NASA: Landing System for Hypothesized Surfaces - Final Report

Iridium Class - 05C: Landing - UGA

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May 6, 2025

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Executive Summary

16 Psyche is a giant metal-rich asteroid located in the asteroid belt between Mars and Jupiter, on average about 438 million kilometers from Earth (~3 AU). The study of Psyche offers a rare opportunity to investigate what is believed to be the exposed core of a protoplanet, providing insight into the planetary formation processes. The exact surface conditions and material properties remain unknown, as the asteroid has never been directly explored. In October 2023, NASA launched the Psyche mission, which aims to enter orbit around the asteroid in 2029. While the orbiter will collect high-resolution imagery and data from orbit, it does not include a lander, leaving critical surface-level insights to be discovered. This gap presents the motivation for designing a hypothetical landing system that could safely touch down and stabilize on Psyche's unknown terrain.

Our team aims to develop a conceptual landing system capable of safely delivering a payload to the surface of the asteroid Psyche. The system must be robust enough to accommodate a wide range of surface conditions, from metallic bedrock to loose regolith, while also contending with the asteroid's weak gravitational field. Key design priorities include ensuring descent stability and precision in selecting a landing site, securing the payload onto unpredictable terrain, incorporating multi-layered redundancy and fail-safes, and addressing payload integration logistics. The scope of the project encompasses subsystem development from orbital approach to final anchoring on Psyche's surface. Deliverables will include a systems-level design model, detailed justifications for design decisions, and considerations for scalability to support future missions targeting similarly uncertain small-body environments.

The proposed landing system for this hypothetical mission features a multi-component design engineered for stability, adaptability, and secure payload delivery in low-gravity, uncertain terrain. Central to the system is the Psyche Lander BUS, which we define as the volume containing mission systems and payloads out of our scope. It is supported by a robust anchoring spike-based mechanism that includes rack-and-pinion gear extension legs and ball-jointed hydraulic extension cylinders for dynamic surface interaction. A peristaltic resin pump, paired with a check valve-plated resin nozzle, enables in-situ anchoring through the controlled deployment of resin into the chosen surface. It, along with the various other subsystems, is protected by a honeycomb crush shock structure. Additional features include an instrumentation rack for landing site identification, data collection, and system monitoring, all integrated with multi-layered redundancies to enhance mission reliability. This design ensures a safe, targeted landing and secure anchoring, even in the unpredictable conditions of small-body surfaces.

To validate the feasibility of the proposed 'Static Spike' concept, extensive simulations and calculations were conducted across both structural and fluid domains. Finite element analysis (FEA) was used to optimize the strength-to-weight ratio of thin-walled components, ensuring resilience during touchdown. In parallel, Computational Fluid Dynamics (CFD) simulations characterized the resin anchoring system, determining the flow behavior and pump power requirements necessary for reliable deployment. Together, these validation efforts confirm that the design can adapt to a range of surface conditions while maintaining structural integrity and anchoring performance.

Introduction and Background

The team has been assigned the challenging mission of designing a landing system upon the arrival of the Psyche asteroid. Psyche, a unique metal-rich asteroid located in the asteroid belt between Mars and Jupiter, presents a rare opportunity to study the planetary cores. The team's objective is to design a landing system that can safely touch down on Psyche's surface while navigating its low-gravity environment so the payload can conduct a detailed analysis of its composition. This project requires innovative approaches to overcome the unknowns of the asteroid's terrain, gravity, and surface conditions to ensure a successful and valuable mission.

There are many problems the team must take into consideration throughout the design process, one of which is low gravity. Due to such low gravity, it is difficult to use the weight of the payload to our advantage for stabilization after landing. There is another unknown, which is the terrain. From satellite imaging, we know there are slopes up to 30 degrees in elevation due to cratering. Without previously being on the surface, it is also unknown how loose the surface is going to be. Such unknowns are what make this project so challenging. The team must design for every possible outcome since there is very little information known about the asteroid.

The landing system that is being designed must be able to function properly in the environment present on the Psyche asteroid. This includes the loose regolith on the surface combined with uneven surfaces and elevations up to 30 degrees. The regolith on the surface has been observed using satellite imaging and is believed to be a loose metallic “dust-like” combination that can be unstable, especially on slopes. During the design process, as the team tries to compensate for these slopes and increase stability as much as possible, it is also important not to forget about how the surface can be loose, which can cause sliding. Another environmental concern that must be addressed is how the regolith can impact any mechanical system if it is blown from the surface onto the mechanism during landing.

Each problem has its relative factors that can affect the system’s functionality as a whole. The low gravity present on the Psyche asteroid can affect how successful our mission is from the beginning. Since we cannot utilize the weight of the payload, it is hard to guarantee that the entire lander maintains contact with the surface of the asteroid at all times. If any reaction forces occur that push the lander off the surface, it would not be possible to guarantee that the lander would return to the surface using the weight and gravitational force alone. The next problem the team must take into consideration is the terrain on the surface of the asteroid. Since there is cratering in some areas that cause steep inclines, a landing system that is built for relatively flat surfaces would be likely to tip over. As long as the team keeps this in mind throughout the design process, it should not become a large possibility for failure.

Many key observations can be used to determine if our identified problems are likely to occur. First of all, if there is no other vertical propellant force of some kind incorporated to maintain contact with the surface at all times, the landing system is likely to fail due to such low gravity on the Psyche asteroid. If the lander is not able to maintain stable contact with the surface, this could compromise the ability to perform successful scientific experiments on the asteroid, resulting in an unsuccessful mission overall. The next problem has some easily noticeable fail points. If the landing system is not able to compensate for an incline of 30 degrees, it is likely to tip over and fail. Depending on the system that is designed, there must be a way to adjust and guarantee the lander will not tip over. By observation, if there is not an adjustable mechanism present, the landing system will likely fail while landing on steep inclines. The failure of this system could damage the communication system or even the ability to return the payload to Earth if necessary. Either of these failure points can result in a complete or partial failure of the mission.

The overall costs of these problems could be astronomical depending on the severity of the failure and the overall damage inflicted on the entire lander. For example, if the landing system fails to account for a slope and the lander tips over, a damaged communication system leads to a failed mission and could cost the company millions in investments toward scientific experiments on the asteroid. Any failure recognized could potentially cost NASA millions in a failed mission and valuable experiments, but also be mild and only cost the company thousands for a new and improved subassembly.

Role	**Description**	**Student**
Team Lead	Organize Team Meetings/Agendas Manage Deadlines/Team Budget Oversee Team Progress/Goals	David Krupp
Operations Lead	Oversee project decision-making Manages overall cost/reliability/safety Formulates alternate plans when necessary	Brice Vandiver
Research Lead	Define Research Goals Organize/Edit/Supervise Research Oversee Data Collection and Analysis	Mason Dade
Prototyping Lead	Plans and Executes Prototyping Plans/Goals Responsible for Prototype Quality Sets Deadlines and expectations for models and prototypes	Kavi Troiano
Communications Lead	Manage External Communications Send regular status updates	Aditya Ramesh

Table 1: Undergraduate Personnel Team Positions

Project Needs

To better understand project requirements and considerations our team is not familiar with, both in spaceflight and geology, several stakeholders were identified and interviewed for their expertise. Outside of the inner circle of this project (including our client and College of Engineering faculty), interviewees included: Dr. Marc Rayman - Jet Propulsion Laboratory, Psyche Mission Chief Engineer, and Dr. Christian Klimczak - UGA, Planetary Geology Associate Professor.

Dr. Rayman provided crucial insight into the current mission to Psyche and what types of challenges they faced in design and launch logistics. He reiterated that in order to fully understand the mission scope, talking to Subject Matter Experts (SMEs) will reveal fine details that traditional research may not yield. Dr. Rayman also revealed that the most challenging piece of the mission design was the power budget and communications given the distance from Earth and NASA's Deep Space Network (DSN). Dr. Klimczak, after being briefed on our mission objectives, was very straight to the point and gave several recommendations on landing methods. He recommended landing in or around a large crater, as crater surface conditions are fairly consistent with loose silt from body-to-body. Dr. Klimczak also gave us several sources to do research on effective systems accounting for loose to stiff silt/regolith conditions.

