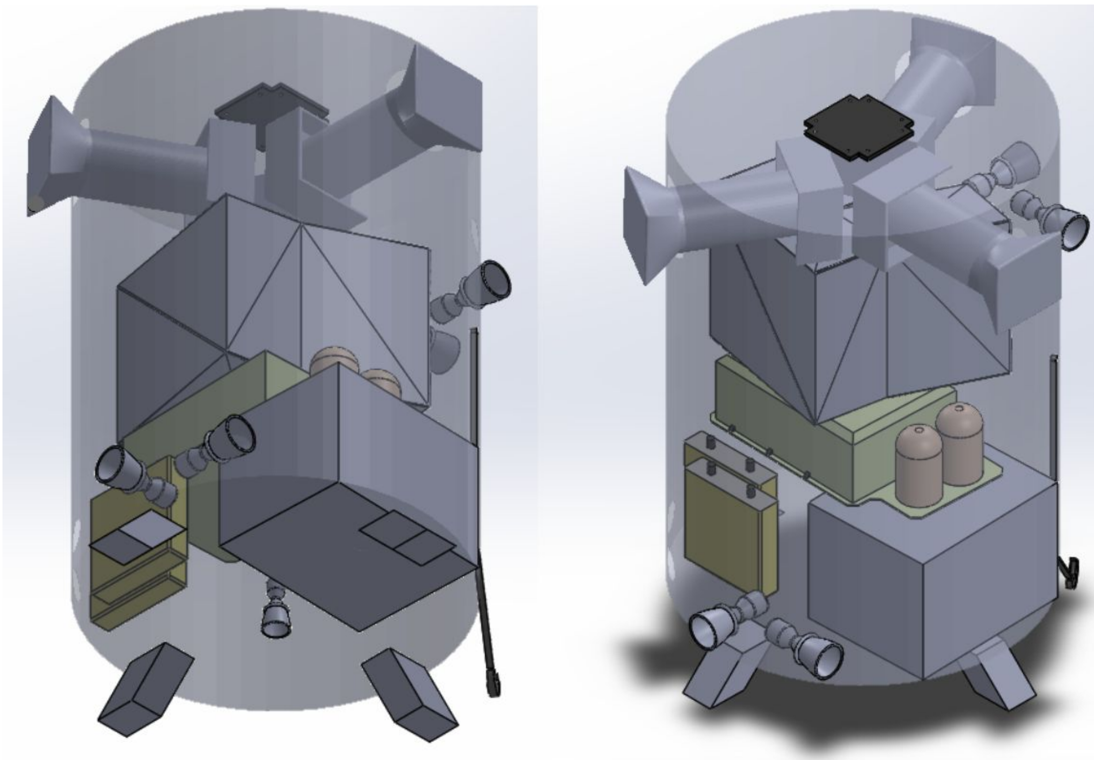
Preliminary Design Review - Ensomnia Lander

Team 18: Latitude



LATITUDE

NASA Lucy Student Pipeline Accelerator and Competency Enabler
Mission Concept Academy

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Section 1: Introduction and Summary

1.1. Team Introduction

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Jane brings technical experience in programming and web development as well as skills in consecutive interpretation.

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Mini brings technical experience in programming with interests in physics and web development.

1.2. Mission Overview

1.2.1. Mission Statement

The objective of this mission is to further explore the ocean world Enceladus and the atmospheric and geological composition of the Southern Pole Tiger Stripes. During the mission, the lander will execute experiments on the surface of Enceladus with various instruments including the Thermal Emission Imaging System (THEMIS) infrared and Mastcam-Z video/camera for visual analysis to identify surface characteristics, Ptolemy gas chromatography and mass spectrometer to identify surface composition, Submillimeter Enceladus Life Fundamentals Instrument (SELFI) for plumes analysis, and Light Detection and Ranging (LIDAR) 3D altimeter/topology modeling to visualize the surface and landing assistance. Data recorded by these experimentation instruments will be sent back to Earth for the team scientists to analyze using the EnduroSat Ultra High Frequency (UHF) ANTENNA III system. The Ensomnia mission strives to obtain results that will allow for a better understanding of the ocean world's surface, subsurface, and atmospheric conditions to indicate how the Earth was formed and if there is more to life outside of the green and blue planet. This is the stepping stone to space exploration and shall open the doors to unimaginable discoveries.

1.2.2. Mission Requirements

The lander is constrained to a mass of 77kg, a stowed volume of 51cm x 51cm x 76cm, and a budget cap of $400M. The engineering and science team has also set system requirements for the design.

The lander must be able to transmit and receive data from the orbiter to be relayed back to Earth as well as store data recorded during periods without a reliable connection to be transmitted when a connection is reestablished. The lander must be able to operate in $\pm 20\,^{\circ}C$ of the expected surface temperature of the landing site. The lander must withstand up to 120% of the expected structural strain during landing without loss of functionality. The lander must be able to withstand 100 kilorads of total-dose radiation without major loss of electronics. The lander must be able to operate autonomously without a direct line of communication to Earth. The lander must be able to autonomously identify a landing site in the defined range and navigate a landing using SLAM technology. Finally, the lander must be able to successfully deploy all of the scientific instruments, LIDAR, NGIMS, Ptolemy, SELFI, THEMIS, and Mastcam-Z, without hardware failure.

1.2.3. Mission Success Criteria

The main scientific objects for this mission are as follows:

(1) Investigate conditions of the plumes within the tiger stripes and the fallen matter, including the chemistry, physical conditions, and potential biological activities.
(2) Investigate how Enceladus interacts with its surroundings and how this affects the tidal forces and recreation of its own surface.
(3) Prepare for follow up missions by establishing characteristics of life along with mapping Enceladus and identifying future landing sites.

By achieving these main objectives, we will be able to further the human comprehension of the solar system and other sea worlds. In order for the mission to be considered successful, the mission must launch within 5/13/2023 - 6/02/2023. The lander entry, descent, and landing procedure must also be completed on target with minimal damage to the payload.

The lander system must have 100% success rate and all instruments deployed properly. The lander should collect 30 small samples from the surface and use Ptolemy to analyze the material. Ptolemy needs to analyze mass spectrometer measurements of plumes and atmosphere to determine the chemical composition with an accuracy 10% and mass to charge ratio range 10-150. Ptolemy also must determine the light element (H, C, N, O) isotopic composition of major components with an accuracy of 1% of volatile and refractory cometary components. Cameras integrated into the rover must take images with a minimum resolution of 1600 X 1200 pixels and infrared images with a minimum resolution of 1920 x 1080 pixels. LIDAR must 3d map 100% of the surface topology of the landing site.

The system must initiate, receive, and store data from instruments between an ultra high frequency range of 300 MHz and 3 gHz. Collected data must be analyzed and results must be communicated back to Earth via integrated communication on lander and orbital satellites every 12 hours. Lastly, the ander remains fully operational for the entire duration of the mission surviving the harsh conditions of Enceladus.

1.2.4. Concept of Operations (COO)

The Enceladus lander will be a secondary payload of a future NASA Saturn mission. After encountering Saturn, 6 year after launch, the lander will wait to descend to Enceladus for five months so that the Sun does not block the connection between enceladus and earth. The lander will separate from the orbiter 220km above the surface of Enceladus and begin descending. The lander will descend while simultaneously mapping the surface and locating ideal landing sites. After touchdown, the lander will establish and verify communications with the orbiter, and communicate with the orbiter once every 12 hours when line of sight is established. The lander is expected to conduct scientific experiments and transmit data for 2 Earth days after touchdown.

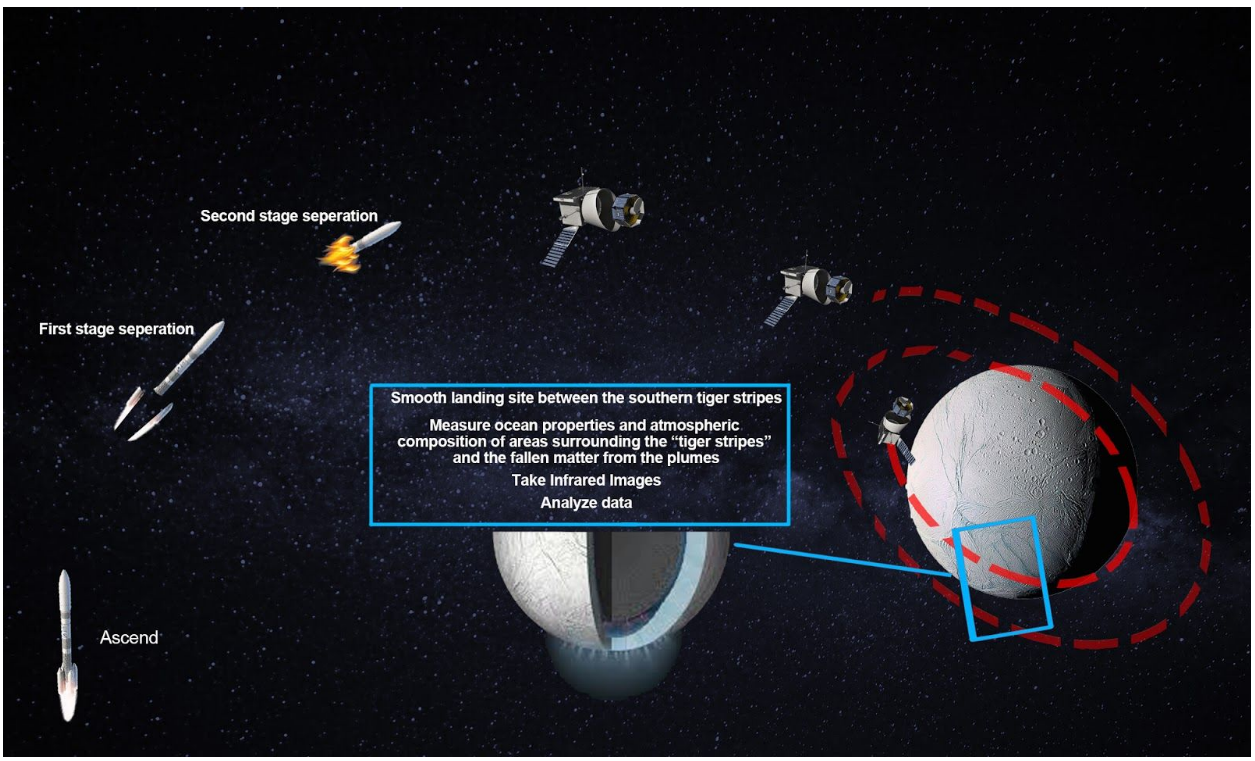

Figure 1: Concept of Operations Graphic

1.2.5. Major Milestones Schedule

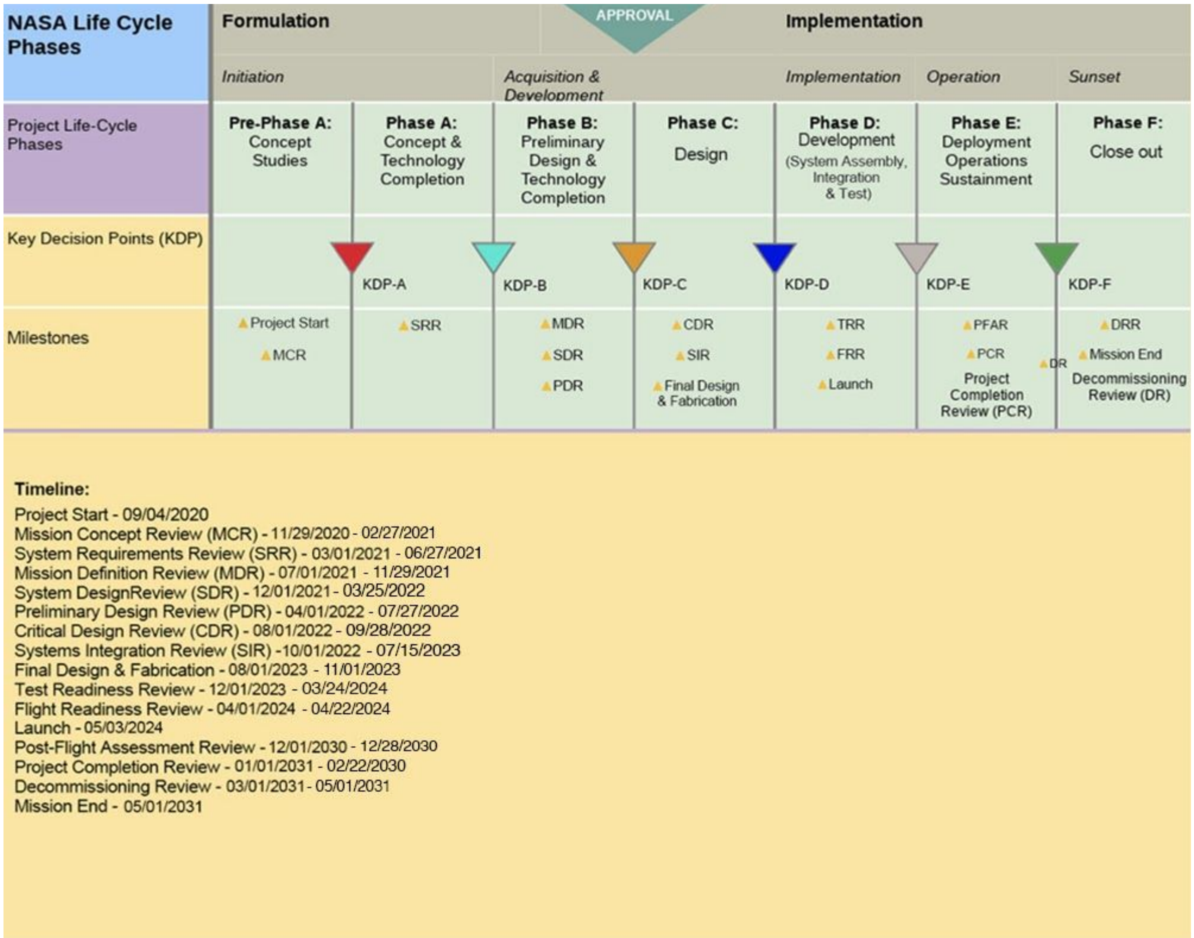

Figure 2: Major Milestones Schedule

Project Start	- 09/04/2020
Mission Concept Review (MCR)	- 11/29/2020 - 02/27/2021
System Requirements Review (SRR)	- 03/01/2021 - 06/27/2021
Mission Definition Review (MDR)	- 07/01/2021 - 11/29/2021
System DesignReview (SDR)	- 12/01/2021 - 03/25/2022
Preliminary Design Review (PDR)	- 04/01/2022 - 07/27/2022
Critical Design Review (CDR)	- 08/01/2022 - 09/28/2022
Systems Integration Review (SIR)	- 10/01/2022 - 07/15/2023
Final Design & Fabrication	- 08/01/2023 - 11/01/2023
Test Readiness Review	- 12/01/2023 - 03/24/2024
Flight Readiness Review	- 04/01/2024 - 04/22/2024
Launch	- 05/23/2024
Post-Flight Assessment Review	- 12/01/2030 - 12/28/2030
Project Completion Review	- 01/01/2031 - 02/22/2030
Decommissioning Review	- 03/01/2031 - 05/01/2031
Mission End	- 5/01/2031

1.3. Descent Maneuver and Lander Summary

The overall structure of the spacecraft will include an orbiter and lander integrated together. The Lander will be constrained to 77 kg in mass with a volume constraint of 197,676 cubic centimeters (51 cm x 51 cm x 76 cm). Based on these limitations, the design of the lander is a cylindrical prism with an outer radius of 25.1 cm and height of 70.2 cm and an overall weight of 39.771 kg. These dimensions will fit inside the constraints of the concept due to the maximum dimensions of the cylinder being 50.2 cm x 50.2 cm x 70.2 cm. The orbiter size and weight is not considered in the design of the lander. The orbiter will remain in the initial orbit as shown in figure 3 relay data between Earth and the Lander. The lander will detach from the orbiter at the beginning apogee and burn in retrograde of the orbit to lower the perigee to 5km above the surface of Enceladus which will last about 9.4283 seconds. The starting velocity for this burn is 106.2913 m/s and the ending velocity after the burn is 101.9598 m/s. The second burn begins 550.8608 seconds prior to touchdown on the surface which will burn in retrograde until Ensomnia has reached the surface of Enceladus. It is split into two parts, one for eliminating all orbital velocity without descending and the other to remove all vertical velocity. For removing orbital velocity, the lander will start at an orbital velocity of 190.6305 m/s and will no longer have velocity after the burn. Meanwhile, the second part begins with a vertical velocity of 33.3481 m/s and comes to a complete stop on the surface of Enceladus. The total change in velocity of the descent maneuver is 228.3101 m/s. The Lander will have integrated landing equipment including thrusters and landing legs. The thrusters are Yuzhnoye's Cyclone-4 30N thrusters and will consist of a main thruster at the bottom base and four reaction control thrusters as depicted in section 3. The landing legs will be simple square cross section beams with the landing surface parallel to the landing edge of the beam. These will be retractable to allow for more volume allocation to other systems.

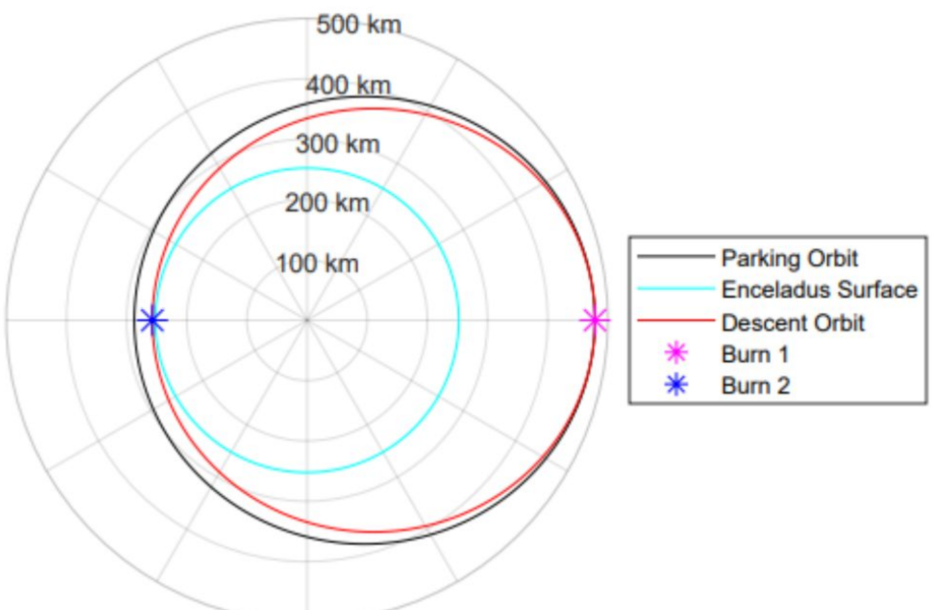

Figure 3: Descent Diagram

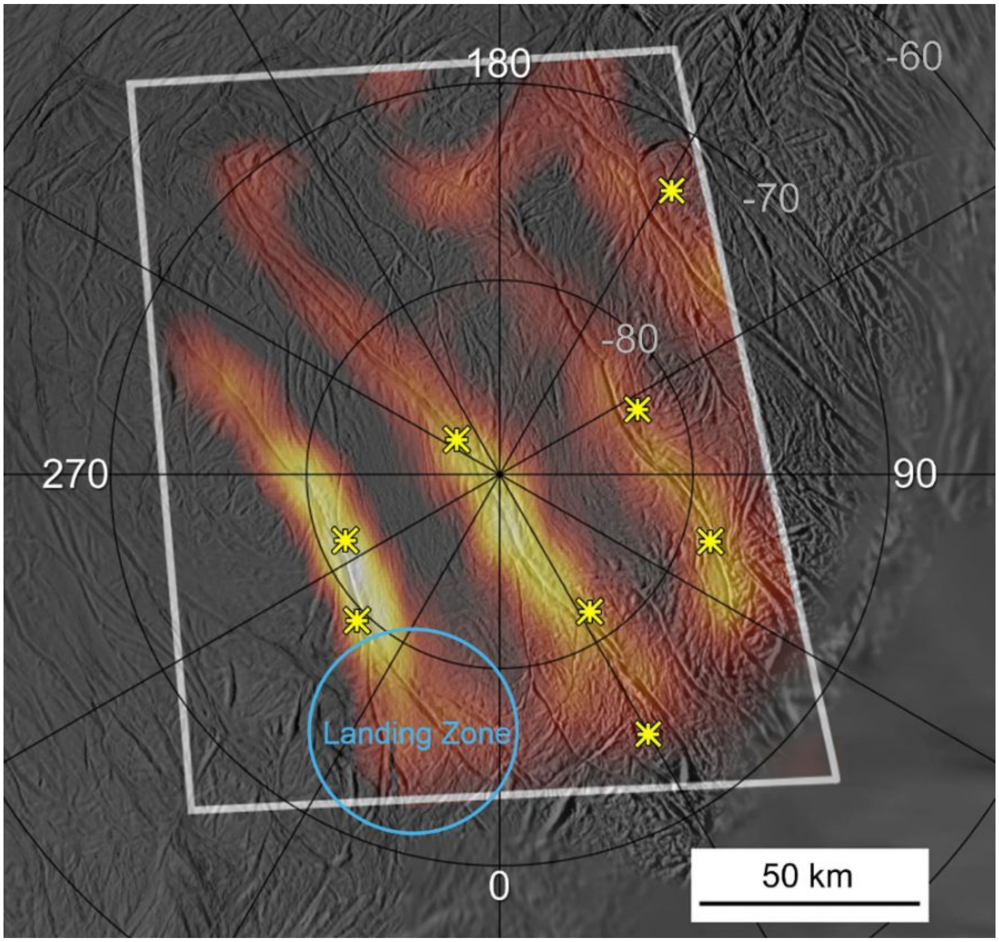

Figure 4: Landing Location
Spencer, 2011

The lander is powered by a set of batteries to supply power to the compute devices, communications systems, thermal management systems, and scientific instruments. The lander communicates with the orbiter via a Ultra High Frequency (UHF) deployable monopole antenna due to their low power consumption as well as low directionality for a reliable connection without the need for tracking the orbiter.

