NASA Psyche Space Elevator

Final Report

Jarel Shahim
Kiefer Gonsalves
Kyle Ledda-Lewaren
Zachary Thomas

2025

PSYCHE

Project Sponsor: NASA Psyche Mission
Faculty Advisor: Sarah Oman

Oregon State University
College of Engineering

DISCLAIMER

ABSTRACT

The NASA Psyche Space Elevator Anchor project delivers the first comprehensive attachment system designed to secure a kilometer-scale space elevator tether to asteroid 16 Psyche's metallic surface. Working with Arizona State University's Psyche Student Collaborations team, our interdisciplinary team successfully designed, prototyped, and tested a 30 lb anchoring device addressing the unique challenges of extreme low-gravity metallic environments.

The system demonstrates autonomous deployment from a compact stowed configuration through four morphing legs equipped with sixteen triangular foot pads, enabling secure attachment across ±34 degree slopes. The sophisticated two-stage attachment approach combines 1,600 N electrostatic adhesion forces for immediate surface grip with permanent thermite bonding creating metallurgical joints for long-term security, achieving a safety factor of two relative to predicted loads.

Comprehensive validation confirmed the system's ability to withstand 100,000 N tensile forces while maintaining structural integrity through ±200 K thermal cycles. SolidWorks finite element analysis validated structural performance across all critical load paths. The development methodology emphasized rigorous risk assessment and iterative refinement through progressive prototyping campaigns from 3D printed mockups to full-scale additively manufactured aluminum and titanium components, ensuring all engineering specifications were met while maintaining manufacturing feasibility. The delivered technology readiness level four prototype provides a solid foundation for advancement toward flight-qualified hardware.

ACKNOWLEDGEMENTS

The team gratefully acknowledges:

Cassie Bowman – NASA Psyche Student Collaborations mentor

Dr. Sarah Oman – Faculty advisor, Oregon State University

Oregon State University Capstone fabrication staff (CapLab)

Oregon State University 3D Printing Club

Psyche Mission Systems Engineering team for technical reviews

Family and peers who provided feedback during design reviews

TABLE OF CONTENTS

Contents

1 BACKGROUND

1.1 Introduction

NASA's Psyche mission has launched an orbiter to a distant metallic asteroid. Upon arrival in August 2029, it will be the first space probe to explore a primarily metallic asteroid [1]. This is scientifically important because, as Weiss et al. speculated in 2023, Psyche is a planetesimal that could give scientists insights into a key phase of planet formation and see the interior of terrestrial planets similar to Earth [2].

In 2024, educational funding awarded to the Psyche mission provided an Oregon State University capstone team the opportunity to design a novel sample retrieval system for the Psyche asteroid. This first capstone team delivered a conceptual space elevator system. A space elevator is a cabled structure tens to hundreds of miles long and is anchored at opposing ends. One end is anchored to the surface of a celestial object like Earth (Terra), or for our design purposes, Psyche. The other end is connected to a space orbiter or station in a geostationary orbit. Many creative design concepts have been posed, most showing large oceanic cement and steel anchor platforms and large satellite shipping hubs as seen in **Figure 1.** Yet, no real products have been implemented and the materials necessary for its real-world application are currently unavailable in the required amount due to manufacturing limitations. However, this is fast changing, and a lot of work has been done in the field of material sciences that are making strides towards developing the methods necessary to manufacture these space age materials. There is much research worldwide into the properties of carbon nanotubes (CNTs), graphene and other materials based upon carbon [3]. These types of materials are necessary for the development of the space tether.

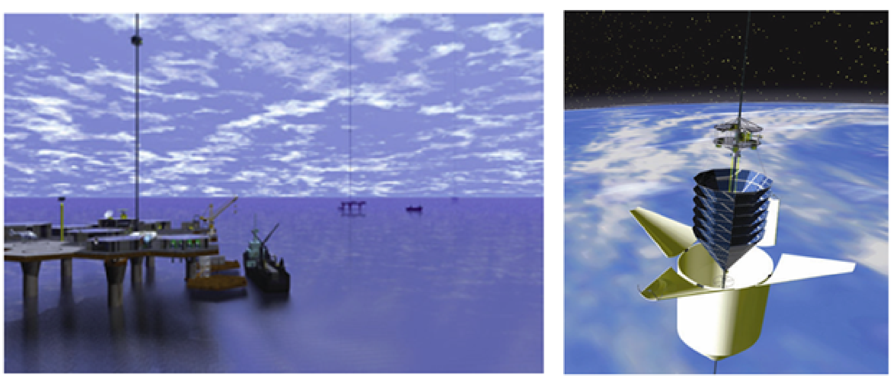


Figure 1. Space elevator foundations, and orbiting shipping hub [3].

The specific elevator design proposed by the previous capstone team uses electricity and a 550 km graphene super laminate tether to move payloads into orbit. Though a lofty concept, space elevator systems pose significant advantages over traditional approaches to landing on extraterrestrial surfaces:

- Limit risk exposure to the main space orbiter.
- Reduce landing costs.
    - o Less chemical fuel.

  - Less expensive landing vehicles.
- Ability to stop lander descent at any altitude with limited power requirements.
- Provide a foundational framework for repeatable return visits.
  - Increase applications for mining throughout and sample extraction.

In contrast, conventional landings generally require launching multi-million-dollar space vehicles into the dark, empty void to eventually make high-precision rendezvous and perform extremely risky landing sequences. Upon completion, usually only a single mission is completed and no space infrastructure is established to aid future endeavors, such as larger scale mining.

This document describes the design of the asteroid anchoring subsystem that will hold the space elevator's graphene super laminate ribbon to the surface of Psyche, as well as the conceptual anchor prototype that was produced, tested, and delivered to the NASA Psyche Mission, the sponsor of this project.

1.2 Project Scope

The NASA Psyche Space Elevator Anchor project encompasses the complete design, development, and prototyping of a surface attachment system specifically engineered for securing a kilometer-scale space elevator tether to asteroid 16 Psyche's metallic surface. This project represents a critical subsystem within the broader space elevator mission conceived by previous Oregon State University capstone teams, focusing exclusively on solving the fundamental challenge of reliable surface anchoring in the extreme conditions of Psyche's surface.

Project Goal:

- **Broad Scope:** Investigate the feasibility and utilization of space elevator technology for future asteroid mining operations on Psyche
- **Refined Scope:** Design and prototype an anchoring subsystem that securely interfaces with the space elevator tether and with Psyche's solid ferritic surface

Psyche: What it is and Why it Matters

We first must become familiar with the interface we are proposing to attach a space elevator tether to. While information is limited, some basic characteristics are provided by Arizona State University's (ASU) Psyche Mission FAQs [4]:

- Psyche is an asteroid approximately 150 miles in diameter.
- Psyche is theorized to be 30-60% ferrous metal, with more aspirational estimates suggesting it is solid metal and the remnant core of an early planetesimal.
- Psyche is estimated to have an average surface gravity of 0.144 m/s^2.
- Psyche is extremely dense, with estimates ranging from 3400 to 4100 kg/m^3.

- Psyche's gravity appears to be about 1.5% of Earth's gravity.
- Psyche experiences one solar day or one full rotation approximately every four hours.
- Psyche's high rotation rate implies an expected high thermal cycling rate with temperatures ranging from 200 K to 75 K between the day and night sides.

By understanding the in-situ surface interface and the dynamic load system we intend to operate in, we can glean useful information which will inform the design of the anchor. Such as:

- Materials – due to Psyche's high rate of thermal cycling, we need materials that have relatively stable thermal expansion properties in this range.
- Kickback – due to Psyche's low gravity, we have to consider how force loads applied to the surface will affect the landing vehicle's ability to stay in contact and not kick off, pushing it back into space.

Psyche is a unique and important environment not only for its potential in scientific discovery, but for its abundance of metal resources. Unvalidated estimates place Psyche's value at ten quintillion dollars. Though the estimated value of Psyche sounds ridiculously high, its gravitas lends to Psyche's viability as a planetary resource. Alone, the remnant planetesimal could provide precious metals to sustain the world's economical requirements for the next millennia. It could also provide the means for jump-starting a large-scale space manufacturing industry. Sending materials into space is expensive, risky, and ultimately exhaustive. Therefore, high-density, low-gravity, mostly metal behemoths like Psyche are primary candidates for humanity's growth into the stars. By utilizing Space elevator technology in conjunction with Psyche-like asteroids, we can develop a low-cost, steady supply chain of ethically sourced metal resources without depleting terrestrial-based reserves.

2 DESIGN PROCESS

2.1 Approach to Problem

To reiterate, the problem we are presented with is to attach the base end of a space elevator tether to an anchoring apparatus that interfaces with the solid ferritic surface of Psyche. To solve this problem, our design team utilized the following design process:

- First, perform preliminary research.
    - o Determine governing environmental factors.
    - o Analyze previous solutions to similar design problems.
- Second, gather, organize and categorize customer requirements.
- Third, turn customer requirements into engineering requirements.
- Fourth, develop solution concepts using a Morphology matrix.
- Fifth, analyze concepts utilizing a Pugh chart.
    - o Statistically weighing concepts feasibility to design parameters.
    - o Down selects concepts to inform design iteration.
- Sixth, prototype down-selected concepts.
- Seventh, perform refining research based on the prototypes' successes and pitfalls.
- Eighth, iterate (repeat steps as needed).

In the team's preliminary design iteration, we scoped out various methods for attaching to objects, including harpoons, nets, pinchers, wedges, and drills using a morphology matrix seen in **Figure 2**. However, each requires a physical connection with the surface and can have an array of mechanical components that could fail during the length of the mission.

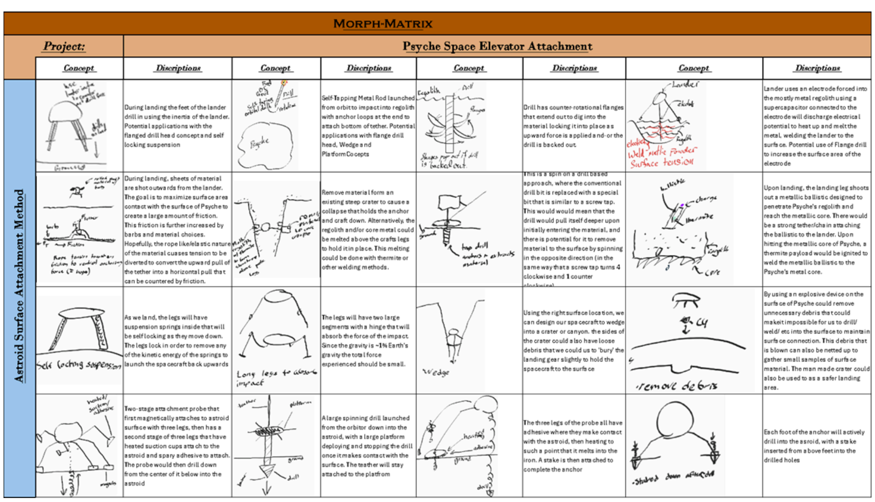


Figure 2. First iteration design morphology matrix for concept generation.