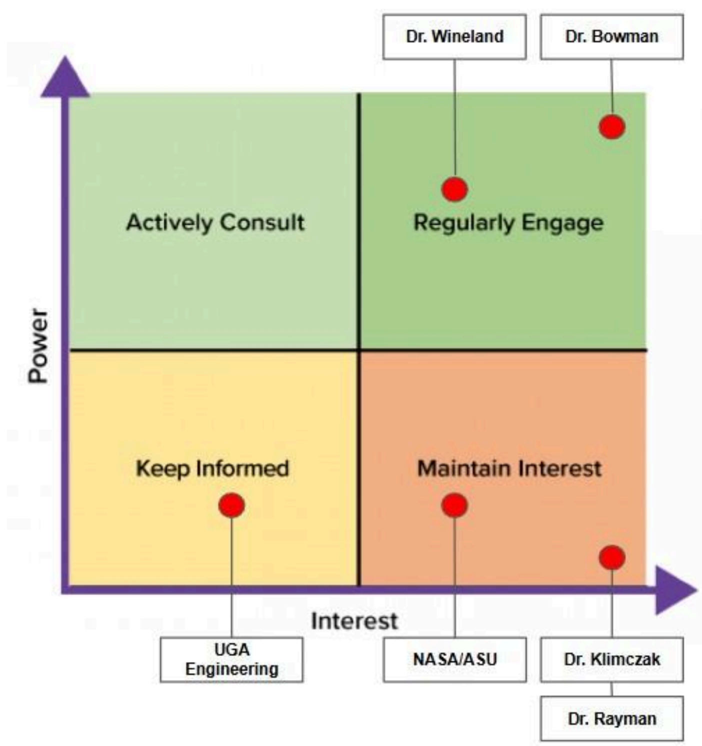

Figure 1: Stakeholder Categorization Plot

Design Objectives

Our objective is to develop a conceptual landing system versatile enough to operate effectively on the surface of 16 Psyche (and possibly other small bodies), despite the significant uncertainties regarding its surface composition, topography, and mechanical properties. The core goals of the system include identifying a viable landing site from orbit, executing a stable and controlled descent, and deploying the anchoring and stabilization mechanisms once contact with the surface is achieved. The scope of this report concludes once the spacecraft is confirmed to be securely at rest on the asteroid's surface.

To address this challenge, our design leverages lessons learned from past missions to small bodies, such as Hayabusa, Hayabusa2, and ESA's Rosetta Philae lander. These missions emphasized the unpredictable nature of small-body surfaces and the critical importance of redundancy. Consequently, our design includes multiple fail-safe features such as independent extension systems, ball-jointed hydraulic supports, and a resin-based anchoring subsystem to ensure mission success even in the event of partial system failure (see **Appendix C**). This multi-layered approach enables our system to adapt in real time to Psyche's unknown conditions and highlights the need for flexibility, autonomy, and robust mechanical design when operating in deep-space environments.

Engineering Specifications

The engineering specifications define the measurable performance criteria that the landing system must meet to ensure mission viability. These specifications are rooted in the environmental conditions expected at 16 Psyche, standard spaceflight requirements, and insights gained from prior small-body missions. At a high level, the system must:

- Achieve a controlled, stable landing under low-gravity conditions.
- Withstand launch and space transit loads, with a minimum Factor of Safety (FoS) of 4 for all primary structural components.
- Operate autonomously with fault-tolerant behavior, minimizing risk from single-point failures.
- Be compatible with spacecraft integration standards, including mass, volume, and power constraints.
- Function within expected thermal, vibrational, and radiation environments during all mission phases.
- Incorporate sufficient redundancy to ensure continued performance in the event of subsystem degradation or partial failure.

These specifications serve as benchmarks for all conceptual subsystems and are summarized in **Table 2**, which outlines the required operational parameters, environmental tolerances, and system-level constraints.

Stakeholder needs	Design Requirement	Acceptance criteria / Specification	Qualification	Regulation (code/standard)
Functionality				
Safe Landing	The lander shall achieve a safe landing without damaging the spacecraft	Verified by virtual simulation completing stable touchdown with no structural damage	Requirement	NASA-STD-8719.13 (Software Safety)
Redundancy	The lander shall include redundancy in key subsystems to ensure continuation of mission-critical functions in the event of a single point failure	Verification that no single failure in critical subsystem leads to loss of mission	Requirement	NASA-STD-8709.22 (Reliability and Maintainability), ECSS-Q-ST-30C (Dependability)
Operational Longevity	The lander shall maintain operational functionality for a nominal mission duration of 30-90 days after touchdown	Verified by power system endurance tests meeting >90 days continuous operational margin	Desired	NASA-STD-4005 (Electric Power Systems), ECSS-E-ST-10-03C (Testing), JPL D-17868 (Environmental Test Requirements)
Structural Integrity	The lander structure shall survive launch loads, interplanetary cruise, and landing shock, retaining full mechanical integrity.	Verified by static load test up to 1.25x maximum expected load	Desired	NASA-STD-5001 (Structural), MIL-STD-1540 (Test Requirements), Launch Provider ICD and GEVS
Sustainability				
Compliance with Planetary Protection	The mission design shall prevent contamination of celestial bodies and comply with debris mitigation guidelines	Verified compliance with planetary protection category requirements	Desired	COSPAR Planetary Protection Policy, NASA-STD-8719.14, ISO 24113 (Space Debris)

Table 2: Design Specification Table

Benchmarking

In order to identify the best approach for our mission, it is best to review how previous missions have addressed similar objectives and challenges. By reviewing existing lander designs, we can better understand what features are effective and what to avoid when landing on small bodies. We highlight three notable missions: NASA's NEAR Shoemaker, JAXA's Hayabusa, and ESA's Rosetta-Philae each showing new methods of deep-space exploration and providing invaluable information for us to analyze.

NASA's NEAR Shoemaker spacecraft, costing $112 million, was launched in 1996 and arrived at the Eros Asteroid in 2000. Although it was the first spacecraft to land on an asteroid, it was not originally designed as a lander, but it survived its unexpected touchdown. NEAR Shoemaker used solar cells for power and carried scientific instruments such as the MSI (Multi-Spectral Imager), MAG (Magnetometer), NIS (Near-Infrared Spectrometer), XGRS (X-ray/Gamma-Ray Spectrometer), and NLR (NEAR Laser Rangefinder). All of these are utilized to study Eros's physical properties, mineral components, morphology, internal mass distribution, and magnetic field (NASA 2004). However, because it was not intended as a lander, it effectively crashed on Eros's surface, surviving by chance. Unlike Shoemaker, our spacecraft would be equipped with the proper landing equipment to avoid such risks.

The Japan Aerospace Exploration Agency's Hayabusa spacecraft, which cost $100 million, was launched in 2003 and reached the Itokawa Asteroid in 2005. It was the first spacecraft to take samples from an asteroid, and the first mission to successfully land and take off from one. Hayabusa featured a cylindrical sampler horn that fired sampling bullets at the asteroid, carried a Minerva lander mounted on its underside, and was propelled by two microwave ion thruster engines (Japan Aerospace Exploration Agency 2019). However, due to communication delays between Earth and the spacecraft, Hayabusa relied on sensors to independently determine tasks as it approached the asteroid, leading to poor decisions and mission complications. Unlike Hayabusa, our spacecraft uses sophisticated new laser communication technology that employs photons to communicate between a probe in space and Earth.

The European Space Agency's Rosetta-Philae spacecraft, which cost $241 million, was designed to study the center of Comet 67P and land a probe on its surface. Launched in 2004 and arriving at the comet in 2014, it was the first mission specifically intended to both orbit and land on a comet. It consisted of an orbiter (Rosetta) and a lander (Philae), both of which used solar cells for power generation. Philae was equipped with two harpoons to anchor itself to the comet, but these harpoons failed to fire, causing the lander to bounce uncontrollably across the comet's surface. Philae ended up in an area with low sunlight and lost communication with Earth after its batteries died (European Space Agency). Unlike Rosetta-Philae, our spacecraft would employ thrusters to ensure a stable landing on Psyche, and it will use the same efficient, lightweight, radiation-resistant solar panels as the Psyche spacecraft, providing sufficient power even in low sunlight conditions.

Codes, Standards, and Regulations

The international rules and regulations that apply to our landing system and the mission as a whole are listed below. Most regulations regarding non-manned missions only apply to low-Earth orbit (LEO) to protect the atmosphere and other spacecraft. For this mission, in particular, the NASA-STD-5001, listed first below, represents the primary source of guidance that will influence this project.

