, the mass of the weight can be increased without resulting in longer rails. The current iteration is only ten inches long. As it is several inches shorter than the previous version, it will have more clearance with the same maximum of 35 degrees.

3.3 Design Iteration 3 Change in Z-Carriage

The Z-carriage sits atop the base plate and moves on what has been designated the z axis via the worm gear. It allows the system to shift the center of mass of the satellite without any additional weights in the specified plane. It is a folded piece of sheet aluminum represented in figures #6 and #7.

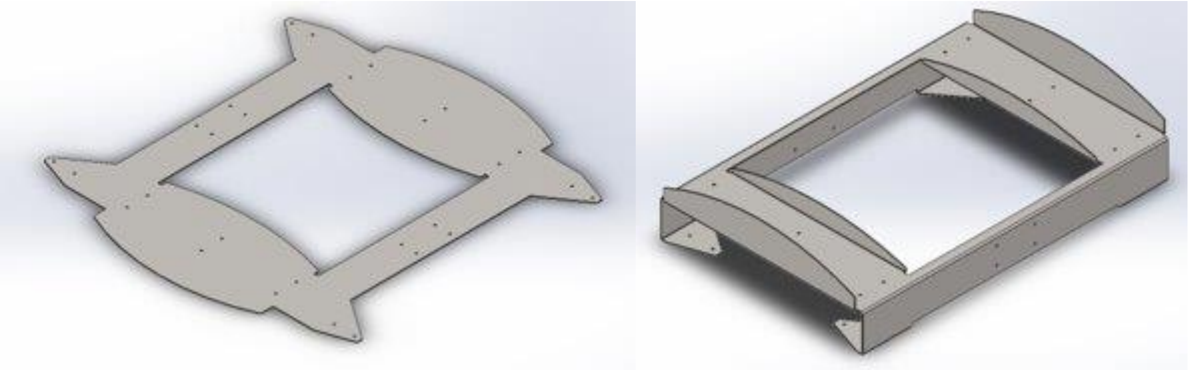
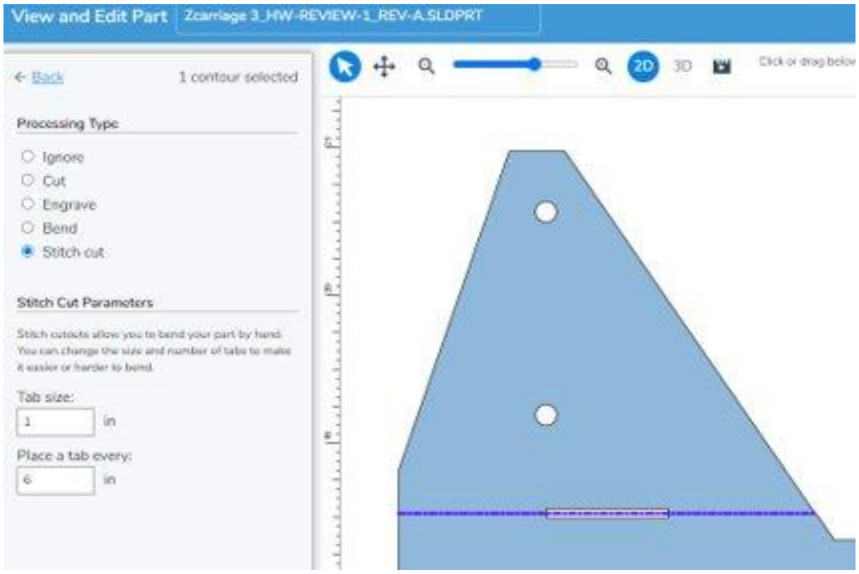


Figure 6 and 7: Z-Carriage Before and After Folding

The original design is identical to the one currently being used except for one thing. There are a few stitch cuts along the points that require bending. shows the addition that will allow this complex folding structure to bend correctly into the desired shape.



Processing Type

○ Ignore
○ Cut
○ Engrave
○ Bend
● Stitch cut

Stitch Cut Parameters

Stitch cutouts allow you to bend your part by hand. You can change the size and number of tabs to make it easier or harder to bend.

Tab size: 1 in

Place a tab every: 6 in

Figure 8: Stitch Cut Along Z-Carriage Bends

According to the manufacturer who is making this part for the team, adding these cuts results in less material on the line of bending. The absence of material means it will bend with less force and the overlapping material will compensate for its missing strength when it is implemented in the fixture.

3.4 Design Iteration 4 Change in the Bearing

The inner bearing is attached to the fixture. It is the interface to the outer bearing. The outer bearing is what holds and allows the system to rotate. Originally it was based on what GA was using. They utilized a spherical air bearing. It is two semi-hemispheres. One rests inside the other. At the bottom of the outer bearing, pressurized air is passed through a hole in the bottom. The air blows the inner bearing up a little, and it is guided by the outer bearing. To get a replication of this system would cost over 1.5 times the total budget. So, the team designed a system of two semi-hemispheres with ball bearing filling the space between, refer to Figure 9.

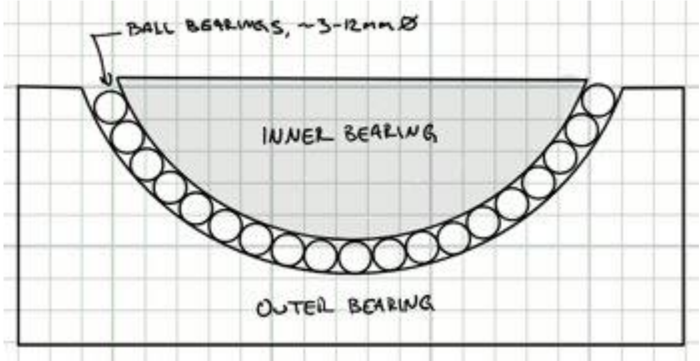


Figure 9: Original Bearing Design

It was discovered that the imperfections of the ball bearings could cause them to bind or roll out of the system. It would also cost over $2,000 to make. The team decided to use three transfer roller bearings as the outer bearing. With them, it was possible to define a plane orthogonal to the inner bearing. The transfer bearings were mounted to 17-degree angled plates to interact with the inner bearing properly. The resulting design is shown in Figure 10.