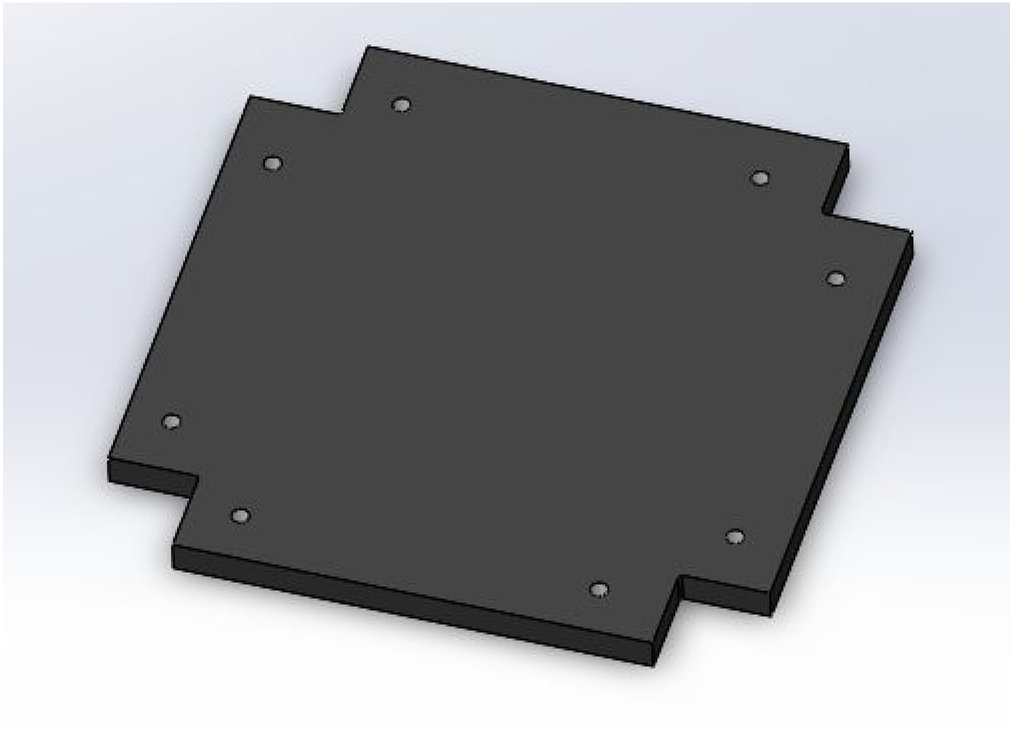

Figure 5: Communications Subsystem

Figure 6: Propulsion Subsystem

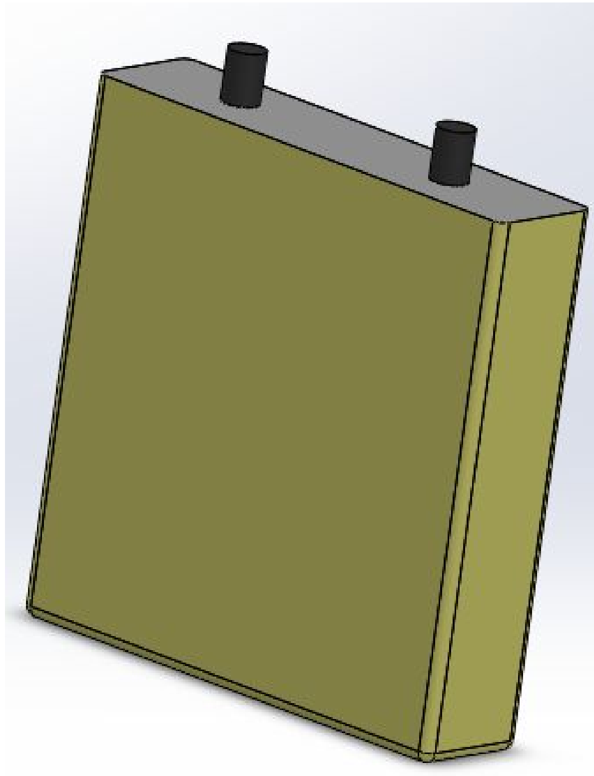

Figure 7: Power Subsystem

1.4. Payload and Science Instrumentation Summary

The lander will be equipped with a variety of equipment to ensure accurate measurements of Enceladus, including ocean properties, atmospheric composition of areas surrounding the "tiger stripes", and fallen matter from the plumes. To achieve this, Ptolemy, and Submillimeter Enceladus Life Fundamentals Instrument (SELFI) have been selected. Ptolemy will be associated with a small arm to collect a sample and then measure organic chemicals and light elements in different temperatures. Ptolemy is also designed to have high-resolution and high-sensitivity to allow the identification of chemical compounds in complex mixtures and of similar mass. SELFI is being created to measure traces of chemicals that are within the plumes of icy particles and water vapor. These two instruments will be crucial in completing mission success criteria (1) to investigate conditions of the plumes within the tiger stripes and the fallen matter, including the chemistry, physical conditions, and potential biological activities. The lander will also be equipped with optical instruments to capture images, assist with landing site selection, and characterize the surface of Enceladus, including Mastcam-Z, Thermal Emission Imaging System (THEMIS), and Light Detection and Ranging (LIDAR). Mastcam-Z, shown in figure 5, has mounted cameras that have the ability to zoom in, focus, and take 3D pictures and video at high speed to allow detailed examination of distant objects. THEMIS, shown in figure 6, can image in the infrared and visible spectrum to map mineral distribution and surface temperatures. LIDAR uses an imaging laser altimeter system to collect data on surface topography and 3-D structure of Enceladus. These instruments will assist in measurements, visualizations, and processes such as lander descent. They will assist in the completion of mission success criteria (2) investigating how Enceladus interacts with its surroundings and how this affects the tidal forces and recreation of its own surface and (3) preparing for follow up missions by establishing characteristics of life along with mapping Enceladus and identifying future landing sites.

The combination of the science instrumentation payload totals approximately 33.96 kilograms and 105,910 cm^3 in volume, within the mission constraints. The overall structure of the lander will be in the shape of a simple cylinder that is hollowed out with inner dimensions of the cylinder as 25cm radius with a height of 70cm. The first instrument inserted into the top of the structure is THEMIS infrared camera. This is followed by Mastcam-Z which has two camera heads and there will be one located on either side of the lander toward the top to allow for a 360 degree unobstructed view. SELFI is the next instrument inserted into the lander and will be located on the top of the lander to allow for the sampling arms to easily access and provide these instruments with samples. LIDAR is then placed inside on the edge of the lander with a hole to allow for an unobstructed view. Ptolemy is the last instrument to be placed and will be located on the bottom so that it can utilize the sampling system associated to obtain the sample and measurements.

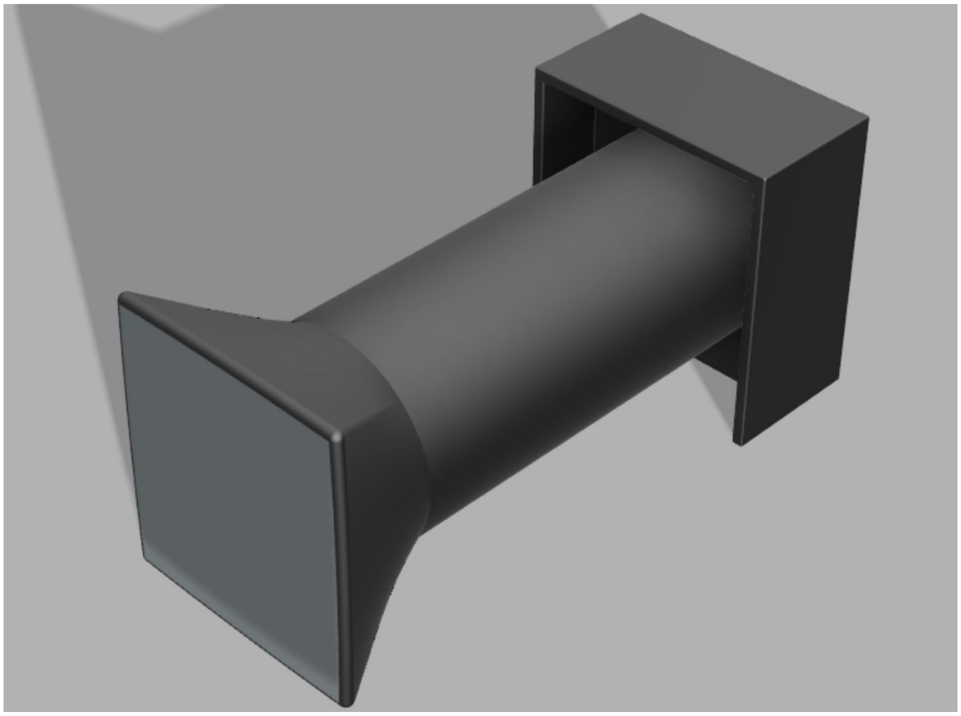

Figure 8: Mastcam-Z Camera Head

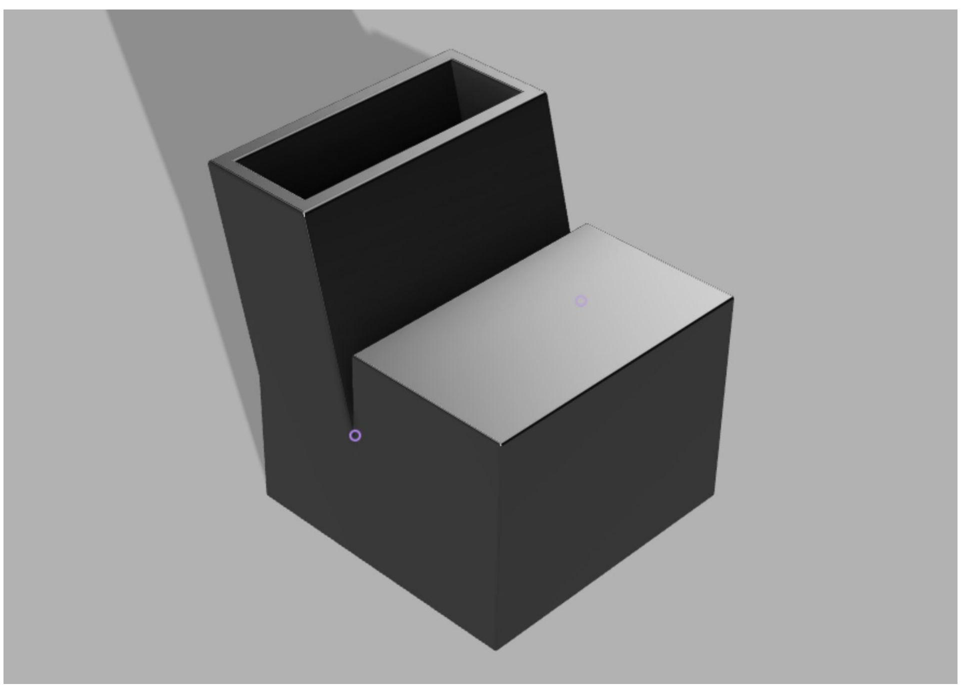

Figure 9: THEMIS

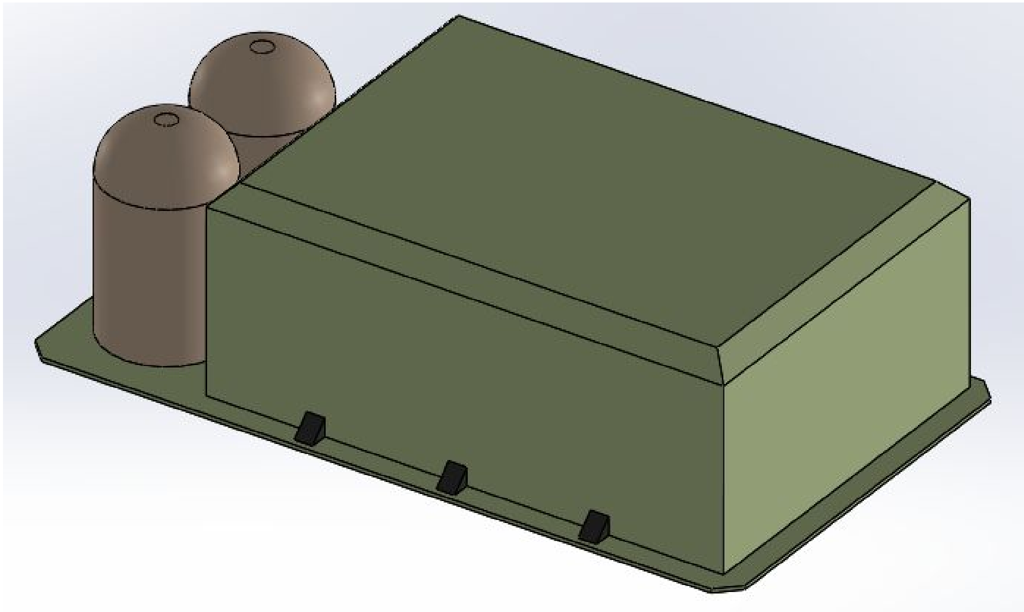

Figure 10: Ptolemy

Figure 11: Sample Collection Arm

Section 2: Evolution of Project

2.1. Evolution of Descent Maneuver and Lander

The descent and lander system evolved significantly throughout the development of the Ensomnia mission with design alterations motivated by scientific requirements and constraints established by the mission. Ensomnia's final design is inspired by previous missions to low atmosphere, low gravity bodies like the Huygens Probe (Kazeminejad et al. 2011) as well as proposed missions like EnEx (Konstantinidis et al. 2014). Rather than iterate the lander as a whole, the team elected to independently iterate each subsystem.

The power subsystem went through three iterations before reaching its final state. Originally, the lander was powered by a solar array. In theory, a solar array allows for an extended mission time and lower system mass due to the decreased mass required for batteries. The distance from the sun however would require the solar array to be significantly larger than would fit within the volume constraints even with innovations in solar panel folding (Grecicius, 2017). Using equation 1 where q_{solar} is the solar flux of the sun (1367 $\frac{W}{m^2 \cdot AU^2}$) (Lockwood, 2001), η_{Panel} is the efficiency of the solar panel (.85) (Barbé, et al. 2019) and r_{Lander} is the distance between the sun and the lander (9.35 AU) (Prangé, et al. 2004), the best case scenario for the energy surface area density of a solar array is 13.29 $\frac{W}{m^2}$. This low density ruled out solar panels as an effective energy source.

$$\frac{P}{A_{Panel}} = \frac{q_{Solar} \cdot \eta_{Panel}}{r^2{}_{Lander}}$$

Equation 1: Energy Surface Area Density for Solar Panels at Enceladus

To replace the solar panels, Radioisotope Thermoelectric Generators (RTGs) were implemented to supply power to the lander. RTGs take advantage of nuclear decay of unstable isotopes which creates heat that is harvested by an array of thermocouples. RTGs have commonly been used on missions far from the sun and solar panels are not viable (Bennet, et al. 2012). The high energy density of RTGs allow for an extended mission; however, the high mass, large volume, and high cost (URSA, 2005) of RTGs ultimately make the solution unfeasible for the mission. The final iteration of the power subsystem consisted of batteries which would be charged by the orbiter. These batteries, while not providing the extended mission time of the solar panels and RTGs, a large battery pack fits within the volume, mass, and cost constraints of the mission while still providing ample mission time to achieve the science requirements of the mission.

The subsystem on Ensomnia which most dramatically evolved was the land maneuverability subsystem. The first iteration of the lander was propelled by a set of 6 wheels. These wheels would transport the instruments from an initial landing site to points of interests like plume sources. Wheels provide the advantage of allowing Ensomnia to land at a safe distance from the plumes such that they do not interfere with descent. Due to the lack of detailed information on the coefficient of friction of surface materials, the wheels were eventually swapped with a ski and tread system. Skis and treads were found to be more reliable in terms of gripping the surface and allowed for the lander to traverse steeper gradients. Skis and treads would also be more resilient to structural instabilities on the surface like powders; however, the materials commonly used in treads like rubber or silicone would likely not survive the six year trip to Enceladus due to radiation and low temperatures degrading the materials. A final iteration of the land maneuverability subsystem considered reusing the engine used to land to hop between locations on the surface of Enceladus. Due to the low gravity, hopping on the surface would be relatively fuel efficient and would allow the lander to travel significantly further than wheels or a ski and tread system. Despite the maneuverability advantages, a hopper system would ultimately introduce too many uncertainties in the mission such as repeated ignition of the engine. The hopper system also could not satisfy the original requirement of the maneuverability subsystem which was to allow Ensomnia to land at a safe distance from plumes and travel to them since the lander would have to land near plumes at the end of a hop anyway. As a final blow to the feasibility of a maneuverability system, after the lander switched exclusively to battery power, the mission time was cut enough that traversing the landscape would take too long. After the multiple iterations of the maneuverability system, the system was ultimately cut since there was no method to meet the initial requirements.

The structure of Ensomnia went through two iterations. Initially, the lander gained the majority of its structural stability from the pressurization of the body. The concept consisted of a thin sheet of aluminum to encase the lander and pressurized by nitrogen gas. This stable gas would extend the lifespan of the lander by protecting it from solar radiation as well as cold welding. The presence of a gas in the lander would also improve the thermal transfer capabilities of the lander by allowing heat to convect from one area of the lander to the other, making thermal control easier. Pressurization did introduce some difficulties in the lander. Since three of the instruments require samples to enter the lander, designing airlocks of each instrument to receive samples introduces too many points of failure for the mission. Pressurization also would be difficult to maintain over the course of the transfer to Enceladus due to previously undetectable leaks in the structure. Due to mass constraints, complexity, and longevity, the outer shell was made thinner and nitrogen gas was removed from the design to reduce the mass of the structure. By using only the inner skeleton of the structure, 18 kg were able to be removed from the structure and allocated to the instruments

The descent profile went through two iterations. The first version of the descent profile consisted of a single maneuver at the periapsis of the parking orbit. This improved the reliability of the descent profile by not requiring the engines to reignite and potentially cause problems; however, would cost extra fuel. By strategically selecting an engine which is rated for automated reignition, an additional burn was introduced at the apogee of the orbit. This retrograde burn lowers the perigee from 35km to 5km such that the second burn would not have to expend as much fuel. By introducing a second maneuver, nearly 1kg of fuel is saved.

2.2. Evolution of Payload and Science Instrumentation

The instruments used to study the environment of Enceladus went through three distinct configuration iterations. Originally, the instrument suite consisted of a Neutral Gas and Ion Mass Spectrometer (NGIMS), a Gas Chromatograph Mass Spectrometer (Ptolemy), the Sample Analysis at Mars tool (SAM), the Submillimeter Enceladus Life Fundamentals Instrument (SELFI), a Light Detection and Ranging Instrument (LIDAR), an Infrared Camera (IR Cam), and the Mastcam-Z. This instrument suite introduced a high amount of redundancy with 4 sampling instruments and 3 optical instruments. This allows the instruments to compare data against each other to ensure accurate data as well as allowing multiple instruments to fail without a loss of scientific capabilities.

Given the mass requirements of the mission however, some instruments had to be cut from the mission. The first instrument to be removed from Ensomnia was SAM. At over 40 kg (Mahaffy, 2020), SAM would take over half of the mass allocation for the lander and was designed for the martian environment, meaning significant modifications would have to be made to account for the lower temperatures, lower gravity, and decreased atmosphere. SAM's scientific capabilities would be taken over primarily by SELFI.

After further design iterations from the engineering team, the team determined that the instruments would not fit within the volume requirements of the lander. To accommodate for the insufficient volume, NGIMS was removed from the lander. NGIMS was selected because it only had a single scientific capability - mass spectrometry - which is also fulfilled by Ptolemy.

The final configuration iteration was due to the change in the structure subsystem. Since the lander was originally pressurized, a significantly cheaper IR camera was selected since it did not have to endure the vacuum of space or solar radiation which it would be otherwise subjected to during the transfer to enceladus. After abandoning the pressurized design of the lander, the IR camera had to subsequently be upgraded as it would be exposed to the elements. Thanks to the mass savings from the removal of the NGIMs unit, the IR camera upgrade still fit within the mass and volume requirements.

2.3. Evolution of Mission Experiment Plan

The initial plan for the mission experiments was significantly longer and also involved a descent through an active plume and traversing the landscape of Enceladus after landing. The extended mission time was allowed by the more advanced power subsystem. Since Ensomnia was originally powered by a solar array, the lander would have been able to operate indefinitely in terms of power. As discussed in section 2.1, the solar cells were later removed from the lander and replaced with RTGs, which were also ultimately removed to be replaced by batteries. This power subsystem change cut the mission time from about forty five days to two days.

The next significant change in the mission experiment plan was adjusting the descent profile such that it does not collide with any active plumes. The descent through a plume would have provided valuable information about what lies deep below the surface of Enceladus; however, the team determined that a descent through jets of water would ultimately be too dangerous to be worth the risk. Another reason which influenced the change in descent profile was the fact that plumes on Enceladus will not necessarily be in the same location as they were when Cassini flew by 25 years before Ensomnia, designing instruments to take data from a surface feature which may not exist given the mass and volume constraints was determined to not be viable for the mission.

The final change was to no longer traverse the landscape of Enceladus. Moving after landing would allow for higher fidelity topology data to be returned to Earth and would allow for Ensomnia to study multiple different points of interest such as plume sites and valleys. With the decreased mission time due to the power subsystem changes, it was determined that it was no longer feasible to expend extra energy to move around after landing.

Section 3: Descent Maneuver and Lander Design

3.1. Selection, Design, and Verification

3.1.1. System Overview

The profile of Ensomnia's descent was optimized using the vis-viva equation where v is the orbital velocity ($\frac{m}{s}$), G is the universal gravitational constant ($6.67408 \cdot 10^{-11} \frac{N \cdot m^2}{kg^2}$) (Klien, 2020), M is the mass of enceladus ($1.08 \cdot 10^{20}\ kg$) (Jacobson, et al. 2006), r is the distance from the lander to the center of Enceladus (m), and a is the semi-major axis (m).

$$v^2 = G \cdot M \cdot (\frac{2}{r} - \frac{1}{a})$$

Equation 2: Vis-Viva

Using the Vis-Viva equation, it was determined that the optimal descent profile would start with a maneuver at apogee burning in retrograde. This engine burn will last for 9.4283 second and will drop the perigee of the orbit to 5km above the surface. The second maneuver will begin 550.8608 seconds before landing and will burn in retrograde until Ensomnia has touched down on the surface of Enceladus. The two maneuvers will expend a total of 6.4649 kg of fuel; however, 7kg of fuel and oxidizer will be stored on the lander to account for attitude changes and SLAM inefficiencies.

Table 1: Subsystem Parameters

Subsystem	**Mass**	**Dimensions**	**Power Consumption**
Structures	10 kg	50.2 x 50.2 x 70.2 cm	0 W
Electronics	1.2 kg	5 x 5 x 2 cm	10 W
Attitude & Control	4.74 kg	5 x 5 x 7 cm (4)	10 W (ignition)
Propulsion	1.16 kg	5 x 5 x 7 cm	10 W (ignition)
Automation	0 kg (software)	0 x 0 x 0 cm (software)	0 W

3.1.2. Subsystem Overview

3.1.2.1 Structures

The structure of the lander will provide support to the mission hardware and secure the propulsion subsystem to the lander. The structure will protect the hardware and facilitate the landing on Enceladus for better control. The shape that the lander has taken is a cylindrical skeleton structure. The structure takes this shape to create a 360 degree view of the surface of Enceladus.

The conditions of the vacuum of space and the surface of Enceladus requires that the structure be able to operate in extremely cold temperatures; oftentimes, this temperature reaches -200 degrees celsius (NASA, 2019). The choice of material is crucial for this reason. An aluminum based material, Aluminum 6061-T6, was chosen to keep the weight of the material down whilst performing under the stated conditions. It was determined that a total of 4.06 kg, or 1502.96 cm^3 , of aluminum will be required to match the desired dimensions of the structure. Additionally, the structure will need to incorporate support beams for instruments to stabilize inside the lander. To manufacture the structure, the CNC machine will need a mold for the aluminum that needs to be shaped. This will be easy to replicate, because the mold is simply the inner structure dimensions.

The structure of the lander is not as digitally demanding as other subsystems. This means the subsystem requires very little, if any, software to complete the mission. The structure will be shaped by a CNC machine, so manufacturing may require a little software. This is a very simple code that only requires the CNC machine to heat the aluminum and roll it into the cylinder shaft shape as well as cut the end caps.

In order to operate successfully, the structure of the system will require a thermal subsystem to regulate the temperature. If the structure were too cold, the integrity of the structure would become unstable. This subsystem can easily be integrated into the walls of the structure to add heat to the inside of the walls. This will ultimately raise the temperature of the structure material and mitigate the risk of integrity failure.