NASA-STD-5001: Structural Design and Test Factors of Safety for Spaceflight Hardware (1996) - Provides structural design and testing standards to ensure the safety and reliability of spaceflight hardware, covering material selection, stress analysis, and testing protocols.

Outer Space Treaty (1967) - Governs the activities of states in the exploration and use of outer space, ensuring it is conducted for the benefit of all humankind. It prohibits the placement of nuclear weapons in space and establishes that celestial bodies are not subject to national appropriation.

ISO 14300-1: Space Systems: Program Management and Quality - Establishes guidelines for managing space system projects, focusing on planning, organization, and quality assurance to meet mission objectives.

Radio Regulations (2020) - Defines international rules for using the radio-frequency spectrum and satellite orbits to avoid interference and ensure equitable access for all space activities.

COSPAR Planetary Protection Policy (2021) - Provides guidelines to prevent biological contamination during space missions, ensuring that Earth and celestial bodies are protected from cross-contamination.

Commercial Space Launch Act of 1984 (as amended) - Regulates commercial space launch activities in the U.S., providing a framework for licensing, safety standards, and liability for private spaceflight companies.

ISO 14620-1: Space Systems: Safety Requirements (2011) - Specifies safety requirements for space systems to minimize risks to personnel, property, and the environment during the design, development, and operation phases.

Design Concept

During the brainstorming phase of the project, each team member contributed three lander concepts (fifteen total) and 2D graphic representations. After consolidating like designs and discarding concepts that had feasibility conflicts, we produced three review-worthy design concepts. To ensure our design selection is as objective and fact-oriented as possible, we have constructed a Weighted Decision Matrix (shown below in **Figure 2**) using weights for each criterion based on the specifications given to us by our Client. Based on the ratings given to each criterion, the Static-Spike design emerged as the clear favorite. This design excels in the areas of stability, durability, and overall system integration with the rest of the spacecraft. Additionally, it provides a strong sense of novelty to space exploration as it incorporates a resin deployment subsystem, which permanently bonds the spikes to its landing site, a concept never executed during a mission.

WEIGHTED
Decision Matrix

Lowest Percent= Best Design Option

CRITERIA	WEIGHTAGE	Articulated Drill		Electromagnet-Harpoon		Static-Spike	
		RATING	TOTAL	RATING	TOTAL	RATING	TOTAL
Stability	15%	2	10.00%	3	15.00%	1	5.00%
Surface Penetration	14%	3	14.00%	2	9.33%	1	4.67%
Durability and Longevity	13%	2	8.67%	3	13.00%	1	4.33%
Weight and Compactness	12%	2	8.00%	3	12.00%	1	4.00%
Surface Adaptability	10%	1	3.33%	3	10.00%	2	6.67%
Energy Efficiency	8%	1	2.67%	3	8.00%	2	5.33%
Ease of Deployment	8%	2	5.33%	1	2.67%	3	8.00%
Redundancy/Backup	8%	2	5.33%	1	2.67%	3	8.00%
Impact on Asteroid	7%	2	4.67%	1	2.33%	3	7.00%
System Integration	5%	2	3.33%	3	5.00%	1	1.67%
	max		TOTAL Articulated Drill		TOTAL Electromagnet-Harpoon		TOTAL Static-Spike
	100%		65.33%		80.00%		54.67%

Figure 2: Weighted Decision Matrix

Below (**Figure 3**), a depiction of the Static-Spike system on the surface of Psyche is shown. This is a rendering of what the system would look like as it is gradually descending to the surface of Psyche. Upon touchdown, the system will deploy its Static Spikes into the loose regolith of the landing site, from there, resin can be pumped under pressure into the surface. This will be accomplished through a series of diffusion orifices located around the tip. As the resin fills the areas below and around the spikes of higher density, it will accumulate and fill upwards and outwards. Once the resin is fully cured, the system will be anchored to Psyche by its own mass combined with the mass of the overlying regolith above the embedded anchoring spikes.

Figure 3: Static Spike Design Concept

System Development

Concept Justification

Although we will not have access to the Psyche spacecraft's hard data until late 2029, preliminary scientific understanding suggests that Psyche is composed primarily of iron and nickel, with the possibility of trace amounts of more exotic metals such as gold and platinum. However, the exact composition will remain uncertain until the current mission provides more direct measurements. NASA's preliminary findings have been derived primarily from long-range radar observations and spectrometric analyses of Psyche's thermal inertia, offering insight into its surface and subsurface properties.

Given this unique composition, tailoring our lander's material selection to its environment is a crucial step toward mission readiness. The lander must be easily distinguishable from orbit and via remote sensing techniques to limit the risk of misidentifying its components as native materials of the landing site. To prevent this "site contamination", the use of distinctive materials, specialized coatings, and controlled reflectivity will ensure that the lander remains spectrally and compositionally separable from Psyche's metallic surface.

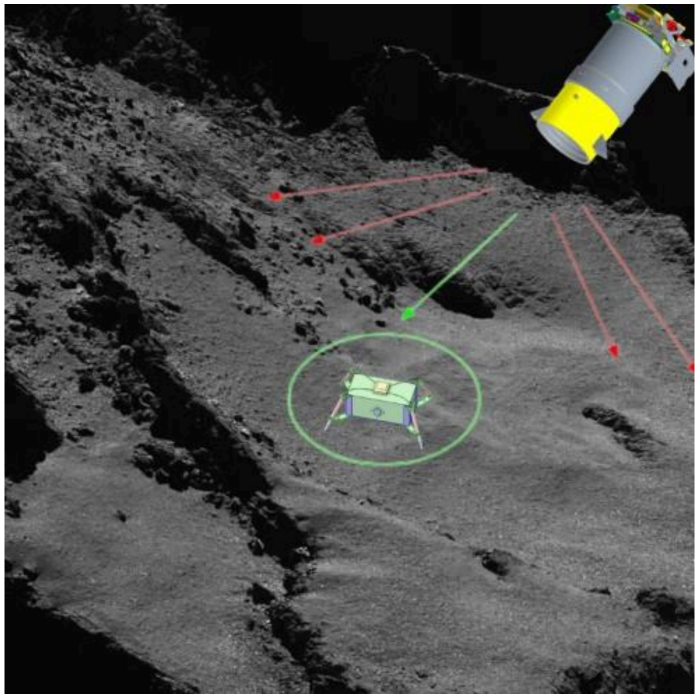

Figure 4: Orbital Viewing Logistics

Similar strategies have been employed in past missions to small bodies, including Hayabusa (I and II) and Rosetta's Philae lander, which incorporated structural modifications to enhance visibility and distinguishability from their respective landing sites. Drawing on the successes and lessons learned from these missions, particularly regarding thermal regulation and material contrast, our lander will be designed with carbon-fiber-reinforced polymer (CFRP) for secondary systems, while its frame and primary structural components will be composed of aluminum alloy. This combination balances structural integrity, thermal adaptability, and detectability, optimizing the lander's performance for Psyche's highly metallic and thermally extreme environment. The working Bill of Materials (BoM) for this system is shown in **Appendix A**.

The majority of the non-structural parts used for mission operations are independent assemblies of their own. In the BoM, those are denoted with ellipsis, as they are constructed with a variety of sub-components. These assemblies, while not necessarily available commercially off-the-shelf (COTS), are found throughout NASA space vehicles. Infrared Imagers and Spectrometers are fairly common in the spacecraft industry; the more specialized instruments included in the instrumentation module/rack include the X-Ray Spectrometer (similar type utilized on the Pathfinder Rover), and the Infrared Microscope (density estimation tool). Not included in the BoM are fasteners; the fastener quantity to prevent shear failure of the lander upon impact was not studied in the project scope. If this design is utilized, more comprehensive load testing with fasteners included would be assigned. In this project's scope, we define all non-welded fastenings (rivets, bolts, inserts) to be titanium-based and anodized to ensure the utmost quality for spaceflight.