One innovative device that shined over all the others is the Electro-Static gripper (ESG) **Figure 3.** ESG's have been used in the commercial Semiconductor Manufacturing and in package handling [5] industries and have recently begun to make appearances in space attachment approaches for its flexibility and versatility. ESG's also come in various shapes, sizes, and orientations to maximize gripping forces. Electroadhesion can enable lightweight, ultra-low-power, compliant attachment in vacuum by using an electrostatic force to adhere to similar and dissimilar materials [5].

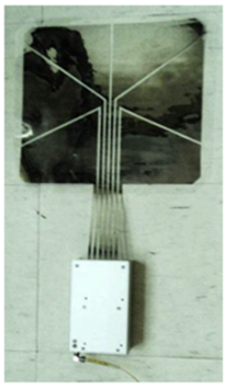



Figure 3. Industrial ES/EA Grippers From ElectroGrip, Co. and GrabIl, Inc.[4]

Another method that shined in the concept generation phase is welding the anchoring device to the surface of Psyche. There are several methods for welding:

- Cold-welding
- Ultrasonic
- Friction
- Induction
- Controlled explosive

Controlled explosive welding Figure 4. is the most promising welding method for our application. Explosion Welding is a solid-phase welding process in which explosives are used to combine components using high energy expansion waves to force components to fuse. With over 260 various combinations of similar and dissimilar metals and alloys having been successfully fused using this process [6].

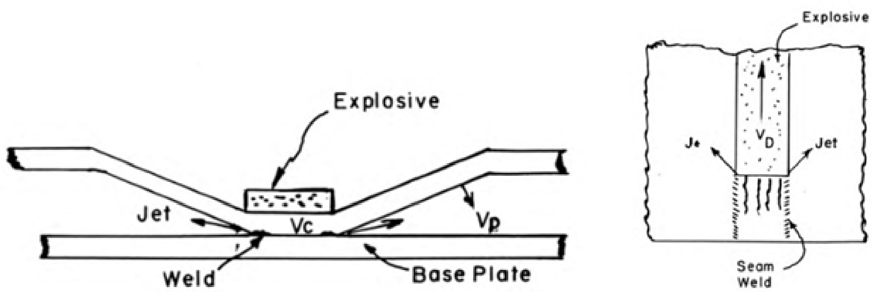


Figure 4. Schematic sketch of parallel plate configuration for NASA-LaRC explosion seam welding[5].

2.2 Customer Requirements to Engineering Specs

As shown in **Figure 5,** the House of Quality (HOQ) follows our design process to address the unique operational constraints imposed by Psyche's environment. This includes the gravitational field approximately 1% of Earth's strength, extreme thermal cycling between 1 K and 200 K, and an assumed predominantly iron-nickel surface composition. The anchoring mechanism must be able to demonstrate bidirectional load capacity exceeding 10kN in tension. Anchoring utilizes innovative hybrid adhesion technologies combining electrostatic forces for initial surface grip with permanent thermite welding for long-term attachment security. The entire anchoring subsystem must mesh with the space elevator tether and the sample delivery apparatus.

Customer Requirements (CRs) to Engineering Specifications (ESs)				
CR#	**CR Description**	**Weight (100 total)**	**Matching Engineering Specification**	**Targets with Tolerances**
1	Needs to be lightweight	5	Total Mass <= 1000 kg	15%
2	Relatively cheap to manufacture	5	Total manufacturing price <= $50 million	40%
3	Withstands temperature variations between night and day side of asteroid	15	Is able to withstand temperatures of ~ 1 - 200K	0%
4	Materials withstand solar radiation (UV)	10	Specific Heat Capacity >= 895 (J/ kg* K) (Al 6061-T6)	15%
5	Able to self-anchor in near-zero gravity environments	10	Is able to land and anchor while experiencing <1% of Earth's gravity (-0.106 m/s^2 minimum)	0%
6	Strong enough material to perform mandatory functions & withstand varied impact conditions	10	Shear Strength >= 205 MPa, UTS >=600 MPa, Yield Strength >= 385 MPa (Al 6061-T6)	5%
7	Able to attach to a solid metallic surface	10	Attach to asteroid composition & a Rockwell Hardness >80 HRB	25%
8	Ability to anchor with an uneven surface	15	Anchors can attach onto surfaces that have height differences of up to 10 meters, handle at least 34 degrees of tilt	20%
9	Ability to interface with tether device	5	Attachment points to each team concept	0%
10	Dimensional tolerance compatibility with other capstone team solutions and overall mission plan	15	Parts and attachments within 0.025 mm tolerance scale to other capstone parts	10%
	Sum	100		

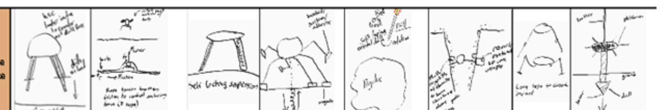
Figure 5. Approved and finalized HOQ.

2.3 Concept Generation (Use PUGH/Morph matrix)

Sixteen unique concepts were generated in a morphology matrix. They were then statistically analyzed using a Pugh chart as seen in **Figure 6.** The following design criteria were formulated from the customer requirements established in the HOQ:

- Lightweight.
- Cheap to manufacture.
- Ability to anchor with uneven surfaces.
- Ability to anchor to solid ferritic surfaces.
- Concept feasibility.
- Compatibility with space tether climber and sample delivery subsystem.
- Attachment speed.
- Successful attachment probability.

Scale 1-5
1 = Low Importance
5 = High Importance



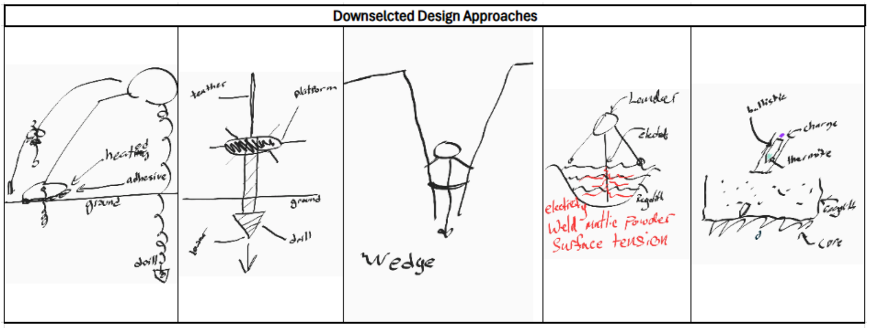
Design Criterion	Weight	Desgin Concpts							
Lightweight	3	1	0	1	0	0	1	1	0
Cheap to manufacture	1	1	-1	1	-1	0	1	1	-1
Ability to anchor in near-zero gravity environments	5	1	-1	-1	1	0	1	0	1
Ability to anchor with an uneven surface	4	0	1	0	1	0	-1	-1	1
Ability to anchor into both a Regolith & Iron-Rich surface	3	1	1	-1	0	0	-1	-1	1
Concept Feasability	3	1	1	1	0	1	1	1	0
Compatibility with other capstone team solutions	5	1	1	1	0	1	-1	0	1
Attachment Speed	2	1	1	0	0	1	1	1	1
Successful attachment probability	4	0	-1	0	1	0	1	-1	1
Anchoring system must be able to live for long time without use (>10 year)	4	0	0	1	1	0	1	1	1
Able to withstand abrasive debris	1	1	-1	1	0	1	1	1	1
Total:	35	Summary/ Results							
Total +1		8	5	6	4	4	8	6	8
Total -1		0	4	2	1	0	3	3	1
Total 0		11	10	11	14	15	8	10	10
Weight Average		65.71%	17.14%	25.71%	45.71%	31.43%	31.43%	8.57%	77.14%

Instructions for Pugh Chart Use In Concept Generation-Refinement

When down-selecting concepts generated in the Morph-Matrix we need to consider various Design Criterion in which to analyze our concepts for further refinement. We have given a weighted score of importance ranked from 1-5 for each design criterion. The design concept generated from the Morph-Matrix are scored (1 / 0 / -1) based on (Highly Meets/ Meets/ Does not Meet) the Design Criteria and a Weighted Average is generated to provide a Percentage of How well the design Satisfies the overall Design Parameters. A weighted average of 100% implies that the associated design concept is best suited for the parameters of the project, scores with a 70% or greater are considered possible design approaches. While anything less than 70% should be rejected from consideration.(Subject to Change)

Figure 6. Shows partial PUGH chart for first design iteration used to down select concepts for compatibility to design criterion.

Downselcted Design Approaches



Each of these designs meets our requirement of at least 70% of the weighted design criteria per approach, and will each be used to create a design that is 100% of our required criteria. They were graded on 11 metrics, with the highest weights of their ability to anchor in near-zero gravity environments & their compatibility with other capstone team solutions. From this selection, we plan to choose based on a team-specific set of criteria based on ability to CAD, a deeper look into concept feasability, induvidual team skill matrices, and sponser input & rankings.

Figure 7. Shows down-selected designs approached based off of PUGH chart for first design iteration.

2.4 Concept Selection

The ESG's and explosive welding were analyzed using the PUGH chart and given a weighted average score greater than 80% based on their compatibility with the design criterion outlined.. This provided the design with a solid direction in which to start prototyping.

The anticipated design solution utilizes ESG's panels fixed to triangular hinged mesh structures that will serve as the anchoring interface. The triangular living hinge mesh structures will allow for the panels to mold to most any irregular surface, optimizing the ESG's ability to make a proper connection point. The ESG that will inspire our future designs is shown in **Figure 8.** This ESG operates at 3 kV and has an electrostatic force of 3.5 N on Ge-coated polyimide film [7]. When considering its effectiveness on nonferrous surfaces, its potential anchoring force on ferritic surfaces is estimated to be greater. The triangular mesh structure will also allow it to fold up and away when not in use. At strategically located nodal points, controlled explosive welding devices will be integrated for hard docking applications.

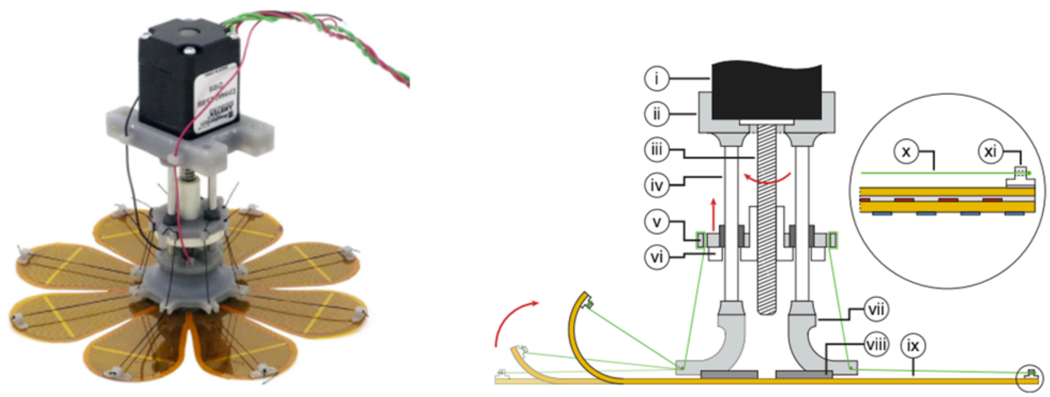


Figure 8. Fabricated Electrostatic Gripper and Schematic highlighting electrode pattern.[7]

2.5 First Physical Proof of Concept

Figure 9 shows the low fidelity proof of concept highlighting the key aspects of the proposed first term design. The rectangular frame is representative of a black box which will house the power supply, motors, actuators and computer-guided controls. The orange cloth shows the ability for living hinges to conform the feet structure to various orientations and surface conditions.

