Progress Report: Structural Analysis for Large-Scale Space Domain Awareness Simulator

Hours Worked per Week: 9

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Abstract

The Space Systems Design Studio (SSDS), led by Dr. Mason Peck at Cornell University, is a research group dedicated to developing advanced spaceflight technologies and demonstrating these innovations through flight experiments. In this particular project, SSDS is interested in creating a large-scale space domain awareness simulator and testbed. The Large-scale simulator consists of two spacecraft, one on a three-axis spherical air bearing with unconstrained dynamics and the other constrained by a six-degree-of-freedom tensegrity actuation system. In this report, we are concerned with the structural modeling of the former spacecraft. We will mainly cover the requirements for the spacecraft, a design trade-off analysis for each structure, and the future of this project.

Introduction

Space Domain Awareness (SDA) involves understanding nearby resident space objects and inferring their intent to inform tactical decision-making through spacecraft autonomy or human command systems. Some key objectives for space domain awareness include: detection of resident space objects, predict atmospheric entry, predict interference in operations, and discriminate objects in the context of missile defense. Our primary focus is on the performance of the large-scale simulator in mimicking a cislunar space environment, driven by the growing advancements in in-space assembly, manufacturing, and the increasing affordability of space access. To explore this, following requirements drive the design of the spacecraft model mounted on the spherical air bearing:

Requirements

- 45 degrees of rotational freedom from air bearing in all directions
- Flight-like appearance
  - Aluminum honeycomb, solar arrays, docking ring
- Cone of view for star tracker
- Support all components and fit all components within structure
- Spacecraft is ~1000 kg with all components

Although flight-like appearance is a requirement, it is ideal for the spacecraft to behave as rigidly as possible. Thus, the spacecraft members will be rigid, non-deployable systems. This includes both the docking ring and the solar array. The spacecraft must also be capable of housing all components within the structure. These components include a cold-gas propulsion system, four control-moment gyros, a high performance IMU, a star tracker, and onboard electronics. Furthermore, the structure must house a proper mechanism that can integrate with the lifting system.

Below is a table of all group members involved in the large-scale space domain awareness simulator:

Table 1: Large-Scale Simulator Team Members and Roles

Name	Role
Ben Gerard	Propulsion for the large-scale simulator
Gabriella Elcsics	Control-Moment Gyros for the large-scale simulator ACS
Hannah Epstein	Structures Lead and Team Lead
Hunter Chubik	Avionics Lead and Finance Lead
Juan Pelaez	Mission Operations Lead
Justin Bak	Structures Modeling for the large-scale simulator
Maria Boza	IMU for the large-scale simulator ACS
Michelle Mobius	Structures design for the large-scale simulator
Nidhi Sonwalkar	Attitude Control Algorithms & Flight Software for the large-scale simulator
Robert Bergbaum	Attitude Control Algorithms & Flight Software for the large-scale simulator
Spencer Bullen	Attitude Control Algorithms & Flight Software for the large-scale simulator

In addition to the project team, a schedule for the project is included below:

Table 2: Project Schedule

Date	**Milestone**
August 2024	Cornell Kickoff
September 2024	UMN/Cornell Collaboration kickoff
October 2024	Small-Scale Simulator operational
November 2024	Upgraded small-scale simulator operational
December 2024	Large-scale simulator PDR
February 2025	Large-scale simulator CDR
March 2025	Begin fabrication of large-scale components
April 2025	Installation of cable mounts and motors complete
May 2025	High Bay Construction complete
June 2025	High-Bay starfield and paint complete
August 2025	Tensegrity control complete
September 2025	Large-scale simulators functional in high bay
October 2025	MOC complete (demonstration complete)