The structure of the system holds one of the largest roles in the mission. Ultimately, if the structure fails, the entire mission will fail. Therefore, all of the instruments depend on the structure properly working. The instruments need to be protected from the plume of the propulsion subsystem during operation of the subsystem which releases extremely fast and hot fumes. Additionally, the instruments could not travel to the planetary body without the structure. This is because the structure encloses the instruments in one central volume to allow ease of control in space. This is true for the other subsystems as well. Propulsion, automation, attitude & control, and electronics require a central location to provide controlled transportation to Enceladus. Therefore, all subsystems depend on the structure subsystem.

3.1.2.2 Electronics

The electronics are responsible for general functionality of the spacecraft, including communications and telemetry. Essentially, the electronics will allow the decision on the orientation of the spacecraft and enable communications among different parts. The automatic landing and probing systems need to communicate back and forth from the sensor and camera to computer systems to incorporate the SLAM algorithm for the lander and rover. The data from scientific instruments needs to be transmitted, recorded, and stored in a data storage. The electronics let these communications to fully functionalize different components for the mission statement.

To operate electronic subsystems, there must be a power source from the battery. A back-up battery in case the main battery shuts down is recommended in case of emergency. The FPGA (field-programmable gate array) and BRAM (block random access memory) are required to run the computer system for the automatic system calculations and computer data storage to store data from scientific instruments. Additionally, the wires to connect different components are necessary depending on the scientific instrument’s requirements. Additionally, to prevent damages from external forces, the electronic subsystem requires external structure to be protected in general and the electrical transformer requires to be encapsulated.

Softwares to store data from scientific instruments are required. Many of the softwares are already available online or built on the instruments for data acquisition and transmission. The data is recorded in a csv format, therefore a software that is capable of storing csv type files and parsing those files is required. Ptolemy II for Ptolemy and any available softwares online to process LiDAR data for LiDAR can be used. For SELFI, a software that records the submillimeter wavelength, traces of chemicals in the water vapor, and icy particles from tiger stripes while also storing them in a proper format.

Additionally, softwares to monitor temperature of the electronics constantly to dissipate heat by turning off electronics that are running unnecessarily if they reach the limit may be required; however, such a situation is very unlikely to happen.

In order for electronics to operate properly, the power needs to operate properly. If any chemicals or radiation are present that would damage the electronics physically, the outer structure needs to function.

Attitude and control, propulsion, automation, and data acquisition, including science instruments, subsystems depend on electronic subsystems.

3.1.2.3 Attitude & Control

The Attitude & Control Subsystem will ensure that the orientation of the lander is desirable and controlled. This subsystem includes the following components to achieve its objectives: sensors to measure the orientation referencing to Enceladus, actuators to apply sufficient torque so that the lander orientation can be adjusted to the desired attitude, algorithms to deliver the commands to the actuators.

Due to the mass and volume limits, the attitude and control Subsystem will not use a separate set of control hardware. Reaction wheels would be ideal, yet a trade-off was made so that the actuators for attitude & controls will be the same thruster and reaction control thrusters as the propulsion system; this is to say that these instruments will serve double purposes instead of having two sets of these instruments. For the sensing hardwares, a gyroscope will be used as the main instrument for determining the current attitude of the lander. A few other sensors will help and serve as redundancies in the system: an accelerometer, a star tracker, and a sun sensor. The gyroscope sensor will be the primary source of reference data, and the accelerometer, the star tracker as well as the sun sensor will validate the data from the gyroscope. No sensors or components would need to be built; all hardware should be Commercial-Off-The-Shelf products.

The Attitude & Controls subsystem will have its own software written by the team to process the data from the gyroscope and the sensors. Using feedback control to the software will command the actuators and stabilize the lander orientation. The program will have a set of parameters designated as the desired orientation of the lander and its position with respect to Enceladus; the feedback control will compare the measured attitude with the desired parameters and the system will decide to send commands to the actuators to adjust the attitude within a specified range of accuracy to the desired orientation.

With the current configuration of sensors and actuators, the Attitude & Control subsystem highly depends on the thrusters shared with the propulsion system; therefore, the attitude & Control subsystem requires the thrusters to function normally and remains active throughout the mission or at least the ability to function on command through communication with the electronics system. It is worth noting that the Attitude & Control subsystem is especially important for this lander because of the turbulent conditions on the surface of Enceladus, i.e. the plumes. The attitude & Control subsystem also needs to be thermally protected so that the sensor and the actuators as well as the relevant electronics can function optimally even within Enceledus's harsh environment.

The Attitude & Control system is important because if the orientation of the lander is not controlled, the instruments, especially the payload would be affected. The Infrared Camera, Mastcam-Z, LIDAR, Ptolemy, SELFI, as well as the sample heater and sample collection arm depends on a desirable attitude of the lander. The electronics system also depends on the attitude & Control because the orientation of the lander will affect the telecommunication ability.

3.1.2.4 Propulsion

The propulsion subsystem of the lander will provide thrust during the entry burns and maintain stability control to successfully land on the surface of Enceladus. There will be a total of five thrusters integrated into the design of the lander. The subsystem includes a main thruster and four reaction control thrusters, all of which are the same thruster. The main thruster will provide thrust in the axial direction of the conic skeleton structure. Meanwhile, the reaction control thrusters will provide thrust in the other two directions (more information found later in this section).

The propulsion subsystem will utilize pre-manufactured thruster engines purchased from Yuzhnoye. Provided our dimensions of the structure, Yuzhnoye will need to scale the thrusters to match the size of the structure specifications. The thruster that is required for the mission is the Cyclone-4 30 N thruster and the lander will need five of these. Additional components for hardware include the fuel tank, sensor for amount of unburned fuel, piping network for the fuel flow, and the fuel and oxidizer for the structure. The fuel tank will need to be custom made for the structure geometry as well as the amount of fuel required for the entry burns. The size of the fuel tank based on the fuel mass requirement was found to be 25cm x 20cm x 18cm based on the required 7kg of fuel and density of 782 $\frac{kg}{m^3}$ (NLM, 2019). The sensor to measure the amount of unburned fuel is a simple liquid sensing device that will be displaced along the height of the fuel tank. Similar to the fuel tank, the piping will also need to be custom built based on the structure geometry and fluid flow rate. The fuel that the thrusters will be utilizing is unsymmetrical dimethylhydrazine, which requires that the oxidizer be different from theoretical air. The oxidizer that the thrusters require is nitrogen tetroxide (Yuzhnoye, 2020).

The propulsion subsystem will need to have a dedicated program to measure how much thrust is needed to complete the two burns planned. Additionally, the amount of time for each burn will be pre-determined to successfully land on the planetary body and integrated into the program. This subsystem will need direct communication to the mission team on Earth to validate the accuracy of the burns real time during the mission (not actually real time due to the distance from the lander to Earth). Due to the amount of automation required for the propulsion subsystem, the bulk of the software needed for this subsystem will come from the automation subsystem.

The propulsion subsystem will need a fuel tank with the required unsymmetrical dimethylhydrazine fuel. A pump will need to be installed to pump the fuel to the thrusters sufficiently due to zero gravity experienced in space and nearly zero gravity on the surface of Enceladus. Additionally, the inside of the lander will need to be heated due to temperatures reaching past freezing point for the fuel. So, the thermal subsystem will need to be included in the propulsion subsystem. The propulsion subsystem also requires a code to carry out the predetermined entry and landing burns during the mission. This is due to the lander distance from Earth causing delayed communication with the mission team. This code will be created and managed by the automation subsystem.

There are a few subsystems that depend on the propulsion subsystem. For one, the structure depends on the propulsion subsystem. The structure could potentially fail if the propulsion system does not successfully complete its entry burns correctly. Additionally, the instrument Ptolemy depends on the propulsion system. The lander will be collecting samples through a drill on the structure and could take contaminated samples if the propulsion subsystem does not work properly. This would ultimately render the instrument useless for the mission. The mission as a whole is dependent on the propulsion subsystem. Due to its importance for transportation to Enceladus, the mission would likely fail if the subsystem were to fail. Without thrusters, the lander can no longer change directions and maintain the correct trajectory. The lander can still pass the planetary body if it is in the correct direction at the time of failure.

3.1.2.5 Automation

Automation is responsible for the landing and probing systems. It is very essential in the mission because it guarantees the safety of the spacecraft by determining the safest zone to land on and utilizes artificial intelligence to automatically act upon surroundings to probe to collect data. Our automation will be featured by the SLAM (Simultaneous Localization and Mapping) algorithm for both landing and probing systems.

A computer system to run the algorithm is needed. A camera, since it depends on the visualization, is essential for automation as well. Because it may go over a gigabyte in its single computation, good data storage and microcontroller are necessary.

SAM will be implemented via a matlab script running on the electronics subsystem. For automation to operate properly, the electronics system must function properly since it depends solely on the power and computer system of the electronic systems. The control of the rover and lander depends on the automation subsystem.

3.1.3. Dimensioned CAD Drawing of Entire Assembly

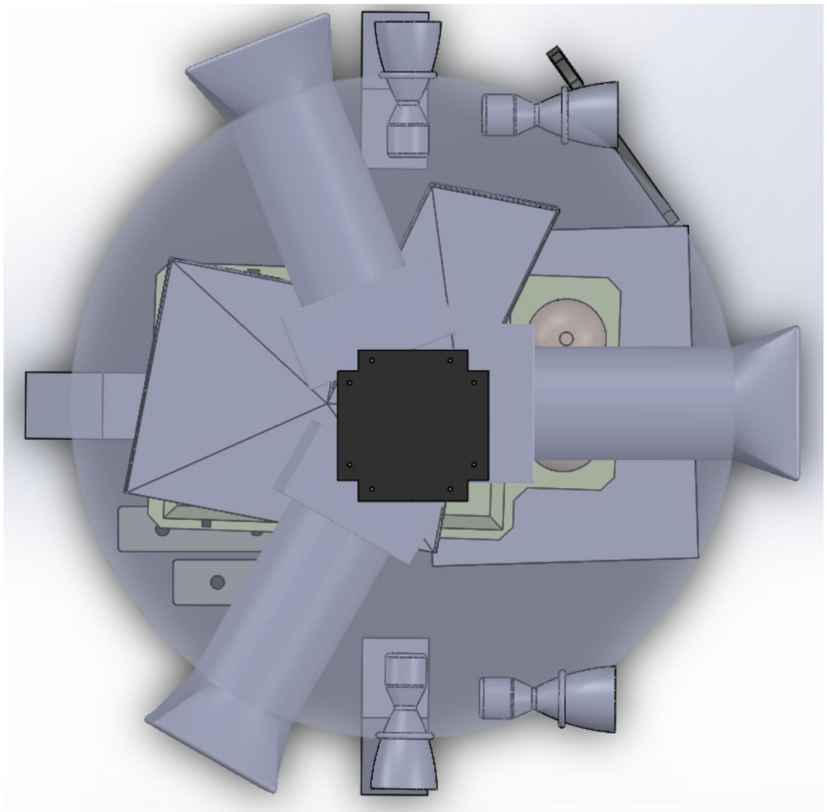

Figure 12: Lander top view

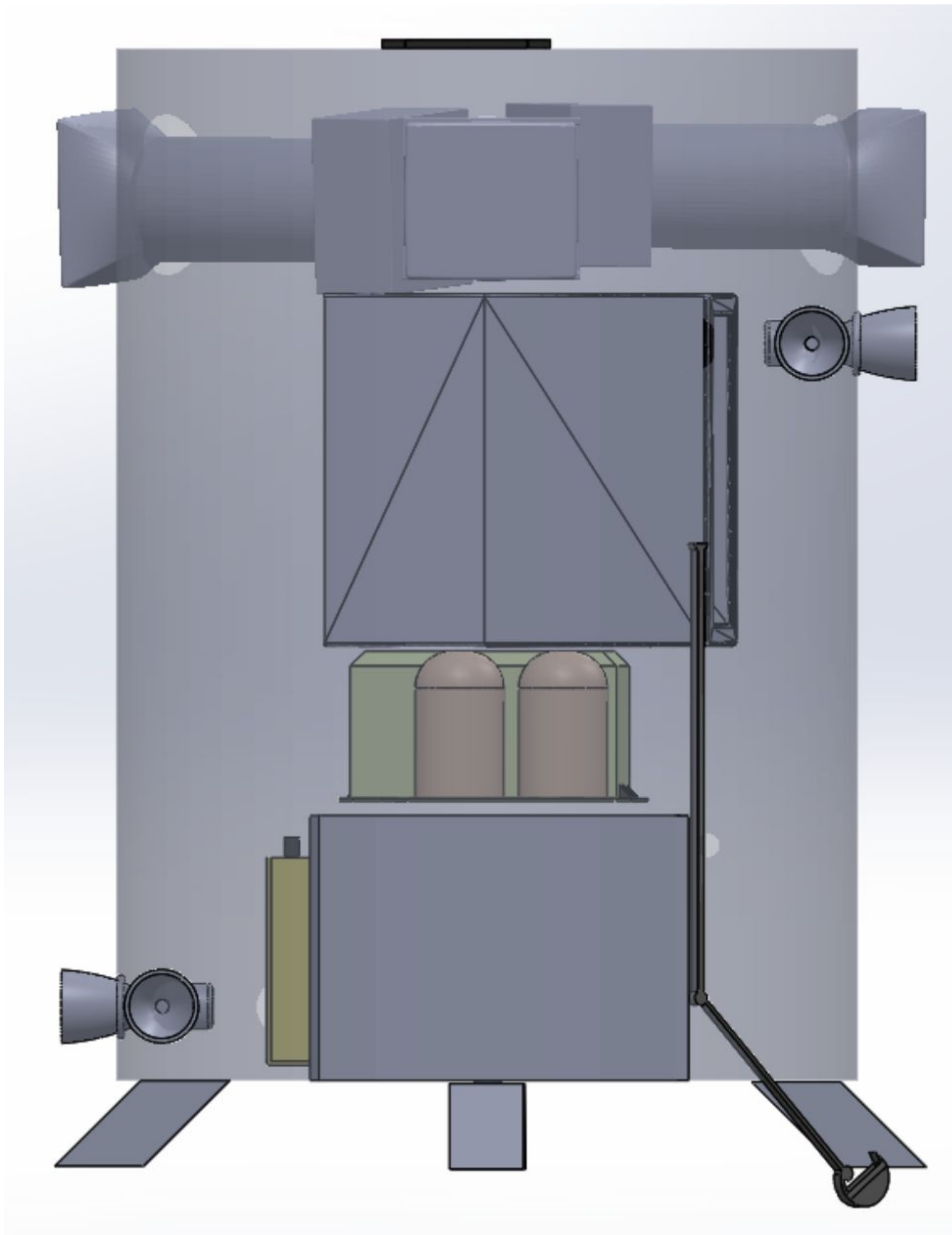

Figure 13: Lander front view

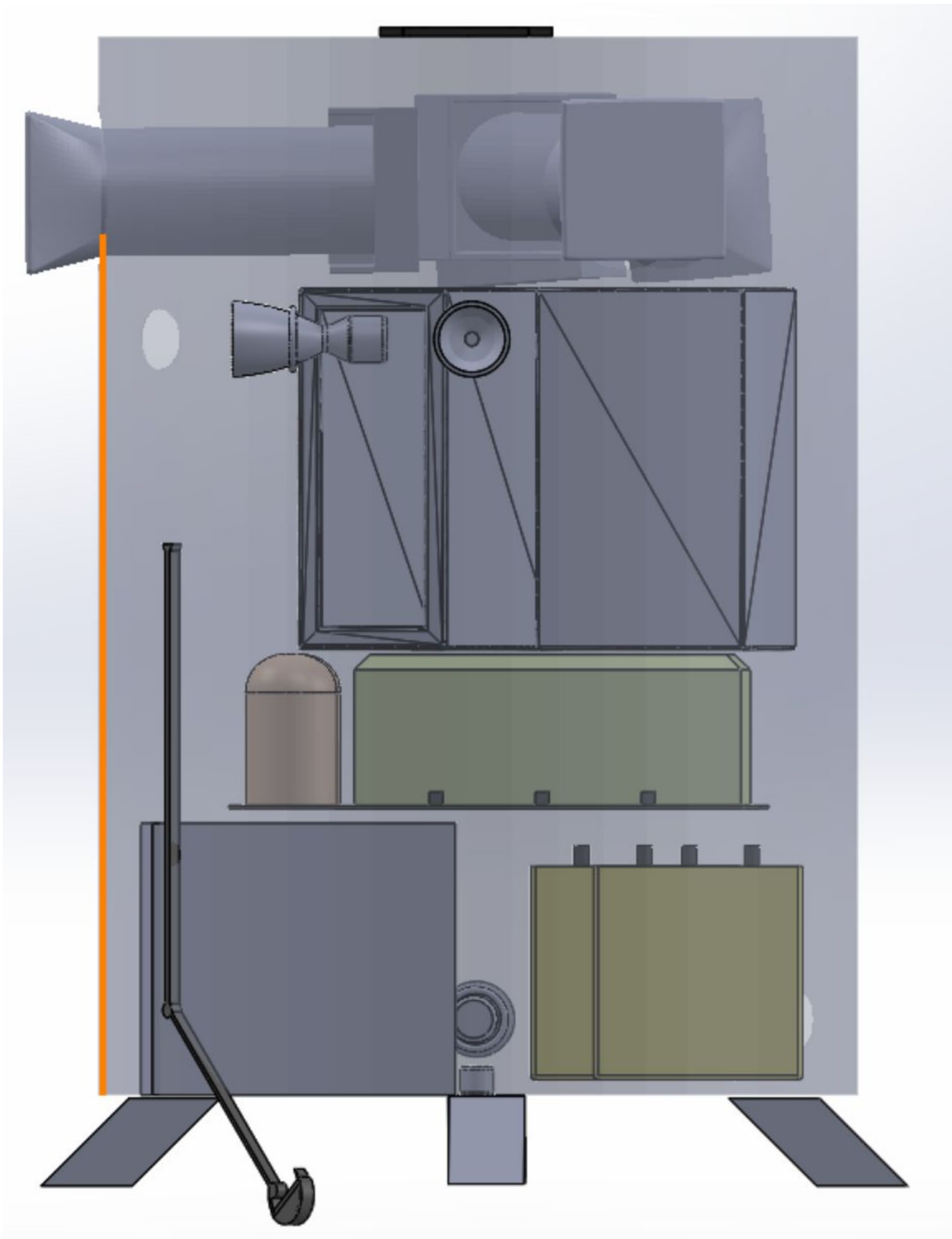

Figure 14: Lander side view

3.1.4. Manufacturing and Integration Plans

3.1.4.1 Structures

The structure of the lander will be in the shape of a cylinder. The manufacturing of the structure will be complex, and will require serious manpower to properly install and secure all components inside the structure. To manufacture the lander structure, a template of the cylinder shape will be made to mold the aluminum into the desired shape. The inner dimensions of the cylinder includes a 25cm radius with a height of 70cm and will be used to form the cylinder shaft. Once the aluminum sheet with the required geometry to fit the mold is acquired, the aluminum will be heated to a temperature just below melting point to press it against the template and form the cylindrical shape. Once the desired shape is formed, the connection point will be welded together. There is no base on the top and bottom of the structure after this step is complete. The top of the structure can be cut in the shape of a circle with a radius of 25.1cm and can be welded to the cylinder shaft. The bottom cannot be welded yet as the instrumentation and support beams need to be inserted. Based on the geometry and weight of the instruments, the location of each instrument was meticulously chosen. For some instruments and the propulsion subsystem, holes (size depending on object dimensions) will need to be drilled into the structure for visibility and access to the outer region of the lander. The location of each instrument is determined by requirements of the instruments. Some instrumentation needs to be at the bottom, while others at the top. The hardware inside of the structure will be oriented with the largest possible dimension of the hardware running parallel to the cylindrical base.

The very first subsystem added into the structure is the piping network and pump for the thrusters which will run along the inside walls of the structure (fuel tank added later). There are three locations where the pipes need to extend to. These locations include the main thruster at the center of the structure bottom base, one of the two coupled reaction control thrusters at the edge of the structure bottom base, and the other coupled reaction control thrusters at the edge of the structure top base (sketch found in section 3.1.4.4.1). Therefore, there will be three pipes and will require three pumps for each pipe. These pumps can be secured to the inside walls of the structure via non-flammable adhesive. The first instrument inserted at the top of the cylindrical structure is the infrared camera. With a mass of 88g and singular dimension of 3.175cm, the instrument is small enough to fit on the inner walls of the structure. The camera will be fitted into its hole and secured into place via non-flammable adhesive due to its low weight. The next piece of hardware added into the structure is the first of the two coupled reaction control thrusters. The thrusters will be inserted into the positioned holes created to reach the outside of the lander. The next instrument to be added into the structure is the Masteam-Z. The Mastcam-Z has a total mass of 4kg and includes all of the following components: camera heads (11cm x 12cm x 26cm), digital electronics assembly (22cm x 12cm x 5cm), and calibration target (10cm x 10cm x 7cm). These camera heads will be positioned 24 cm apart from each other (center to center) to provide stereo vision. Due to the cylindrical shape of the structure, the cameras will instead be positioned so that the entire perimeter of the structure is covered. This is attained by placing the camera heads 120 degrees from one another, or an arc length of 52.6cm. Once the cameras are inserted into the correct position and holes, support beams will be added inside the structure to secure the cameras. The support beams will need to be welded to the structure interior to ensure integrity. The Mastcam-Z digital electronics assembly and calibration target can be secured to the same support beams as the camera heads, but instead underneath. The next instrument to be added into the structure is the SELFI. SELFI is designed to be 38cm x 23cm x 20cm with a mass of 10.7kg and requires that it be on the top of the structure. This instrument will be secured with support beams at the closest point to the top base and the instrument may still fit. The support beams will be welded to the inside of the structure. The next instrument to be inserted into the structure is the light detection and ranging (LIDAR) instrument. This instrument has a volume of 0.0137 m^3 (assuming a perfect cube: 24cm x 24cm x 24cm) and mass of 3.56kg. Due to the amount of mass, the instrument will require another support beam. Once inserted into the structure, support beams will be added and welded underneath the instrument and secured. The next instrument to be inserted into the structure is the Ptolemy. This instrument is designed to be 10cm x 20cm x 35cm and a mass of 4.5kg. Ptolemy will be secured into place via support beams underneath once the instrument is in place and will need to be welded into the inside walls of the structure. Following Ptolemy, the second of the two coupled reaction control thrusters will be secured into the pre-drilled holes to reach the outside of the lander. The next piece of hardware to be added into the structure is the fuel tank. The fuel tank will be placed on the bottom of the inside base. To insert the fuel tank, the base of the structure will need to be manufactured first. This is the easiest to develop as it is a simple circular base. Before attaching the fuel tank, the sensors to measure the unused fuel will need to be installed. A hole for the Cyclone-4 thruster and fuel tank will need to be created before attaching the fuel tank to the inside of the base. Now that the prerequisites have been completed, the fuel tank can be attached to the inside base. The Cyclone-4 geometry requires that the thruster be integrated in two steps. Step one is to attach the thruster combustion engine component to the inside wall of the base. That way, the thruster nozzle can fit through the hole without complications. Finally, the base of the elliptic cone can be attached to the structure by welding the connecting surface.

As stated before, the structure subsystem does not require any software to successfully carry out the mission. Therefore, no software integration is required for the structure.