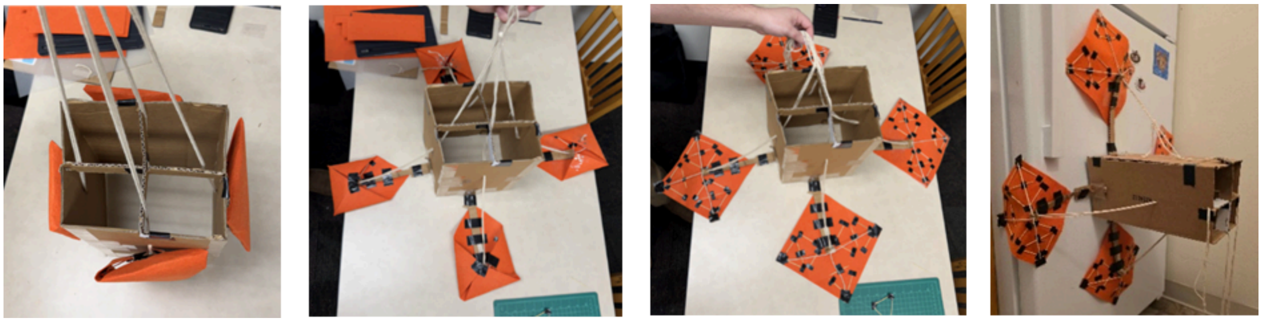


Figure 9. First iteration low fidelity prototype showing deployment process and mounting capability. Black tape represents nodal locations for explosive welding devices.

2.6 Design Iteration Method

In order to develop a higher fidelity prototype from our initial design concept, the product underwent significant changes to incorporate the following design methods, which guided the evolution to the final product.

- Finite Element Analysis (FEA)
    - Utilized to test the structural survivability of components based on material properties and applied loading scenarios that mimic the extremes the design would experience while in situ (i.e., when deployed on Psyche).
- Design for Manufacturing and Assembly (DFMA)
    - The design of the final product takes into account the key Tenets of DFMA
        - Simplification of Design
            - Foot Design was simplified to show key morphing applications.
        - Standardization of components and materials
            - Most structural and mechanical components are tested and poised to be space-grade Aluminium and Titanium alloys for strength-to-weight ratios that are ideal for space applications.
            - Impacts FEA
        - Tolerancing management
            - Intentional use of tolerancing management to incorporate friction and pressure fits for mechanical and structural components of different materials.
                - Allows for more desirable joining of components at significantly low temperatures. Cold welding of press-fit components is intended.
        - Environmental considerations
            - Radiation exposure is the leading cause of temperature variations in structural components.
                - Overscoped on project. More deliberate tests are required to analyze each component

        - Effective manufacturing processes
            - Metal Additive Manufacturing
                - Idealized manufacturing technique
            - Plastic 3D printing for cheap, high-fidelity prototypes
                - Mimics the idealized manufacturing technique
            - Potential Alternatives
                - 7-9 Axis milling of structural components
    - The importance of DFMA allows for cheaper production costs and faster throughput of production.
- Low Fidelity Production
    - Using 3D printed components to physically assess design functionality and potential modes of failure.

2.7 Key Design Limitations

The design iterations methods were chosen with consideration of the following:

- Team expertise concentrated in mechanical engineering rather than electrical or propulsion systems
- Academic timeline constraints requiring focused deliverables within two semesters
    - Limiting prototype to manufacture period
    - Limiting prototype construction to 3D printing
- Budget limitations necessitate prototype-level rather than flight-qualified materials and components
- Laboratory safety requirements limiting explosive welding testing to proof-of-concept demonstrations
    - The concept of explosive welding became a stretch goal for future design based on the complexities of integration

2.8 Summary

Considering the design iteration methods as outlined led to the final design within reasonable acceptability for projected deliverables. However, given the scope of the project, many considerations were neglected in the design, such as:

- Propulsion and Guidance Systems
- Power Requirements and Supply
- Thermite Bonding Activation System

These considerations were neglected due to the complexity of incorporation for the length of the project. The project addresses technology readiness level advancement from initial concept to demonstrated prototype functionality, providing essential validation of core technical approaches while identifying specific areas requiring continued development for eventual flight implementation.

3 Design Solution

This section presents the final anchoring system design that emerged from the systematic development process, documenting the key design decisions, performance validation results, and lessons learned throughout the implementation phase. The design solution represents the culmination of iterative refinement guided by finite element analysis, design-for-manufacture-and-assembly principles, and comprehensive prototype testing. While the ambitious scope of a complete space elevator system necessitated focused attention on the critical anchoring subsystem, the delivered solution successfully demonstrates all required functionality while providing a clear foundation for future development phases.

The following sections detail the final system architecture, quantify achieved performance against established specifications, and analyze the testing results that validate system readiness for a technology readiness level four (TRL-4) demonstration. Critical design modifications implemented during the development process are discussed alongside their technical rationale, providing insight into the engineering trade-offs that shaped the final configuration.

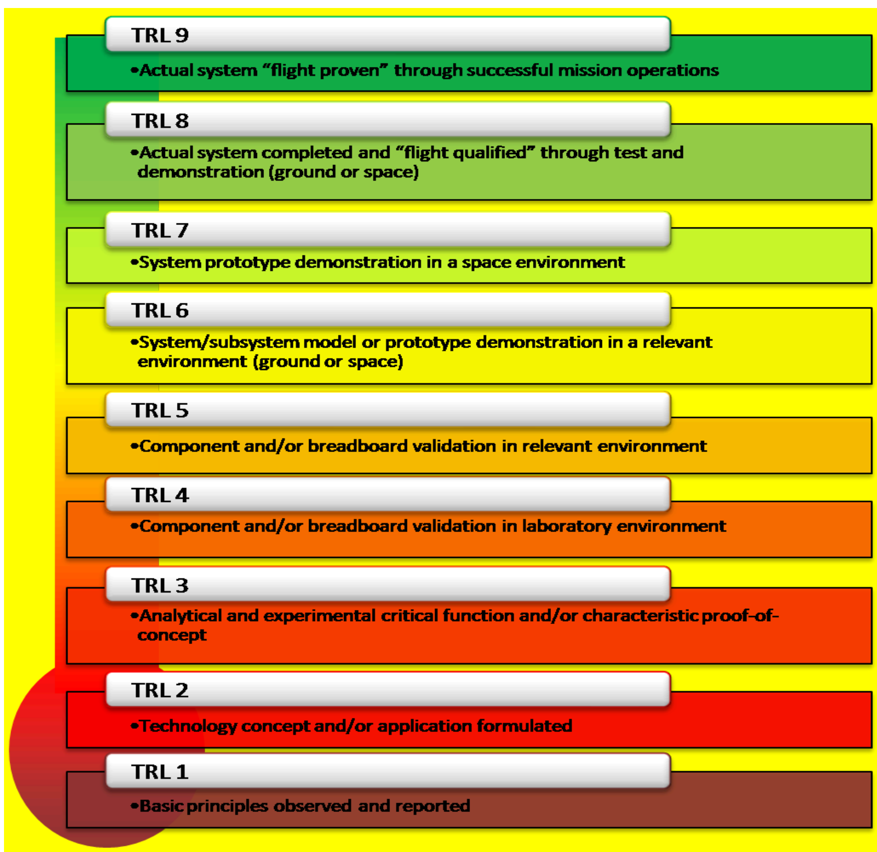
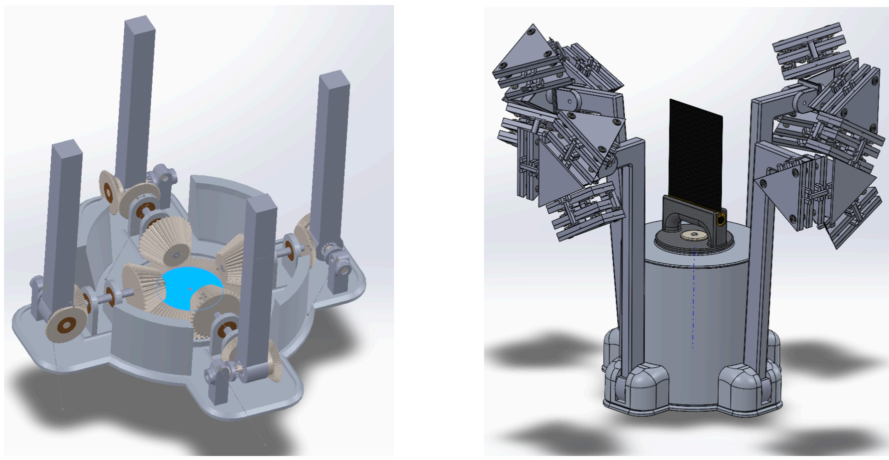


Figure 10: Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the project's progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest [8].

3.1 Beginning of Term Design

The team started off the term with the initial design as seen in Figure 1, which served as the foundation to build off of for the term. The initial design had some major flaws, but it served as the proof of concept for what was intended for the final design.



(A) First Iteration Gear System. (B) First Iteration of Full Concept

Figure 11: Main base structure of the driving mechanism

In Figure 11 (A), we have the main base structure of the driving mechanism for controlling the actuation of the legs and to arrest the legs from moving when the leg comes into contact with irregular surface conditions, as expected from the surface of Psyche. Figure 11 (B) shows the first iteration of the whole device connected to a mockup of the space elevator tether via a rotating gimbal with 2 degrees of freedom. It also shows the initial foot design in their stored positions. The foot design serves as a stretch goal to incorporate a compact multi-armature foot pad to interface with irregular surface conditions. The triangular design of the foot pads serves the purpose of guaranteeing surface contact between the foot pad and the surface due to the triangle's unique interaction between pivot points. The number of linkages between the foot pads lends to the degrees of freedom for which the feet can conform to large irregularities while ensuring the most surface area contact of the foot pad. The foot design is such that the shape, in conjunction with the intended method of attaching to the ferritic metal surface of Psyche, hinges on optimal surface area contact.

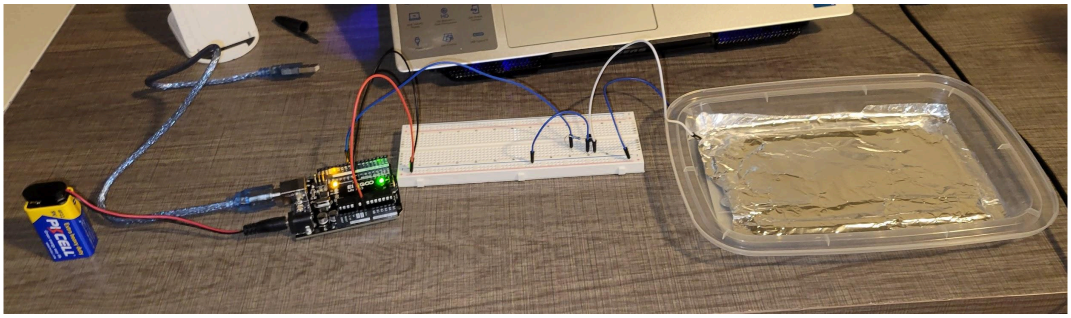


Figure 12: Electrostatic Adhesion Prototype.