Design Review

The analysis of this section focuses on the three main designs developed for the large-scale spacecraft mounted on the spherical air bearing. The driving requirements for the geometry of these designs are the rotational freedom of 45 degrees, which we discussed in the requirements section, and one indirect requirement not previously discussed. This requirement is to minimize the machining of the honeycomb panels required for the design. As these honeycomb panels are typically sold in rectangular dimensions with Imperial units (ft), a rectangular prism of 5 by 5 by 4 feet (length $\times$ width $\times$ height) is created to meet both previously discussed requirements. From this derived rectangular prism, three designs are created, each of which prioritizes different requirements. The Space Systems Design Studio is working in tandem with the University of Minnesota on this project. As the University of Minnesota are primarily responsible for the design of tensegrity system which holds the second large-scale spacecraft, it is important to establish an envelope which the structure of the grounded spacecraft spans. This way, the tensegrity system can be designed to avoid this envelope. As the outer geometry of the spacecraft is fixed at this point, this envelope is created by sweeping this geometry around the center of rotation, with 45 degrees of freedom in each direction. This envelope can be found in Appendix I.

COTS Design

The Commercial-off-the-Shelf (COTS) Design is driven primarily by the use of commercially available parts. In this design, the only custom parts used are the bumper for the spherical air bearing and the plate that connects to the spherical air bearing. Joint brackets are mounted on the base of the spherical air bearing plate to a square cross section, ensuring the star-tracker field of view. This cross section is then connected via more joint brackets to the top section of the spacecraft. This provides structural integrity within the spacecraft; however, the use of joint brackets is not optimal for rigidity. Furthermore, the nature of the rectangular prism derived from the requirements is not conducive to a simple truss structure beneath the honeycomb panels, as seen in Figure 2 and 3. This leads to redundant bracketing, which is not only inefficient from a structural standpoint but also impedes the manufacturing process and drives cost up unnecessarily. Thus, the COTS design is viewed as a fallback option, as the structural integrity of the design is sound.