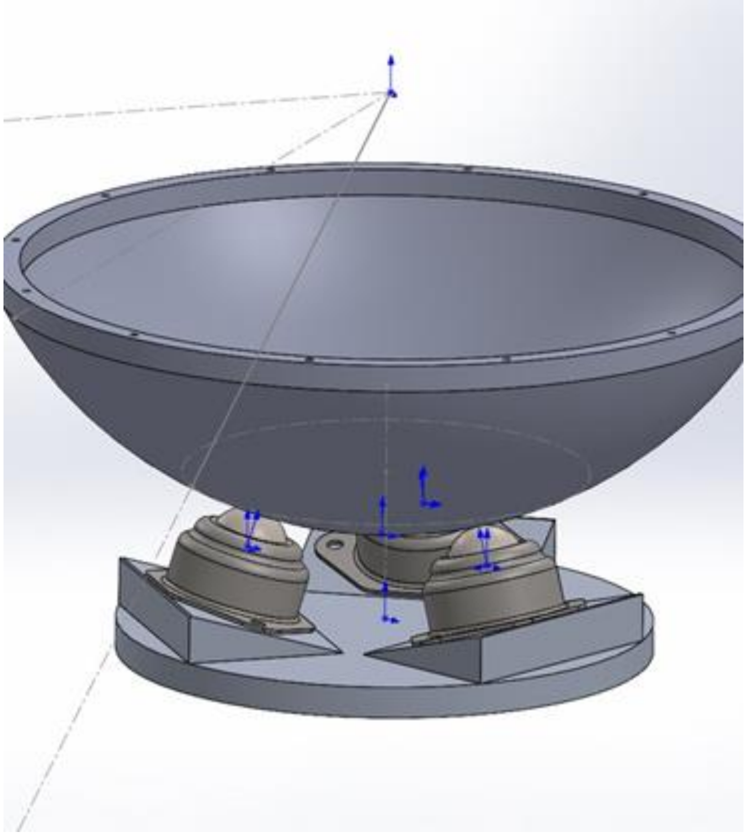


Figure 10: Transfer Roller Bearing System

The inner bearing became the issue, as it would be impossible to machine a hemisphere on the hawse. According to Dr. Perry Wood, it would be difficult to mount without rolling, and the depth would interfere with the component holding the tool by being too big against the steep curves. Figure 11 demonstrates the solution.

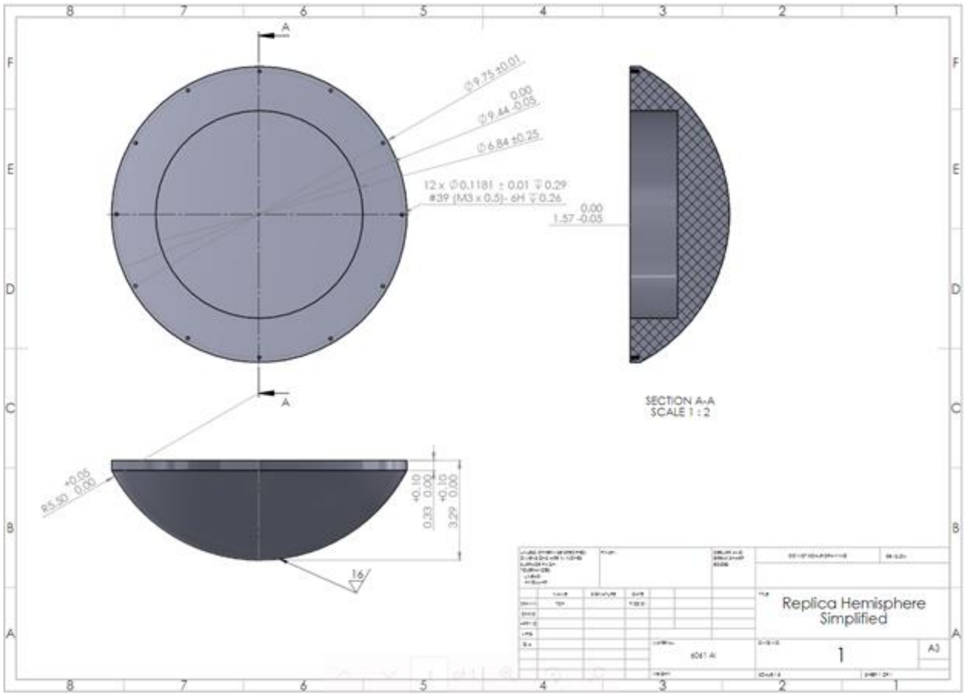


Figure 11: Simplified Inner Bearing

The bearing was made from a cylindrical piece of aluminum stock. That made it easier to mount. Also, a perfect hemisphere was not made on the inside. Instead, a cylindrical cavity was made to reduce weight without bumping into the tool holder via depth or curvature. An additional piece of stock was purchased for the transfer bearings. The plate will be bolted to a table as the stand, with the angular brackets attached. The inner bearing will then interact with the transfer bearings to form the pseudo-spherical air bearing.