Final Rendering

As noted in the Engineering Specifications, the lander BUS in this design has a fixed volume of 3.375 m³, based on a cube with 1.5-meter sides. This value is informed by comparable small-body lander payloads, such as Hayabusa and Philae, and is paired with an estimated mass of 500 kg (~650 kg total lander mass). The 150 kg total landing system does not include the mass of the cold gas used in thrust modules, as well as the relative mass of the resin the craft will be carrying to the surface. Aside from those consumables, the largest independent component of the system is the subframe. It attaches all structural components and assemblies to the BUS and leaves a very accommodating area of the payload open to the surface, allowing for various surface interactions to take place. The only major component that does not rely on the subframe for placement is the resin reservoir, which we place on top of the BUS for ease of conduit routing. This strategy does pose certain challenges, such as a heightened center of mass. It may be advisable to locate the reservoir at the base of the subframe, next to the cold gas storage. Though this does increase the complexity of the tubing required to route the resin, as well as the required power of the pressurized pumping system.

Our finalized extendable spike concept is 1.5 m long, with a 0.25 m long tapered nozzle ending at 1 cm in diameter for suitable surface penetration. The Spike Stow is roughly 1.25 m long, meaning that in the stowed configuration, the spikes run 0.7 m farther than the bottom of the stow (this value accounts for honeycomb crush media, as well as excess resin conduit). This excess is crucial to the process our system takes when landing, as after the actuation of the hydraulic system (spikes angled), the impact of touchdown will compress our shock system 2-10 cm before spike extension can take place. Again, this process can be seen step-by-step in **Appendix C**. The physical spike configuration described above can be seen below in **Figure 5**.

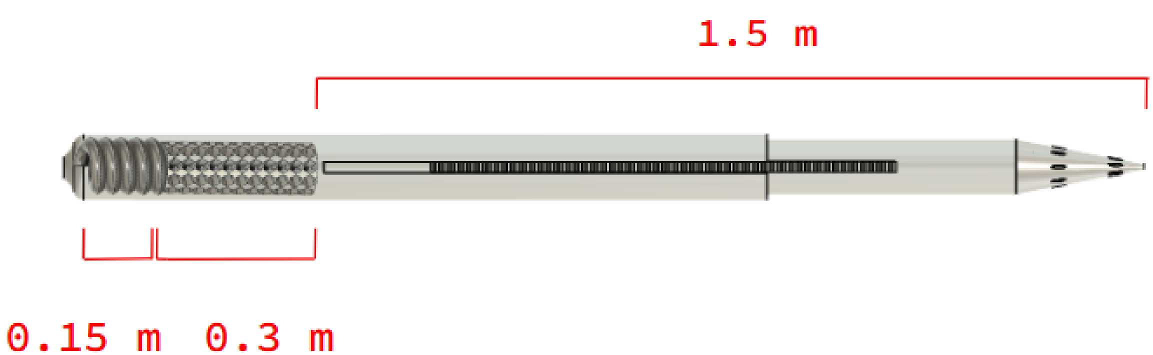

Figure 5: Spike Design Criteria

The aforementioned spike extension system operates on a rack and pinion design with a brushless DC gear motor driving the spike into the surface. Given that our system will take advantage of its thrust modules for stability (keeping itself from pushing off the surface), the DC motor should be fairly low-torque (~3 Nm). Because penetration is proportional to linear velocity, it is advantageous to extend slowly into the surface; in this case, we have chosen 10 cm/s based on the average bulk modulus estimated on Psyche. From this, we extract that the motor must turn at 38.2 RPM, and consume 22 W of input power (70% efficiency).

Further up the spike, the honeycomb crush cartridge is located directly above the spike. Undeformed, it would occupy 30 cm of total spike length. At the chosen 0.75 pcf density of the honeycomb, this is a liberal amount of material. Maximum expected impact force (possible on one spike) remains 0.148 kN; this would deform roughly 10 cm of the cartridge. The excess was incorporated to adhere to the NASA-STD-5001 and secure a reasonable FoS. Calculations detailing these features may be found in the Prototype Evaluation/Validation section. Inspiration for this system was taken from the Apollo missions, which used similar technology (Rogers, 1972).

Figure 6: Shock Cartridge and Coil Excess

The final small amount located at the top of the stow is reserved for excess resin conduit required as the spike extends into the surface. The 3 cm diameter conduit occupies 15 cm of stow length with five total coils. These values yield a 1.1 m total excess length for extension. This grants the lander the 1 m of total penetration into the surface that we sought out for total stability. Similar to the shock system, calculations detailing this system can be found in the Prototype Evaluation/Validation section. Below is pictured the fully extended configuration of the Static Spike concept.

Figure 7: Fully-Extended Lander Configuration

Resin Specifications and Resin Delivery System

The resin delivery subsystem is one of the most innovative and lowest technology readiness level (TRL) elements of this design, and its successful deployment is pivotal to the anchoring strategy of the Static Spike system. Its function is to inject a chemically curing adhesive resin into the surface of Psyche, permanently securing the lander. This mechanism is activated after spike extension, and its formulation and flow dynamics must accommodate the extreme and unknown surface conditions of the asteroid. The full CAD rendering of the resin system (with accompanying flow diagram) can be found in **Appendix B**.

To meet the mechanical and environmental demands of deep-space anchoring, our team based the resin specification on the proven properties of EPO-TEK 353ND, a NASA Goddard-approved epoxy. However, EPO-TEK's reliance on heat curing at 150°C makes it incompatible with the autonomous and low-energy requirements of this system. As such, the resin proposed for this mission must exhibit similar structural properties but cure through a two-part chemical process. The following target specifications were identified for an ideal formula:

- **Cure Method**: 2-part chemical cure (no heat required)
- **Cure Temperature**: 0°C or lower preferred
- **Viscosity**: Medium (500–2000 cP), thick enough to avoid early deployment, but low enough to flow under pump pressure
- **Working Time (Pot Life)**: >3 minutes to allow for in-system mixing and delivery **Final Shear Strength**: >5 MPa
- **Glass Transition Temperature (Tg)**: ~90°C
- **Outgassing Performance**: Meets NASA ASTM E595 with TML <1.0%, CVCM <0.1%
- **Radiation Resistance**: Withstands low-energy cosmic radiation for 30+ days

The resin delivery architecture is housed in a pressure-rated CFR tank located at the top of the payload BUS. From this tank, a piston-driven pump routes resin through a Teflon-coated transfer tube to the base of each anchoring spike. Inside each spike stow, coiled tubing (1.1 m in total length) allows for extension during spike deployment without disconnection. To initiate the reaction, a primer is first drawn into the system via a secondary intake and mixed with the base resin inside an internal chamber immediately upstream of the spike nozzle. The mixing process is mechanically driven by the same piston pump, which powers a small impeller to fully mix the primer and base. Once combined, the mixed resin flows through side-wall ports distributed near the spike tip, diffusing into the regolith as the spike reaches its final penetration depth (See **Figure 8**). This design ensures even distribution of the resin into the surrounding areas and fills voids beneath and around the spikes. The geometry of the spike was refined to accommodate this flow, thickening the spike tip to improve performance under stress while keeping the needed wall thickness for lateral resin pumping.

Figure 8: Resin Nozzle Configuration/Spike Penetration Tip

Studies exploring the mechanical behavior of regolith-resin composites, such as those involving lunar simulants (LHS-1), have demonstrated tensile strengths exceeding 25 MPa and compressive strengths approaching 100 MPa at optimal resin mix ratios (~20%). These findings provide encouraging validation that a high-performance adhesive can be formulated to secure payloads under extraterrestrial conditions, provided the curing and delivery mechanics are optimized for microgravity and thermal extremes (Tafsirojjaman 2025). The feasibility of this system is supported by a CFD study modeling resin flow through U-bend tubing, shown in **Figure 9**, which showed consistent velocity profiles and manageable pressure drops, even through tight curves. Continued experimental work should focus on vacuum-curing tests and regolith injection studies to confirm long-term holding and bonding performance.