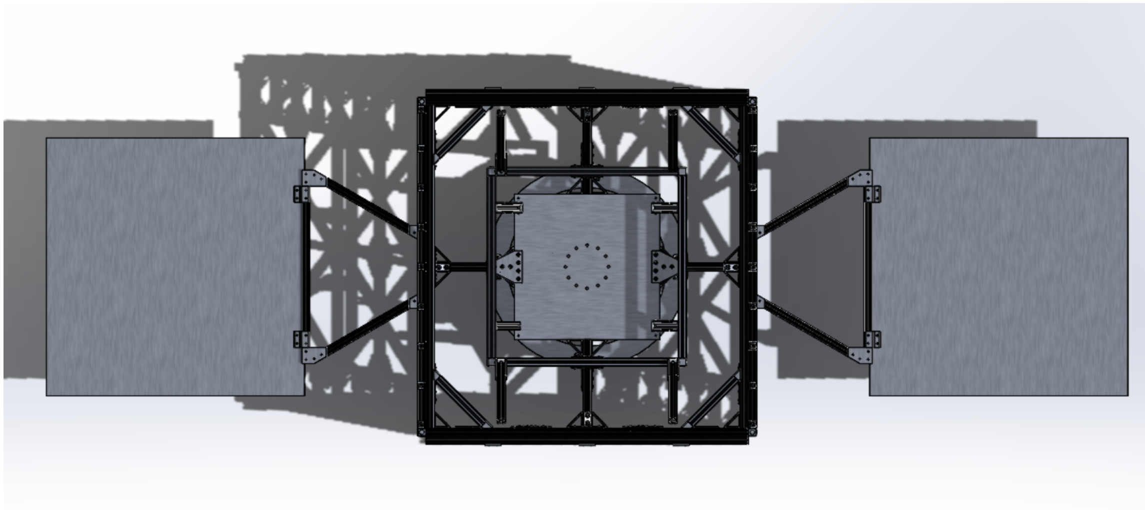


Figure 1: COTS Design Top View

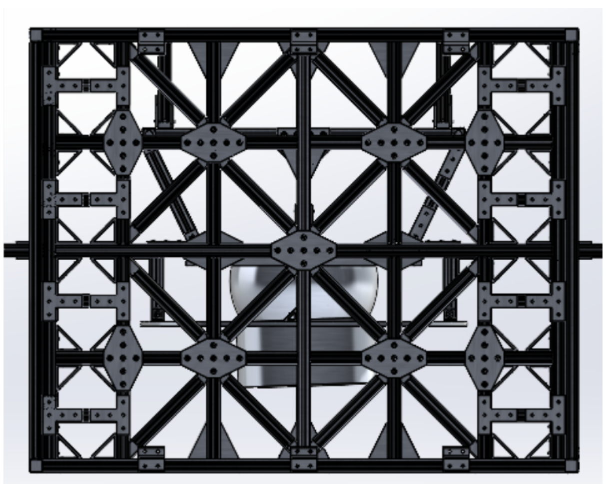


Figure 2: COTS Design x-z Plane

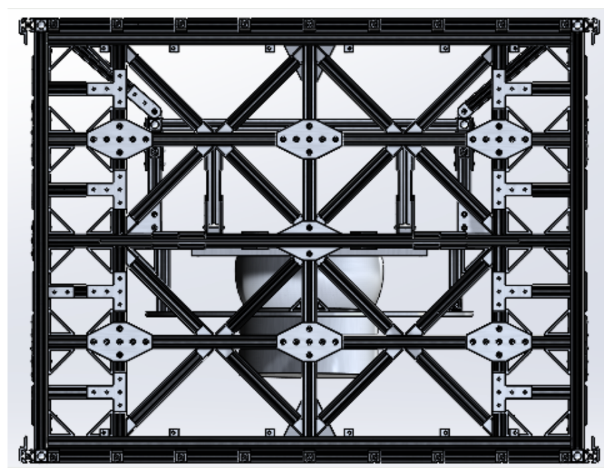


Figure 3: COTS Design y-z Plane

Custom Design I

The logic behind both Custom Design I and II is that the honeycomb panels themselves are capable of resisting large amounts of shear. Thus, a simpler inner-truss design connecting the nodes of the outer shell and the inner bearing system is created. The first design aims to create a fully custom inner-truss system, which is held together via welding or another rigid connection technique. One advantage of this design is the ability to create a perfectly rigid inner structure. In addition, Custom Design I establishes a bumper system on the top and bottom planes of the outer structure. This feature is desirable as the outer sections can connect directly to a rigid body, making the spacecraft resistive to shear in both x and y directions. Furthermore, the outer bumpers create a well-defined volume for integrating other spacecraft components and effectively establish the star tracker's field of view. The outer bumper rings are connected to the outer structure via commercially-off-the-shelf panel connectors.