3.5 Design Iteration 5 Change in Satellite Brackets

The original Satellite brackets were designed and modified from the system General Atomics (GA) was utilizing. The approximation used as the first iteration is visible in Figure 12.

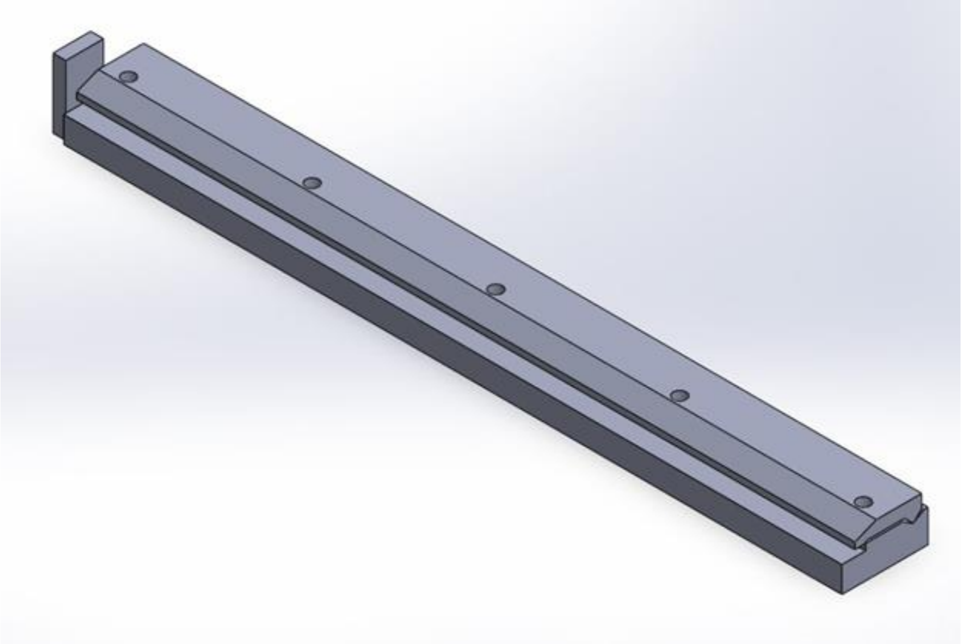


Figure 12: First Satellite Brackets

When attempting to machine these parts, there were three problems that were rectified in one redesign. The centerline of the bolt holes was off kilter. That meant the bolt holes would be interfered with by the chamfer on the side of the top bracket; it made the bolt holes ineffectual. Secondly, that part was not possible to machine on the manual mills. The Base Plate and Inner Bearing took several weeks to make on the hawse. So, these brackets needed to be manufactured manually on the mills. However, they were over complicated. It would have taken weeks to mill them. Finally, they were too long. To total length of each part was 14 inches. That is long enough to exclude them from being made on anything but the hawse. These issues were addressed and Figure 13Figure 14
Figure 15 will be referred to explain how.