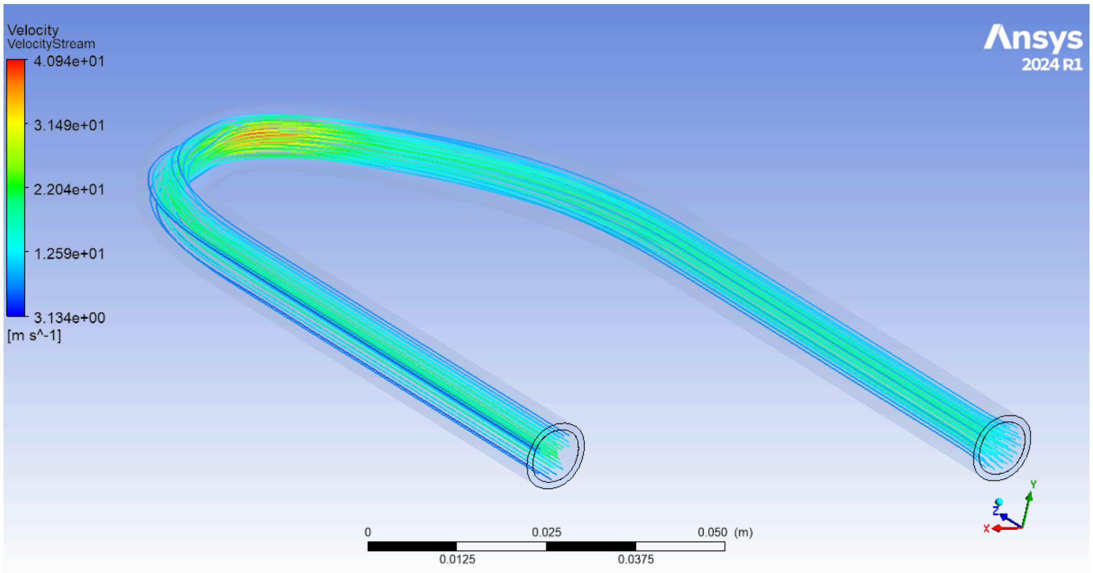

Figure 9: CFD Analysis of Pump/Resin System

Instrumentation

The proposed lander concept requires a specific instrumentation package, both for surface science and to ensure autonomous, stable operation during descent and anchoring. To support this, several systems have been identified and integrated into the spacecraft architecture.

Descent and landing operations are managed by the onboard Attitude Determination and Control System (ADCS), which makes use of a downward-facing Light Detection and Ranging (LiDAR) for terrain navigation and altitude estimation. The LiDAR provides high-resolution point cloud data at < 1 m scale, enabling both hazard avoidance and optimal landing site targeting in real time. This system operates with inertial measurement units (IMUs) and star trackers to maintain attitude awareness during final descent.

In orbit and throughout the landing phase, remote sensing payloads will be deployed to evaluate local surface composition and to constrain density models of the regolith. A Gamma-Ray and Neutron Spectrometer (GRNS) is used to determine elemental abundance by measuring high-energy photon and neutron emissions caused by cosmic ray interactions. Complementing this, an X-ray Spectrometer (XRS) measures solar-induced fluorescence in the uppermost centimeters of the surface. These instruments jointly provide a foundational understanding of Psyche's metallicity, silicate content, and porosity indicators, which in turn inform both landing site selection and anchoring feasibility (Costa 2023).

Further geological modeling is enabled by a gravimetry package, utilizing Doppler tracking of the lander's trajectory from orbit to derive local gravitational anomalies. These measurements, in combination with the mass and shape models acquired from orbiter imaging, contribute to bulk density calculations. While indirect, this data is essential for estimating structural support and stability at the landing zone.

Once contact with the surface is made, the Static Spike system is activated. Each of the four anchoring spikes is outfitted with a linear displacement feedback sensor along the rack extension shaft. These sensors continuously monitor penetration depth and resistance torque encountered by the DC motor during deployment. This enables adaptive control logic to halt a spike if it encounters unexpected resistance, such as a solid metallic substrate. Each spike also integrates a force-sensing resistor (FSR) at its base to confirm ground contact, log instantaneous impact force, and report any asymmetries across the array. This data is routed to the lander's onboard computer (OBC), which handles spike-level logic before passing telemetry to the avionics system (Kolf 1968). Together, these systems comprise a diverse network of instrumentation designed to maximize surface data while ensuring mechanical and positional stability. Where possible, designs from previous small-body missions are implemented to maintain feasibility and reduce technical risk.

Thrust Module Details

The lander is equipped with four symmetrically distributed thrust modules, mechanically integrated into the outer faces of the payload bus. These modules serve a critical role in controlling lander orientation and velocity during descent, anchoring, and limited post-landing repositioning. Each module is designed for omnidirectional thrust control, with nozzle assemblies angled at 45 degrees relative to the payload's primary axes. This configuration provides control across all six degrees of freedom, enabling pitch, yaw, and roll correction, as well as fine-tuned translational adjustments.

The thrust module housing is machined from 7071-T6 aluminum, chosen for its strong balance of structural strength, corrosion resistance, and weight efficiency. This material provides adequate protection for the internal plumbing and control hardware while maintaining compatibility with the lander's structural framework. The geometry of each housing is optimized to sit flush with the lander bus exterior, reducing exposed edges and minimizing the risk of debris accumulation during descent. Each module interfaces with a section of the cold gas system, which includes high-pressure storage, regulation, and distribution conduit routing. These internals are constructed from 321 stainless steel, which has been chosen for its proven performance in high-pressure, cryogenic, and chemically inert applications. All conduits and junctions within the system are welded or sealed using flight-rated fittings, with a focus on minimizing possible leak paths and maintaining thermal stability.

Nozzle ports are arranged to distribute thrust loads evenly through the center of mass and are reinforced at the base with internal bracketing to absorb mechanical stress during usage. The current mechanical design allows for isolated module control and thrust vector blending, which will support closed-loop descent and stabilization once propulsion dynamics are completed. This subsystem represents a primary driver of the descent profile and plays a key supporting role in surface touchdown and correctional maneuvering. As such, mechanical robustness and solid subsystem integration are prioritized during this phase of the design process. Further development will address exact nozzle placement based on the payload center of mass and thermal management for long-duration operations.

Figure 10: System CAD Model, Cold Gas System Exposed

To estimate the mass of N_2 needed for descent corrections and rebound/extension assist, we can rearrange the well-known Rocket Equation to solve for propellant mass. When performing these calculations, we take the specific impulse of 70s for typical N_2 thrust modules, as well as Earth's gravitational constant. We use Earth's constant because the specific impulse of gases is always measured in relation to Earth's properties here as a standard. 10 m/s is estimated for the total amount of velocity change to be had during the course of the descent to the surface. This is a healthy overestimate for the relatively short travel time the lander will take.

$$\Delta V = 10\, m/s \qquad m_o = 650\, kg \qquad I_{sp} = 70\, s \qquad g_o = 9.81\, m/s^2$$

$$\Delta V = I_{sp} \cdot g_o \cdot ln(\frac{m_o}{m_f})$$

$$m_{prop} = m_o \cdot (1 - e^{\frac{-\Delta V}{I_{sp} \cdot g_o}})$$

$$m_{prop} = 650\, kg \cdot (1 - e^{\frac{-10}{70 \cdot 9.81}}) = 9.43\, kg$$

This figure represents our estimation for only the descent portion of the landing cycle. To account for sufficient gas during the spike extension phase, we will double this figure. To account for the possibility of payload/BUS separation back to the orbiter, we triple the figure. To retain at least this level of thrust security (it being a core system to mission success), plus a FoS, we will settle on a figure of 40 kg of N_2.

Prototype Evaluation/Validation

In validating our system architecture, key emphasis was placed on the physical interactions expected during the landing sequence, particularly the initial ground contact and subsequent anchoring events. Calculations were carried out to establish impact force tolerances, material deformation requirements, and minimum component lengths needed to ensure anchoring reliability under conservative assumptions.