The intended method for attaching the foot pads to the surface is based on the electrostatic force generated by parallel plate capacitors, based on our initial design as seen in Figure 12. This attachment method consists of placing thin flat electrode sheets separated by a dielectric barrier that prevents short circuit contact and promotes the induction of an electric field pulling the negative electrons from the negative (bottom sheet) electrode and surrounding negative electrons towards the positively charged (top sheet) electrode. The force generated by the parallel plate capacitor when subjected to Voltages upwards of 3 kV would be sufficient to attract a comparative attaching force of 1 Newton or approximately 0.25 lbf. per square inch of surface area contact. This was the starting point for our attachment method.

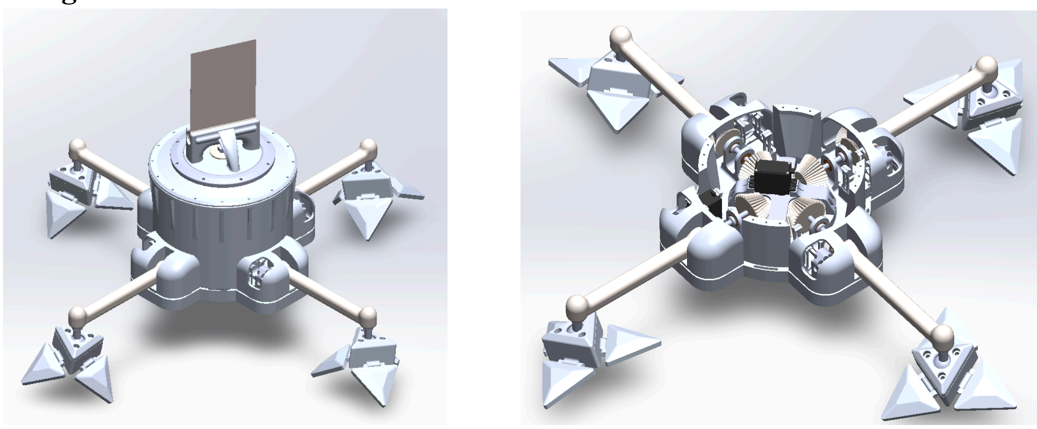
3.2 Description of Solution

The final anchoring system design represents a sophisticated integration of autonomous deployment mechanisms, adaptive surface interface systems, and hybrid adhesion technologies optimized for the unique operational environment of asteroid 16 Psyche. Building upon the iterative design methodology outlined in previous sections, the delivered solution successfully addresses the fundamental challenge of securing a space elevator tether to an irregular metallic surface while operating reliably in extremely low-gravity conditions.

The complete system architecture centers on a four-leg distributed design that provides redundant load paths and accommodates surface irregularities through independent leg articulation. Each leg incorporates 19 degrees of rotational freedom about its ankle joint, with individual foot pads capable of approximately 180 degrees of rotation about their hinge points. This extensive range of motion enables comprehensive surface conformance across slopes up to 34 degrees while maintaining optimal contact area for maximum adhesive force generation.

3.3 Project Results

3.3.1 CAD Design iterations

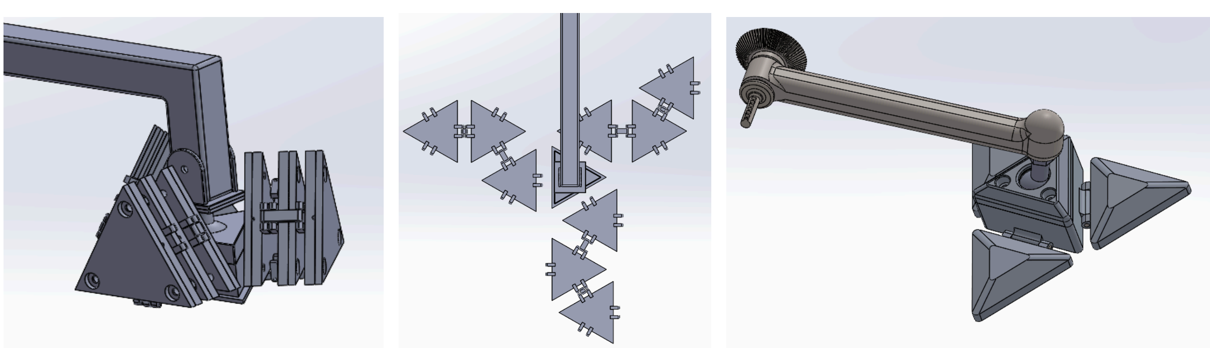


(A) Full Assembly (B) Main Assembly Interior View

Figure 13: Final Assembly

The team's final design is shown above in Figure 13 (A) and (B). When compared to the initial design shown in Figure 11, several vital aspects have changed.

- Incorporation of readily available components.
  - Impacted the design of the main base structure to allow for easy attachment of driving motors
  - Impacted Leg/Ankle pivot point for Leg/Foot Assembly
    - Simplified ball ankle to limit failure points
  - Required adjusting of Leg Caps/Pivot support structures to allow for component assembly.
    - Effective change made from low-fidelity production and physical assessment of assembly
- Incorporation of symmetrically distributed fasteners to ensure structural survivability through load distribution and stress localizations
  - Required FEA of loading on the tether and main housing
- Incorporation of the gimbal constraint ring to limit deformation when under load.

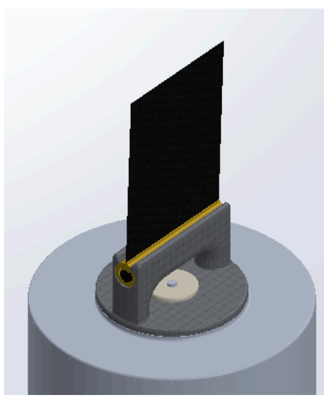


(A) Initial Foot/Leg Design (B) Initial Foot/Leg Deployed (C) Final Foot/Leg Assembly

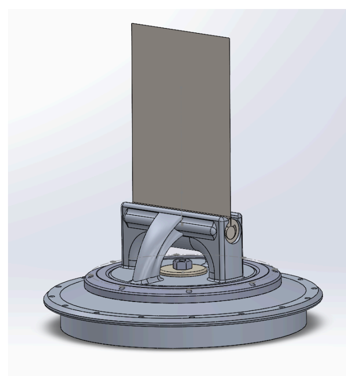
Figure 14: Final Leg and Foot Mechanism

As seen in Figure 14 (A), we have our final foot design, which allows for 19 degrees of rotation about the center point of the ankle, with each foot pad having approximately 180 degrees of rotation about the hinge points. As seen in our initial design, Figure 14 (A-B), the leg has been adjusted to incorporate aspects of DFMA as the main impactor for design iteration considerations. We were not able to incorporate foot pad articulations through control systems due to time constraints. However, the new design shows the validity of the surface conforming engineering requirements for attaching to irregular surface conditions.

- New additions to the design
    - Simplified foot design
        - Incorporation of readily purchased materials
    - incorporation of 100 lbf magnets per foot pad
        - Needed to adjust the design to include magnets over electrostatics due to the failure to prototype a successful electrostatic attractor device under earth-based environmental factors
            - Components purchased for the prototype are the most likely to contribute to the failure of the initial design prototype
            - Further iterative Research and Development (R&D) is required to show the validity of the electrostatic attractor mechanism



(A) Initial Top Plate Assembly



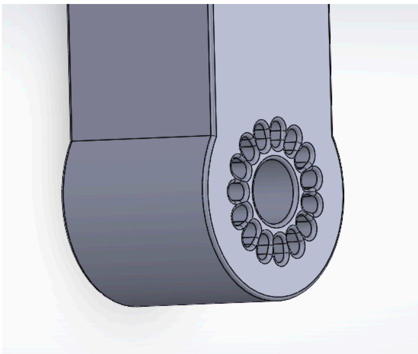
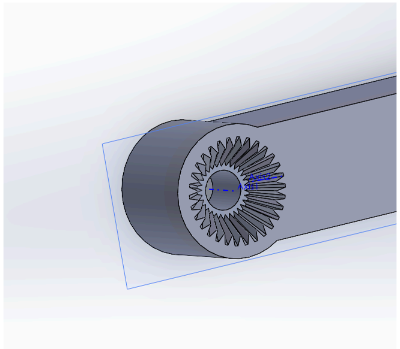
(B) FinalTop Plate Assembly

Figure 15: Top Plate Assembly & Tether Gimbal

In Figure 15, we can see the evolution of the design of the attachment point between the tether and the main structure. In (A), adjustments were made to turn the flat plate the gimbal is attached to in (B) to allow for a robust attachment structure interface between the tether and the main body.

- Final design incorporates a similar structure but constrains the attachment point between the tether holding keyway and the gimbal
    - Constraining ring interfaces with plate and gimbal to restrict the deformation potential from loading
    - Swept perpendicular bridge from plate to the side profile of the gimbal decreases the

potential for the keyway to deform open due to loading.
- Distributed fastener hole profile allows for simple assembly while maintaining rigid support between the main shell of the anchor housing

(A) Initial Leg Locking/Drive Interface (B) Final Leg Locking/Drive Interface

Figure 16: Leg Locking/Drive Interface Iterations

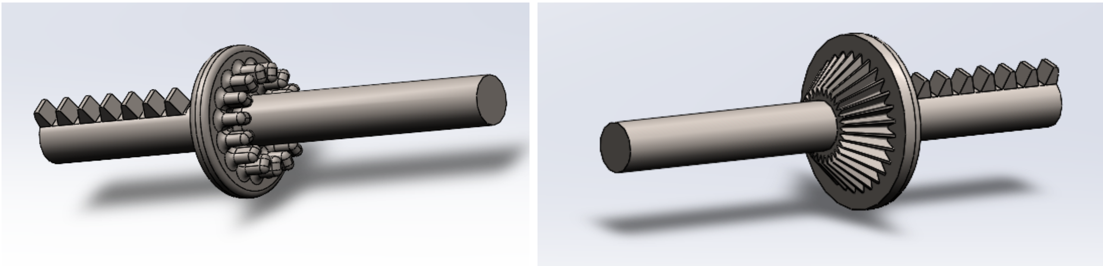
Figure 16 shows the interface of the locking/driving mechanism of the legs. In the final design of the leg's pivot point a geared interlock was required over that of pin style seen in (A) this change off was made for a smoother meshing interface with the locking pin and the drive gear as well as reduces the potential for stress failures from the thin walls connecting the axle hole with the main structure of the leg.

- FEA was utilized to show failure points of the Pin-hole structure in the initial design
- Physical prototyping of the locking mechanism showed shear failure of the pins on the gears when interfacing with the leg from misalignment.
- Final meshing interface reduces misalignment errors and shear potential under loading conditions.