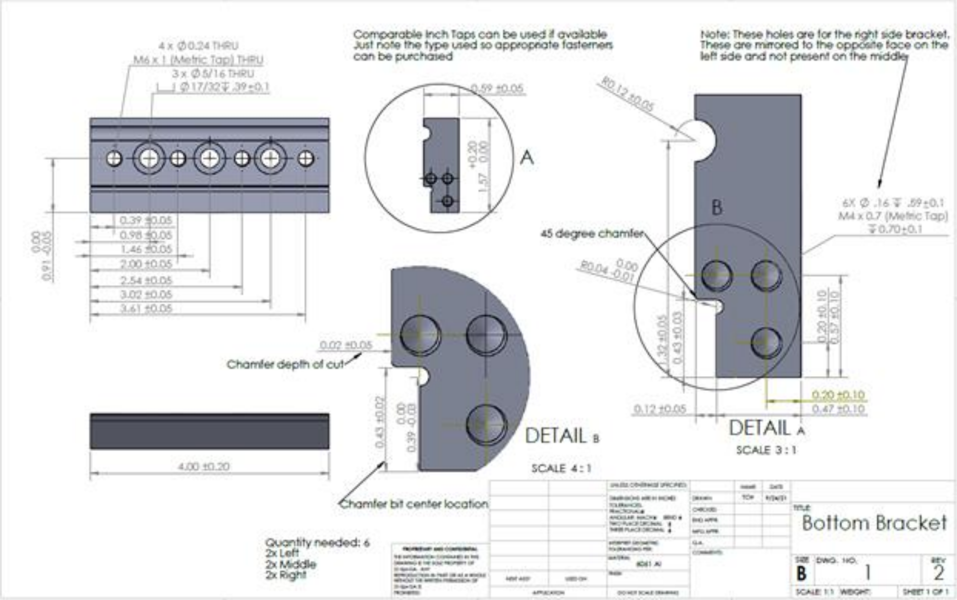


Figure 13: Bottom Satellite Bracket

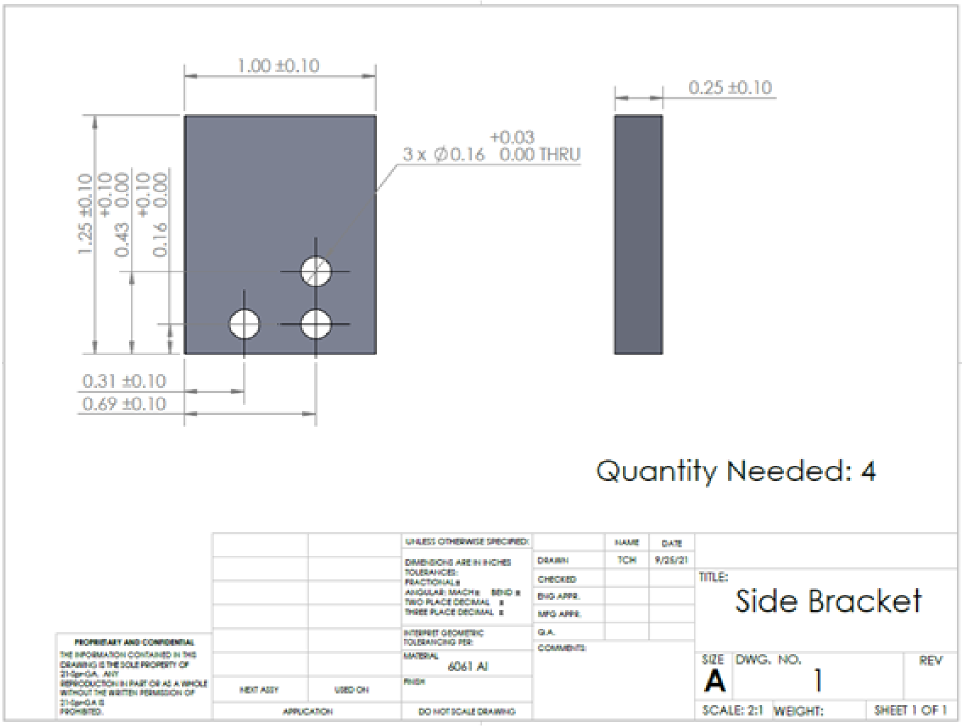


Figure 14: Side Satellite Bracket

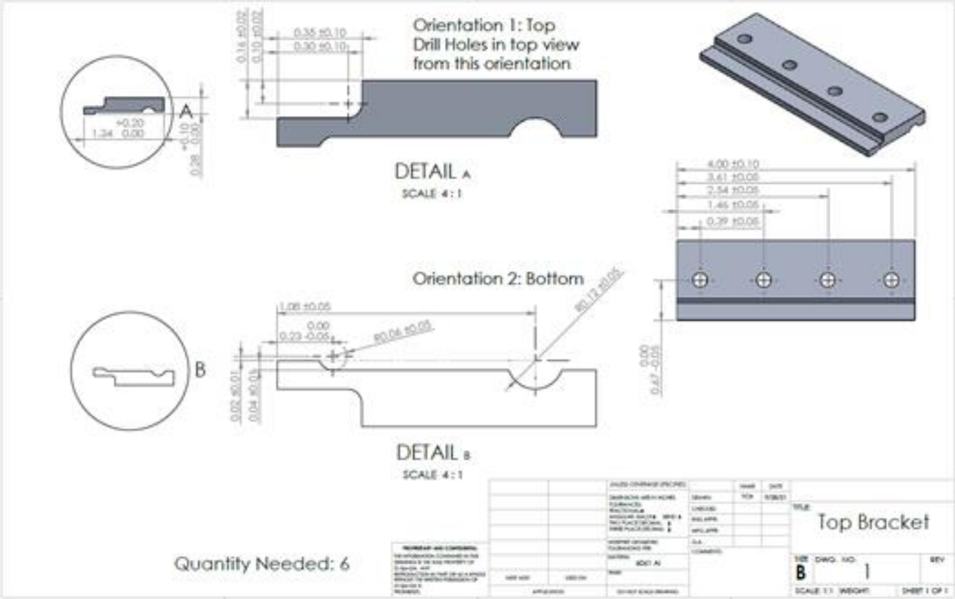


Figure 15: Top Satellite Bracket

The chamfer that interfered with the bolt holes was replaced with changing levels and circular corners to prevent fracture propagation. The parts were simplified and shortened. The total assembly of brackets requires six top and bottom plates now, but it became easy to make them. The evidence of this claim is in the fact that the team is almost done making them when this memo was submitted.

3.6 Design Iteration 6 Change in Satellite

The satellite being made is a stand in for testing purposes. It is a place holder for a multimillion-dollar piece of machinery. Therefore, if there are any issues with the fixture or bearing stand, the expensive one will not be destroyed. Last semester the team 3D printed a one third scale model. The first full-scale model was a simple 12U satellite made using a 3D printer. There were holes in it to allow for cylindrical leg weights, they are shown in Figure 16.

Figure 16: Leg Weight

Each one weighed one pound. They were leg weights that belonged to one of the team members. They did not have enough to reach the required weight of 24 kg and they took up too much space. The stretch goal for the General Atomics team was to allow the fixture to accommodate 3U, 6U, and 12U satellites. Therefore, in the second iteration, it was in pieces. The 12U Satellite would be printed in four quadrants that could be attached and detached. One quadrant would be the equal dimensions of a 3U. Two next to each other would have the structure of a 6U. This version can be seen in Figure 17.

Figure 17: 3D Printed 3U satellite

The final change made was that each quadrant was adjusted to have a cavity in them. One cavity could hold a C-channel that can hold weights or spacers. The weights are made of steel squares, the spacers consist of filament with a variety of infills. Using a combination of these two block types, it became possible to adjust the center of mass un each satellite section. The client told the team the fixture needed to be able to handle a given range for the center of mass. With this satellite, it is possible to simulate every position in that range. Figure 18 show the completed 12U assembly.