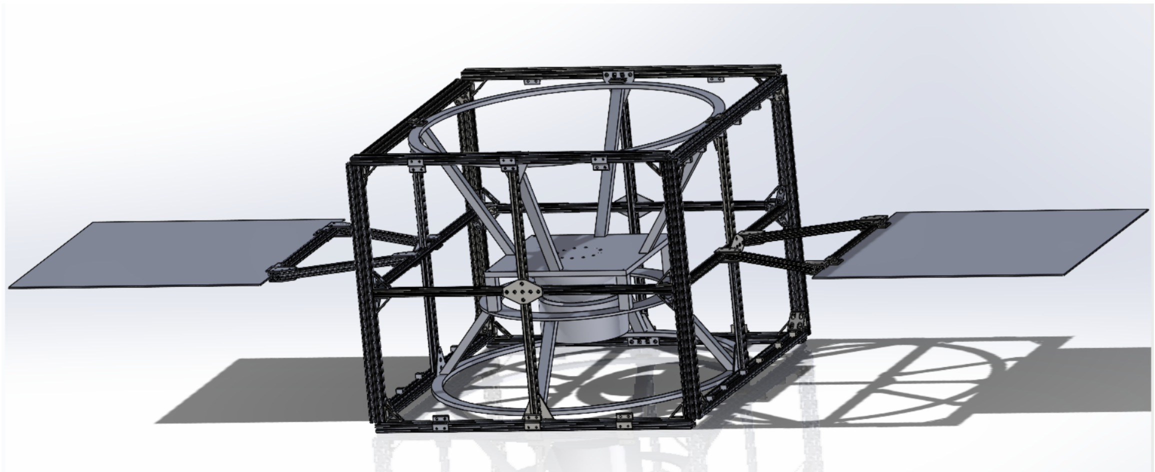


Figure 4: Custom Design I Isometric View

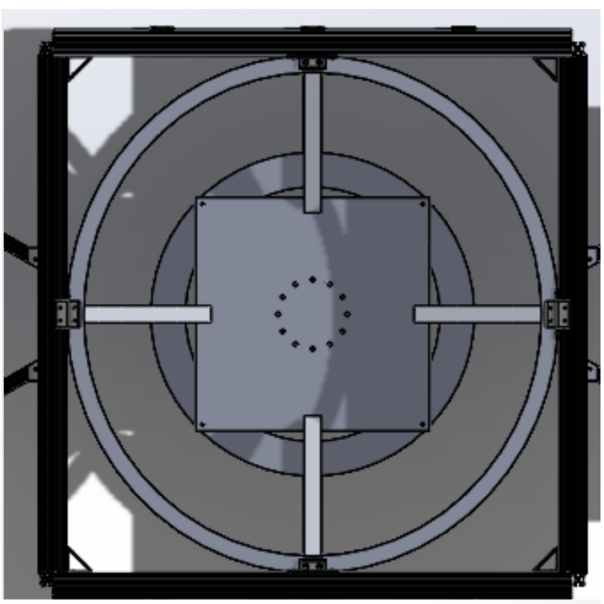


Figure 5: Custom Design I Top View

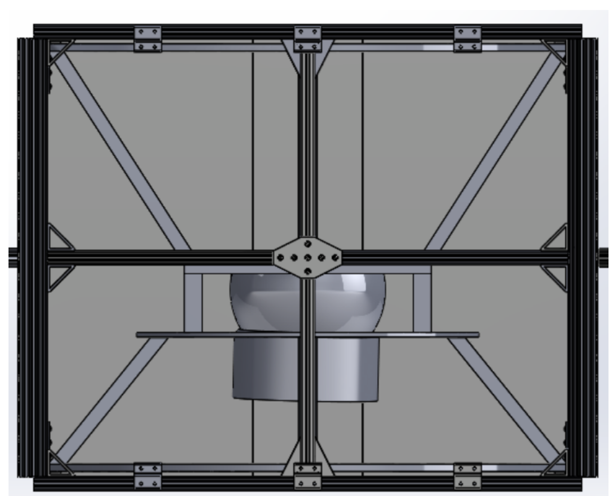


Figure 6: Custom Design I Side View

Custom Design II

Custom Design II aims to provide an internally rigid structure while mitigating custom parts machining. This is accomplished by creating custom parts that connect to 80/20 aluminum parts on the corner nodes of the outer structure and on the spherical air bearing system. This effectively resists bending in all three-dimensional directions with use of additional braces on the top and bottom panels of the spacecraft. One design consideration is the structural integrity of the connections between the 80/20 truss members and the custom parts.