(A) Initial Meshing Drive Gear (B) Final Meshing Drive Gear

Figure 17: Leg Drive Gear Iterations

Figure 17 shows the evolution of the meshing drive gear for the leg. (B) Shows the most current design of the meshing drive gear. Similarly to the design decisions made for the leg, the drive gear follows the same reasoning as its development of the meshing interface of the leg's pivot point.



(A) Initial Pin Lock/Axle (B) FinalPin Lock/Axle

Figure 18: Pin/Axle Leg Locking Mechanism

Figure 18 shows the evolution of the meshing locking pin/axle for the leg. (B) Shows the most current design of the axle. Similarly to the design decisions made for the leg, the axle follows the same reasoning as its development of the meshing interface of the leg's pivot point

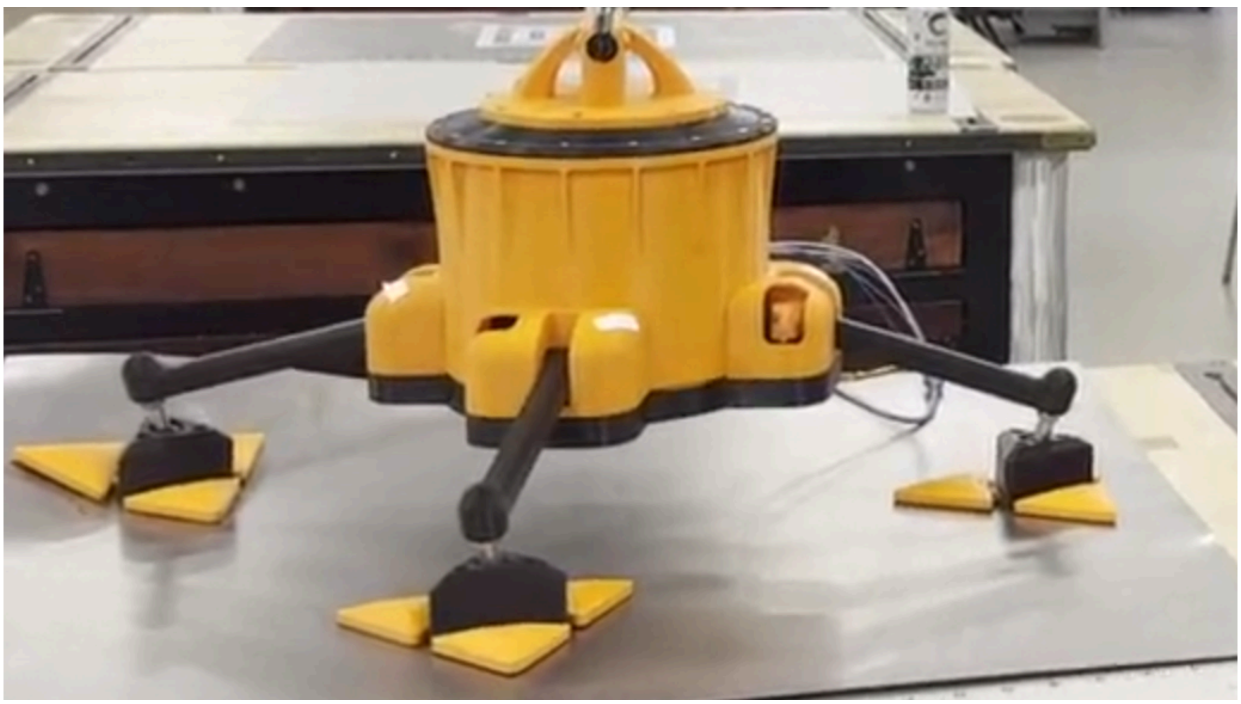


Figure 19: *This figure shows the completed 3D printed prototype. From this prototype, we can see the connecting surface points with the triangular feet. Each foot is able to hinge nearly 180 degrees vertically to attach to the irregularly shaped surfaces of Psyche. Each leg is also able to deploy 90 degrees from an upright position to the body to the position shown with a maximum range of 110 degrees. This deployment along with the hinge capabilities of the feet allows us to accommodate our engineering specification of at least 34 degrees for the range of motion that the anchor can successfully attach to. This prototype also portrays the free range of motion for the gimbal, which is connected to the tether of the space elevator satellite.*

Space Elevator Anchor Demonstration.mp4

Video 1: Shows Demonstration of 3d-printed prototype

3.3.2 Electrostatic Simulations

For ***Figures (20 - 23)*** below, we used Python to program our design parameters and figures demonstrating electrostatic adhesion. Our design currently has a mass of 23 lbs if made from Aluminum and Titanium components without the electrical components inside. We can then assume that our electronics will increase the weight by roughly 7-8 lbs, thus, we can assume that our anchor will weigh 30 lbs on Earth's surface. We also know that the gravity at the surface of Psyche is about 1% of Earth's gravity, which gives us a calculated weight of 0.3 lbs. If there are a total of 16 feet in our design and 100 Newtons of force generated per foot, we can expect our design to generate 1600 Newtons of electrostatic force on the surface of Psyche. This gives a factor of safety of 1198 in terms of weight on Psyche's surface versus the electrostatic force generated.

This reassures us that we are able to successfully land on the surface of Psyche with our final product design and be able to hold the anchor in a fixed position. Since the base end of the tether is theorized to have negligible force exertion impacting the structure due to the physics of the space tether and its length. Therefore, the force exerted by the anchor is such that it is meant to create a fixed tail-end point so it does not move about from the dynamic motion of the asteroid. The tension of the tether ideally would be negligible since the orbiter still has to maintain relative position through its own station-keeping mechanisms.

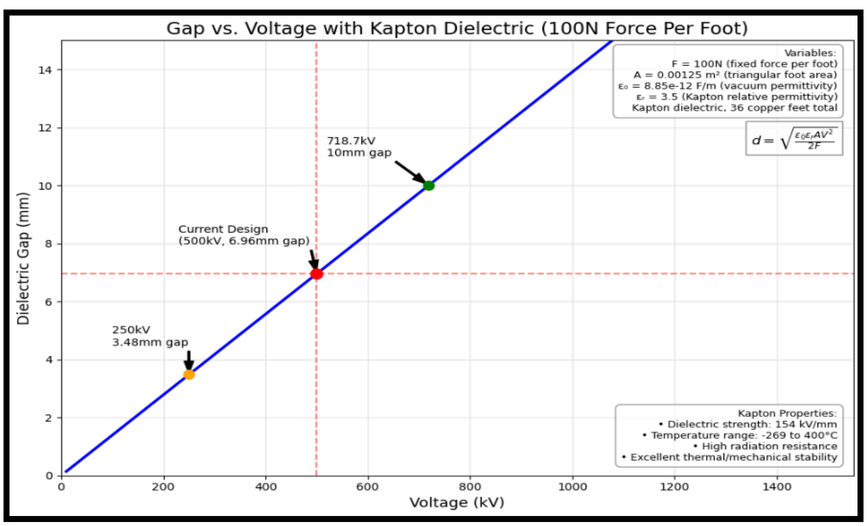


Figure 20: This graph demonstrates the linear relationship between the gap of the dielectric for the electroadhesion and the voltage. For this design, we had a fixed force per foot of 100 N, as this was our goal in order to have a high FOS when it comes to the weight of our design and the electrostatic force generated on the surface of Psyche. Our design works off a 500 kV voltage potential difference and will require a 6.96 m gap for the electrostatic adhesion to function as intended for landing.

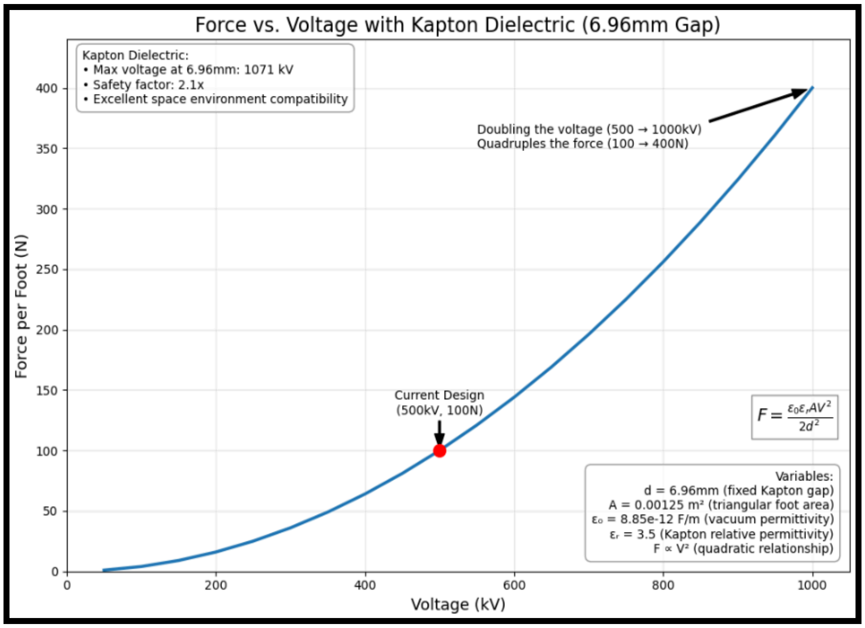


Figure 21: This graph demonstrates the relationship between the electrostatic force generated per triangular foot versus the change in voltage. Using our calculated gap from Figure 12, we can see that at our current design using 500 kV of electrical potential difference, we can expect to generate 100 N of electrostatic force.

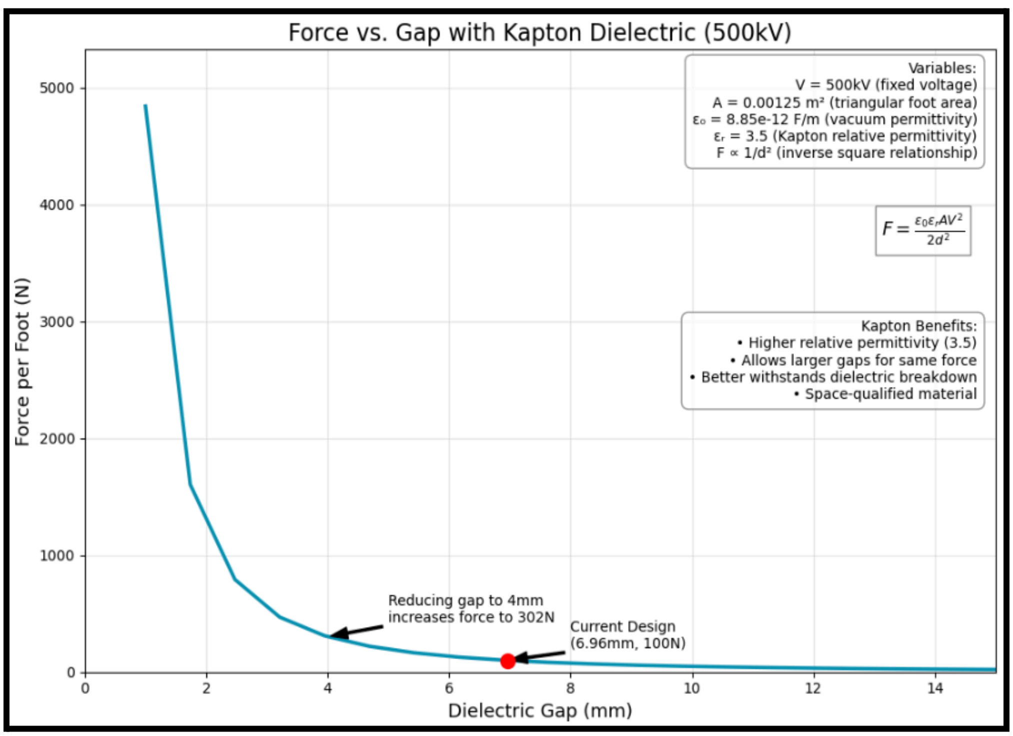


Figure 22: This graph demonstrates the force generated per foot versus the dielectric gap between electrodes. With our design gap of 6.96 mm and voltage of 500 kV, we can expect to generate 100 N of electrostatic force.