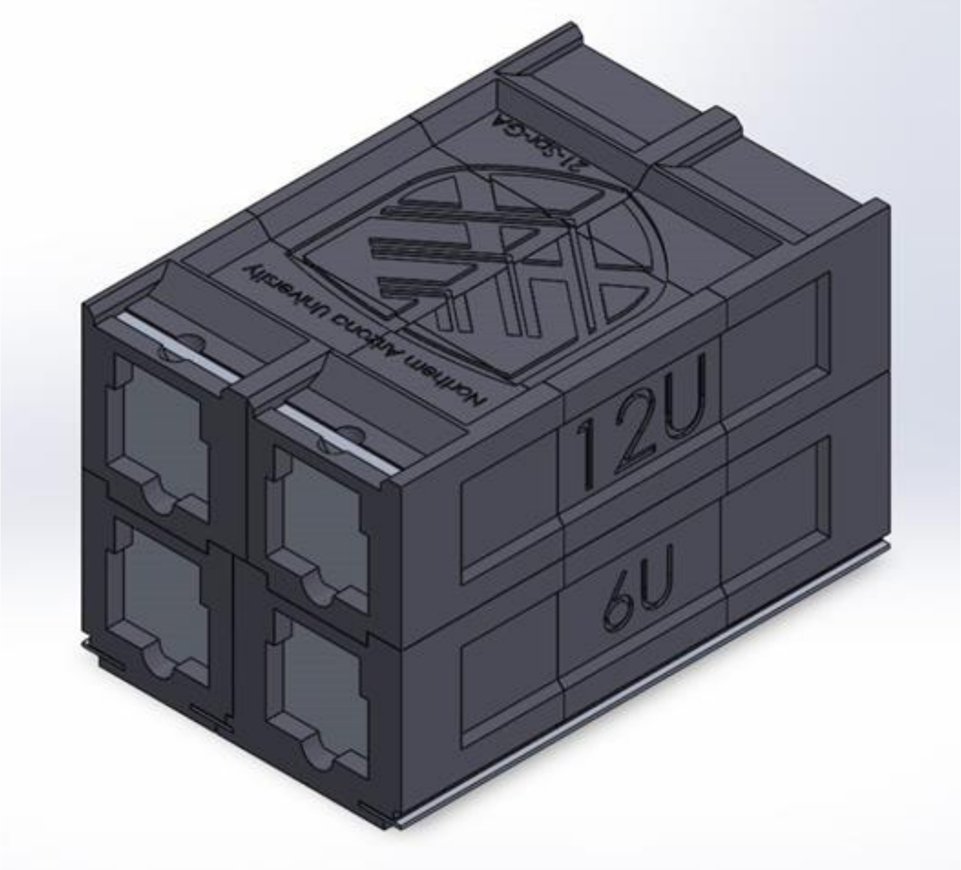


Figure 18: Completed 12U Assembly

4 Future Work

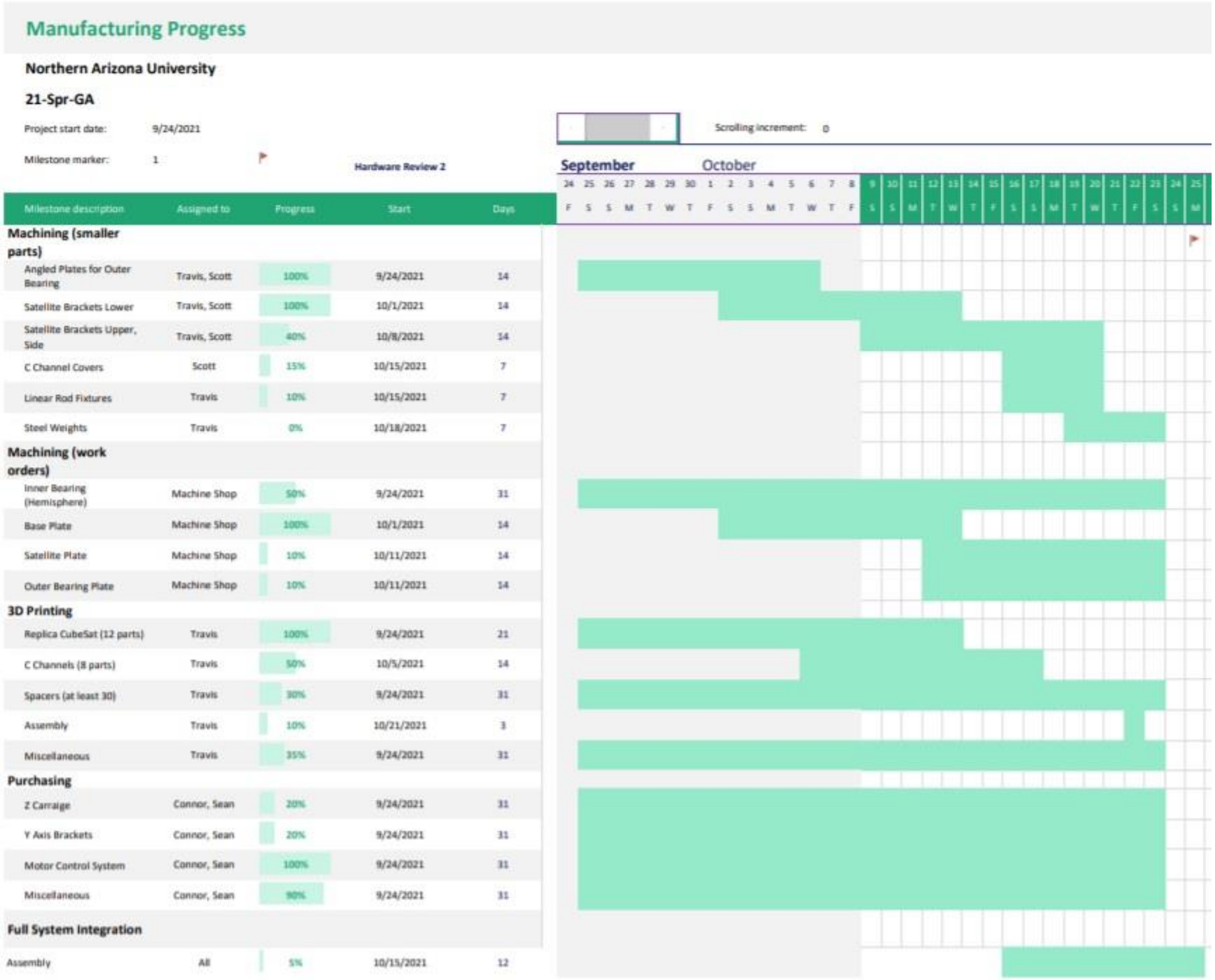
The following section will detail the plans for the remainder of the design and implementation of the system. It will discuss the remaining design choices to be made, rough schedule for manufacturing and assembly, and current plans for testing and alterations of the design that may be necessary. A Gantt chart will be provided to show the schedule that the group intends to stick to completing the project on time.