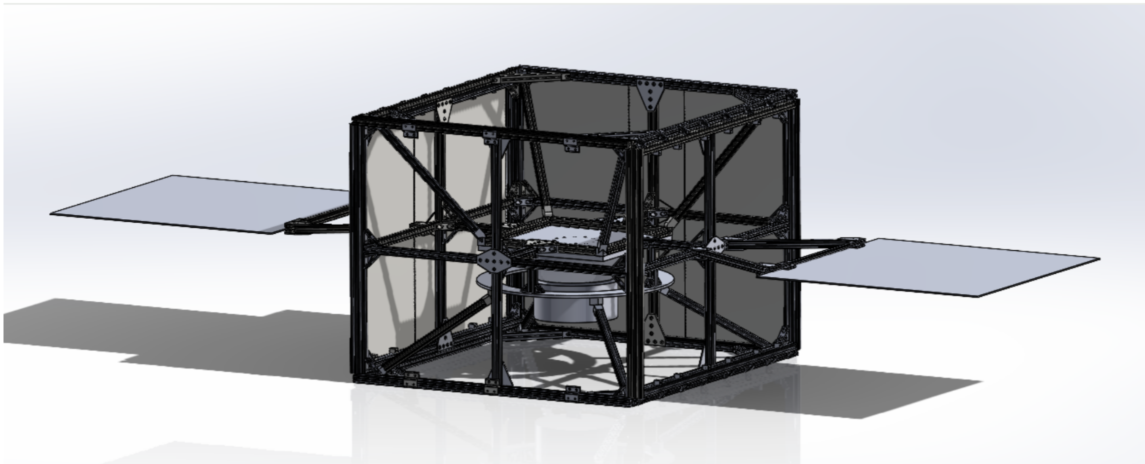


Figure 7: Custom Design II Isometric View

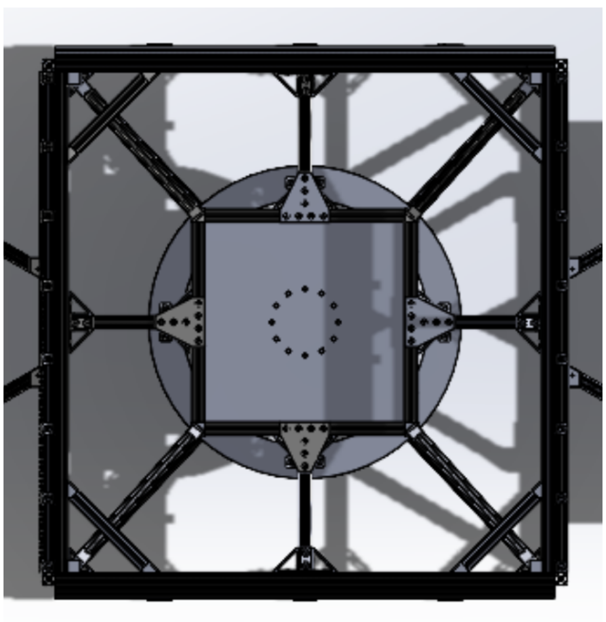


Figure 8: Custom Design II Top View

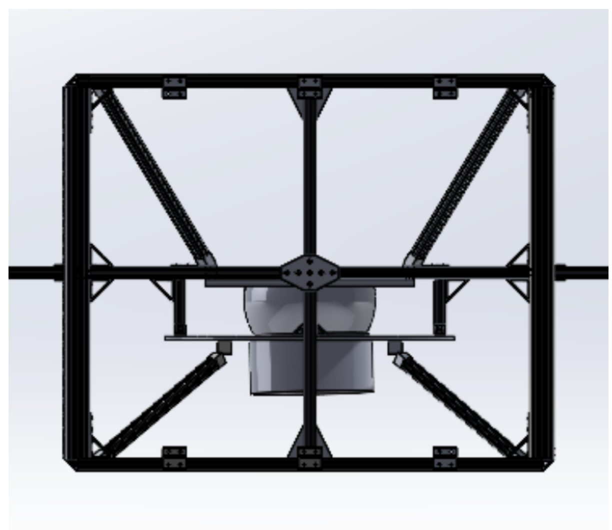


Figure 9: Custom Design II Side View

Custom Parts

The custom parts created for Custom Design II are shown below:

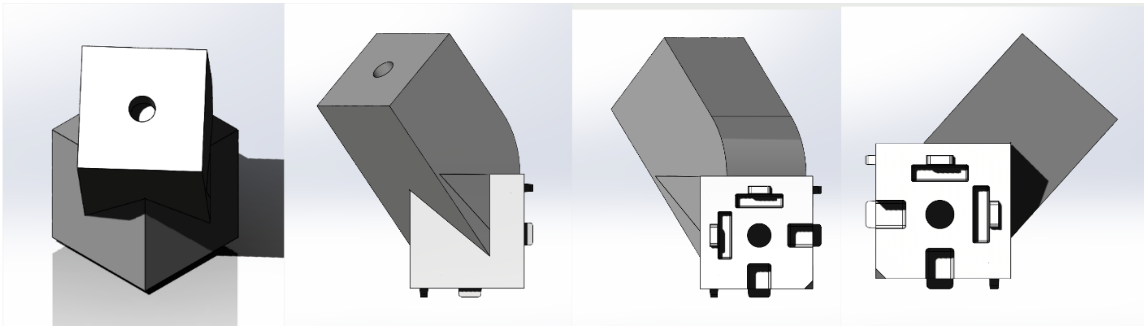


Figure 10: Custom Part I

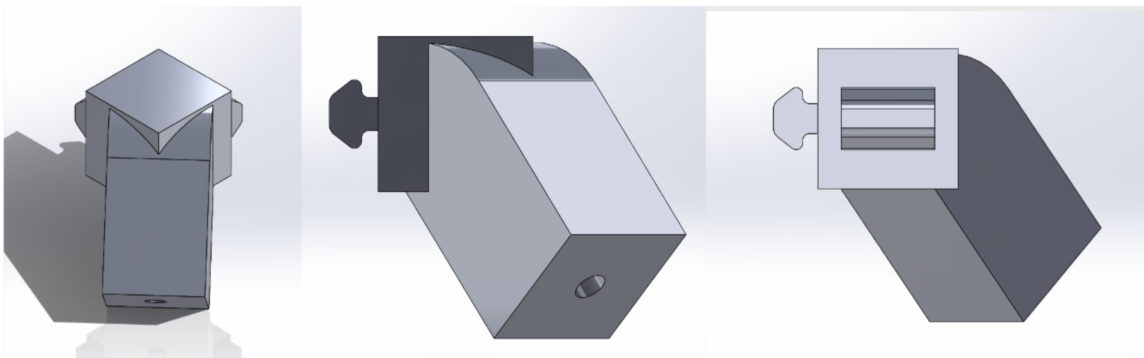


Figure 11: Custom Part II

The custom parts are created to join with the 80/20 members seamlessly to create an efficient inner-truss structure. The design of the custom parts in Figure 10 and Figure 11 vary with respect to the members they are connected to. The only change in design of these parts are the angles of the planes to which the connection to the 80/20 beams are juxtaposed. The custom parts in Figure 11 connect to the outer corners of the spacecraft structure, while the parts in Figure 10 connect to the spherical air bearing system.

Comparison of Designs

In Solidworks Mechanical, Aluminum-6065 is assigned as the material for all parts in each design. Using the 'Mass Properties' function, the Table below is derived:

Table 3: Comparison of COTS, Custom Design I and Custom Design II

Design	Mass (kg)	Volume (m^3)	Surface Area (m^2)	Principal Inertia Matrix ($kg{\cdot}m^2$)
COTS	236.57	0.24	104.36	$\begin{bmatrix} 92.86 & 0 & 0 \\ 0 & 164.91 & 0 \\ 0 & 0 & 205.61 \end{bmatrix}$
Custom I	193.9	0.19	74.48	$\begin{bmatrix} 71.18 & 0 & 0 \\ 0 & 140.63 & 0 \\ 0 & 0 & 168.94 \end{bmatrix}$
Custom II	182.12	0.18	79.46	$\begin{bmatrix} 62.92 & 0 & 0 \\ 0 & 139.45 & 0 \\ 0 & 0 & 163.11 \end{bmatrix}$

In the table above, we compare the mass, volume, surface area, and the principal inertia matrix for each of the three designs previously discussed. It is important to note that the volume displayed in the table is the effective volume of the sum of all parts, and not the total volume of the geometry itself. Thus, the effective volume available for the other spacecraft components is verified through an independent geometrical analysis. The principal moments of inertia are used mainly as a sanity check, as the intended spin direction of the spacecraft is in the z-axis direction.