3.1.4.2 Electronics

All the necessary hardware is purchasable. For FPGA (field-programmable gate array), a radiation-hardened Kintex UltraScale XQRKU060 FPGA will be used. FPGA does not require additional microcontrollers and has BRAM already on the layout on the selected model. For RAM, without adjustment to the SLAM algorithm for faster computation, any model above 8 GB will be suitable since SLAM requires high memory consumption, preferably above 16 GB. To run all these subparts of the electronics, the battery requires to supply 23 W. For storage, one 3D-mapping of SLAM algorithms can take upto 800 MB (Guivant & Nebot, 2003). An estimated minimum of 160 GB is required, therefore a micro SD card capable of 256 GB from SanDisk can be used.

Most of the necessary softwares are available online as open-source softwares. For analysis, there should be a software that would associate values from scientific instruments and link among extracted data to determine important information for the mission.

3.1.4.3 Attitude & Control

All hardware can be purchased. There is a fair amount of attitude and control sensors and even packaged whole systems to choose from. Using COTS will also mitigate some of the unnecessary risks related to unknown or untested technology.

As status earlier, the attitude & control software will be written by the team because the program, a feedback control, should be rather implemented and there are many customized dependencies and logic to this lander. Also, because each of the instruments and sensors are after all unique in the sense that their physical properties are unique to that specific instrument or sensor, it is important to build the control program in house.

3.1.4.4 Propulsion

The propulsion subsystem includes a network of piping for the fuel flow, a pump to move fuel from the fuel tank to the thrusters, a fuel tank to house the unused fuel, sensors to measure the amount of unburned fuel, and the Cyclone-4 thrusters. The piping network, pumps, fuel tank, and thruster combustion engine component will be pre-installed during the assembly of the structure. The sensor will be integrated inside of the fuel tank at points along the height that includes three fourths, one half, and one fourth of unused fuel volume. The Cyclone-4 thruster nozzle will be the only component of the propulsion subsystem that will be integrated separately. The main thruster nozzle will be inserted into the hole at the structure base that is coincided with the circular base. The dimension of this hole will be determined based on the thruster nozzle throat geometry. The nozzle will fit into the hole and attach to the thruster combustion engine component that is already installed inside of the structure. As for the reaction control thrusters, a total of four Cyclone-4 thrusters will be located at the top/bottom and left/right of the structure subsystem. Two of the thrusters will be integrated together, one facing in the x-direction and the other in the y-direction for a 2-dimensional flow (the axial direction of the structure is the z-axis). The thrusters will be secured onto the inside of the structure in the formation described above. Holes for the nozzles will be made into the structure to allow the thrusters to reach the outside of the lander. A full sketch of the thruster placement is found below. This completes the propulsion subsystem hardware integration.

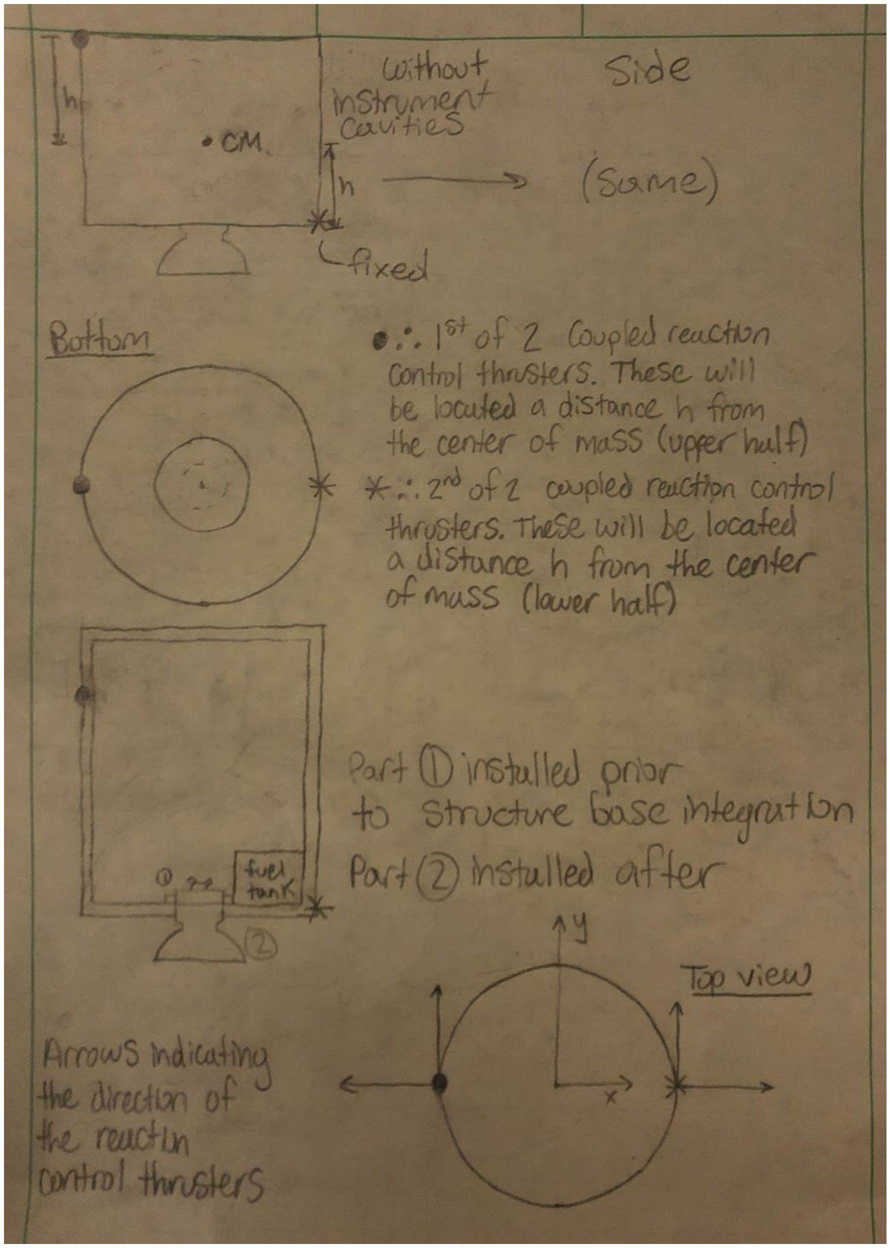

Figure 15: Sketch of structure and propulsion layout

The propulsion subsystem software will require knowledge of change in velocity of the entry burns, thruster specific impulse, entry burn durations, entry burn locations (distance from surface of Enceladus), and mass flow of the fuel during the entry burns. Once these values are known, the program will need to be built. The program will essentially calculate the required variables for the subsystem and inform the main thruster about the timing of the burn and the duration of the burn. Due to the automation requirement of this program, the software to determine these variables will be handled by the automation subsystem.

3.1.4.5 Automation

The automation subsystem is exclusively software which will be run on the electronics subsystem. This subsystem cannot be built physically except being installed on electronic devices.

The automation software can be built in several different ways depending on which programming languages, tools, or frameworks are being used. For the MATLAB tool, C/C++ is used.

3.1.5. Verification and Validation Plans

3.1.5.1 Structures

Due to the low gravity of Enceladus and the low force of the thrusters, the structure subsystem will work as designed as long as the structure can withstand the weight of the mission payload inside the structure. However, tests should be run to ensure that the structure can withstand the forces of the thrusters. One of which being a bending stress test. The force of the thruster in the center of the structure base is likely to cause bending due to its positioning from the fixed border and the thickness of the material chosen. This ultimately causes bending stress and will need to be verified that the material can withstand the maximum 30 N force from the thruster before installation of hardware. If the structure does not cause significant bending (deformation) or fractures, the structure will perform as planned without issues. An additional test should be conducted for the reaction control thrusters as well. A torsional test will provide insight on if the structure can withstand the torsional effects of the control thrusters. If the structure is damaged by means of deformation or fracture, the structure will certainly fail during the mission. The requirements of the structure will be met if the test results are positive. The torsional and bending stress validation tests will be conducted for both Earth surface temperature conditions, and the temperatures experienced in space as well as on Enceladus. Once fully assembled, the thrusters can be tested to confirm that the structure will remain intact during the required entry burns. Theoretically, the structure material is able to remain intact under Earth surface conditions. If the structure fails the assembly test, then the mission will certainly fail. Another condition would be that the structure survives the vibrations encountered during launch from Earth and caused by the entry/landing burns. This wave-like movement can easily be simulated after the final assembly is complete to ensure the hardware validity. If the structure is damaged in a significant way (i.e. weld points disconnect, fractures on surface, permanent deformation), the lander will not be mission ready. Otherwise, the structure subsystem passes the vibration test. The final condition that needs to be met is that the structure can carry out the mission under extreme temperatures reaching -200 degrees celsius. This can be tested through a simulation under this extreme temperature condition. If the structure remains intact with no fractures or cavities after simulating the burns, it will remain stable.

3.1.5.2 Electronics

The radiation can degrade electronics, and the ionizing radiation can defect microprocessors. To prevent total ionizing dose (TID), the radiation-hardening process is used and must go through single event effects (SEE) testing to ensure that the radiation-hardened electronics can endure extreme radiation conditions. It can be prevented by using already radiation-hardened microprocessors instead of going through the process manually. To prevent overcurrent and over-temperature problems on batteries, the design of the battery should have built-in protection circuits.

To test if softwares functions properly, it must be tested before the launch with similar settings and environmental conditions to Enceladus. Since SLAM algorithm heavily relies on the Mastcam-Z, infrared camera, and LiDAR and there is no given guarantee of landmarks along its path, it should have the ability to navigate through empty fields. Alternatively, for landing, it should be able to detect the safest zone to land on even on a light-reflective, icy surface. It will check rigorously to see if the loop closure gets solved when a previously-visited location is revisited. For other softwares, it should check if the scientific instruments are capable of detecting and recording the correct quantities and quality of data.

3.1.5.3 Attitude & Control

Because the attitude and control system would be all contracted out, and all the sensors and actuators have a relatively reliable fight history, the team decides to establish baselines for performances to evaluate the sensors and the actuators. The implementation of the hardware will be tested after construction of Ensomnia by ensuring that the lander can balance itself when hung from a point off axis of its center of gravity.

For the attitude and control programs to be integrated with the rest of the software, the team will gather test cases from simulations, flights with similar conditions, etc. These test cases will include extreme conditions such as borderline unstable conditions.

3.1.5.4 Propulsion

Prior to mission launch, the propulsion subsystem will need to be tested to verify the hardware. To do this, the main thruster will be function tested through various burns prior to full system assembly. This is to ensure that the product purchased from YuzhnoyeIf functions as designed. If the thruster passes the functionality test, the system can be assembled. Another burn test will be administered for the propulsion subsystem once final assembly is complete. Validity of the propulsion subsystem is measured by successful burns, which means that the fuel entering the thruster is at a constant rate and no burn pulsing occurs (fuel does not enter the thruster at a constant rate causing pulsating pattern). Successful burns with no damage to the structure subsystem and the tank-pipe-pump-thruster network validates that the thrusters will function as planned with the fully assembled lander.

To ensure that the propulsion subsystem software works correctly, the propulsion subsystem will do a complete software test prior to final assembly. The run through of the program will test whether the program completes the burns at the correct time and duration. The software becomes validated if the timing and duration matches that of the desired magnitude. An additional criterion is that the program is able to run entirely autonomously. Again, the subsystem is validated if the program can complete the test successfully with the desired values.

3.1.5.5 Automation

The hardware where it is implemented should be able to run the software. It must be tested before the launch if the hardware can handle rigorous experiments using the SLAM algorithm.

The rover with the automation system installed must be tested before launching. Through excessive, rigorous testing with expected environments of Enceladus, it must ensure that the SLAM algorithm works on different visualizations processed by cameras. For example, the SLAM algorithm can be tested on icy, shiny surfaces where it reflects too much light, in dark places with no lights, or a combination of both circumstances. It should also account for any chemicals or geographical features that would block camera vision from retracing back to unique geographical markings to localize the rover.

3.1.6. FMEA and Risk Mitigation

Likelihood of Occurrence	Criteria: Possible Failure Rates/Probability of Failure	Rating
Extremely High	Probability of Failure During Process >0.1	10
Very High	Probability of Failure During Process 0.1 < 0.05	9
High	Probability of Failure During Process 0.05 < 0.01	8
Moderately High	Probability of Failure During Process 0.01 < 0.005	7
Moderate	Probability of Failure During Process 0.005 < 0.001	6
Moderately Low	Probability of Failure During Process 0.001 < 0.0005	5
Low	Probability of Failure During Process 0.0005 < 0.0001	4
Very Low	Probability of Failure During Process 0.0001 < 0.00005	3
Extremely Low	Probability of Failure During Process 0.00005 < 0.00001	2
Remote	Probability of Failure During Process <0.00001	1

Figure 16: Occurrence Ranking Criteria

(NASA, 2009)

Mission Impact (1-5)		
Effect	**Criteria: Severity of Effect**	**Rating**
Very Serious Mission Capability Effect	>75% loss of Mission Capability	5
Serious Mission Capability Effect	>50% loss of Mission Capability	4
Moderate Mission Capability Effect	>25% loss of Mission Capability	3
Minor Mission Capability Effect	>10% loss of Mission Capability	2
No Mission Capability Effect	No impact on Mission Capability	1

Figure 17: Severity Ranking Criteria

(NASA, 2009)

Mitigation Criteria	Likelihood of Mitigation by Design or Controls	Rating
None	There is no Mitigation of the Failure Mode or its subsequent Failure Effect	10
Very Remote	There is a very remote probability the Design will mitigate the Failure Mode or its subsequent Failure Effect (less than 10% probability for mitigation)	9
Remote	There is a remote probability the Design will mitigate the Failure Mode or its subsequent Failure Effect (10 > 20% probability for mitigation)	8
Very Low	There is a very low chance the Design will mitigate the Failure Mode or its subsequent Failure Effect (20 > 30% probability for mitigation)	7
Low	There is a Low probability the Design will mitigate the Failure Mode or its subsequent Failure Effect (30 > 40% probability for mitigation)	6
Moderate	There is a Moderate probability the Design will mitigate the Failure Mode or its subsequent Failure Effect (40 > 60% probability for mitigation)	5
Moderately High	There is a Moderately High probability the Design will mitigate the Failure Mode or its subsequent Failure Effect (60 > 80% probability for mitigation)	4
High	There is a High probability the Design will mitigate the Failure Mode or its subsequent Failure Effect (80 > 90% probability for mitigation)	3
Very High	There is a Very High probability the Design will mitigate the Failure Mode or its subsequent Failure Effect (90 > 99% probability for mitigation)	2
Almost Certain	There is an almost certain probability the Design will mitigate the Failure Mode or its subsequent Failure Effect (> 99% probability for mitigation)	1

Figure 18: Mitigation Ranking Criteria

(NASA, 2009)

Mission: Ensomnia			Systems Engineer: Payton Case				FMEA Date: 11/29/2020			
			CSO: Zoe Fang							
Subsystem	Component	Potential Failure Mode	Potential Cause of Failure	Occurrence	Potential Effects of Failure	Severity	Mitigation Factors	Mitigation	Recommended Actions	Action Taken
Structure	main frame	structure does not remain intact; experience a ultimate tensile stress of 414 MPa or larger	crash landing due to failure in the propulsion system (improper landing speed)	3	complete system failure and mission failure	4	Structure is designed with a factor of safety	9	Reorient	Use arm to reorient the lander
		considerable damage to overall structure	improper orientation of the lander with proper descent velocity which causes undesirable loading on the structure	2	improper orientation after landing, potential loss of function of some instruments	3	Structure is designed with a factor of safety	9	Reorient	Use arm to reorient the lander
		high speed collision with other large man-made or debris satellites	considerably high density of particles in the outer region of Enceladus	2	complete system failure	5	Transfer orbit is selected to avoid any debris	8	Land early	Use thrusters to land early before more debris impacts
		low peed collision with other small man-made or debris satellites	considerably high density of particles in the outer region of Enceladus	1	minor damages to the casing, most other subsystems remain intact	2	Transfer orbit is selected to avoid any debris	7	Land early	Use thrusters to land early before more debris impacts
Electronics	power unit	complete or partial loss of power supply	physical damage to power subsystem, overcurrent, or battery malfunction	5	failure to operate any data collection, mission failure	2	Batteries are designed to edure the conditions of space	8	redundency design, emergency power supply or backup battery system	Enagage secondary battery
	hardware	physcial damage	collision with other bodies, crash landing, unexpected radiation, excceeding operating temperature	3	incapaciated eletronics and damage to other subsystems	3	system reboot given functional power source	9	redundency design, emergency power supply or backup battery system	Enagage secondary battery
	software - SLAM	errors within the SLAM algorithm	errornous logic within code or system encounter untested conditions, overclocking, hindering camera vision from detecting objects	3	less than ideal landing cite, loss of automatic probing functionalities	4	exhaustive trouble shooting simulations and testing	7	consider extreme cases and corner cases for testing and simulation	LIDAR override of altitude
	software - data storage	loss of partial stored data or failure to store data	errornous/inefficient loop closure detection orlack of known landmarks	2	loss of data collected, incomplete mission objectives	3	delete similar mapping for storage space	8	Send to Earth	Communicate corrupted data with Earth for data repair
	sensor and actuactor	physical damage to sensors or actuators	crash landing, collision with other bodies	2	lack of input to the subsystem; subsystem disabled	4	redundency and repurposing other instruments	8	Redundency	Compare data against multiple sensors

Figure 19: Lander FMEA Page 1

Attitude & Control	software	system unequiped to handle unknown conditions on Enceladus	lack of knowledge or consideration during design, testing, validation; lack of specific knowledge about the conditions at the landing site	3	paralyzed subsystem; should the attitude become unideal, possibility of mission failure	3	exhauastive research; larger margin of error and tolerance designed into the system, exhaustive simulation and testing of corner cases	7	Enage secondary safety method	Utilize state and trigger to account for unpredicted disruptions
	software	data loss during transmission; unexpected longer communication time	unstable connections from the communication subsystem	4	system over/under adjust due to inaccurate real time attitude detection	2	integrated design with communication and automation subsystem	6	Retry transmission	Increase reliablility on automation, resend data
	actuactor	ineffective actuator while the lander attitude error is tolerable	hardware failure of the propulsions system as the actuactors here are repurposed	3	loss of partial data collection abilities	3	smaller time constant, and faster response time and settling time	8	Disable faulty hardware	Completely disable faulty actuator and descent with 4 thrusters
	actuactor	ineffective actuator while the lander is completely turned over	hardware failure of the propulsions system as the actuactors here are repurposed	2	fail to collect samples or other data; mission failure	2	build redundency, allow remote control of the lander attitude if possble, faster response time	9	Reorient	Attempt to use arm to reorient the lander
propulsion	overall device network	clogging, fracture, or leak at any of the junctures or stress concentration	imporper modelling, design, or testing; unexpected manufacturing error	4	complete mission failure	4	detailed validation and testing; high fidelity modeling and simulation	7	Land early	Land early to prevent further damage
	proprellant	depletion of fuel	fracture in tank structure,valve not fastened or coming loose due to vibration	4	complete failure of mission (only of the depletion happens near the surface of Enceladus, some instruments can still function)	4	thorough testing and validation; no method of remote mitigation after lauch	8	Decrease mass	Eject instruments to save mass so less fuel is required
automation	SLAM	failed recognition of previously visited location	improper detection markers	3	data storage filled up with useless and repeated data of the same location; lander navigate to unsafe location, causing missio failure	3	testing and simulation, validation on proper detection loop closure	7	Override	LIDAR override of altitude

Figure 20: Lander FMEA Page 2

3.1.6.1 Structures Subsystem Failure Modes

For the structure subsystem, there are many failures that could potentially occur. If the structure does not remain intact due to exceeding ultimate tensile stress of 414 MPa (Holt, 1996), the entire system and mission will fail. There are a few scenarios where this could occur, so it is entirely possible depending on the performance of various subsystems. A likely scenario is improper landing speed causing a crash landing due to failure of the propulsion subsystem. Other modes of failure may cause some damage to the structure, but will not result in complete mission failure. This scenario will occur if the landing speed is correct, but the orientation of the structure is improper. In this case, the lander will either land on its side or will tip over upon landing. If the structure does not land on the cylinder base, the structure will more than likely be undamage. However, some of the instruments will be rendered useless as they cannot administer the experiments planned. As for the case of falling on its side, the structure will be slightly damaged but not nearly enough to completely fail the material due to the low gravity on Enceladus. The likeness of causing damage to the structure during landing is just as likely as the total mission failure cases. This is because it relies on the same subsystems as before. Another failure mode would be colliding with other satellites. These satellites could be man made, like the orbiter, or debris from other bodies in the universe. The likeliness of this occurring is somewhat high, due to the amount of particles in the outer regions of Enceladus. The result of this failure mode would depend on the size, and speed of the collision. A faster, or larger, particle would cause catastrophic failure of the structure subsystem. Meanwhile slower, or smaller, particles would likely cause minuscule damage.

3.1.6.2 Electronics Subsystem Failure Modes

For the electronics subsystem, the failure mode can be analyzed into two categories, hardware failures and software failures. Hardware failures can be further analyzed and divided into general physical damage on hardware and issues with power supply. Within software, SLAM algorithm and data storage and processing are the two stress points for failures.

Physical damage to hardware is not likely to occur unless there was miscalculation on launch or orbiter that leads to collisions with an asteroid while the spacecraft is in orbit. The potential cause of this failure mode include colliding with an asteroid, hard landing, landing on a risky zone, unexpected amount of radiation on Enceladus surface, over-exceeding temperature range. Power supply failure is also not likely to happen unless both the primary power system and the backup power system fail, which can be caused by physical damage of the power system, overcurrent, and depletion of battery or power source before mission completion. In the event of a power system complete failure, automatic sample and data acquisition will stop, leading to mission failure. To mitigate hardware failures mentioned above, system reboot at minimal level for troubleshooting could help should some power remain. Should the power system completely fail either during or before data acquisition, a secondary power source(likely the battery system) should be engaged. To act on the mitigation, an emergency power supply or battery should be designed and implemented to supply a small electronics subsystem at the minimal level of power for analysis on what has gone wrong.

Software failure is unlikely to happen as the SLAM algorithm is well-established and should be tested thoroughly before deployment. Such situations should be avoided due to software testing via multiple models and examples prepared beforehand, but, if they do, the likelihood of such occurrence is very minimal. In general the SLAM algorithm and other programs running for this mission could have errors due to inefficient design, overclocking, high complexity leading to complex chain of errors, or improper input due to sensor failure. Data storage issues could occur due to the remapping of the known locations, which is likely a result of improper loop closure detection. If the SLAM algorithm fails,the probing system will be parapyzed unless manually controlled. If data storage is full, data acquisition would be insufficient since no more data can be collected.To mitigate, the team needs to design a validation and testing plan to troubleshoot the software and delete similar mappings for storage space. Acting on the mitigation, thorough testing needs to be designed for different and extreme environments. The algorithm needs to have adaptability in case of error, and ability to implement emergency plan systems should also be designed and tested.

Generally, if the electronics system or battery fails to power electronics, all automatic systems cannot run and cause conflicts in data sampling using scientific instruments. The battery must be installed far away from any heat-generating components, out of direct sunlight, or radiation exposure. In case of abnormal circumstances of overheat or overcurrent, there must be options to turn off electronics immediately. It is very unlikely to happen if electronics were tested thoroughly under harsh conditions before launching, however, unforseen exposure to radiation and heat may happen. A good way to mitigate such situations is to have emergency power ready to run analysis via troubleshooting and detecting what has cut the power source at the minimal level. If the power source is entirely cut, the hardware aspect of electronics subsystem will be affected and there are no reduction measures; however, if it's a problem with the software not running properly, it can run through troubleshooting to automatically back-up data and reboot or reconfigure software to operate again.