4.1 Further Design

Manufacturing of several aspects of the project is already underway. The base plate, inner bearing (hemisphere), satellite plate, and outer bearing stand have already been submitted to the machine shop and are in the process of being made by the staff there. Several of the smaller parts have also been started by a few members of the group that have taken the necessary training to work in the shop. The angled plates for the outer bearing that hold the transfer roller bearings are complete and considerable progress has been made on the satellite brackets. The other parts that are being manufactured outside of the group such as the bent sheet metal parts have been submitted and are being sent to us. The 3d printed satellite is nearing completion as well.

If there are no unforeseen mechanical problems, all manufacturing elements for this iteration of the project have been accounted for and are either complete or in the process of being done, either by the machine shop staff, the group members that are working there, or one of the companies that we are purchasing from. All 3d printed parts of the project are currently on schedule as well, with only minor setbacks from running out of filament briefly between shipments and a few days of the printer being down when the part cooling fan broke.

Over the next few weeks, the remaining satellite brackets, covers for the 3d printed CubeSat, and linear rod fixtures will be machined by the group members that are able to work at the shop. The steel stock will also be cut down to appropriate lengths on the band saw to function as the weights for the CubeSat. The remaining work orders will be completed within approximately two weeks as well depending primarily on the time that the outer bearing takes on the Haas. The last of the 3d printed parts are expected to be completed within no more than two weeks, based on the estimated arrival time of the next order of filament. Once that is complete, the part can be J.B. Welded together and used shortly after for testing purposes. Figure 19 shows the Gantt chart for the expected timeline of the remaining manufacturing parts to be completed.



Manufacturing Progress

Northern Arizona University

21-Spr-GA

Project start date: 9/24/2021

Milestone marker: 1

Hardware Review 2

Milestone description	Assigned to	Progress	Start	Days
Machining (smaller parts)				
Angled Plates for Outer Bearing	Travis, Scott	100%	9/24/2021	14
Satellite Brackets Lower	Travis, Scott	100%	10/1/2021	14
Satellite Brackets Upper, Side	Travis, Scott	40%	10/8/2021	14
C Channel Covers	Scott	15%	10/15/2021	7
Linear Rod Fixtures	Travis	10%	10/15/2021	7
Steel Weights	Travis	0%	10/18/2021	7
Machining (work orders)				
Inner Bearing (Hemisphere)	Machine Shop	50%	9/24/2021	31
Base Plate	Machine Shop	100%	10/1/2021	14
Satellite Plate	Machine Shop	10%	10/11/2021	14
Outer Bearing Plate	Machine Shop	10%	10/11/2021	14
3D Printing				
Replica CubeSat (12 parts)	Travis	100%	9/24/2021	21
C Channels (8 parts)	Travis	50%	10/5/2021	14
Spacers (at least 30)	Travis	30%	9/24/2021	31
Assembly	Travis	10%	10/21/2021	3
Miscellaneous	Travis	35%	9/24/2021	31
Purchasing				
Z Carraige	Connor, Sean	20%	9/24/2021	31
Y Axis Brackets	Connor, Sean	20%	9/24/2021	31
Motor Control System	Connor, Sean	100%	9/24/2021	31
Miscellaneous	Connor, Sean	90%	9/24/2021	31
Full System Integration				
Assembly	All	5%	10/15/2021	12