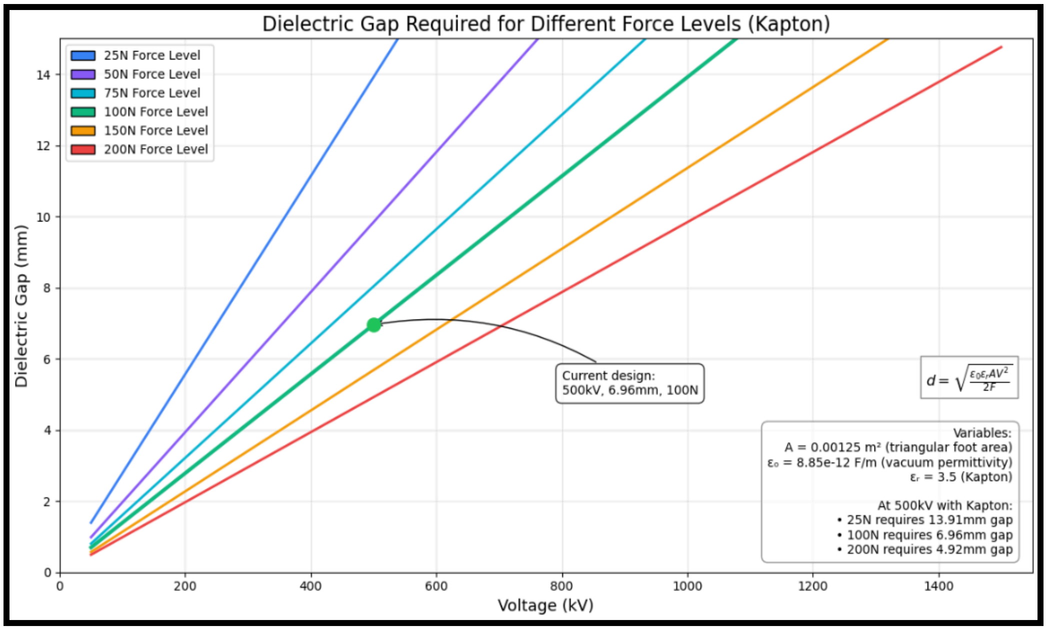


Figure 23: This graph demonstrates the dielectric gap required across varying voltages for different levels of force per foot. As voltage increases, the required dielectric gap also increases to prevent electrical breakdown. This graph continues to confirm our calculated use of 500 kV of electricity with a 6.96 mm gap of dielectric tape while generating 100 N of force on each foot.

3.3.3 Finite Element Analysis

Reliability

Locking Mechanism Validation.mp4

Video 2: Shows interlocking mechanism for the leg on the physical prototype and proof of the drivetrain interface.

Foot Morphing and Locking mechanism.mp4

Video 3: Shows the morphological capabilities of the foot through CAD constraining and geared locking/ driving mechanism.

2nd Iteration Drive Train & locking Mech.mp4

Video 4: Shows the potential of the drivetrain to drive all legs under one motor control.

Robust

VonMise Leg Axle.mp4

Video 5: Shows the Potential stress seen on the leg axle being held by the axle fixture of the base plate.

First Iteration FEA 5000N Load on leg.mp4

Video 6: Shows potential failure points of leg when constrained by the leg support/ geared locking mechanism housing.

FOS First iteration leg-informs Design Iteration.mp4

Video 7: Shows First Iteration failure points leg locking mesh structure to a 5000 N load—informed future iterations' designs to reduce potential failure points of the leg.

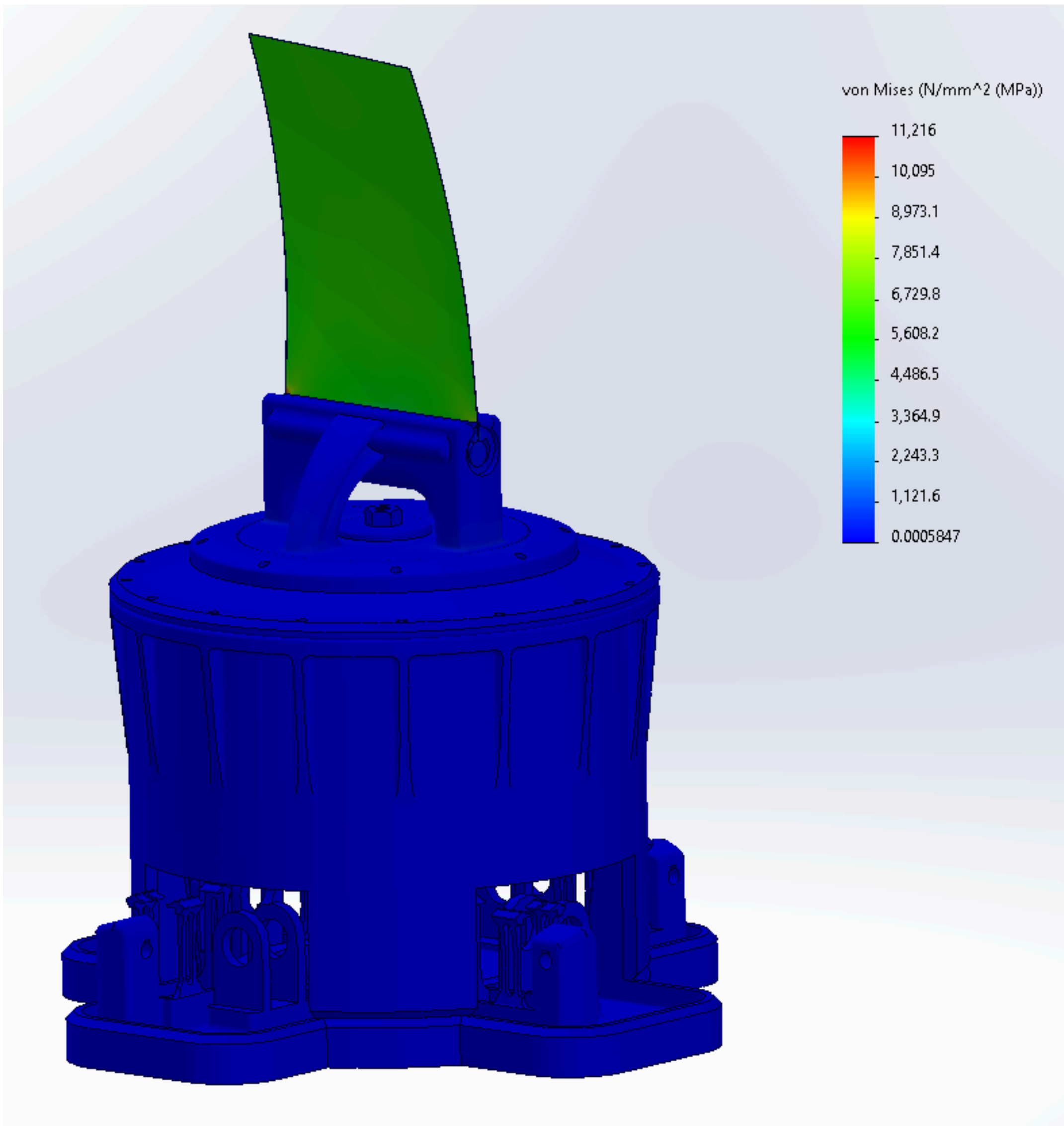


Figure 24: FEA analysis of the tether that is connected to the black body gimbal. The tether is experiencing **100,000** N of perpendicular force.

FEA Main Body 10000N.mp4

Video 8: Shows Von Mises stress of the gimbal attached to the main shell with 100,000 N of tensile load applied to the tether.

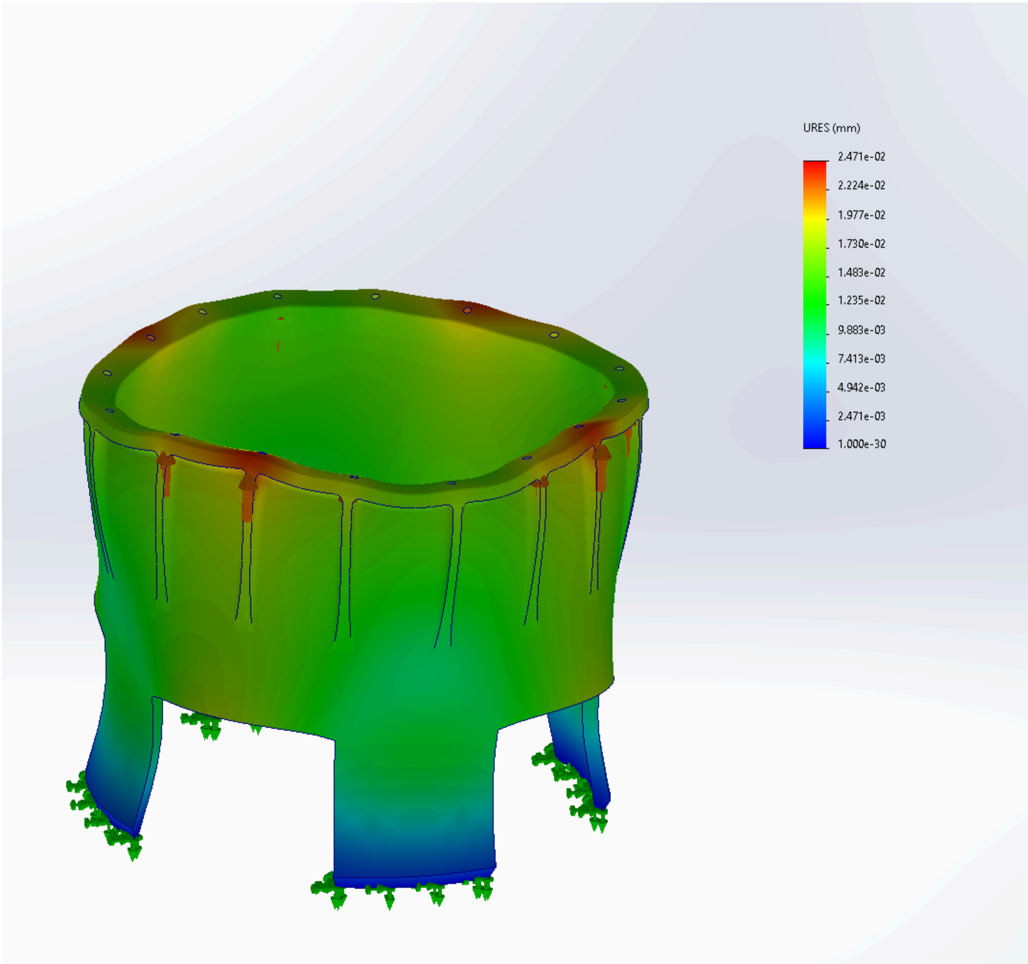


Figure 25: FEA analysis of the upper black body experiencing **100,000** N of axial force without base plate and top plate structures to constrain the shell from deformation. The intent of this test was to verify potential stress points from the distributed load across the mounting points transferred to the rib supports of the main shell. Acted as a visulization tool for iterative design of the shell.