3.1.6.3 Attitude & Control Subsystem Failure Modes

The Attitude & control subsystem could have a range of failures due to its need of software data processing and hardware integration with a multitude of other subsystems. For hardware, should any of the sensors be endangered by the environment as they will be exposed on the outside of the lander, that will automatically disassemble the Attitude & Control system because the sensors are the input of this subsystem. If the sensors are intact, the next point for potential failure is within software. Given that no similar missions have been done on Enceladus, there could be conditions and situations that the software cannot process or understand, which will leave the system paralyzed because the system would not be recognized for a situation with a need of adjustments through the actuators. Had the team not known about the plumes, the software validation would not include test cases of the lander being pushed over to its side or turned over, which then would cause confusion in the system and lead to the lack of actions. The software program is also subject to issues with data transmission and the time delay of the system could cause a significant amount of over adjustment or inaccurate real time sensor data. Should the actuators fail, depending on the situation, the mission could be completely jeopardized. While the actuators fail when the orientation is slightly less than ideal, the other subsystems including propulsion and the payload could still execute their original tasks. Without the actuators, the images and samples could be less ideal, but rather there is still a possibility of sample and data collection. Should the actuators fail while the lander is completely turned over, it is less likely that the other systems and the payload could meet the mission objectives.

3.1.6.4 Propulsion Subsystem Failure Modes

The propulsion subsystem has modes of failure of its own. This system could have issues including clogging, fracture, or leakage of the tank-pipe-pump-thruster network, depletion of fuel, and software failure. The clogging, fracture, or leak of the tank-pipe-pump-thruster network is not very likely to occur, but will cause total failure of the mission. There is no way that the team can manually unclog or seal the fracture in the network without physical access to the lander. Depletion of fuel is also not very likely because backup fuel will be added into the fuel tank for precautionary measures and the reaction control thrusters. The result of this scenario entirely depends on the time of fuel depletion. If the fuel depletion occurs just before the surface of Enceladus, the mission is not entirely failed. Some of the instruments can still perform their desired experiments. However, if the fuel depletes further away from Enceladus, then the structure of the lander will more than likely be destroyed and the mission has failed. If the software were to fail, which is more likely to happen than the other two cases, the result of the mission would vary. More often than not, however, the result will be a total mission failure.

3.1.6.5 Automation Subsystem Failure Modes

The SLAM algorithm might fail to recognize a previously-visited location and re-map entirely again, which would fill up the data storage too quickly. It can be as bad as only allowing around 200 mappings with 160 GB (minimum) and 320 mappings with 258 GB (maximum). It is not as likely if a proper detection algorithm for loop enclosure is built, in which MATLAB utilizes already. Therefore, it is very unlikely to happen unless geographical features on camera differ per movement to the point where the algorithm cannot recognize landmarks that have been tagged by external influences. In the worst case, if the SLAM algorithm has any errors that were not caught beforehand, it may lead the lander or rover to unsafe zones and destroy the machine. For more detail, refer to 3.1.6.2 software failure.

3.1.7. Performance Characteristics and Predictions

3.1.7.1 Structures

In order to operate, the structure subsystem will need 4.06kg (1502.96 cm^3) of Aluminum 6061-T6. The thickness of the structure will be 0.1cm, so a sheet of this material with the desired volume and thickness is required. The structure will also need aluminum support beams for the instrumentation support. These beams will span the inner diameter of the cylinder to provide weight support while on Earth and securing it to the walls while experiencing zero gravity in space. The cross-section of these beams are square in shape with a side length of 1 cm.

It is expected based upon the information given in the concept that the structure subsystem will perform as designed. The structure material is metal and will be strong enough to be effective in protecting the instruments. The largest applied force on the lander if the mission is successful is 30 Newtons, with a factor of safety of 1.5 it will be considered as 45 Newtons, which will cause a maximum bending stress of 0.2265 Pa and tensile stress of 2.5455 kPa experienced by the bottom base; meanwhile, Aluminum 6061-T6 can bear up to 414 MPa. Additionally, the thickness of the structure will be effective in allowing other subsystems to take on more mass. There are no extreme external forces acting on the structure, at most 45 Newtons if no failure modes occur, that could lead to failure. The cold conditions experienced in space and on Enceladus are not extreme enough to fail the integrity of the structure subsystem for the mission requirements.

3.1.7.2 Electronics

The electronics system needs to be supplied with 23 watts when running. The XQRKU060 FPGA can only endure –55°C to +125°C. The electronics subsystem must be insulated from any radiation via a faraday cage (Xilinx, 2020). The storage must have a minimum of ~160 GB. A micro SD card capable of 256 GB will be used, with an average mass of 4.53 g.

These electronics subsystems are expected to work because running on the battery system will always produce heat to counteract the low mean surface temperature of Enceladus. The storage of 256 GB is expected to work because of loop closure detection from the SLAM algorithm that will not save additional mappings.

The electronics system is expected to be powered by the battery without overheat or overcurrent. The SLAM algorithm for probing is expected to detect loop closure to ensure that it does not store previously-visited location data as new data into the data storage. This will save space for a new location in the future.

3.1.7.3 Attitude & Control

The attitude & control system will have identical requirements as the propulsion systems and the electronics system as the actuators are repurposing the thrusters and sensors have similar operating conditions as the electronics system components. The attitude and control system heavily relies on these two systems, which means the integration and validation for these two systems will also be important for the attitude & control subsystem.

The attitude and control system will be expected to perform with a precision of 95%. This might seem rather large compared to other systems because with a higher precision, the system will need a significantly larger amount of resources, especially power and momentum from the propulsion system, which could overload the other systems and risk more important objectives of the mission.

3.1.7.4 Propulsion

The propulsion subsystem will need five pre-manufactured Cyclone-4 thrusters to provide the thrust and stability control that is necessary to complete the mission successfully. Additionally, lines of code will need to be developed to complete the mission autonomously which will be integrated into the automation subsystem. The propulsion subsystem will require communication between the mission team and the lander to actively verify the lander trajectory and amount of unburned fuel.

It is expected that the propulsion subsystem works as planned and completes a successful landing. The main thruster provides enough force that the lander will effectively land on the surface of Enceladus, but not too much that causes an unstable landing. The tank-pipe-pump-thruster is not very likely to fail, so expectations are set high for this subsystem.

3.1.7.5 Automation

It needs a decent FPGA and data storage with an estimated minimum space of 160 GB. The better electronic subsystems will make automation processing a lot faster. It is expected to work on FPGA because the FPGA model chosen is more than enough to run the high complexity of SLAM algorithm while running other software for scientific instruments. The data storage at minimum space of 160 GB is expected to work as well due to the enhanced EKF-SLAM algorithm that will better detect unique features around Enceladus surface which means it will better detect loop closure.

Because it is automated, the subsystem is expected to calculate very accurately and precisely without possible human errors for landing and probing. Since it’s automatic, it would not require constant communication back and forth with controllers from Earth, therefore the process of probing should be faster as well.

It is expected to work in such ways because of fast and accurate calculations done by computer rather than by humans. Having the step of communication skipped is definitely an important factor in reducing the time as well as human errors.

3.1.8. Confidence and Maturity of Design

3.1.8.1 Structures

The hardware that the structure subsystem needs is the aluminum 6061-T6 material for the lander enclosure and support beams for the inside of the structure. The supports beam concept has been around in engineering for many years, so this general hardware component is very well developed. The structure material, Aluminum 6061-T6, is meant to withstand extreme temperatures and remain structurally stable. The beginning stages of the 6061 aluminum alloys started in 1935 and has become more well established over the years. This aluminum is used more frequently for equipment, wings, and fuselages in the aerospace industry due to its high stress ceiling (CMRP, 2020). This specific 6061 aluminum alloy has the largest ultimate stress of all the alloys. Additional studies of this material were conducted for use in space by Italian scientists and engineers in 2004 to observe the thermal behavior of the material (Barucci, et al. 2004). Therefore, the structure material is well researched and developed in the aerospace industry.

3.1.8.2 Electronics

The hardware is relatively well-tested and successful in similar environments on the ground; however, there are no missions resembling the condition of Enceladus using the same, or similar, hardware. The hardware has gone through SEE testing for radiation-hardness and the temperature range. Since experiments were not performed at a space environment level, the TRL of electronics hardware is 6.

The TRL of the electronics system softwares is level 6 given that the SLAM algorithm was tested on arctic surfaces (Chebotareva, et al. 2020). However, the probing automation using the algorithm was never demonstrated on a space environment that resembles the environment of Enceladus.

3.1.8.3 Attitude & Control

All components are purchased and all are COTS, which most of them also have flight history to prove reliability of the technology; however, because these components have not been tested on a flight to Enceladus, TRL for the hardware should be level 7 at the highest.

Although built in house, there are very similar programs as well as packages available which have been tested on actual missions. Therefore the TRL should be 7, also given the simplicity of a feedback control program.

3.1.8.4 Propulsion

The hardware that makes up the propulsion subsystem includes the main thruster and four reaction control thrusters that are the Cyclone-4 thruster, a pump to move the fuel from the fuel tank to the thruster, unsymmetrical dimethylhydrazine fuel for the thrusters, nitrogen tetroxide for the oxidizer, a fuel tank to store the unused fuel, sensors to measure the amount of unburned fuel, and a piping network to deliver the fuel to the thruster. The developmental history of the Cyclone-4 30 N thruster is unknown, so we are assuming it to be slightly outdated or obsolete for a majority of space exploration missions. This is a reasonable assumption because there is no information utilizing the Cyclone-4 thruster in other space exploration missions and it produces low thrust. The fuel tank, sensing equipment, piping network, and pump are technologies that have been existent in the engineering industry for quite some time so the hardware is up to date. As for the fuel, the thruster requires that the fuel be a specific type (unsymmetrical dimethylhydrazine). The fuel itself has been in the market as far as the 1960s, which means it has been in the industry for quite some time. This could mean that the fuel is extremely outdated, or has been tweaked overtime. There is very little information on the development of unsymmetrical dimethylhydrazine, so it is assumed to be up to date with current knowledge of all rocket engine fuel types. As for the oxidizer, the research of nitrogen tetroxide as an oxidizer has only recently begun (Ross, 2012). So, the oxidizer chosen is not entirely developed and could lead to potential risks.

For the software that is required out of the propulsion subsystem, the program code is very achievable with the programming technology today. Writing a program to complete main thruster burns at a specific time and duration has been improved overtime with the response time decreasing, ultimately increasing the accuracy of the program. Therefore, the software of the propulsion subsystem is well developed.

3.1.8.5 Automation

Although the automation algorithm has been demonstrated in other NASA missions, such as Mars rover, it was never tested on an environment similar to Enceladus especially with customized hardware for the mission. It is not enough to say it was demonstrated in a space environment. The probing system has been experimented on icy surfaces like the Arctic, however. Therefore, the TRL of automation subsystem hardware is 6.

The TRL of software is at level 6 because the SLAM algorithm for landing and probing was never tested on icy surfaces like Enceladus in real missions, although it has been analyzed and experimented within Earth (Gonzalez, et al. 2019).

3.2. Recovery/Redundancy System

3.2.1 Structures Subsystem Safety Controls

The lander structure will not exceed ultimate stress conditions due to the material properties of the structure. A large factor of safety is ideal for recurring missions, but the proposed mission concept does not require reuse of the lander. If the structure were to completely fail during landing, the mission as a whole has been failed depending on the severity of the damage. A factor of safety of 1.5 will be used to mitigate the failure mode, which would mean that the 30 Newton force experienced will be considered as a 45 Newton force. This is due to the high stress tolerance of the aluminum alloy chosen. Another step to prevent this is to iteratively perform the strength tests as described in other sections to ensure all possible outcomes of failure will result in full functionality of the lander. This includes forces like those to stop the lander on Enceladus if the propulsion system were to fail. This can be simulated with the gravity of Enceladus and intentionally cause damage to the structure. If a failure mode does occur during these experiments, the team will brainstorm and resolve the issue with the structure subsystem. In the event the lander does not completely fail and is instead damaged, the team would need to carry out a review of the damage site. This would need to be done through the instruments onboard the lander. Once the damage is observed, the team shall brainstorm and determine what needs to be done to still achieve a majority of the mission objectives. The mission can carry on with more conservative approaches.

3.2.2 Electronics Subsystem Safety Controls

In the event of overheat or overcurrent, it should immediately turn off the corresponding component. If electronics cannot function without battery, it will extract from other sources such as other batteries present in the spacecraft or from a back-up battery at a minimal level to run through the back-up system to troubleshoot what may have caused sudden shutdown.

3.2.3 Attitude & Control Subsystem Safety Controls

Should the Attitude & Control system fail completely, the lander could very possibly fail its scientific objective. If the attitude and control system starts to see instability, the attitude and control system should try to use its actuators to correct the orientation.

3.2.4 Propulsion Subsystem Safety Controls

The propulsion subsystem failure modes have more severe results than the other subsystems. However, the failure modes are not as likely to occur. If the piping network delivering fuel to the thrusters is clogged or fractured, a backup piping subsystem will be utilized to shift the fuel flow from the nearest of the three pipes with respect to the inside of the lander to the thruster(s) in need of fuel. A valve will be placed at these pipe connection points to shift fuel flow if this scenario occurs. If fuel depletion occurs, the team will need to access the location with respect to Enceladus and speed of the lander at the time of the occurrence. The decision afterwards will vary depending on these two variables. To avoid this failure mode, the team will include additional fuel as a buffer for this occurrence. An additional 10% of fuel will be added to account for this buffer. If the propulsion software were to fail either by conducting incorrect burn durations or times, the team would need to reevaluate the burn durations, directions, and times based upon the current location and speed of the lander to successfully land. This can either be done manually by communication through the lander, or the program can be corrected and updated. For all the scenarios listed, the team would need to conduct a review of what went wrong and how the subsystem can be improved for future funded missions.

3.2.5 Automation Subsystem Safety Controls

For mapping, in the case of full data storage, similar mapping results should be deleted if we were to make the rover explore more. For probing, if it fails to foresee a dangerous area and has entered the risky zone, the analysis based on the measurements from scientific instruments should command the rover to return to its previous location. For landing, if it fails to land on the safest zone or was not able to move as it expected due to external forces, its automatic system will lead the machine into the safer zone.

3.3. Payload Integration

3.3.1 Structures Subsystem

The Ptolemy requires an access point through the structure to conduct experiments. The SELFI requires an access point through the structure to conduct experiments. The LIDAR requires an access point through the structure to conduct experiments. The Infrared Camera requires an access point through the structure to conduct experiments. The Mastcam-Z requires an access point through the structure to conduct experiments.

3.3.2 Electronics Subsystem

The electronic subsystem needs to supply power and data storage for Ptolemy to function and store its data to be parsed. It also needs Ptolemy's data in combination with other data to determine if the area is safe to probe without running into conflicts. The electronic subsystem needs to supply power and data storage for SELFI to function and store its data to be parsed. It also needs SELFI's data along with others from different scientific instruments to determine if the area is safe to probe without running into conflicts. The electronic subsystem needs to supply power and data storage for LIDAR to function and store its data to be parsed. Its data is determined in consideration with other data for automatic systems. The electronic subsystem needs to supply power and data storage for the IR camera to function and be able to carry visualization of its digitized image to the SLAM algorithm to be analyzed for automatic system. Its measurements will contribute to determination of if the area is safe to be probed. The electronic subsystem needs to supply power and data storage for the Mastcam-Z to function and be able to carry visualization of its digitized image to the SLAM algorithm to be analyzed for automatic systems.

3.3.3 Attitude & Control Subsystem

The attitude and control would support the Ptolemy system so that the instrument can be oriented correctly to measure the composition; the attitude and control system does not directly output any influence to the Ptolemy system. The attitude and control would support the SELFI system so that the instrument can be oriented correctly to capture the measurement and assessment; the attitude and control system does not directly output any influence to the SELFI system. The attitude and control would support the LIDAR system so that the instrument can be oriented correctly to measure; the attitude and control system does not directly output any influence to the LIDAR system. The attitude and control would support the Infrared Camera system so that the instrument can be oriented correctly to take pictures of the interested region; the attitude and control system does not directly output any influence to the Infrared Camera system. The attitude and control would support the Mastcam system so that the instrument can be oriented correctly to capture images; the attitude and control system does not directly output any influence to the Mastcam system.

Section 4: Payload Design and Science Instrumentation

4.1. Selection, Design, and Verification

4.1.1. System Overview

This lander has four main payload and science instrumentation subsystems, thermal, communications, power, and data acquisition. Thermal, communications, and data acquisition subsystems all utilize power from the power subsystem. Power will be stored in lithium ion batteries and will be delivered at 4.1V. The total battery mass will be 3.2 kg and be able to supply 492 Wh over the course of the mission. The thermal subsystem will draw from the electronics and power subsystem to ensure steady Imm state temperature of the lander is within the operating limits during transfer to Eceladus, descent, and after landing. The thermal system will trigger overcooling at -15 °C and the sample heater will be activated. The thermal system will trigger overheating at 30 °C and non-essential instruments will be instructed to shut down. The communication system will take data stored by the electronics subsystem and relays it to the orbiter when line of sight is established. The communication system will utilize a lightweight antenna that will immediately deploy after disconnection with the orbiter. The data acquisition subsystem consists of all of the science instrumentation including THEMIS infrared camera, Mastcam-Z, LIDAR, Ptolemy, SELFI, a sample heater, and sample collection arm. This system will collect all mission data.

Data Acquisition	Acknowledge retrieval of scientific data	Raw Data		
Science instrumentation commands	**Electronics**	Receipt of Acknowledge Transmission of Data		
	Acknowledge Transmission of Data	**Communication**		
33.96 Watts to Instrumentation for operation	23 Watts to Electronics subsystem	3.5 Watts to Communication subsystem	**Power**	Maximum of 50 Watts to heaters
Maintain operating temperature	Read Thermal System Data			**Thermal**

Figure 21: N^2 Chart

Table 2: Payload Parameters

Payload	Mass	Dimensions	Power Consumption
Thermal Control	0.2 kg	0 x 0 x 0 cm (wires)	0 W
Communications	1.2 kg	5 x 5 x 2 cm	3.5 W
Power	3.2 kg	13.77 x 15.51 x 2.68 cm	0 W
Infrared Camera	11.2 kg	20 x 10 x 10 cm	14 W
Mastcam-Z	4 kg	11 x 12 x 26 cm	17.4 W
LIDAR	3.56 kg	2 x 5 x 10 cm	22 W
Ptolemy	4.5 kg	10 x 20 x 35 cm	28 W
SELFI	10.7 kg	38.1 x 22.86 x 20.32 cm	10 W
Sample Heater	0.35 kg	2 x 3 x 6 cm	50 W
Sample Collection Arm	0.664 kg	70 x 1 x 1 cm	5 W

4.1.2. Subsystem Overview

4.1.2.1 Thermals

The thermal management focuses on the selection of materials and implementation of heaters and electronics controls to ensure that the steady Imm state temperature of the lander is within the operating limits during transfer to Eceladus, descent, and after landing.

Fourteen K-type thermocouples will be used to monitor the temperatures of the communications subsystem, power subsystem, IR camera, Mastcam-Z, LIDAR, Ptolemy, SELFI, Sample Heater, Sample Collection Arm, electronics subsystem, attitude & control subsystem, and the propulsion subsystem. K-type thermocouples were selected because of their large range of temperature detection of −195 °C to 1100 °C, ensuring reliable temperature readings at the expected temperature range of the mission (Kus, et al. 2015). AZ-93 will be used to coat sections of the outer surface of the lander to regulate the steady state temperature of the system. AZ-93 was selected thanks to its high emissivity and low absorptivity (Gaier, et al. 2008) allowing minimal application of the coating to the lander. The thermal subsystem will communicate with the sample heater (Section 4.1.2.4.7) to work as a heating element for the lander to prevent freezing. The electronics subsystem (Section 3.1.2.2) will also communicate with the thermal subsystem to shut down instruments in the event of overheating.

A simple software package will be used to manage the thermal state of the lander. Data from the thermocouple array will be used to predict the temperature trends of each temperature sensitive component of the lander. Should the thermal subsystem detect that the lander has crossed the temperature threshold for overcooling, a signal to the sample heater will be sent to activate and heat the lander until the temperature has been once again normalized. If an overheating threshold is broken, a signal to the electronics system requesting to disable active instruments to reduce the heat output will be sent. Data will be processed from the thermocouples at a rate of 100Hz during descent burns, 10Hz after landing, and 1Hz during transfer to enceladus. These frequencies were selected to balance low power consumption with high data resolution during transient states of the lander. The overcooling trigger will be -15 °C; should this threshold be passed, the sample heater will be activated. The overheating trigger will be 30 °C; should this threshold be passed, non-essential instruments will be instructed to shut down.

The subsystems which require proper thermal subsystem operation to function are the communications subsystem, power subsystem, IR camera, Mastcam-Z, LIDAR, Ptolemy, SELFI, Sample Heater, Sample Collection Arm, electronics subsystem, attitude & control subsystem, and the propulsion subsystem. Each has specific thermal operating ranges and will be monitored by the thermal subsystem to maintain that range. The lander as a whole is required to remain between -20 °C and 40 °C for the majority of the mission to maximize the lifespan of the components on the lander.

The thermal subsystem depends on the proper operation of the electronics subsystem, sample heater, and power subsystem. The electronics subsystem is used by the thermal subsystem to prevent overheating as well as to process the data from the 15 thermocouples monitoring the lander. The sample heater is used by the thermal subsystem to prevent overcooling of the lander. Finally, the power subsystem is used by the thermal subsystem to provide power to all the processes of the thermal subsystem. The thermal subsystem does not directly consume power; however, when using the sample heater to heat the lander, the maximum power draw is 50W.

4.1.2.2 Communications

The communications subsystem takes data stored by the electronics subsystem and relays it to the orbiter when line of sight is established. Data sent includes instrument readings to be sent back to Earth for research and analysis as well as subsystem states which will be used to improve the design of future missions.

The communications subsystem will consist of a modified off the shelf antenna system. The EnduroSat UHF ANTENNA III is a deployable lightweight (85g), and low power (5 W when transmitting) antenna. The antenna will deploy immediately after disconnecting from the orbiter.

The only software controlling the communications subsystem will be the controller for the deployment of the antennas. This software is embedded into the hardware of the antenna and only requires a signal from the electronics subsystem to deploy. After the deployment of the antennas, the communications subsystem will be primarily managed by the electronics subsystem.

The communications subsystem requires the proper functioning of the power subsystem as well as the electronics subsystem in order to operate. The power subsystem supplies power to the communications array while the electronics subsystem controls what data is to be transmitted and received by the communication subsystem.

The IR camera THEMIS, Mastcam-Z, LIDAR, Ptolemy, and SELFI all indirectly depend on the proper operation of the communications subsystem. While the lander should theoretically be able to successfully operate without Earth intervention after launch thanks to the automation subsystem, if the communications subsystem fails, none of the instrument data will reach Earth and the mission would be a failure.

4.1.2.3 Power

The power subsystem is responsible for delivering power to all of the instruments and subsystems which require power on the lander. Power will be stored in lithium ion batteries and will be delivered at 4.1V. Should an instrument or subsystem require a different voltage, transformers will have to be included on said subsystem. This is done in order to improve the efficiency of the overall power subsystem. An important assumption about the power subsystem is that the orbiter will have a method of powering the lander and that the battery will be fully charged when disconnected from the orbiter.