Landing Impact Force

Given our assumed descent velocity of 0.5 m/s and total lander mass of 650 kg, the kinetic energy at touchdown equates to 81.25 J. To resolve this energy into an effective impact force, we approximated a penetration depth based on a bulk regolith density of 3.77 g/cm³. Solving through the impulse-energy relation and accounting for the distributed force over our projected 0.53 m spike penetration, we obtain a net impact force of 0.153 kN. This value is treated as a system-level impact, distributed across the entire anchoring architecture, and is foundational in selecting our structural and material tolerances.

$$KE = \frac{1}{2}(650\ kg)(0.5\ m/s)^2 = 81.25\ Joules$$

$$F = \rho g A d^2, \text{ solving: } d = 0.53\ m$$

$$F_{\text{impact}} = \frac{KE}{d} = \frac{81.25\ J}{0.53\ m} = 0.153\ kN$$

Honeycomb Shock Absorption

To address energy dissipation during touchdown, we incorporated crushable honeycomb cartridges within each spike, sized to absorb the full mechanical impulse from landing. Energy per leg was determined by dividing the total kinetic energy evenly across the four support legs:

$$E_{\text{per spike}} = \frac{81.25\ J}{4} = 20.3125\ Joules$$

$$\sigma_{\text{crush}} = \frac{E}{A \cdot x} = \frac{20.3125\ J}{(0.010293\ m^2)\cdot(0.1\ m)} = 19,732\ Pa = 19.73\ kPa$$

Assuming an impact angle of 70° from vertical and a contact area of 0.010293 m² (this allows for a 3 cm hole in the middle of the shock for the resin conduit), the resulting stress in the honeycomb structure was calculated at 19.73 kPa under full deformation. At a crush depth of 10 cm, this remains within the mechanical performance limits of aluminum 5052-H39 honeycomb core at 0.75 pcf, a configuration that maintains both resilience and good mass characteristics. Additional margin is built in beyond the expected 10 cm deformation to preserve a Factor of Safety consistent with NASA-STD-5001 recommendations.

Resin Tubing Requirements

As part of the anchoring mechanism, excess resin tubing must remain flexible and deployable during spike extension. Tubing is coiled within the upper stow region of each spike in a 3 cm diameter helix. With five complete coils over a 15 cm axial section, and a mean loop radius of 3.5 cm, the total stowed length was found to be approximately 1.1 m. This value provides the full 1 m extension margin required to match the maximum spike deployment depth, ensuring continuous delivery of resin during the anchoring sequence without risk of tension failure or disconnection. These coils are accommodated directly above the honeycomb shock section, completing the spike's vertical stack with minimal space conflict.

$$N_{\text{coils}} = \frac{x}{d} = \frac{15\ cm}{3\ cm} = 5\ coils$$

$$Mean\ radius\ of\ loop:\ r = \frac{7\ cm}{2} = 3.5\ cm$$

$$Length\ per\ Coil:\ L = 2\pi r = 2\pi(3.5\ cm) = 21.99\ cm$$

$$Excess\ Length:\ L_{\text{excess}} = N_{\text{coils}} \cdot L = (5)(21.99) = 109.95\ cm \approx 1.1\ m$$

Thin-Walled Component Stress Analysis

Autodesk Fusion's Shape Optimization and Static Loads toolkits were used to selectively test components of our system. Components were chosen based on structural necessity and material size to load comparison. The Spike Stow Collar and the Upper Swingarm Bracket were prime candidates in this case. Below in **Figure 11** the results of the stow collar stress analysis are shown; the legend to its right displays units of MPa. All stresses in the following analyses are Von Mises stresses.

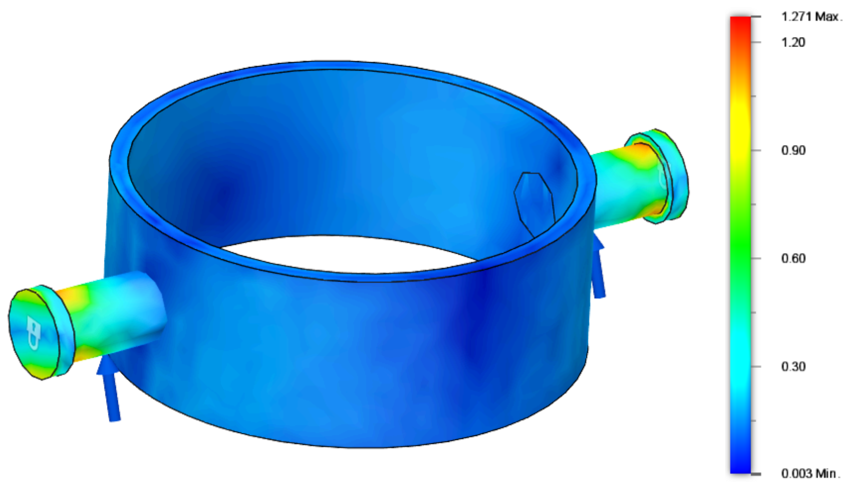

Figure 11: Spike Stow Collar Stress Analysis

The Upper Swingarm Bracket was also analyzed with the addition of Shape Optimization being run to determine what sections of the component can be reduced, reducing overall system weight. **Figure 12** below shows the shape optimization graphic of the original part when first modelled. The legend is not included here for ease of understanding. The colored segments of this graphic are utilized material sections that channel the primary amount of stress induced by a load. The transparent sections receive negligible stress, enough to be cut from the part, yielding the final version of our component. Displayed after the shape optimization run is the final stress analysis of the edited component in **Figure 13**.

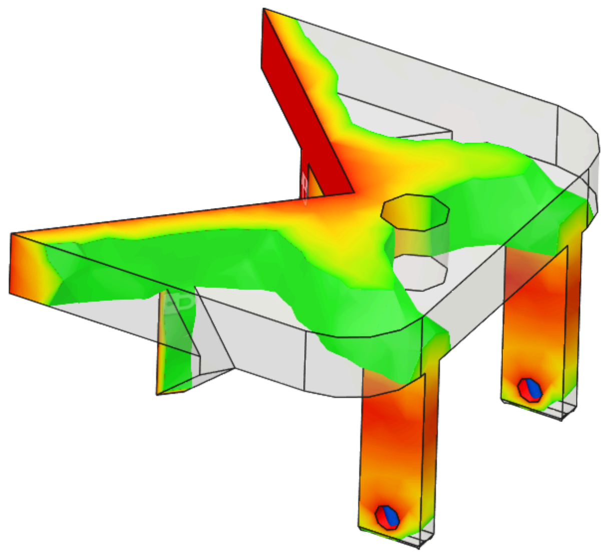

Figure 12: Upper Swingarm Bracket Shape Optimization

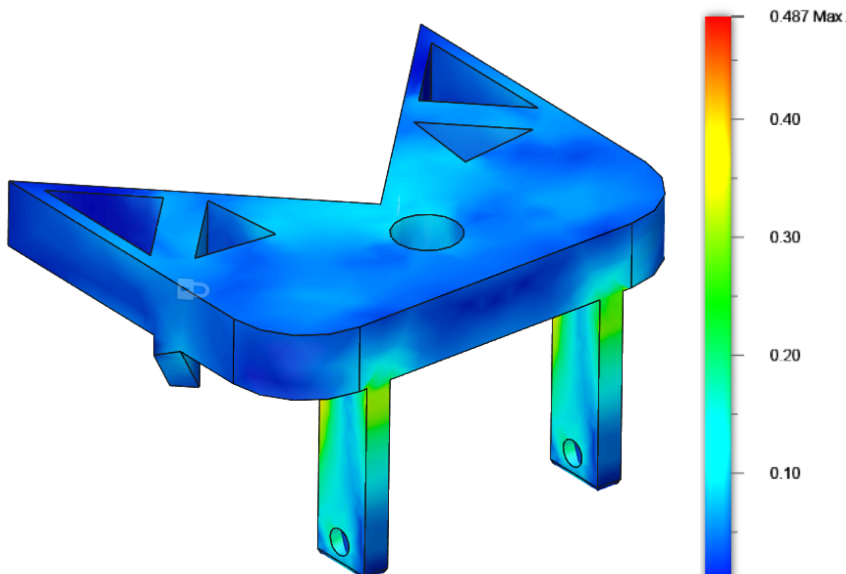

Figure 13: Upper Swingarm Bracket Stress Analysis

Impact

This conceptual design for a small-body landing system provides a feasible solution to the technical and operational challenges associated with anchoring on low-gravity, poorly defined surfaces such as those on Psyche. In particular, the system is engineered to remain functional across a wide range of surface compositions and structural responses, prioritizing adaptability, redundancy, and autonomy. These design choices reflect an overall goal of expanding the options available for future planetary exploration missions where direct surface interaction is both scientifically valuable and operationally uncertain.