VonMise Main hell Unconstrained by Top-Plate and Base Plate Structures.mp4

Video 9: Shows the expected deformation of the upper black body while experiencing 100,000 N of axial force.

FEA Main Shell loading via Fastner points 10000N.mp4

Video 10: Shows the Factor of Safety of the main shell with 100,000 N (~1 tonne) of distributed load via 16 fasteners points symmetrically spaced.

Each of these FEA analyses were all completed using SolidWorks. As we can see from our designs, the body and fastener points are able to withstand loads up to 100,000 N of force with minimal to no deformation. Since our project is mainly going to be experiencing forces in the vacuum of space, we are confident within our design capability to survive the travel from Earth, as well as function properly during descent and landing.

4 LOOKING FORWARD

This chapter focuses on helping two audiences:

1. **The Psyche Student Collaborations Team (Client)**: To outline a clear, phased plan for enhancing the anchor from its current prototype.
2. **Future Capstone Teams**: To transfer all previous documents, iterations of CAD,and robotics. Highlighting failure points, and suggesting process improvements to our current prototype that would be expected of a functioning product.

4.1 Technical Gaps In Current Prototype

Material System Transition: Our current 3D printed prototype validates our designs mechanical concepts for durability, but cannot withstand space environment conditions. Immediate priority requires transitioning to metal fabrication using titanium alloys or aluminum 6061-T6 to achieve thermal stability, structural integrity, and vacuum compatibility. These materials will be able to maintain their structural integrity through temperature fluctuations of ±250 K.

Power System Architecture: Our current prototype relies on an external 12V power adapter for the robotic systems. Future iterations will require integrated power generation, battery storage, and a power distribution capable of providing at least 1,600 lbf of electrostatic adhesion force for an extended period of time.

Thermite Welding Inclusion: Our present design does not demonstrate any proof-of-concept involving thermite welding with the surface of Psyche. Including these breaching points into the feet will be able to secure the anchor in a fixed position to the surface, after a connection with the surface has been achieved with the electrostatic grippers.

4.2 Future Design Enhancements / Recommendations for Future Capstone Teams

Design Area	Current Design	Suggested Change	Expected Benefit
Foot Design with Electrostatic Adhesion	Our prototype uses Neodymium magnets as proof-of-concept substitutes for the electrostatic adhesion, preventing validation of the actual attachment system.	Develop a functioning electrostatic gripper with a 0.96mm dielectric gap (for a vacuum), 500kV power output, and controllable electrodes to achieve the theoretical 1,600N of electrostatic force.	Enable realistic testing of the electrostatic gripper with an on-command activation/deactivation controls
Thermite Design	Thermite welding has only been conceptual. Placement needs to be engineered for space-qualified ignition systems.	Develop electrically-initiated thermite charges and thermal isolation for prevention of early detonation.	A functional, reliable controlled bonding agent that permanently fixes our anchor to the surface.
Booster/ Thruster Design	Our current prototype does not include any sort of propulsion system that would be able to get the anchor to the surface of	Include flight-proven propulsion systems, such as Hall-effect or ion thrusters into the design of the black	Guaranteed deployment reliability under extreme conditions that will be

	Psyche from initial attachment to the space elevator.	body.	experienced at Psyche.
Gearing	Our current gears and other moving parts are made purely out of PETG 3D filament, which is unable to withstand any harsh conditions to be expected in space.	Transition to machined or additively manufactured titanium framework with optimized topology for minimal tolerances.	Gear capability of achieving actual load capacity matching FEA predictions, space environment durability.

Topic	Pain Point Observed	Improvement Suggestion
Early Requirements Freeze	Scope creep and unexpected stakeholder expectations consumed roughly 30% of design time in the second semester.	Establish formal customer requirements by week 4, and implement requirement changes and engineering specifications by weeks 6-8 within the first term. This ensures the team enough time to begin prototyping and finding failure points.
Version Control	CAD file management became chaotic with multiple team members making iteration changes with unorganized file locations.	Implement a single file that contains all CAD files organized by part name. Real time check-in/ check-out protocols so that only one person can work on a single CAD file.
Prototyping Budget	A $500 budget limited our purchasing power to 3D printing materials, preventing metal prototype fabrication.	Ensure a larger budget through industry sponsorship for metal fabrication, machining, and advanced testing capabilities with higher quality parts.
Specialist Access	Our teams lack of electrical engineering expertise limited power system development towards electrostatic adhesion	Incorporate electrical engineering students or recruit interdisciplinary members for complex subsystems involving electronics.
High-Quality Manufacturing Access	Limitations to the university 3D printers prevented our team from manufacturing parts with metal.	Establish partnerships/ gain membership with local machine shops or aerospace suppliers for metal component fabrication.

5 CONCLUSIONS

Psyche, and other metallic asteroids, offer great opportunities for science, future exploration, and space-based economies. The orbiter on route to Psyche will reveal these opportunities in greater detail upon its arrival in August 2029. While it is on route, NASA and ASU have identified the need to prepare for follow up missions to Psyche, and potentially other asteroids. These efforts involve not just engineering solutions, but also educational development, personnel development, and creating societal interest in these missions.

Throughout the project, iterative design processes were used to create concepts, down-select, and form a physical prototype. At each point in the physical design process, each subsystem was updated to improve the performance. This resulted in several highly effective subsystems, namely the tether gimbal, drive train for the four legs, the ankle and feet of the lander, and the triangular electrostatic adhesion pads. The end result is a prototype that conforms to uneven surfaces, attaches to slopes at and greater than 34 degrees, and resists hundreds of pounds of tether forces. These capabilities were tested in a laboratory environment, thus validating the system as a TRL-4 prototype by NASA guidelines. Had it been made from space-grade materials, our finite element analysis shows that the system has a factor of safety above 2.0, and will not fail under tether forces as high as 100,000 N, even during thermal cycles of ±200 K. This capability was achieved iteratively, based on the results of previous simulations and led to improved versions of the tether gimbal and black body subsystems.

The NASA Psyche Space Elevator Anchor project successfully demonstrated the feasibility of asteroid surface attachment metallic environments. Our team achieved all primary objectives by delivering a validated TRL-4 prototype that meets performance requirements while establishing a clear pathway toward flight-qualified hardware. Project success stemmed from rigorous verification-driven development, combining analytical validation with empirical testing to build confidence in design decisions. This iterative approach enabled continuous refinement while maintaining focus on critical performance parameters. Despite this success, the project has an enormous amount of required work to become an actual space flight ready system (TRL-8). In fact, despite being designed as a viable concept for asteroid attachment, many of the short term objectives of our sponsor are educational.

5.1 Engineering Design Principles and Societal Considerations

Our development approach systematically applied fundamental engineering design principles while addressing broader societal factors that extend beyond technical performance requirements. The design process emphasized iterative refinement, verification-driven validation, and systems thinking to produce solutions addressing the unique challenges of space-based asteroid operations.

Verification and Validation Framework: Comprehensive V&V processes provided confidence in design decisions through multiple complementary approaches. Analytical validation using finite element analysis confirmed structural performance under extreme loading conditions, while prototype testing demonstrated mechanical functionality and deployment reliability. This systematic approach to validation ensures design maturity appropriate for continued development toward flight-qualified hardware.

Environmental Stewardship: Design decisions reflected broader responsibilities regarding space environment protection and long-term sustainability. The permanent attachment approach generates no orbital debris while providing extended operational capability, addressing growing concerns about space environment preservation. Material selection prioritized space-qualified components with established environmental compatibility, while systematic contamination control measures prevent compromise of sensitive scientific instruments or operational environments.

5.2 Project Validation and Impact

Economic Considerations: Design-for-manufacture principles reduced development costs while improving reliability through proven commercial components. Achievement of all technical objectives within a $514 academic budget demonstrates engineering approaches scalable to larger programs. Our enabling technology contributes to space resource accessibility with transformative economic potential, and metallic asteroids like Psyche contain mineral resources potentially worth quintillions of dollars, representing pathways for global economic development while addressing terrestrial resource scarcity.

Safety Assurance and Risk Management: Formal FMEA analysis identified 22 potential failure modes with comprehensive evaluation of probability, consequence, and detectability. Design modifications and operational procedures reduced maximum risk priority numbers from 196 to 95. Conservative structural analysis maintained safety factors exceeding 2.0 for all critical load paths, while multiple independent load paths provide enhanced reliability under worst-case operational conditions.

6 EXPLICIT REFERENCES

[1] NASA, 2025, "Psyche," NASA [Online]. Available: https://science.nasa.gov/mission/psyche/. [Accessed: 02-Feb-2025].

[2] Weiss, B. P., Merayo, J. M., Ream, J. B., Oran, R., Brauer, P., Cochrane, C. J., Cloutier, K., Elkins-Tanton, L. T., Jørgensen, J. L., Maurel, C., Park, R. S., Polanskey, C. A., de Soria Santacruz-Pich, M., Raymond, C. A., Russell, C. T., Wenkert, D., Wieczorek, M. A., and Zuber, M. T., 2023, "The psyche magnetometry investigation," Space Science Reviews, **219**(3).

[3] Knapman, J., 2015 "The Status of Space Elevator Infrastructures", New Space, 3(4), PP. 219-230

[4] 2023, "Psyche mission FAQ: Psyche Mission - A Mission to a Metal World," Psyche Mission [Online]. Available: https://psyche.asu.edu/mission/faq/. [Accessed: 25-Jan-2025].

[5] Bryan, T., Macleod, T., Gagliano, L., Williams, S., and McCoy, B., 2015, INNOVATIVE ELECTROSTATIC ADHESION TECHNOLOGIES [Online]. Available: https://ntrs.nasa.gov/citations/20150021399. [Accessed: 25-Jan-2025].

[6] Otto, H., and Wittman,1977, "Evaluation Of NASA-Langley Research Center Explosion Seam Welding", NASA, Washinton DC

[7] Schaler, E., Ruffatto III, D., Glick. P., White. V., and Parness. A., 2017, "An Electrostatic Gripper for Flexible Objects", *International Conference on Intelligent Robots and Systems,* 1, PP. 1172-1179

[8] Manning, C. G. (2023, September 27). Technology readiness levels. *NASA Space Communications and Navigation Program*. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

7 IMPLICIT REFERENCES

ASTM International. (2015). ASTM E595-15, Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment. West Conshohocken, PA.

ASTM International. (2016). ASTM E1559-16, Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials. West Conshohocken, PA.

Burov, A. A., Guerman, A. D., Kosenko, I. I., & Nikonov, V. I. (2018). Tethered spacecraft in asteroid gravitational environment. Acta Astronautica, 144, 272-278.