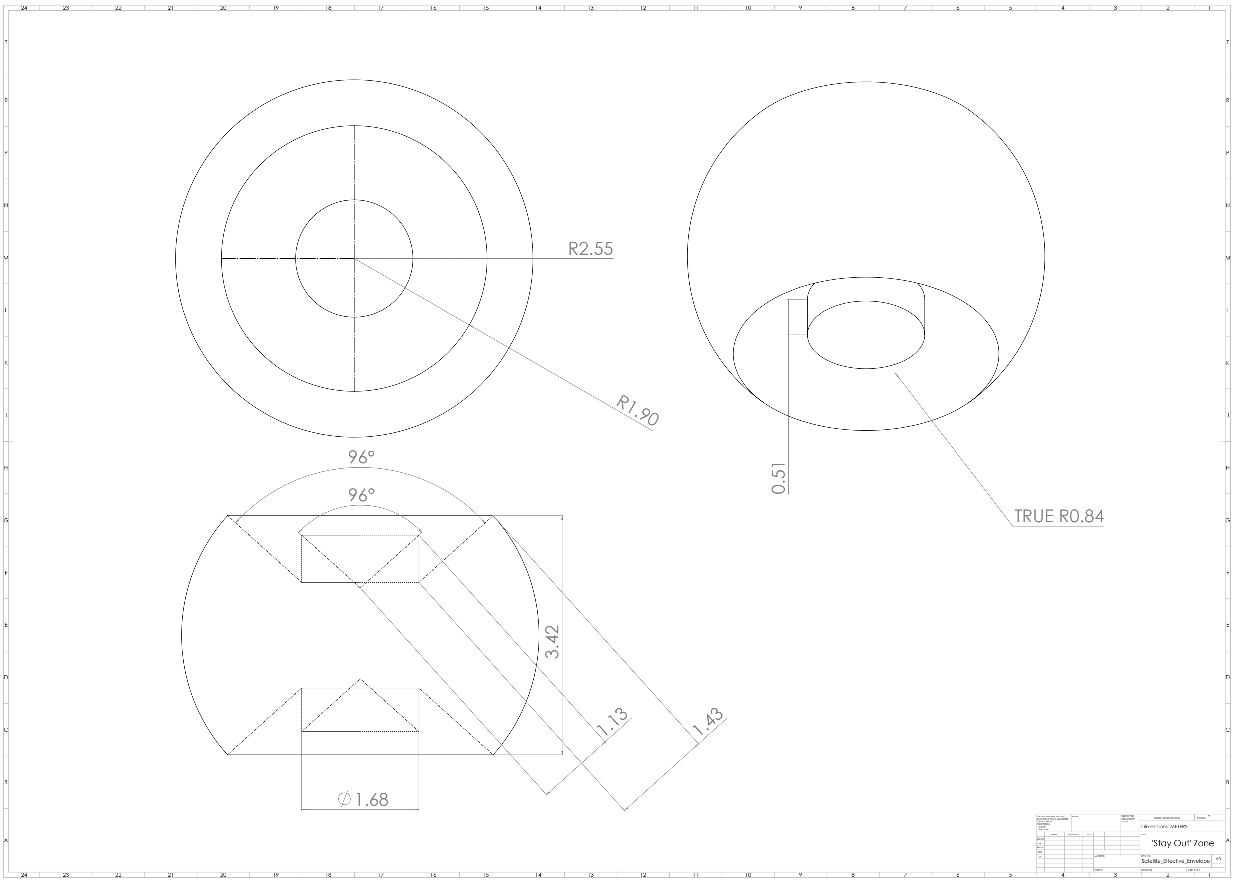
As all designs are in accordance with the mass requirement and spin-axis sanity check, the other requirements are analyzed to choose a design to continue the project. As discussed in the 'COTS Design' section, the COTS design has structural redundancies which over-complicates the manufacturing process and drives cost up. Therefore, the decision lies between Custom Design I and Custom Design II. Custom Design II aims to create a custom inner-truss structure while minimizing the use of machining, totaling 16 custom parts. While the creation of these parts is helpful from a manufacturing standpoint, there are questions in regard to the structural stability of these joints. In comparison, Custom Design I utilizes the ability of machining to create one rigid inner truss member, which connects directly to the outer spacecraft structure. As this structure is perfectly rigid, it is preferred as the design to move forward with in this project.

Action Items

With Custom Design I established as the design choice moving forward, several action items guide the ongoing development of the large-scale spacecraft structure. To determine the modal frequencies of the structure, its geometry undergoes a free-free analysis and a supported modal analysis in ANSYS Workbench. The fabrication process progresses through collaboration with vendors and coordination with the machine shop. The integration of all components within the spacecraft is also being established. Finally, the large-scale spacecraft structure integrates with the satellite lift mechanism in coordination with Juan Pelaez.

Appendices

Appendix I: Stay-Out Envelope



Appendix II: COTS Design Drawing