The Static Spike anchoring concept, coupled with resin-based stabilization and shock absorption, introduces a design that can be scaled or modified for other microgravity targets. Its relative mechanical simplicity, paired with embedded sensor feedback for adaptive control, offers a potential path forward for landers tasked with operating in environments where regolith cohesion, surface hardness, and topography are unknown before or at the time of descent. The approach demonstrates how subsystem-level tuning (e.g., in spike extension velocity, crush cartridge deformation, and resin deployment) can be used to limit broader uncertainties in the mission. From a scientific perspective, this system structure stands to improve the value of orbital datasets by enabling ground-truth validation. Surface density models, element distributions derived from orbital spectrometry, and gravitational field approximations can all be measured with direct contact. Such data would be critical in refining models of planetary differentiation and small-body exploration, particularly for M-type asteroids like Psyche, whose formation histories remain unknown.

In all, this work contributes a systems-level reference point for future missions targeting small, irregular, or under-characterized bodies. The design is intentionally conservative in its assumptions yet forward-leaning in its redundancy and instrumentation logic, offering both a feasible concept and solid ground for future investigation into anchoring technologies and descent system autonomy.

Summary, Recommendations, and Future Work

Upon completion of this project, our team will have developed a scalable, concept-level landing system designed specifically for small body exploration missions. The design addresses the unique challenges presented by 16 Psyche, including its uncertain surface composition, low gravity, and the absence of numerous successful prior landing missions. By integrating mechanically adaptive anchoring spikes, resin stabilization, and autonomous descent instrumentation, the system offers a flexible approach that can be adapted to other unknown small bodies across the solar system. With the scheduled arrival of NASA's Psyche Orbiter in 2029, there is reasonable potential for a follow-up surface mission to be proposed. This landing system concept is intended to serve as a foundational candidate for such a mission. Our team's goal is that this design will progress into further development phases and eventually be considered for mission implementation.

To support continued development, the following recommendations are provided:

- Conduct joint and fastener placement analysis under launch and impact conditions
- Develop and test the proposed resin formulation in vacuum and low-temperature environments
- Analyze lander bottom for impact if surface be too sparse to support the lander
- Refine the payload integration strategy and define a full-scale lander configuration
- Simulate orbital dynamics and descent timing in coordination with orbiter operations
- Perform cost modeling and identify opportunities for mass and power optimization

These next steps will help transition the design from a conceptual framework into a viable candidate for future small-body landing missions, enabling direct surface science and technology validation in deep space environments.

Contributions

Team Member	Main Project Contributions	Signature
David Krupp	CAD Model, Stress Analysis, Spike Extension System, 3D Model, System Flowchart, Resin Deployment System	*David Krupp*
Brice Vandiver	Background Research, Calculations, Conceptual Models, Poster Presentation	*Brice Vandiver*
Mason Dade	Background Research, CFD Resin Analysis, Pump Research	*Mason Dade*
Aditya Ramesh	Background Research, Engineering Calculations	*Aditya Ramesh*
Kavi Troiano	Additional Research, Parts of resin and extension systems, Ideation	*Kavi Troiano*

Table 3: Team Contributions

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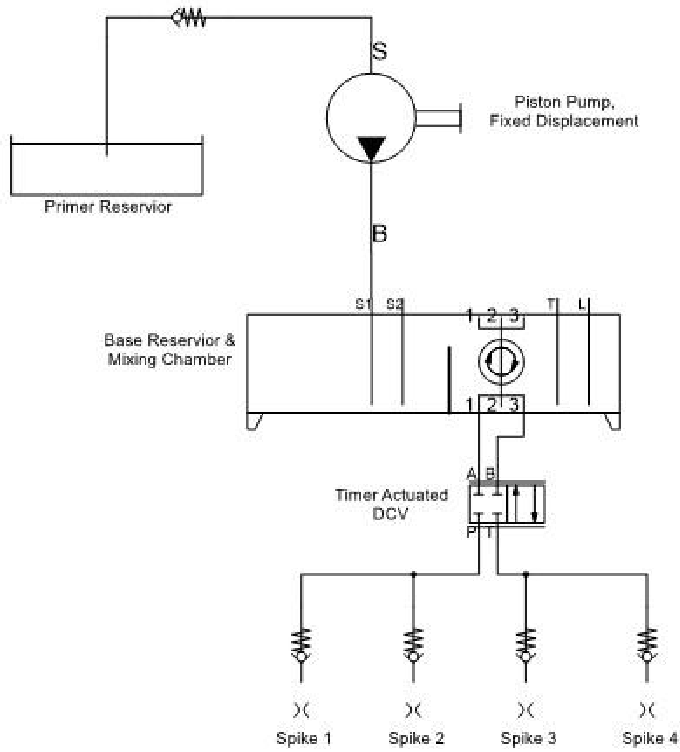
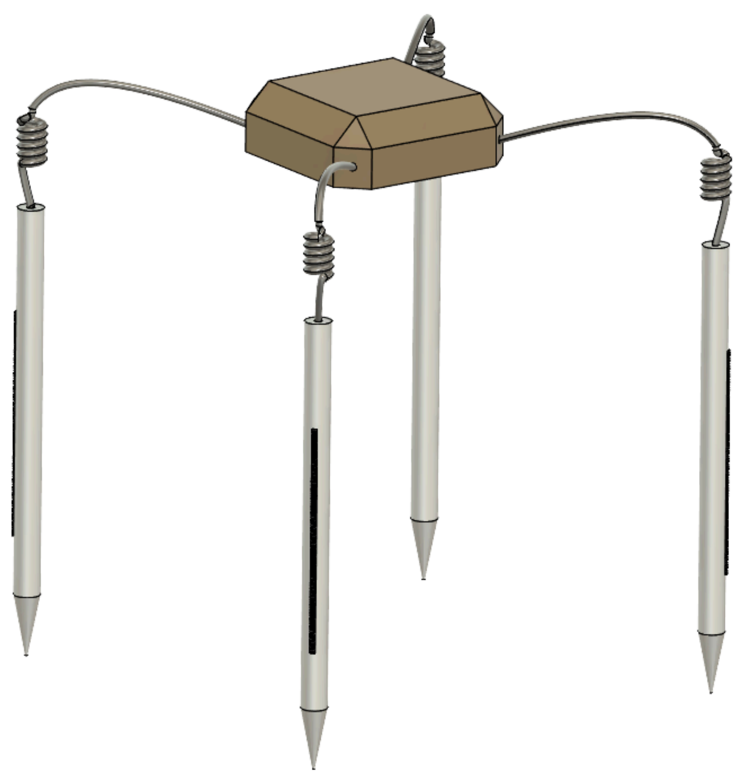
Appendices