Figure 19: Manufacturing Progress and Schedule

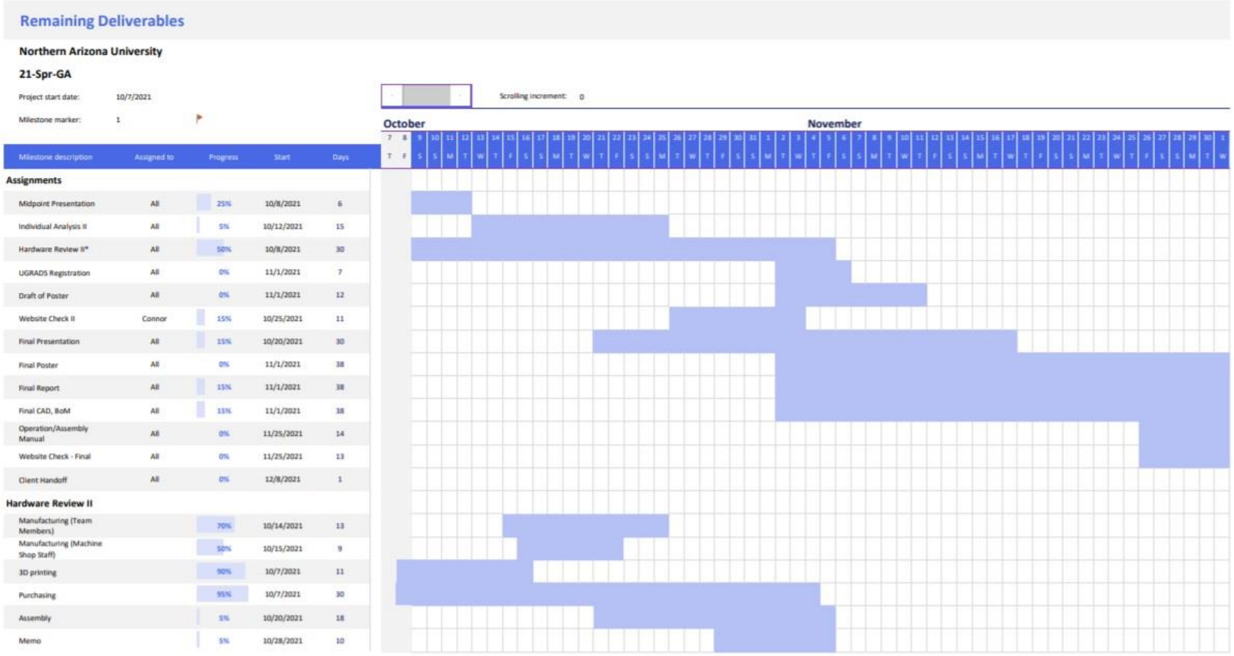
The difficult and time-consuming manufacturing processes were focused on first to ensure sufficient time to complete them. The 3D printer owned by one of the group members has also been running nearly constantly for multiple weeks and has already gone through over 7 kg of filament. Despite the given percentages, the overall completion of the manufacturing is ahead of schedule to be complete before

Hardware Review 2 as most of the difficult parts have already been machined or printed. The other benefit to this is that the slight setbacks that have occurred such as the part cooling fan breaking on the 3D printer rendering it inoperable for a few days or requests for redesigns to simplify the machining process from the shop have not set us back too far and we are still expected to have the full system assembled before the second hardware review.

A few minor changes are expected to need to be made if parts do not meet the requirements or if different aspects of the project do not mate properly. This will be done as is necessary throughout the remainder of the time dedicated to this project. In order to prevent issues in the future, we have pre-emptively ordered some additional stock material and 3d printer filament to lessen the lead time of any parts that need to be redesigned. It is also our hope that as more of the parts are completed or are delivered, some of the sub-assemblies can be assembled and it will be known early if there will be need for redesigns.

4.2 Schedule Breakdown

As manufacturing of this iteration is nearing completion, the next step, barring the need for major redesigns due to mechanical issues, will be focusing on testing and implementation of the coding aspect of this project. Significant work has already been done towards the setup of the code and the process for which we intend to determine the center of mass of the system after the CubeSat is fixed. A bit of time is currently devoted to solving the initial coding bugs that are to be expected and ensuring that the system operates the way we intend it to. After the coding aspect of this project is running as intended, we will begin testing procedures to determine the efficiency of our system. Figure 20 details the current schedule of the remaining deliverables and the rough outline for how we intend to meet each delivery.



Remaining Deliverables

Northern Arizona University

21-Spr-GA

Project start date: 10/7/2021

Milestone marker: 1

Milestone description	Assigned to	Progress	Start	Days
Assignments				
Midpoint Presentation	All	25%	10/8/2021	6
Individual Analysis II	All	5%	10/12/2021	15
Hardware Review II*	All	50%	10/8/2021	30
UGRADS Registration	All	0%	11/1/2021	7
Draft of Poster	All	0%	11/1/2021	12
Website Check II	Connor	15%	10/25/2021	11
Final Presentation	All	15%	10/20/2021	30
Final Poster	All	0%	11/1/2021	38
Final Report	All	15%	11/1/2021	38
Final CAD, BoM	All	15%	11/1/2021	38
Operation/Assembly Manual	All	0%	11/25/2021	14
Website Check - Final	All	0%	11/25/2021	13
Client Handoff	All	0%	12/8/2021	1
Hardware Review II				
Manufacturing (Team Members)		70%	10/14/2021	13
Manufacturing (Machine Shop Staff)		50%	10/15/2021	9
3D printing		90%	10/7/2021	11
Purchasing		95%	10/7/2021	30
Assembly		5%	10/20/2021	18
Memo		5%	10/28/2021	10

Figure 20: Remaining Deliverables Gantt Chart

Most of the deliverables are self-explanatory and will be completed as the due date approaches with the necessary time for each assignment allotted based on the Gantt chart above. As the primary focus of this memo is to detail how we will go about completing what is necessary for the second hardware review, additional focus was placed on the subsections of that assignment. The same process will be done for the larger remaining assignments as the due date approaches. Outside of the pre-determined assignment structure, there will be additional focus placed on testing the system and integrating everything once the manufacturing is completed. Some work has already been done on the coding aspects of this project, but it will be difficult to accurately state the progress on that until we are able to properly test the system with all the parts integrated together. In order to prepare for testing, some discussion has already been held on how we intend to test the system.

Our current testing plans are as follows:

1. A design of experiments will be formulated to test a single aspect of the overall system corresponding to the engineering requirement that we are questioning if we have met. For this example, the testing plan will refer to the ability to accurately determine the center of mass.
2. The experiment will be conducted, and results will be recorded. For this example, we will have all parts of our design measured and will calculate the center of mass of the system we are using by hand based on the configuration of the weights in the replica CubeSat. We will then compare this to what our system has determined the center of mass to be through the IMU measurements and remote calculations that are performed. For the x and z directions, this can be confirmed visually based on the orientation of the system, but the y center of mass will have to be confirmed analytically.
3. Our test results will be compared with the expected results to see if the engineering requirements have been met. If they have, the results will be recorded, and the next engineering requirement will be addressed. If not, the system will be modified until we are able to meet the requirements within our allowed tolerances.