The batteries used in the power subsystem will be two EaglePicher Lithiated Nickel Cobalt Aluminum Oxide 60Ah batteries (Eaglepicher, 2019). The total battery mass will be 3.2 kg and be able to supply 492 Wh over the course of the mission.

All battery management will be handled by the thermal subsystem and the electronics subsystem so no software is used in the power subsystem. The subsystems and instruments which require the proper operation of the power subsystem are the thermal subsystem, communications subsystem, IR camera, Mastcam-Z, LIDAR, Ptolemy, SELFI, Sample Heater, Sample Collection Arm, electronics subsystem, attitude & control subsystem, propulsion subsystem, and the automation subsystem.

The power subsystem relies on the proper operation of the electronics subsystem and the thermal subsystem. The electronics subsystem will control the output of the battery and direct power to certain subsystems and instruments. The thermal subsystem will manage the temperature of the battery and prevent freezing or overheating.

4.1.2.4 Infrared Camera

The system detects and measures the infrared energy of objects and the camera converts that data into an electronic image that shows the apparent surface temperature of the object being measured.

The THEMIS infrared camera was produced for the Mars Odyssey to capture thermal images of Martian bodies, Phobos. THEMIS consists mainly of a microbolometer for infrared detection, a silicon focal plane for visible detection, a visible/ infrared beamsplitter, and a three-mirror anastigmat telescope.

The THEMIS infrared camera software will reside on the spacecraft computer to perform formatting and data packetization. There are four main commands that can be given over an RS-422232 synchronous serial command line including: (1) IR camera on/off/stand-by; (2) visible camera on/off/stand-by; (3) calibration flag shutter control and electronics synchronization; and (4) instrument parameter settings (gain, offset, integration time, etc) (Christensen, et al. 2001). The visible imaging portion of THEMIS runs on the main CPU and internal digital sensor processor.

The subsystem has an orbital average power of about 14 Watts in order to operate. The power, electronics, and thermal subsystems must be functioning for THEMIS infrared camera to properly operate. No other systems depend on the infrared camera, as it is collecting its own category of data.

4.1.2.5 Mastcam-Z

The Mastcam-Z is the camera system that will be incorporated on the lander. The Mastcam-Z has multiple cameras that have zoom and focus capabilities. These cameras can take 3D images and video at a high speed. This allows for detailed examination and record keeping during and after the mission.

The Mastcam-Z is being produced for the Perseverance rover on the next mission to Mars. The system consists of a camera head, digital electronics assembly, and calibration target. The team anticipates purchasing the entire system in the three pieces and assembling it on the lander.

The Mastcam-Z will utilize the advanced AI software tools designed to assist spacecraft. This will control the rotation, activation, zoom, focus, and any other camera features required. There are software packages and libraries that allow for communication and use existing software to control all processes.

When in use, each of the dual cameras need 11.8 Watts of power in order to operate. When in standby, each of the dual cameras need 7.5 Watts of power. The power, electronics, and thermal subsystems must be functioning for Mastcam-Z to properly operate.

No other systems depend on the Mastcam-Z subsystem of Data Acquisition but will contribute to the landing of the lander and probing on Enceladus.

4.1.2.6 LIDAR

LIDAR stands for Light Detection and Ranging. It is a remote sensing method that uses pulsed lasers to measure ranges. This is imperative to obtain measurements from the surface to allow for a safe and accurate landing. LIDAR will also be key to measure and model the topography of the surface of Enceladus.

The team will be purchasing a LIDAR system and then integrate onto the lander. The LIDAR system will utilize the advanced AI system that is being integrated between multiple instruments and subsystems. It will control when to take readings and will operate in single autonomous mode. LIDAR will use about 22 Watts of power when actively obtaining measurements. The power, electronics, and thermal subsystems must be functioning for LIDAR to properly operate. The Attitude and Control subsystem depends on the success and accuracy of LIDAR. The landing on Enceladus by the lander also depends on LIDAR and its accuracy.

4.1.2.7 Ptolemy

Ptolemy determines the chemical and stable light isotopic composition of the material on a planet or comet. Samples are collected by the SD2 drilling system, which harvests ice and dust from near-surface areas and sub-surfaces depth of up to 20 centimeters. The sample drilling system drills into the surface of the planet, and then a sampling tube is extended from the drill to pick up the sample. The drill is then moved back to its home position, ready to deliver the sample to the Ptolemy. Then, the samples are delivered to Ptolemy’s sample heater subsystem, which are heated and the analytical systems purify and identify the volatiles released from the samples. The ion trap mass spectrometry obtains precise measurements of stable isotopes of the elements, hydrogen, carbon, nitrogen, and oxygen, in various forms found on the planet. The data collected from the Ptolemy compares the water on the surface of the planet and the water from Earth's oceans; it also studies the nature of organic material on the planet and compares the samples to other Solar System bodies (Lizia 2014).

The team will be purchasing an assembled Ptolemy gas chromatography and ion trap mass spectrometer. The team will also purchase the Sample Drill and Distribution system (SD2) (4kg) to collect the samples from Enceladus. The team will be decreasing the number of samples and removing three of the four sample heater subsystems for a custom sample heater. The Ptolemy will take 10 samples from Enceladus.

The software will not need to be made because it is incorporated into Ptolemy. The software Ptolemy uses is written in FORTH because FORTH can take advantage of the processor's internal stack-based structure. The software controls the experiment for each measurement cycle, collects the data, formats and pre-processes data, handles data communication with the control and data management system, and compresses the data.

The subsystems need samples from Enceladus to operate properly. The Sample Drill and Distribution system (SD2) will collect samples of Enceladus in multiple forms, and those samples will be passed into Ptolemy's sample heater subsystem to identify which samples are organic elements. No other subsystems depend on the Ptolemy to work.

4.1.2.8 SELFI

The Submillimeter Enceladus Life Fundamentals Instrument will observe molecular species on Enceladus that are important to life and the formation of water and habitability. SELFI will analyze and perform the following functions on Enceldus's core:

- Assess the plume compositional variability
- Measure the spatial/temporal variabilities in the plume chemical compositions
- Monitor elements such as H20, d180, HDO, and d170
- Using remote sensing, constrain the oxidation state of Enceladus's subsurface ocean using H2O2 and O3 and utilize H2S and SO2 spectral signatures (links to prebiotic molecules)
- SELFI's continuum observations will measure surface temperature from 30 - 250 Kelvin with .1 K resolution. This will also enable the correlation of observed plume activity with surface temperature
- Analyze all 14 molecular species and collect data on molecular species which will be discovered on Enceladus but weren't discovered through prior observations.

To reduce technical risks, SELFI must be built via advanced technology and architecture to make submm spectroscopic measurements of Enceladus plumes.

- Design, build and test microwave assembly to equip SELFI with the capability to perform multitude of functions
- Leverage already developed GSE for SELFI development. If necessary assemble duplicate hardware
- RF low noise amplifier design from Northrop Grumman Aerospace Systems
- Single side band (SSB) mixer and LO
- If assembly goes down converter using MMIC elements
- Digital spectrometer using next generation RTG4 FPGA

Advanced AI software tools will be used and designed to assist spacecraft, and other SELFI systems in operating robustly even if faced with hardware malfunctions or unexpected events on Enceladus. Software packages and libraries to communicate with Enceladus and use existing software to control processes such as heating, trajectory, data analysis, etc.

The SELFI instrument will consist of fine radiometric resolution, high spectral resolution, multiple continuum channels and a high dynamic range, necessary to map Enceladus across its 30 K to 250 K temperature range. Mastcam-Z, IR camera, to help with analyzing atmosphere and environmental composition above Enceladus's surface and also on its surface.

4.1.2.9 Sample Heater

The sample heater is a ceramic chamber surrounded by a resistive heating coil. This is then mounted to the rest of the lander via a polyurethane structure thanks to its low thermal conductivity of .02 (Young & Sears 1992). The sample heater is used by the Ptolemy to melt surface samples before being analyzed. The sample heater is also used to heat the lander in the event of overcooling. To improve the efficiency of the sample heater as a lander heater, a small electric motor will be used to move a piece of metal to make direct contact with the ceramic chamber to bypass the insulation during heating.

Since the surface of Enceladus is expected to consist mainly of ice and carbon dioxide at the landing site (Brown, et al. 2006), the heater only has to heat the sample to 1 °C to liquify the sample. This will be achieved by using an aluminum chamber. This chamber will be then surrounded by a copper coil where current is run though to heat the chamber. To bypass the insulating, a motor will be required to articulate a piece of copper to make contact with the heater to bypass the insulation. This small assembly will be enclosed in a 3cm x 3cm x 4cm volume. The sample heater will consume between 50W to melt samples and heat the lander.

The sample heater will be directly controlled by the electronics subsystem, no dedicated software is required to operate the subsystem. The sample heater requires the proper operation of the electronics subsystem and the power subsystem. Without the electronics subsystem, the sample heater will not be able to activate or deactivate. Without the power subsystem, the sample heater will not have the power required to melt samples.

The Ptolemy depends on the proper operation of the sample heater. Since the Ptolemy only scans liquified samples, it will not be able to record any data without the sample heater.

4.1.2.10 Sample Collection Arm

The sample collection arm is a robotic arm consisting of 3 joints. This arm will be mounted to the side of the lander with one joint located on the lander, one joint located midway through the arm, and one joint at the end of the arm. At the end of the arm, a small bucket with a jagged edge is attached to scrape the surface in the event the surface is too hard to scoop.

The joints will be articulated by 3 brushless DC motors. Brushless DC motors were selected for the relatively low torque application and long life span (NASA, 1999). Each motor will be a Moog DBH-0472 brushless motor (MCG, 2020). At just 11.33 grams, the motor provides a high torque of .706 (m-Nm) for the package size. The arm will be constructed out of a lightweight aluminum structure.

The arm will have a simple software set to control the motors. Since the arm only has 1 axis of mobility, the robotic arm can use a simple script to first attempt to scoop samples from the surface and scrape the surface to get shavings if scooping is ineffective. The software will use the power consumption of each motor to model where the arm is as well as how much force is acting on the arm. Should the model indicate that the scoop cannot penetrate the surface, scrapping will be engaged.

The arm requires the proper operation of the electronics subsystem and the power subsystem. The electronics subsystem will run the software to control the arm while the power subsystem will power the motors which articulate the arm.

SELFI, NIGMS, and Ptolemy all rely on the proper functioning of the sample collection arm. If the sample collection arm cannot achieve its requirements, these instruments will not be able to scan any samples.

4.1.3. Manufacturing Plan

4.1.4.1 Thermals

AZ-93 will be applied as a paint onto the outer structure of the lander at the end of the manufacturing of the structure. The coating will only be applied to the structure and not the instruments to prevent potential interference. The thermocouples will be manufactured and integrated at the same time that the subsystem which they will be monitoring are being manufactured. One thermocouple will be dedicated for the communications subsystem and attached to the PCB controller of the antenna. One thermocouple will be dedicated for the power subsystem and will be attached to the battery pack, one thermocouple will be dedicated for the IR camera and will be attached to the PCB adjacent to the IR sensor. One thermocouple will be dedicated for the Mastcam-Z and will be attached to the PCB or the controller. One thermocouple will be dedicated for the LIDAR and will be attached to the PCB adjacent to the sensor. One thermocouple will be dedicated for Ptolemy and will be attached to the PCB of the controller. One thermocouple will be dedicated for SELFI and will be attached to the PCB of the controller, one thermocouple will be dedicated for the sample heater and will be attached to the interior of the heating core. Two thermocouples will be dedicated for the sample collection arm, one at each of the joints. One thermocouple will be dedicated for the electronics subsystem and will be attached to the PCB of the central computer. One thermocouple will be dedicated for attitude & control subsystem and will be attached to the interior of the monopropellant tank. Finally, 2 thermocouples will be dedicated for the propulsion subsystem, one on the interior of the fuel tank and one on the interior of the oxidizer tank. After the subsystems have all been manufactured, the thermocouples will all be wired into the computer managed by the electronics subsystem but controlled by the thermal subsystem software.

The thermal subsystem will also accept any temperature data from integrated temperature sensors in other subsystems to improve the temperature predictions of certain components. For example, if the electronics subsystem has a temperature probe integrated into the CPU to determine the clock speed, the thermal system will accept the data, adjust the frequency, and integrate it into its temperature threshold prediction model.

The thermal subsystem will also have direct control over the sample heater. Since the thermal software is run on the electronics subsystem computer, no additional connections will have to be made. Commands to activate the sample heater will be sent by the thermal software, to the rest of the computer, and subsequently to the sample heater to activate or deactivate. The thermal software will also have control over the operation of many of the instruments on the lander. Depending on where on the lander an overheating threshold is broken, certain instruments will be disabled to reduce power consumption in that area. Commands to disable instruments will be sent from the thermal software, to the rest of the electronics subsystem, and subsequently to the instruments being commanded to shut down.

4.1.4.2 Communications

To integrate the off the shelf communications array, EnduroSat will be contracted to tune the antennas to the environment of Enceladus and the Orbiter. Given that the antenna array is a completed subsystem, it will be integrated in the final stages of manufacturing. Software support will be provided by EnduroSat. Given the minimal software used by the communications subsystem, software integration will be at the end of manufacturing.

4.1.4.3 Power

Due to the inherent risk of fire associated with high capacity batteries, the power subsystem will be integrated at the end of manufacturing. Since the batteries are being manufactured by a subcontractor, the batteries will simply slot in to a support structure specified in the structures subsystem. Due to the lack of software used by the power subsystem, no software integration is required.

4.1.4.4 Infrared Camera

Given that the THEMIS will be bought as a complete instrument, it will be integrated in the final stages of manufacturing onto the body of the lander. THEMIS will come with software which will be integrated with other instruments in the final stages of manufacturing.

4.1.4.5 Mastcam-Z

Given that the Mastcam-Z will be bought as a complete instrument, it will be integrated in the final stages of manufacturing. Mastcam-Z will come with software which will be integrated with other instruments in the final stages of manufacturing.

4.1.4.6 LIDAR

Given that LIDAR will be bought as a complete subsystem, it will be integrated in the final stages of manufacturing. LIDAR will come with software which will be integrated with other instruments in the final stages of manufacturing.

4.1.4.7 Ptolemy

The subsystems of Ptolemy will not need to be built because they are built into the Ptolemy. However, it will need to be modified to have one oven instead of four ovens, as the other ovens are not needed. This is handled by the sample heater subsystem, and it will be integrated once the sample heater is complete. The subsystem software is built into the Ptolemy and will not need to be built separately.

4.1.4.8 SELFI

The SELFI instrument will be built using existing models from the previous missions it has flown on, however it will have weight and volume constraints based on the final size of the lander. Additional materials and specifications will be added and decided nearer the end to make sure that the instrument operates in the space/Enceladus’s environment.

SELFI will use artificial intelligence (AI) (Good, 2017) to seek out targets and use a laser that can determine the molecular composition of surface materials. Similar to the Mars Rover Supercam, which examines rocks and soils with a camera, laser and spectrometers to seek organic compounds that could be related to life, the laser beam mounted on SELFI will excite the chemical bonds in a sample and produce a signal depending on which elements are bonded together - a technique called Raman spectroscopy. The software will be integrated into the subsystem in the final stages of manufacturing since it already exists and the advanced AI has been previously used in SuperCam.

The SELFI instrument and its software is still in the early stages of production. In previous missions such as the NASA's Mars Exploration Program, A.I. software on NASA's Curiosity Mars rover helped it zap dozens of laser targets on the planet, becoming a frequent science tool when the ground team was out of contact with the spacecraft. This same software has proven useful enough that it's already scheduled for NASA's upcoming mission, Mars 2020. Therefore, the same A.I. software could be used to perform the same functions on the surface of Enceladus.

4.1.4.9 Sample Heater

The sample heater will be constructed separately from the rest of the lander in order to streamline the manufacturing process. The structure to mount the heater to the rest of the lander will be 3D printed and then used to integrate the system to the rest of the lander at the end of manufacturing. The sample heater will be located between the drill of Ptolemy and the sample analyzer. Due to the lack of software dedicated to the sample heater, no software integration is required for the sample heater.

4.1.4.10 Sample Collection Arm

The sample collection arm will be one of the first subsystems manufactured due to its complexity and precision requirements. The arm will be constructed out of aluminum using the motors specified in the hardware description. After manufacturing and validation, the arm will then be attached via screws to the rest of the lander.

The software controlling the arm will be stored and run by the electronics subsystem, it will be integrated after the manufacturing of the central computer is complete. Due to the simplicity of the software running the arm, this software will be made exclusively with Python.

4.1.4. Verification and Validation Plan

4.1.4.1 Thermals

The AZ-93 coating will be verified by measuring the emissivity and absorbance of the applied coating and comparing it to the expected values. Emissivity will be measured using the two temperature method as it does not need to make many of the assumptions about geometry like other methods (Watson, 1992). Absorbance will be measured by sending a set amount of radiant flux into the surface and measuring the radiant flux transferred into the surface (Verhoeven, 2009). AZ-93, has an emittance between .89 and .93 and an absorptance between .14 and .16 (Gaier, 2008). Should the measured emissivity and absorptivity fall within this range, the coating will be considered to be valid.

The thermocouples will be validated before and after installation on each subsystem. Validation will be conducted by exposing each to a range of known temperatures and determining if each fall within an acceptable accuracy. Should the thermocouple have more than 1 °C of error, it will be replaced with a functioning thermocouple.

Validation of the sample heater will be covered in section 4.1.4.4.7 and validation of the electronics subsystem will be covered in section 3.1.5.2.

The software will be validated by simulating both nominal states where all temperatures are normal to ensure that no safety measures are unintentionally enabled as well as failure states to ensure that when thresholds are crossed, the software takes proper action to save the lander.

The software will also be validated by testing how the software deals with bad data. Should a thermocouple start producing faulty data, the software must recognize that the thermocouple is producing bad data and not that the lander is overheating or overcooling. For example, if the thermocouple reading in the SELFI goes from 10 °C to 900 °C in .01 seconds, the software should be able to recognize that the thermocouple has failed and not that the instrument has spontaneously spiked hundreds of degrees in less than a tenth of a second.

4.1.4.2 Communications

The communications subsystem will be validated by testing wireless communication capabilities after hardware integration. This will be done by attempting to connect the lander to Earth's existing satellite network in Low Earth Orbit (LEO). If the lander can communicate with satellites in LEO, it will be more than sufficient to communicate with the orbiter at Enceladus.

Software validation will consist of ensuring that the deployment mechanism activates simultaneously with the deployment of the lander from the orbiter as well as ensuring that the deployment mechanism does not prematurely activate.

4.1.4.3 Power

The power subsystem will be validated by testing the overcurrent protection, overpressurization, overheating, and overcooling. The batteries will be subjected to high current draw, high pressures, high temperatures, and low temperatures both independently and as a combination of multiple hazardous environments. If the power subsystem can operate from -20°C to 40°C and can hold a charge after being subjected to -40°C, it will be determined to be thermally resilient. If the battery can handle continuous output of 250 amps, it will be determined to be validated for overcurrent protection. Finally, if the safety valve opens when subjected to high pressures, the power subsystem will be determined to be resilient to pressure changes. Due to the fact that the power subsystem has no dedicated software, no validation is required.

4.1.4.4 Infrared Camera

We can validate the hardware of the infrared camera by looking at some objects of different distances away to determine if the camera works better with farther distances, as it was designed for such. As this camera has been used on previous missions, that mission data can also help to validate the hardware.

We can validate the infrared camera by testing its ability to differentiate and filter between different wavelengths of light. We can photograph some different types of waves such as visible light and microwaves and use the images obtained to determine if the camera is telling a difference. As this camera has been used on previous missions, that mission data can also help to validate the software.

4.1.4.5 Mastcam-Z

The Mastcam-Z instrument will be validated by testing the cameras ability to rotate, calibrate, focus, and obtain accurate test images. If it can take accurate images in different environments, like harsh or minimal lighting, then it should be able to perform on Enceladus.

The software validation for Mastcam-Z will occur through the assurance of proper calibration of cameras, proper image processing, and ability to be in active or standby mode in test simulations.

4.1.4.6 LIDAR

LIDAR hardware will be validated by testing lasers pulse at the correct rate to obtain distance and topography measurements of various objects. The software validation for LIDAR will occur through the assurance of proper calibration of distance using pulsing lasers and the ability to be in active or standby mode.

4.1.4.7 Ptolemy

The Ptolemy hardware will be validated when the structural analysis via finite element modeling, shock and random vibration testing, and demonstrated operations across a representative range of environmental conditions is completed. The Sample Drill will also be tested under the conditions of a thermal vacuum chamber under conditions which simulate the operational environment of the lander. The Ptolemy software will be validated when it receives commands from the control and data management system.

4.1.4.8 SELFI

SELFI will be validated by the use of analytical techniques to predict the suitability of a design. SELFI will also be tested on earth in a condition similar to that of Enceladus to make sure it doesn’t malfunction and performs the required analysis.

The software will be validated through how it performs or functions when integrated into the subsystem on earth. Since the molecular composition and chemicals already exist, testing the software using software validation steps would give a bigger picture on if it’ll function properly on Enceladus.

4.1.4.9 Sample Heater

The sample heater will be validated by subjecting it to a vacuum at 210K. If the sample heater can still melt pure water ice at this temperature, it will be deemed thermally effective.The lander heating capabilities will be verified by testing if the motor can consistently move the copper to make an effective thermal interface with the heater and the structure of the lander. There is no software dedicated to the sample heater which must be validated.

4.1.4.10 Sample Collection Arm

The sample collection arm will have to work around a number of constraints set by the difference in environment to validate the hardware. Due to the extremely low gravitational acceleration at .113 m/s^2 (Less, et al. 2014), the arm will not be able to operate on the surface of earth under normal conditions. To validate the model then, multiple tests will be conducted. First, simulations will be conducted to validate the structural stability of the arm. Next, a scale model which accounts for gravitational differences will be constructed to validate the overall design. To validate the arm itself, the arm will be tested on NASA's Weightless Wonder. This will allow the arm to operate with the precise artificial gravity of Enceladus by adjusting the rate in which the plane drops.

The software will be validated by testing if the software can detect when the surface is too hard to scoop samples into the lander. This will be done by monitoring the power draw of the motors as the scoop makes contact with the surface. A marginal increase indicates that the arm was able to penetrate the surface while a spike indicates that the scraping function will need to be used.

4.1.5. FMEA and Risk Mitigation

Using the same FMEA legend from section 3, a FMEA chart has been developed for the payload of Ensomnia.