Cohen, S., & Misra, A. K. (2015). Static deformation of space elevator tether due to climber. Acta Astronautica, 113, 198-208.

Faizullin, L. F., & Pikal. (2019). Tether system motion analysis of the various space debris' anchor point positions. IOP Conference Series: Materials Science and Engineering, 502(1), 012076.

Hirschi, C. R., & Minor, M. A. (2004). Testing and evaluation of an automated tether management system for microgravity extravehicular activities. IEEE International Conference on Robotics and Automation, 2, 1424-1429.

International Organization for Standardization. (2019). ISO 24113:2019, Space systems — Space debris mitigation requirements. Geneva, Switzerland.

Kuzuno, R., Ishii, N., & Yamazaki, M. (2022). Dynamics and Energy Analysis of Nonequatorial Space Elevator Using Three-Dimensional Nonlinear Finite Element Method Extended to Noninertial Coordinate System. IEEE Access, 10, 53178-53190.

Luo, S., Zhang, Y., & Tang, G. (2022). The Stability Analysis of a Tether for a Segmented Space Elevator. Aerospace, 9(7), 376.

NASA. (2014). NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware.

NASA. (2016). NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft.

NASA. (2014). NASA-STD-5017, Design and Development Requirements for Mechanisms.

NASA. (2016). NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware.

NASA. (2010). NASA-STD-4005, Low Earth Orbit Spacecraft Charging Design Standard.

Viale, A., Ceriotti, M., & McInnes, C. R. (2021). Dynamics of a Nonrigid Orbital Siphon at a Near-Earth Asteroid. Journal of Guidance, Control, and Dynamics, 44(1), 137-148.

Viale, A., McInnes, C. R., & Ceriotti, M. (2020). Dynamics of an orbital siphon anchored to a rotating ellipsoidal asteroid for resource exploitation. Acta Astronautica, 176, 153-164.

8 APPENDICES

8.1 Appendix A: Budget Analysis

	Item Name	Brand	Quantity	Unit Cost	Total Cost	Price Checked With Receipt	Source	Date Purchased (Requested)	Date Received
Electronic Hardware	**12V Power Supply**	ALITOVE	1	$9.58	$9.58	Yes	Amazon Link	4/4/2025	4/9/2025
	10pcs **High Voltage Generator DC** 6-12V to 1000KV 1000000V	XIITIA	1	$24.79	$24.79	Yes	Amazon Link	4/4/2025	4/9/2025
	[4-Pack] MG996R 55g **Servo Motors**	Deegoo-FPV	1	$17.99	$17.99	Yes	Amazon Link	4/4/2025	4/9/2025
	40KG Digital **Servo Motor 360 Degrees**	DIYmall	1	$28.99	$28.99	Yes	Amazon Link	4/4/2025	4/9/2025
	22 awg **Silicone Electrical Wire** (100ft)	Haerkn	1	$16.98	$16.98	Yes	Amazon Link	4/4/2025	4/9/2025
	99.9% Solid Bare **Copper Wire** 18 Gauge	YEZHET	1	$20.45	$20.45	Yes	Amazon Link	4/4/2025	4/22/2025
	SN74HC595N IC 8-Bit **Shift Registers**	Texas Instruments	1	$7.35	$7.35	Yes	Amazon Link	4/4/2025	4/9/2025
	5PCS GY-521 6 DOF mpu6050 **Accelerometer Sensor Module**	Stemedu	1	$13.70	$13.70	Yes	Amazon Link	4/4/2025	4/9/2025
	ELEGOO MEGA R3 Board (**Arduino Mega Board**)	ELEGOO	1	$21.84	$21.84	Yes	Amazon Link	4/4/2025	4/9/2025
	320pcs M3 **Circuit Board Mounting Kit**	Lystaii	1	$9.99	$9.99	Yes	Amazon Link	4/4/2025	4/9/2025
	Pro 950 **Polyimide Film Tape**, 7500V Dielectric Strength, 36 yds Length x 1" Width	Pro Tapes	1	$13.56	$13.56	Yes	Amazon Link	4/4/2025	4/9/2025
	Epoxy Resin Kit 72OZ	Puduo	1	$36.99	$36.99	Yes	Amazon Link	4/4/2025	4/9/2025
Mechanical Components	51110 **Thrust Ball Bearings** 50mm x 70mm x 14mm Chrome Steel ABEC3 Single Row Roller 2pcs	uxcell	1	$13.19	$13.19	Yes	Amazon Link	4/4/2025	4/9/2025
	20-Pack R4-2RS Bearings, ID 1/4 x OD 5/8 x 0.196 inch **Small Ball Bearings**	Donepart	1	$15.99	$15.99	Yes	Amazon Link	4/4/2025	4/9/2025
	2 Pack, 1" **Ball Adapter** with M10 x 1.25 x 15 Threaded Post Compatible with RAM Mounts B Size 1 Inch Ball Double Socket Arm	BRCOVAN	2	$17.14	$34.28	Yes	Amazon Link	4/4/2025	4/9/2025
	M5 x 0.8 mm Thread, 12 mm **Long Bolt** (50 Count)	McMaster-Carr	1	$5.05	$5.05	Yes	McMaster-Carr Link	4/15/2025	4/21/2025
	Class 04, M5 x 0.8 mm Thread Medium-Strength Steel **Thin-Profile Hex Nut** (100 Count)	McMaster-Carr	1	$3.78	$3.78	Yes	McMaster-Carr Link	4/15/2025	4/21/2025
	M18 x 2.5 mm Thread, 45 mm Long Alloy Steel **Socket Head Screw** Black-Oxide (5 Count)	McMaster-Carr	6	$12.76	$76.56	Yes	McMaster-Carr Link	4/15/2025	4/21/2025
	PETG 3D Printer Filament 1.75mm, (2.2lbs), (Orange)	OVERTURE 3D	2	$21.54	$43.08	Yes	Amazon Link	4/25/2025	4/29/2025
	PETG 3D Printer Filament 1.75mm, (4.4lbs), (Black (2-Pack))	OVERTURE 3D	2	$29.68	$59.36	Yes	Amazon Link	4/25/2025	4/29/2025
	Magnetic Sheets with adhesive(10 pack)	HTVRONT	1	$11.98	$11.98	Yes	Amazon Link	5/7/2025	5/14/2025
	40 PCS Stainless Steel Small Torsional Spring, 4.5mm **Tiny Torsional Springs**	EATAKWARD	1	$8.89	$8.89	Yes	Amazon Link	5/14/2025	5/20/2025
	Grtard 8 Pack **Neodymium Cup Magnets**, 100LBS Holding Force Strong Rare Earth Magnets	Grtard	2	$9.98	$19.96	Yes	Amazon Link	5/14/2025	5/20/2025
				Total Spent:	$514.33				
				Total:	$514.33				
				Remaining Budget:	-$14.33				

Figure 26: Finalized Bill of Materials with verified prices and documented purchasing and receiving dates for all items.

8.2 Appendix B: Full FMEA

Subsystem	Failure Mode	Effect	Cause	SEV	OCC	DET	RPN	Recommended Actions
Thermite Bonding	Premature ignition	Catastrophic mission failure, potential damage to spacecraft	Control system failure, external heat, impact	10	4	6	240	Implement triple redundant safety systems, thermal insulation, mechanical safety locks
Adaptable Feet	Incomplete surface contact	Insufficient adhesion, unstable attachment	Surface irregularities exceeding design parameters, debris	8	6	5	240	Increase adaptability range, add more articulation points, improve feet compliance
Deployment Mechanism	Leg deployment failure	Inability to establish contact with surface	Mechanism jamming, motor failure, control error	9	5	5	225	Add redundant actuation paths, manual override capability, improved lubricants
Electrostatic Adhesion	Power system failure	Loss of initial grip before thermite bonding	Circuit damage, battery failure, connection issue	9	4	6	216	Redundant power systems, distributed power architecture, fault detection
Thermite Bonding	Incomplete thermite reaction	Weak or partial permanent bond	Contamination, improper mixture, insufficient heat	8	5	5	200	Multiple ignition points, improved thermite formulation, reaction monitoring
Central Hub	Gear system failure	Inability to control leg positions	Excessive loads, foreign object, manufacturing defect	7	5	5	175	Strengthen gear design, add protection against debris, quality control improvements
Tether Interface	Gimbal lock	Restricted movement causing stress on attachment	Extreme angle conditions, control system error	8	4	5	160	Redesign gimbal to prevent lock positions, add sensors to detect approaching lock
Adaptable Feet	Thermal damage to feet	Degraded adhesion capability	Extreme temperature cycling, radiative heating	7	4	5	140	Improve thermal protection, select more resistant materials, add thermal breaks
Control System	Software failure	Improper sequencing of operations	Coding error, radiation effects, memory corruption	8	3	5	120	Radiation-hardened components, watchdog timers, redundant processing
Leg Structure	Ball joint failure	Limited range of motion, improper foot orientation	Vacuum welding, debris contamination, excessive load	6	4	5	120	Alternative joint materials, protective boots, preload adjustments

Figure 27: FMEA table analyzing potential failure modes across ten critical subsystems with risk assessment metrics (SEV, OCC, DET, RPN). Highest risks identified include incomplete surface contact of the adaptable feet (RPN 240) and premature thermite ignition (RPN 240) with corresponding mitigation strategies.

8.3 Appendix C: Standards, Codes, and Regulations

Standard Number or Code	Title of Standard	How it applies to Project
ASTM E595	Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment	Ensures materials selected for the attachment system will not outgas in space vacuum, which could contaminate sensitive instruments or mechanisms
ASTM E1559	Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials	Provides additional testing protocols for material outgassing relevant to long-term space operations
NASA-STD-5001	Structural Design and Test Factors of Safety for Spaceflight Hardware	Guides structural design decisions ensuring appropriate safety margins for launch and operation
NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft	Provides requirements for materials selection, particularly relevant for the thermite bonding system
ISO 24113:2019	Space systems — Space debris mitigation requirements	Ensures our design minimizes potential space debris generation if components fail
NASA-STD-5017	Design and Development Requirements for Mechanisms	Guides the design of the deployable legs and actuating mechanisms
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware	Ensures fracture control in our structural components, particularly important for the adaptable feet
ECSS-E-ST-33-01C	Space engineering - Mechanisms	European standard for space mechanisms that provides additional guidance for our gear system and deployable components
MIL-STD-1540D	Test Requirements for Launch, Upper-Stage, and Space Vehicles	Outlines testing requirements applicable to our attachment system
IEEE 1156.1	Environmental Specifications for Spaceborne Computer Modules	Guides the design of our control electronics for the electrostatic adhesion system
AIAA S-114-2005	Moving Mechanical Assemblies for Space and Launch Vehicles	Provides guidance for our moving assemblies, specifically the ball joints and gear systems
NASA-STD-4005	Low Earth Orbit Spacecraft Charging Design Standard	Though not in LEO, this standard provides guidance on managing static charge in space environments

Figure 28: Compliance matrix listing twelve applicable industry standards covering materials testing, structural design, space systems engineering, and safety requirements to ensure the anchor system meets aerospace industry standards.