As this process is iterative, this will take a significant amount of time and will continue until all requirements are met or the timeline for the project has expired. The exact time in which we will start this process is to be determined based on the completion of the manufacturing elements and the time it takes to integrate the motor control system.

With this schedule determined for each of the smaller deliverables, and particularly for the manufacturing elements of the project given how many there were to account for, it should be relatively easy to remain on track and have the project completed on schedule. In the event of major mechanical issues that require redesigns, it is our hope that we are far enough ahead of schedule to still be able to have a functional design in such an event.

5 Appendices

5.1 Figures

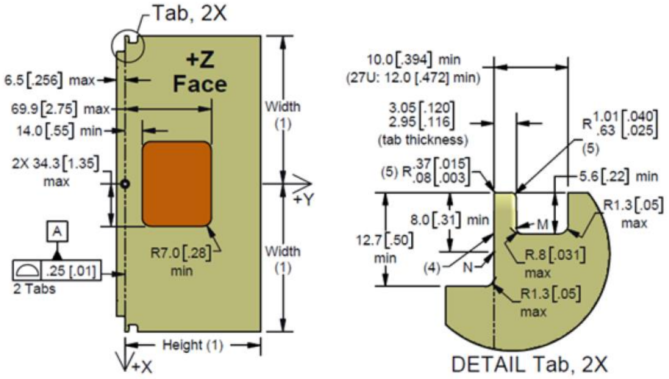


Figure 21: Satellite rail dimensions in mm (inches bracketed) [1]

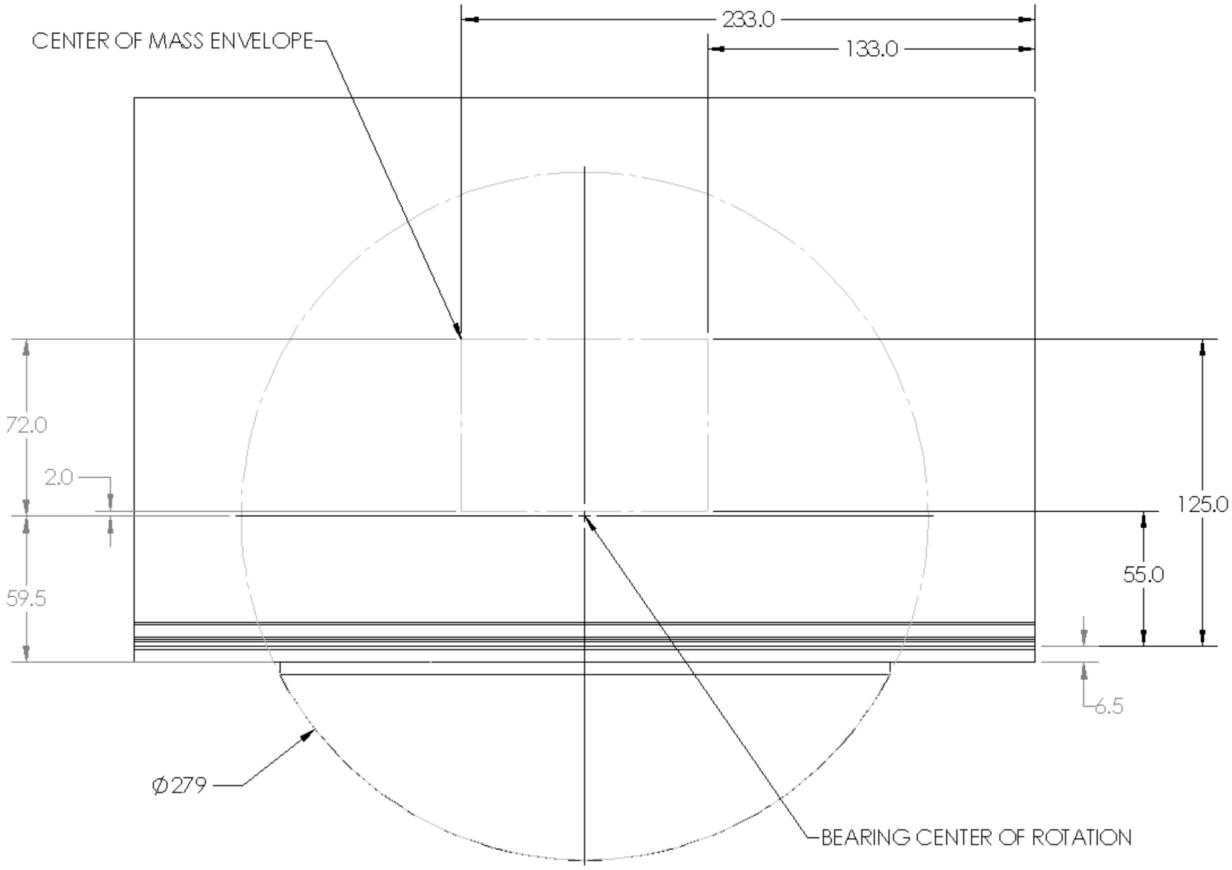


Figure 22: 12U CubeSat mounted directly on inner bearing

5.2 References

[1] Planetary Systems Corporation, "Payload Specification for 3U, 6U and 12U," 06 08 2018. [Online]. Available: https://www.planetarysystemscorp.com/wp-content/uploads/2018/08/2002367F-Payload-Spec-for-3U-6U-12U.pdf.