Mission: Ensomnia			Systems Engineer: Payton Case			FMEA Date: 11/29/2020			
			CSO: Zoe Fang						
Subsystem	Component	Potential Failure Mode	Potential Cause of Failure	Occurrence	Potential Effects of Failure	Severity	Mitigation Factors	Mitigation	Recommended Actions	Action Taken
Thermal Control Subsystem	Coating	AZ-93 chipped off of the structure	Debris	5	Thermal control inefficiency	2	AZ-93 applied properly	3	Decrease power consumption	Decrease simultaneous instrument runtime
		Debris obstructs the AZ-93 coating, changing the emissivity and absorbance	Debris	4	Thermal control inefficiency	2	Short mission time prevents significant dust buildup	5	Decrease power consumption	Decrease simultaneous instrument runtime
	Thermocouples	Thermocouples produce bad data	Manufacturing Error	2	Thermal control failure	3	Thermocouples properly installed and callibrated	4	Supplement data	Temperature data from the integrated subsystem temperature probes will supplement the faulty data
		Thermocouples are displaced from their intended location	Insufficient Adhesive	1	Thermal control failure	3	Thermocouples properly installed and callibrated	4	Supplement data	Temperature data from the integrated subsystem temperature probes will supplement the faulty data
	Instrument	Instrument cannot be disabled	Electronics glitch	1	Thermal control failure	3	Instruments tested and verified to be successfully disabled before launch	5	Decrease power consumption	Adjacent instruments and inessential subsystems will be disabled
	Sample Heater	Sample heater insufficient to heat the lander	Power subsystem inefficiencies	2	Thermal control failure	3	Sample heater calibrated before launch	4	Increase power consumption	Additional instruments will be enabled to produce extra heat
		Sample heater damaged and cannot activate	Debris	2	Thermal control failure	3	Sample heater protected by structure	4	Increase power consumption	Additional instruments will be enabled to produce extra heat
	Instrument	Lander is overheating	Too many instruments running at once	5	Thermal control failure	3	Thermal simulations validate the thermal state of the lander	2	Decrease power consumption	High power instruments will be disabled
		Lander is overcooling	Not enough instruments running	5	Thermal control failure	3	Thermal simulations validate the thermal state of the lander	2	Increase power consumption	Sample heater will be enabled
		False overcooling threshold passed	Thermocouple error	4	Thermal control inefficiency	2	Thermal simulations validate the thermal state of the lander	4	Decrease power consumption	Supplemental temperature data will instruct the sample heater to shut down
		False overheating threshold passed	Thermocouple error	4	Thermal control inefficiency	2	Thermal simulations validate the thermal state of the lander	4	Return to nominal	Instruments will be restarted
	Electronics	Electronics subsystem processing data inaccurately	Electronics glitch	2	Thermal control inefficiency	2	Software Validation	5	Assume nominal	Assume nominal
	Thermocouples	Thermocouple data lost	Electronics glitch	2	Thermal control inefficiency	2	Software Validation	5	Supplement data	Temperature data from the integrated subsystem temperature probes will supplement the faulty data

Figure 22: Payload FMEA Page 1

	Electronics	Supplemental temperature data lost	Electronics glitch	2	Thermal control failure	3	Software Validation	5	Supplement data	Thermocouple data will be exclusively used to determine the state of the lander
Communications Subsystem	Antenna	Antennas are damaged	Debris	1	Communications inefficiencies	2	Antenna can operate without deployment	5	Activate redundancy	Redundant channel activated
		Antennas fall off	Debris	1	Communications inefficiencies	2	Antenna can operate without deployment	5	Activate redundancy	Redundant channel activated, up to 3 antennas can fall off
		Antennas are obstructed	Failed Landing	4	Communications inefficiencies	2	Antenna can operate without deployment	5	Activate redundancy	Redundant channel activated
		Antennas are not instructed to deploy	Electronics glitch	1	Communications inefficiencies	2	Software Validation	5	Activate redundancy	Even without deploying, the antenna should be able to communicate at a decreased rate at the cost of extra power
		Antennas are instructed to deploy too early	Electronics glitch	1	Communications inefficiencies	2	Software Validation	5	Activate redundancy	The orbiter is designed to not be damaged by an early deploy of the antenna
Sample Collection Arm	Arm	Surface cannot be penetrated	Surface harder than expected	4	Cannot collect samples	4	Overengineer arm power	4	Scrape surface	Engage scraping function
		Motors not strong enough to lift samples	Arm collecting too large of a sample	3	Cannot collect samples	4	Overengineer arm power	4	Decrease forces on arm	Reduce sample size
		Arm cannot reach the surface	Failed Landing	4	Cannot collect samples	4	SLAM accurately lands the lander	4	Reorient to reach surface	Attempt to lower landing legs
		Arm becomes jammed	Motor failure	2	Cannot collect samples	4	Overengineer arm power	4	Reset	Attempt to reset arm
		Scraping not engaged	Electronics glitch	1	Cannot collect samples	4	Software Validation	5	Reset	Detect that no samples are getting to instruments and reset arm
		Arm never engaged	Electronics glitch	1	Cannot collect samples	4	Software Validation	5	Reset	Reset electronics subsystem
Power Subsystem	Battery	Battery overheats	Thermal control failure	3	Power efficiency decreased	4	Thermal simulations validate the thermal state of the lander	4	Decrease power consumption	Disable any non-essential subsystems and all instruments
		Battery overcools	Thermal control failure	3	Power efficiency decreased	4	Thermal simulations validate the thermal state of the lander	4	Increase power consumption	Engage the sample heater to heat battery
		Battery overpressurized	Overheating	3	Power efficiency decreased	4	Thermal simulations validate the thermal state of the lander	3	Decrease power consumption	Disable power to all systems except the electronics subsystem to prevent overcurrent
		Battery disconnects	Vibrations	4	Power Lost	5	Battery vibration tested before launcg	4	Nothing can be done	Mission failure
		Battery sends too much current	Overpressurization	3	Power efficiency decreased	4	Overcurrent protection implemented and tested before launch	4	Decrease power consumption	Redirect current
		Battery not delivering proper voltage	Overcooling	2	Power efficiency decreased	4	Thermal simulations validate the thermal state of the lander	4	Reset and adjust	Adjust transformers on the electronics subsystem
		Battery not holding charge during transfer	Overcooling	3	Power efficiency decreased	3	Thermal simulations validate the thermal state of the lander	3	Reset and adjust mission schedule	Adjust instrument usage and mission length to account for power changes

Figure 23: Payload FMEA Page 2

Infrared Camera	Camera	Camera overheats	Thermal control failure	2	Collecting innacurate data	3	Thermal simulations validate the thermal state of the lander	4	Shut down	Disable camera immediately to prevent overheating
		Camera is overpressurized	Overheating	2	Collecting innacurate data	3	Thermal simulations validate the thermal state of the lander	3	Shut down	Disable camera immediately until pressure is normal again
		Camera is sent too much voltage	Power subsystem failure	1	Camera fails	4	Power Subsystem tested and validated before launch	4	Shut down	Shut down
Mastcam-Z	Camera	Image processor fails	Electronics glitch	2	Camera fails	4	Software Validation	5	Supplement data	Attempt to use other cameras for processing
		Motors to rotate camera fail	Electronics glitch	2	Camera cannot collect as much data as expected	3	Software Validation	5	Reorient	Attempt to move lander
		Lens or Filter crack	Debris	2	Obstructutions in the images	3	Structure protects the lens	4	Supplement data	Take extra images and stitch together
		Image processing fails	Electronics glitch	1	Data lost	4	Software Validation	5	Data repair	Send raw data to earth and process manually
LIDAR	Laser	Intensity of Laser is Wrong	Electronics glitch	1	Altitude data inaccurate	5	Software Validation	5	Software adjustment	Attempt to account for laser intensity changes in software on the electronics subsystem
		Wavelength of Laser Changes	Electronics glitch	1	Altitude data inaccurate	5	Software Validation	5	Software adjustment	Attempt to account for laser intensity changes in software on the electronics subsystem
	Electronics	Failure to accurately process laser to distance	Electronics glitch	1	Altitude data inaccurate	5	Software Validation	5	Data repair	Send raw data to earth and process manually
Ptolemy	Electronics	Failure in the high-voltage converter	Power Subsystem error	1	Data collection failure	4	Software Validation	4	Reset	Reset the instrument
Sample Heater	Heater	Insufficient power	Power Subsystem error	3	Cannot heat samples or the lander	4	Power Subsystem tested and validated before launch	4	Smaller samples	Reduce sample size to allow for faster melting
	Motor	Motor cannot make a good connection between the heater and structure	Vibrations	4	Cannot heat the lander	4	Vibration testing before launch	3	Reset	Attempt to reset motor
	Heater	Heater becomes clogged with samples	Power Subsystem error	3	Cannot deliver samples to SELFI	3	Sample port properly sized for samples	4	Remove clog	Attempt to melt the clog out
		Too much power	Power Subsystem error	2	Overheating samples and the lander	4	Power Subsystem tested and validated before launch	4	Cool the heater	Insert excess samples to attempt to cool the heater

Figure 24: Payload FMEA Page 2

4.1.5.1 Thermal Subsystem Failure Modes

Various failure modes exist for the thermal subsystem and will be organized by hardware failures and software failures.

Hardware Failure Modes:

- AZ-93 chipped off of the structure
- Debris obstructs the AZ-93 coating, changing the emissivity and absorbance
- Thermocouples can produce bad data
- Thermocouples are displaced from their intended location
- Instrument cannot be disabled
- Sample heater insufficient to heat the lander
- Sample heater damaged and cannot activate

- Lander is overheating
- Lander is overcooling

Software Failure Modes:

- False overcooling threshold passed
- False overheating threshold passed
- Electronics subsystem processing data inaccurately
- Thermocouple data lost
- Supplemental temperature data lost

4.1.5.2 Communications Subsystem Failure Modes

Various failure modes exist for the communications subsystem and will be organized by hardware failures and software failures.

Hardware Failure Modes:

- Antennas are damaged
- Antennas fall off
- Antennas are obstructed

Software Failure Modes:

- Antennas are not instructed to deploy
- Antennas are instructed to deploy too early

4.1.5.3 Power Subsystem Failure Modes

Various failure modes exist for the communications subsystem and will consist exclusively of hardware failure modes due to the lack of software control exclusive to the subsystem.

Hardware Failure Modes:

- Battery overheats
- Battery overcools
- Battery overpressurized
- Battery disconnects
- Battery sends too much current
- Battery not delivering proper voltage
- Battery not holding charge during transfer

4.1.5.4 Infrared Camera Subsystem Failure Modes

There are potential failure modes with the infrared camera subsystem. It could possibly overheat in operation which would stop it from working properly, it could be overpressurized, or it could be sent too much voltage and the system would become fried.

4.1.5.5 Mastcam-Z Subsystem Failure Modes

Various failure modes exist for the Mastcam-Z subsystem and will be organized by hardware failures and software failures.

Hardware Failure Modes:

- Image processor fails
- Motors to rotate camera

- Lens crack
- Filters crack

Software Failure Modes:

- Image processing fails

4.1.5.6 LIDAR Subsystem Failure Modes

Various failure modes exist for the LIDAR subsystem and will be organized by hardware failures and software failures.

Hardware Failure Modes:

- Intensity of Laser is to high
- Wavelength of Laser changes

Software Failure Modes:

- Failure to accurately process laser to distance

4.1.5.7 Ptolemy Subsystem Failure Modes

There are potential failure modes with the Ptolemy subsystem.

- The a failure in the high-voltage converter

4.1.5.8 SELFI Subsystem Failure Modes

- SELFI can't analyze organic molecules due to different composition that weren't discovered with Cassini
- Navigational error due to incorrect commands
- Laser not able to detect target materials
- Atmospheric changes on Enceladus might disrupt the system

4.1.5.9 Sample Heater Subsystem Failure Modes

Various failure modes exist for the sample heater subsystem and will consist exclusively of hardware failure modes due to the lack of software control exclusive to the subsystem.

Hardware Failure Modes:

- Sample heater receiving insufficient power
- Motor cannot make a good connection between the heater and structure
- Heater becomes clogged with samples
- Sample heating receiving too much power

4.1.5.10 Sample Collection Arm Subsystem Failure Modes

Hardware Failure Modes:

- Surface cannot be penetrated
- Motors not strong enough to lift samples
- Arm cannot reach the surface
- Arm becomes jammed

Software Failure Modes:

- Scraping not engaged
- Arm never engaged

4.1.6. Performance Characteristics

4.1.6.1 Thermals

The thermal subsystem does not have any hardware which is not part of another subsystem other than the AZ-93 coating and the thermocouples. AZ-93 does not require any power or data to function properly as it is a passive thermal management measure. Thermocouples also do not require power to operate. This is due to the fact that thermocouples measure temperature by creating voltage between 2 different metals (Fenton, 1980). Since thermocouples create their own voltage, it thus has no external power requirements. The thermal subsystem is expected to keep the entire lander between -10 °C and 40 °C as all of the instruments and subsystems will be able to operate in this temperature range.

4.1.6.2 Communications

In order to perform adequately, the antenna array requires 5 W of power when in communication with the orbiter. It also requires an unobstructed view of the Enceladus sky. The communications subsystem will be able to communicate at a frequency between 435 - 438 MHz at a gain of less than 0 dBi at a circular polarization, with two redundant channels.

4.1.6.3 Power

The power subsystem must be stored at a temperature between -40°C and 40°C in order to prevent damage to the battery pack. The power subsystem will be able to store a maximum of 492 Wh of with a maximum continuous current of 250 amps at 4.1 volts. This allows for the estimated mission time to be about 36 hours after landing if instrument usage is strategic.

4.1.6.4 Infrared Camera

The THEMIS infrared camera will require about 14 Watt of power to operate. The subsystem has been verified to operate in a temperature range of 30°C to -30°C (Christensen, 2001). This subsystem will require an unobstructed view of the surface of Enceladus. The infrared camera is expected to obtain visible and infrared photographs for the mission to compare with previous ones. THEMIS has five visible bands, 0.425 microns, 0.540 microns, 0.654 microns, 0.749 microns, and 0.860 microns, an instantaneous internal rate of 6.2 Mbits/sec, and a data rate to spacecraft of <1.0 Mbits/sec for visible imaging. The visible imager has 2.66 degree cross-track by 2.64 degree down-track FOV with 0.045 18 m IFOV in 1024 x 1024 pixels at nadir. THEMIS has ten infrared bands,6.78 microns (used twice), 7.93 microns, 8.56 microns, 9.35 microns,10.21 microns, 11.04 microns, 11.79 microns, 12.57 microns, and 14.88 microns, an instantaneous internal rate of 1.17 Mbits/sec, and a data rate to spacecraft of 0.6 Mbits/sec for IR imaging. The IR imager will have 4.6 degree cross-track by 3.5 degree down-track FOV with a 100m IFOV at nadir and an IR focal range of 320x240 pixels covered by 10 −1-μm-bandwidth strip filters in nine different wavelengths. (Christensen, 2020).

4.1.6.5 Mastcam-Z

When in use, each of the dual cameras need 11.8 Watts of power in order to operate. When in standby, each of the dual cameras need 7.5 Watts of power (NASA, 2020). Mastcam-Z has been tested and verified to withstand temperatures up to -130° c for an extended period of time (Bell, et al. 2020).This will require an unobstructed view of the landing target and surface of Enceladus.

The Mastcam-Z is expected to capture 360° images, 3-dimensional images, and zoom capable videos. It has an image size of 1600 by 1200 pixels and 2 megapixel color quality.

4.1.6.6 LIDAR

The LIDAR subsystem is expected to utilize a diode-pumped, laser transmitter that emits 1.064 micrometer wavelength laser pulses, a 0.126 m diameter telescope, a silicon avalanche photodiode detector, and a time interval unit with 14 nsec resolution to acquire topography and distance measurements (NASA, 2020). The LIDAR subsystem is expected to emit a 1.064 micrometer wavelength laser pulses. By emitting this laser, LIDAR is expected to obtain a reliable shape model and accurate distance for landing within 8 cms.

4.1.6.7 Ptolemy

The Ptolemy subsystems require 10 Watts of power. The Ptolemy needs to be on the surface to drill to reach the samples needed (Todd, et al 2006). The Ptolemy subsystem is expected to collect data about the surface of Enceladus through analyzing samples of Enceladus's surface.

4.1.6.8 SELFI

SELFI can provide definitive identification for molecular species in a global context, even when observing through dust and/or ice, due to its resolving power >107. SELFI has high sensitivity and will be able to detect many trace molecular species which are biomarkers. The sensitivity of the instrument is expected to increase with an amplifier designed for a 557 GHz signal. This will improve the ability to measure small quantities of water and traces of other gases, even at the cold temperatures, and explore the whole system of surface vents on Enceladus

4.1.6.9 Sample Heater

The sample heater will require 50 watts from the power subsystem to operate. It also requires solid samples to be dispensed into the heating chamber. The sample heater is expected to melt surface samples within 30 seconds and then dispense the sample into Ptolemy. The heater will also be capable of varying its power consumption based on the heating needs of the lander.

4.1.6.10 Sample Collection Arm

At peak torque, the arm will require a maximum of 36 W but it is expected to use significantly less power during sample collection. The arm should be able to deliver 10 gram samples to the instruments up to 30 times before the lander runs out of power. The arm may also be able to be used to maneuver the lander in the event that the motors controlling the cameras on the lander fail; however, this is a last resort as this maneuver would likely damage the arm.

4.2. Science Value

4.2.1. Science Payload Objective

4.2.1.1 Payload Objective Overview

The payload of Ensomnia has its intrustruments broken up into two categories; optical analysis and sample analysis. The IR Camera, Mastcam-Z, and LIDAR fall into the optical category and the main objective of these instruments is to provide data about Enceladus on a macroscopic level via topological and thermal data. Ptolemy and SELFI are sampling instruments and the objective of these instruments is to provide data about Enceladus on a microscopic level via surface composition data. By collecting both macroscopic and microscopic data, a holistic model of Enceladus can be developed back on Earth to better understand the conditions on the surface of Enceladus.

4.2.1.2 Infrared Camera

The goal of this instrument is to take high-resolution infrared photographs of Enceladus to compare to previous mission images to determine how the surface of Enceladus has changed.

4.2.1.3 Mastcam-Z

The goal of this instrument is to take high-definition video, panoramic color and 3D images of the Enceladus surface and features in the atmosphere with a zoom lens to magnify distant targets.

4.2.1.4 LIDAR

The goal of this instrument is to use lasers to accurately measure distance for safe landing and obtain surface topography information.

4.2.1.5 Ptolemy

The goal of Ptolemy is to take samples from the planet's surface and analyze the stable isotope ratio measurements for light elements and identifying the sample gases.

4.2.1.7 SELFI

The goal of SELFI is to determine the chemical composition of Enceladus' interior ocean, the abundance of the chemicals found in the plumes, and detect even minute traces of water and gases coming from the surface of Enceladus. Furthermore, this instrument would indicate the potential for life on Enceladus as well as Europa.

4.2.2. Creativity/Originality and Significance

4.2.2.1 Payload Originality and Significance Overview

Ensomnia aims to repeat some experiments conducted by Cassini with more advanced instrumentation to compare against existing data while also employing new instruments to take new data. Mass spectrometry was conducted on the material ejected by the plumes by the Cassini mission so Ensomnia will conduct mass spectrometry on the compounds which have settled on the surface of Enceladus. Since the plume ejection would have come primarily from the subsurface ocean of Enceladus, the samples collected by Ensomnia may have a different composition which can be compared against. New instruments like SELFI and the Mastcam-Z are also used to gather unique data about the icy moon.

4.2.2.2 Infrared Camera

This instrument is a common mission instrument and has been used before in many different variations for multiple different missions. This data will be significant because it will demonstrate better quality images of Enceladus to enhance our understanding of how the surface of Enceladus is changing and the temperatures above and below the surface to determine whether life could survive on Enceladus.

4.2.2.3 Mastcam-Z

This instrument is slated to be used on the 2020 Mars mission putting Perseverance rover on the surface (Bell, 2020). This instrument is in final development stages and has yet to be used on the surface of any planetary body. This instrument has 360° camera and video capabilities with zoom to allow unseen images of Enceladus's surface and topography. This data will be significant because it will be new and better-quality images of the Enceladus. Much of Enceladus has not been explored and the scientific world would benefit from understanding the surface make up for what type of life could potentially reside there. To be successful, the instrument will need to capture accurate 3d images and high resolution video of the surface.

4.2.2.4 LIDAR

LIDAR was designed, built and tested at the Institute of Space and Astronautical Science (ISAS) in Sagamihara, Japan part of the Japan Aerospace Exploration Agency (NASA, 2020). The primary LIDAR objective was to determine the distance between the HAYABUSA spacecraft and Itokawa to ensure a safe touch and go sampling of the asteroid. The LIDAR helps to navigate the lander during descent and can help identify the macrostructure of the surface of the tiger stripes to estimate the age range of the surface. As no mission has ever landed on Enceladus, this instrument will assist in new and more accurate measurements that have yet to be taken on Enceladus. The data will be significant because it will act as an altimeter and provide distance information to assist with the landing. It will also allow the team to gain surface topography measurements to better understand the topography of Enceladus. To be successful, the laser must use a specific wavelength and process data to obtain accurate distance measurements.

4.2.2.5 Ptolemy

Ptolemy was aboard the Philae lander element of the Rosetta mission to comet 67P/Churyumov-Gerasimenko. The organic materials on Enceladus and the planet composition found from Ptolemy will later be compared to life and organic material from Earth, determining whether Enceladus holds life, or the potential for life (Todd, et al. 2006). The data will be significant because it will help identify whether life exists on Enceladus. The Ptolemy must be on the surface of the planet, and the SD2 must retrieve the surface samples; the samples must be delivered to the sample heater subsystem to be analyzed. The data will be significant because it will help identify whether life exists on Enceladus. The Ptolemy must be on the surface of the planet, and the SD2 must retrieve the surface samples; the samples must be delivered to the sample heater subsystem to be analyzed.

4.2.2.7 SELFI

SELFI is still in the works and it will be ready to add to the Enceladus mission, whenever the original mission proposal is approved. SELFI hasn't yet been tested on any planetary surface, so it will have to be initially tested on earth in several stages. The instrument is currently being designed at the Goddard Space Flight Center (GSFC) and if it is successfully developed and delivers the expected results, then it will eventually be part of a proposal for a future mission to Saturn as well (Glister, 2017). The deliverables will be significant because they will analyze the molecular structure inside Enceladus's plumes and surface composition to better understand the existence of life, if it exists. SELFI will also look for amino acids formation and how closely it relates to those found on Earth. To be successful, the instrument must use a high strength laser beam to break hard surface rocks or grains and collect samples with a low probability of getting them mixed.

4.2.3. Payload Success Criteria

4.2.3.1 Payload Success Criteria Overview

The payload will be considered to have had a successful mission if their scientific requirements are met to a standard such that scientists on Earth can extract meaningful analysis about the surface conditions of Enceladus.

4.2.3.2 Infrared Camera

In order for the IR camera to have successfully completed its scientific objectives, it will need to take at least fifty IR images during descent to the Surface and at least fifty IR images after landing. These images must be free of any artifacting or corrupted data and must be in focus.

4.2.3.3 Mastcam-Z

For Mastcam-Z to successfully complete its scientific objectives, it will need to map at least 400 square kilometers of the surface of Enceladus with a resolution of at least one hundred pixels per meter on the surface before landing. The data must be delivered to the electronics subsystem before landing such that the Simultaneous Localization and Mapping (SLAM) algorithm can determine a landing location. After landing, Mastcam-Z must map the surface within a fifty meter radius of the landing site with a resolution of ten thousand pixels per meter on the surface. This data must also be free of any corruption.

4.2.3.4 LIDAR

For the LIDAR to successfully complete its objective, it must provide the altitude of the lander to the electronics subsystem at least ten times per second with a maximum inaccuracy of plus or minus ten centimeters such that the SLAM algorithm can accurately guide the lander to a landing zone.

4.2.3.5 Ptolemy

For Ptolemy to successfully complete its mission, it must first accurately identify the compounds in the calibration sample within a margin of error of plus or minus 1% for each compound. Any calibration error will be mitigated by adjusting the entire dataset to match the calibration expectations. After landing, Ptolemy must analyze at least 30 surface samples.