Appendix A - Bill of Materials

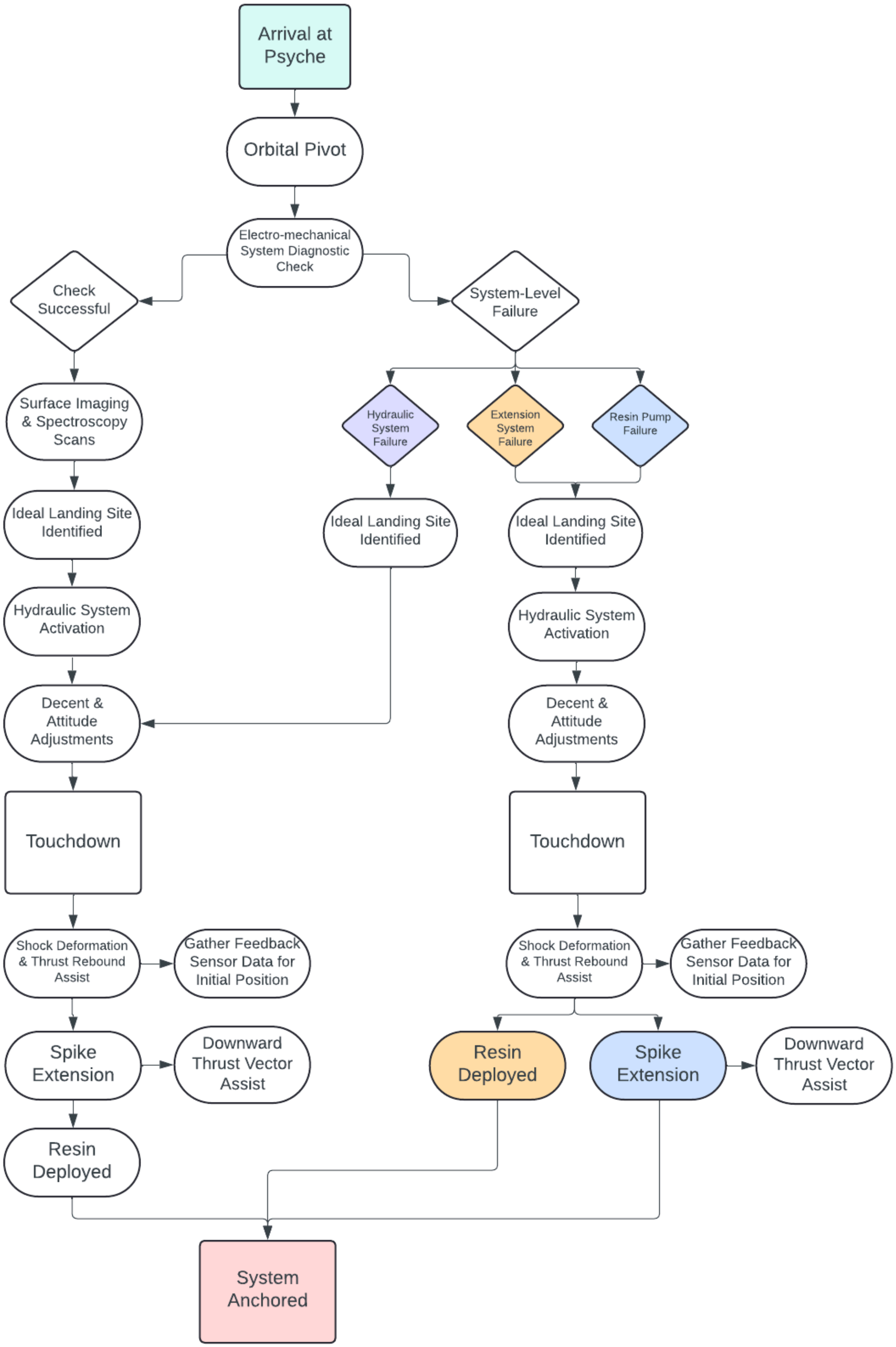
Component	Quantity	Subsystem	Material
Upper Stow Bracket	4	Lander Legs	7075 Aluminum
Lower Stow Bracket	4	Lander Legs	6061 Aluminum
Spike Shock	4	Lander Legs	6061 Aluminum
Spike Stow	4	Lander Legs	7075 Aluminum
Spike	4	Lander Legs	7075 Aluminum
PE Transfer Tubes	4	Resin Reservoir	PTFE Teflon
CFR Tank	1	Resin Reservoir	PEEK inner, 6061 Aluminum outer
Peristaltic Pump	1	Resin Reservoir	……………………….
Electrical Harness	1	Instrumentation	……………………….
21 N Thrust Module	4	ADCS	……………………….
Stainless Steel 100L Tank	1	ADCS	321 Stainless
LiDAR	1	ADCS	……………………….
AMICA (Asteroid Multiband Imaging Camera)	1	Instrumentation	……………………….
Star Tracking Optical Sensor	1	Instrumentation	……………………….
GRNS (Gamma Ray Neutron Spectrometer)	1	Instrumentation	……………………….
XRS (X-Ray Spectrometer)	1	Instrumentation	……………………….
Gravimetry Package	1	Instrumentation	……………………….
Linear Displacement Sensor	4	Instrumentation	……………………….
Force Sensing Resistors	4	Instrumentation	……………………….
Magnetometer	1	Instrumentation	……………………….
Radiometer	1	Instrumentation	……………………….
Subframe	1	Frame	7075 Aluminum

Appendix B - Resin Deployment System



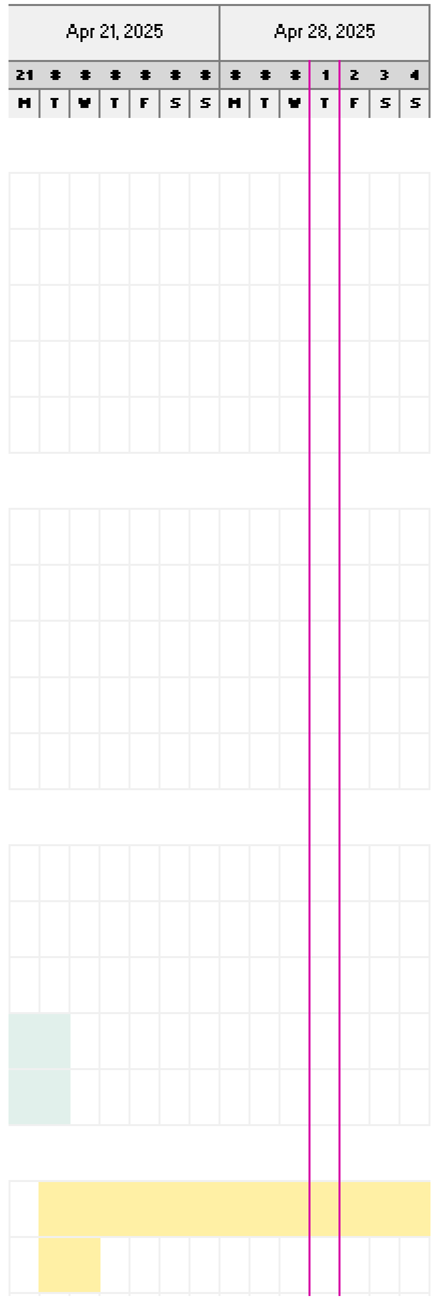


Appendix C - Landing System Process Flowchart

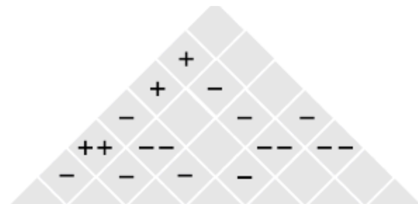


Appendix D - Project Gantt Chart

TASK	ASSIGNED TO	PROGRESS	START	END
Initiation				
Project Scope	Whole Team	100%	9/9/24	9/20/24
Team Charter/Research	Whole Team	100%	9/9/24	9/30/24
Communicate Findings	Aditya Ramesh	100%	9/9/24	9/30/24
Develop Semester Plan	David Krupp	100%	9/30/24	10/7/24
Geologist Review	Aditya Ramesh	100%	9/30/24	10/21/24
Planning and design				
Feasibility Review	Whole Team	100%	10/21/24	10/25/24
Software/Format Selectio	Brice Vandiver	100%	10/21/24	10/25/24
System Intricacy Review	Mason Dade	100%	10/25/24	10/28/24
Design Tasks Assigned	David Krupp	100%	10/28/24	10/29/24
CAD Modeling Primary	David Krupp	100%	11/1/24	2/24/25
Execution				
System Simulation	David Krupp	100%	11/1/24	3/10/25
Final Report Scientific Dra	Whole Team	100%	3/20/25	4/1/25
Professional Review Org.	David Krupp	100%	3/28/25	4/7/25
Final Report Sectional Ad	Whole Team	100%	3/31/25	4/22/25
3D Models/3D Printing	David Krupp	100%	2/26/25	4/22/25
Evaluation				
NASA - ASU Submission	Whole Team	100%	4/22/25	5/6/25
Capstone Showcase	Whole Team	100%	4/22/25	4/23/25



Appendix E - House of Quality (QFD)



Customer Expectations	Customer importance rating (1 = low, 5 = high)	Percent of customer importance rating	*Weight/Compactness*	*Durability/Longevity*	*Estimated Cost*	Complexity	Impact on Asteroid	Instruments Necessary	Impact on Sensors	Competitor research: *Hayabusa*	Competitor research: *Rosetta-Philae*
			▼	▲	▼	▼	▼	▼	▼		
Stability	4	18%	○			△	○	○	⊙	3	2
Surface Penetration	4	18%		△		○	⊙		○	1	1
Reliability	4	18%	△	⊙	○	○		○		2	2
Surface Adaptability	3	14%			△	⊙	△	○	○	4	2
Energy Efficiency	2	9%		△		△		△	○	2	3
Ease of Deployment	2	9%	△			△		△		3	1
Redundancy	2	9%	○	△	○	○		○		1	2
System Integration	1	5%	○		△	○			⊙	3	3
Importance rating			27	44	22	68	51	43	72		
Percent of importance			8%	13%	7%	21%	16%	13%	22%		