4.2.3.7 SELFI

For SELFI to successfully complete its mission, it must first accurately identify the compounds in the calibration sample within a margin of error of plus or minus 1% for each compound. Any calibration error will be mitigated by adjusting the entire dataset to match the calibration expectations. After landing, SELFI must analyze at least 30 surface samples.

4.2.4. Experimental Logic, Approach, and Method of Investigation

The infrared camera achieves its deliverables by taking 2 dimensional, high resolution images. The Mastcam-Z achieves its deliverables by taking 3 dimensional images and high-resolution videos at rates of 4 fps or faster for subframes with zoom. The camera is able to resolve between about 150 microns per pixel (0.15 millimeter or 0.0059 inch) to 7.4 millimeters (0.3 inches) per pixel depending on distance (Bell, 2020). LIDAR achieves its deliverables by emitting a 1.064 micrometer wavelength laser pulses and the reflection is measured with a sensor to acquire distance and topography measurements (NASA, 2020). The Ptolemy achieves its deliverables by analyzing the surface and gas samples of Enceladus. The samples taken from the SD2 drilling system would be taken to the sample heater subsystem where the samples would be heated and the resultant gas purified, quantified and sent to the mass spectrometer (STFC, 2020). SELFI will have fine radiometric resolution, high spectral resolution, multiple continuum channels and a high dynamic range, required to map Enceladus across its 30 K to 250 K temperature range (Racette, et al. 2019).

4.2.5. Testing and Calibration Measurements

4.2.5.1 Infrared Camera Testing

The infrared camera can be calibrated on earth using different wavelengths and types of lights to test it. THEMIS instrument is radiometrically, spectrally, and spatially calibrated prior to delivery. The THEMIS images will be calibrated using periodic views of the internal calibration flag when closed, imaged, and reopened at selected intervals. This subsystem acquires calibration data every 3-5 minutes (NASA, 2020).

4.2.5.2 Mastcam-Z Testing

The Mastcam-Z can be calibrated on Earth with objects of known size. The dual cameras will photograph and take videos on objects on Earth to ensure proper image size and resolution. The Mastcam-Z has an incorporated calibration target that is 10x10x7 cm that provide a variety of colors, grey tones, and differing reflective surfaces to calibrate the instrument (NBI, 2020).

4.2.5.3 LIDAR Testing

The LIDAR system can also be tested on Earth. It will need to be calibrated to accurately calculate distance from items. The distances and sizes of boxes will need to be known and compared to what is calculated using the LIDAR system. Using complex algorithms, LIDAR systems can be calibrated by detecting the corners of the boxes in the point clouds even in low resolution situations (Pusztai & Hajder, 2017).

4.2.5.4 Ptolemy Testing

Ptolemy has been vibration tested and designed to withstand temperature variations from -55ºC to +70ºC during the flight to the planet (Todd, et al. 2006). These tests will be conducted again to validate the installation after it has been integrated into Ensomnia.

4.2.5.6 SELFI Testing

SELFI can be tested on earth to analyze the composition of chemicals and compounds that support life. Similar testing methods being designed for SELFI, would give a better idea of the formation and existence of life on the icy moon.

4.2.6. Precision of Instrumentation, Repeatability of Measurement, and Recovery System

4.2.6.1 Payload Precision and Repeatability Overview

The TRL of the THEMIS infrared camera is estimated to be a 9. Infrared cameras have been used on the Odyssey mission to Mars. The TRL of Mastcam-Z camera is estimated to be a 9. The original Mastcam was utilized on the Mars Curiosity Rover in November of 2011, and Mastcam-Z is currently on its way to Mars on the Perseverance rover. The TRL of LIDAR is estimated to be a 6. Similar methods have been used on other missions, like to Itokawa, but no mission has ever landed on Enceladus. The TRL of Ptolemy is estimated to be a 9 because it has been used on another mission, the Rosetta mission to comet 67P/Churyumov-Gerasimenko. The data from Ptolemy is said to be highly accurate (Wright, et al. 2015). Laboratory characterization and environmental testing will mature key instrument subsystems from TRL 4 to 6 for SELFI meaning that the prototype has not yet demonstrated the capability to perform all the functions required since it is still in development.

The TRL of the thermal subsystem is estimated to be at an 6. While very similar methods of thermal management have been used on similar missions, no missions have landed on Enceladus and the use of a sample heater as a thermal management tool has not been done in a real mission before. Since the selected communications subsystem has been tested on multiple cubesats and has been verified by NASA, NASA has established the TRL of this subsystem as a 9 (NASA Ames, 2018). The TRL of the sample collection system is expected to be a 6. Arms attached to landers and rovers are commonly used to deliver samples to instruments; however, this specific design has not been mission tested. Given that the selected battery packs have been used on missions to Mars, we estimate the TRL of the power subsystem to be at 8 since the batteries have not been used on a 6 year mission like the mission to Enceladus. Since resistive heaters are commonly used in satellites and heaters, that technology has an estimated TRL of 9; however, since using a sample heater as a heating element for the entire lander is a largely untested design, the estimated TRL of this technology is 4.

4.2.6.2 Recovery

4.2.6.2.1 Thermal Subsystem Safety Controls

Table 3: Thermal Safety Controls

Failure Mode	**Safety Control**
AZ-93 chipped off of the structure	Less instruments will be allowed to run at the same time to compensate for the decreased cooling capacity
Debris obstructs the AZ-93 coating, changing the emissivity and absorbance	Less instruments will be allowed to run at the same time to compensate for the decreased cooling capacity
Thermocouples produce bad data	Temperature data from the integrated subsystem temperature probes will supplement the faulty data
Thermocouples are displaced from their intended location	Temperature data from the integrated subsystem temperature probes will supplement the faulty data
Instrument cannot be disabled	Adjacent instruments and inessential subsystems will be disabled
Sample heater insufficient to heat the lander	Additional instruments will be enabled to produce extra heat
Sample heater damaged and cannot activate	Additional instruments will be enabled to produce extra heat
Lander is overheating	High power instruments will be disabled
Lander is overcooling	Sample heater will be enabled
False overcooling threshold passed	Supplemental temperature data will instruct the sample heater to shut down
False overheating threshold passed	Instruments will be restarted
Electronics subsystem processing data inaccurately	Assume nominal

Thermocouple data lost	Temperature data from the integrated subsystem temperature probes will supplement the faulty data
Supplemental temperature data lost	Thermocouple data will be exclusively used to determine the state of the lander

4.2.6.2.2 Communications Subsystem Safety Controls

Table 4: Communications Safety Controls

Failure Mode	**Safety Control**
Antennas are damaged	Redundant channel activated
Antennas fall off	Redundant channel activated, up to 3 antennas can fall off
Antennas are obstructed	Redundant channel activated
Antennas are not instructed to deploy	Even without deploying, the antenna should be able to communicate at a decreased rate at the cost of extra power
Antennas are instructed to deploy too early	The orbiter is designed to not be damaged by an early deploy of the antenna

4.2.6.2.3 Sample Collection Subsystem Safety Controls

Table 5: Sample Collection Safety Controls

Failure Mode	**Safety Control**
Surface cannot be penetrated	Engage scraping function
Motors not strong enough to lift samples	Reduce sample size
Arm cannot reach the surface	Attempt to lower landing legs
Arm becomes jammed	Attempt to reset arm
Scraping not engaged	Detect that no samples are getting to instruments and reset arm
Arm never engaged	Reset electronics subsystem

4.2.6.2.4 Power Subsystem Safety Controls

Table 6: Power Safety Controls

Failure Mode	Safety Control
Battery overheats	Disable any non-essential subsystems and all instruments
Battery overcools	Engage the sample heater to warm the battery
Battery overpressurized	Disable power to all systems except the electronics subsystem to prevent overcurrent
Battery disconnects	Mission failure
Battery sends too much current	Redirect current
Battery not delivering proper voltage	Adjust transformers on the electronics subsystem
Battery not holding charge during transfer	Adjust instrument usage and mission length to account for power changes

4.1.6.2.5 Infrared Camera Subsystem Safety Controls

Table 7: Infrared Camera Safety Controls

Failure Mode	Safety Control
Camera overheats	Disable camera immediately to prevent overheating
Camera is overpressurized	Disable camera immediately until pressure is normal again
Camera is sent too much voltage	System may be fried, in which case it will be shut down immediately.

4.1.6.2.6 Mastcam-Z Subsystem Safety Controls

Table 8: Mastcam-Z Safety Controls

Failure Mode	Safety Control
Image processor fails	Attempt to use other cameras for processing
Motors to rotate camera fail	Physically move lander
Lens or Filter crack	Take extra images and stitch together
Image processing fails	Send raw data to earth and process manually

4.1.6.2.7 LIDAR Subsystem Safety Controls

Table 9: LIDAR Safety Controls

Failure Mode	Safety Control
Intensity of Laser is Wrong	Attempt to account for laser intensity changes in software on the electronics subsystem
Wavelength of Laser Changes	Attempt to account for laser wavelength changes in software on the electronics subsystem
Failure to accurately process laser to distance	Send raw data to earth and process manually

4.1.6.2.8 Ptolemy Subsystem Safety Controls

Table 10: Ptolemy Camera Safety Controls

Failure Mode	Safety Mode
Failure in the high-voltage converter	limited the flight model’s mass range

4.1.6.2.9 Sample Heater Subsystem Safety Controls

Table 11: Sample Heater Safety Controls

Failure Mode	**Safety Control**
Sample heater receiving insufficient power	Reduce sample size to allow for faster melting
Motor cannot make a good connection between the heater and structure	Attempt to reset motor
Heater becomes clogged with samples	Attempt to melt the clog out
Sample heating receiving too much power	Insert excess samples to attempt to cool the heater

4.2.7. Expected Data & Analysis

4.2.7.1 Infrared Camera Expectations

The infrared camera is expected to produce digital images that are easily observable to indicate the data collected by the camera. The camera will take visible and infrared images in the day and night time to best gather thermal and geological data. The instrument uses a multi-spectral approach which is unique and will allow for data on localized deposits to be associated with hydrothermal and subsurface water therefore enabling 100-meter images of terrain to be captured in each pixel of every image.

4.2.7.2 Mastcam-Z Expectations

The Mastcam-Z instrument system is expected to take 360-degree images, 3-dimensional images, and zoom capable videos. The Mastcam-Z will assist in the characterization of Enceladus's overall landscape, geology, and topography of the surface at the landing site. The instrument will also provide operational support of mission landing, sample extraction, and comparisons to previous Enceladus images.

4.2.7.3 LIDAR Expectations

The LIDAR is expected to provide topographical measurements regarding the surface of Enceladus to better understand the surface structure and geography. The LIDAR is also expected to provide distances of the lander from the surface of Enceladus to provide assistance in lander landing.

4.2.7.4 Ptolemy Expectations

The Ptolemy is expected to measure the isotopes ratios of hydrogen, carbon, nitrogen, and oxygen; the ratios act as a “fingerprint” and help identify where the water on Enceladus originated from. The Ptolemy will yield the degrees of isotopic fractionation that have occurred, which will also help determine from where the organic elements came from and the temperatures at which the samples were formed (STFC, 2020**).**

Table 1. MAVEN Deep Dip Ephemeris

Deep Dip	Orbits	Latitude	SZA[a] (°)	LTM[b] (hr)	L_s (°)	EUV irradiance[c] (W·m^{-2}·nm^{-1})	T_{iso}[d] (K)
1	714–747	42.6°N	109.1	18.3	291.1	1.95×10^{-3}	232 ± 10
2	1059–1086	3.8°S	9.3	11.9	328.6	1.67×10^{-3}	260 ± 7
3	1501–1538	62.6°S	110.4	3.5	11.4	1.31×10^{-3}	129 ± 7
4	1802–1838	63.9°S	91.1	16.0	37.5	1.21×10^{-3}	220 ± 7
5	3285–3327	33.2°N	96.5	5.2	166.9	1.23×10^{-3}	135 ± 8
6	3551–3586	2.9°S	166.4	0.7	194.1	1.18×10^{-3}	127 ± 7
7	5574–5620	63.6°N	87.0	20.3	49.4	8.93×10^{-4}	173 ± 5
8	5909–5950	18.9°N	25.0	13.7	76.3	8.60×10^{-4}	194 ± 8

Note. Values are means at periapsis over each Deep Dip unless otherwise noted. EUV = extreme ultraviolet. FISM-M = Flare Irradiance Spectral Model-Mars.

[a] Solar zenith angle.

[b] Local time.

[c] Mean daily spectral irradiance at Mars for wavelengths ≤ 90 nm from FISM-M.

[d] Mean temperature in the isothermal region between CO_2 densities of 10^7 and 10^9 cm^{-3} with associated 1 σ variability.

Figure 25: Sample Ptolemy Data

4.2.7.6 SELFI Expectations

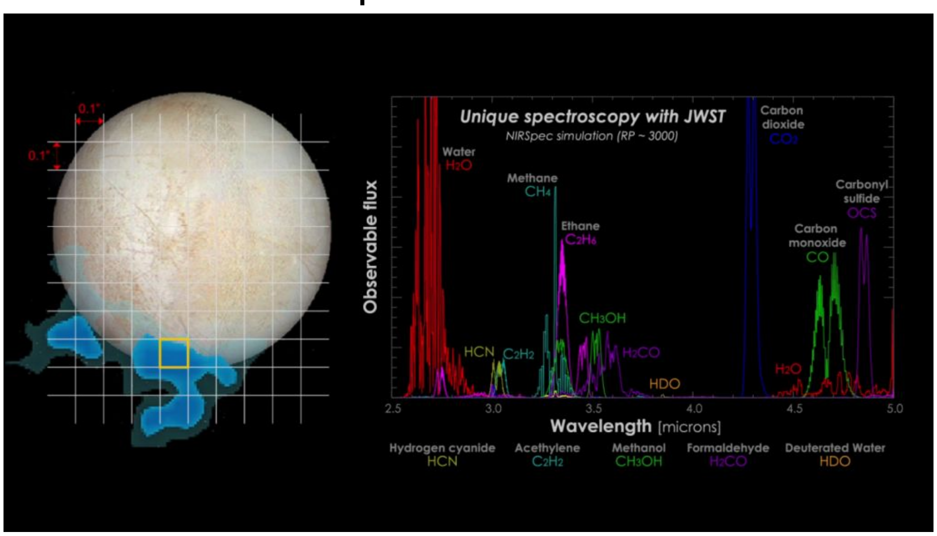

Figure 26: Expected SELFI Data

The above diagram depicts possible results from one of Enceladus's plumes. Increasing SELFI's sensitivity using an amplifier will boost the signal and will allow the instrument to detect even minute traces of water and gases coming from its surface. Other improvements in the design include a more energy-efficient and flexible radio frequency data-processing system, as well as a sophisticated digital spectrometer for the RF signal. This latter improvement will employ high-speed programmable circuitry to convert RF data into digital signals that can be analyzed to measure gas quantities, temperatures, and velocities from Enceladus' plumes. These enhancements will allow SELFI to simultaneously detect and analyze 13 different types of molecules, which include various isotopes of water, methanol, ammonia, ozone, hydrogen peroxide, sulfur dioxide, and sodium chloride (Williams, 2017).

Section 5: Safety

5.1. Personnel Safety

5.1.1. Safety Officer

Zoe Fang will be the safety officer for Team Latitude, and through the help of the entire team and extensive research on risk management, Section 5 will detail the safety considerations that Team Latitude propose for this mission. Zoe Fang will also assist in the process of risk management in other sections of the mission, such as keeping track of the risks and evaluating them throughout the design process using the risk analysis grid as well as a living document for the detail of each individual risk, including technical, safety, schedule and budget risks.

For safety research, the team was prompted to brianstorm potential safety concerns regarding the environment as well as the personnel safety. Using data sheets and sample operating manuals, the safety officer and the team prepared mitigation plans in response to the identified hazards, which will be discussed in the following sections. The team is also proposing for a Non-Advocate Review(NAR) to thoroughly evaluate and analyze the lander manufacturing processes, testing procedures, as well as the team's analysis on the operating environment of Ensomnia; through a NAR, any overlooked risks due to internal biases or familiarity should be identified, and the risk of exposing the personnel to unknown hazards is decreased. The safety officer conducted more research into risk management, especially using the NASA Risk Management Handbook. From there, the team will also monitor the status of each risk and the team will continue to revise the mitigation plan proposed below.

5.1.2. Personnel Hazards

Manufacturing Hazards

Manufacturing hazards are caused when heavy equipment is mishandled. For the production of the main structure, Computer Numerical Control machines (CNC) are specified for use. This will reduce some of the direct exposure of sharp cutting edges or any other manual tools; however, the use of CNC machines has its own hazards. For example the use of lathes or mills involve high speed operating blades or mill tips, which should anything like hair or strings get caught in the machine, that poses life threatening danger to the operator (Dunbar & Litkenhous, 2019).

Falls

Falls are caused by either slippery, unstable, or uneven walking surfaces.

Electrical Hazards

Electrical hazard includes exposed wiring, improper wiring, lack of signage for high voltage or high current, overheating of components due to excess current, etc.

COVID-19 Pandemic and Immune System Health

COVID-19 is a respiratory illness in humans caused by the coronavirus. There is currently a global pandemic, in 2020, and produces symptoms that can be severe and, in extreme cases, lead to death. Symptoms include, but are not limited to, fever, cough, shortness of breath, sore throat, and fatigue.

Welding Fires

Caused by sparks, hot slag (droplets of liquid metal), and torch flames, welding can be a source of hazard for the personnel using the equipment. Additional risks include igniting flammable vapors in the air and combustible materials touching a hot workpiece (Bell, 2004).

Battery Hazards

Thermal runaway or battery fires are commonly caused by extreme abusive conditions that may be the result of the faulty operation or catastrophic failure during both manufacturing and the mission. Abusive conditions typically fall under three categories, overheating, overpressurizing, and puncture. Failure of the battery is characterized by the release of toxic gases, jets of flames, and explosion (Sun, et al. 2020).

Propulsion Testing

Propulsion testing is entirely dangerous on its own. Most tests are experimental, so at any moment the test could fail and create new hazards. The fuel chosen for Ensomnia is 1,1-Dimethylhydrazine, a colorless liquid with a distinct smell, similar to ammonia; it is flammable with an acute toxicity through oral contact, dermal contact, or inhalation. It will also cause skin and eye irritation or corrosion. It is also a category 1B carcinogen. Handling this propellant is a hazard to the personnel as well as the environment (CDN, 2015). The oxidizer chosen is Dinitrogen tetroxide, or Nitrogen dioxide, which is considered hazardous by the OSHA standards. It poses similar danger as 1,1-Dimethylhydrazine, which includes corrosion/irritation through eye and skin contact and inhalation. It is also stored under high pressure, so handling the container is another hazard. This gas will also displace oxygen and cause suffocation when mishandled. It can also cause frostbite when coming in contact (Airgas, 2018). In general, storing the propellant and the oxidizer on site could also incur accident leak or spill, which could cause flame/fire/explosion when both substances leak in proximity.

Lander Testing

Landing malfunction can be caused by inaccuracy in the automatic landing system. The risks include erroneous landing on unsafe locations that are unknown and hard-landing, negatively affecting devices and causes consecutive malfunctions in other systems. In the occasion that the lander malfunctions during testing, a few hazards could threaten the personnel. Should the structure testing malfunctions, pieces of the structure could come loose even break from the main frame, which will drop or break from the frame at high speed, injuring personnel on site. To test the structure, strain and stress, burn and vibration, and temperature tests are required to validate the structure. During burn and vibration testing, dust and debris could appear due to fractures or pieces coming loose should the structure fail unexpectedly. As the team is responsible for this safety analysis, there could be overlooked risks and hazards due to the team's familiarity of the project; these are particularly dangerous because without pre-determined mitigation, the personnel would be exposed to unknown hazards and left with little knowledge to react in time, which could develop into larger crises.

Dust and Debris

Dust and debris can be a respiratory hazard and a fire hazard in the workplace. Due to the use of CNC machines and potentially other manual tools, metal shaving can pose danger for its sharp edges which can cause cutting and should it be inhaled it would cause respiratory conditions (Tuffwrap, 2020).

5.1.3. Hazard Mitigation

Manufacturing Hazards

To prevent these hazards, it is best to reduce the mass of equipment travelling, creating risk coverage, and creating alternate capabilities that the mission requires. These hazards can also be reduced through extensive training and the requirement of wearing PPE. THis would require administrative structure and safety procedures to put in place before the manufacturing process begins. It is also important to give restricted access to the manufacturing site and specific machines. Individual machines should have their one safety standard of Procedures (SOPs) and only personnels who are cleared with the specific SOP can operate certain machines (Dunbar & Litkenhous, 2019).

Falls

Falls can be mitigated by mandating the use of proper footwear which provides good support to the wearer while working on site. Regular maintenance and cleaning of working surfaces will also be employed to ensure that all floors are in good condition. Railings will also be installed in any area with either changing elevation or with overhangs.

Electrical Hazards

Electrical Hazards can be mitigated through a series of safety procedures and supervised operation procedures. All electrical components must be inspected and well labeled. All components with dangerous electrical components must be well labeled and a kill switch must be in place. A “lock out tag out” procedure should also be in place so that other personnel who are not familiar with certain electrical components will be protected through the procedures.

COVID-19 Pandemic -and health related

COVID-19 is highly contagious, and if team members present symptoms, they should not attend work. Employees working on site must wear an approved facemask at all times and are encouraged to minimize physical contact and follow social distancing guidelines where possible. Proper PPE like face masks and latex gloves will be provided by Latitude. Any employee that tests positive for COVID-19 will be tested weekly and will be provided PTO for all the time where they had the virus plus 2 weeks of recovery after testing negative. Workers should be limited to essential travel with wellness surveys to ensure safety. If a positive test occurs within the team, all those exposed and positive should quarantine for 14 days.

Welding Fires

There are ways to mitigate these risks with equipment typically used complementary to the welding gun. Protective equipment like a welding helmet, gloves, and non flammable clothes are to be used to protect the personnel responsible for welding. However, this does not completely mitigate the risks involved. Sparks can travel as far as 35 feet so any potential flammable material or vapors needs to be separated from the welding site. Keeping the welding site in a separated room would suffice. No flammable materials or vapors are permitted inside of the welding site. To prevent hot slag from dripping onto the workers, the welding surface needs to be elevated at an angle to drip down into a collection bowl. Additionally, personnel shall have knowledgeable experience on welding to prevent hazardous scenarios (Bell, 2004).

Battery Hazards

The risk of battery failure can be mitigated by storing batteries in cool, dry places, and out of direct sunlight. Batteries will also be stored in a closed, hardshell container such that the risk of puncture is low. Any battery tests will be conducted without personnel in the area and with the safety officer at the ready to control any potential fires.

Propulsion Testing

A plan needs to be put into effect to prevent these risks associated during testing. A designated area needs to be cleared during the testing so if the test were to fail, the personnel is out of range of the explosion far from danger. Additionally, a kill switch will be integrated into the test system to immediately stop the test for any reason to prevent a catastrophe. As indicated earlier, the propellant chosen, 1,1-Dimethylhydrazine, is extremely hazardous when handling; to mitigate any potential danger related to this material, all personnel who might come in contact will require PPE and thorough training to be aware of the potential danger. The temperature also needs to be monitored and controlled to below the flash point, which is 5 °F or - 15 °C (CDN, 2015). When handling the oxidizer, procedures, training, and safety precautions such as PPE similar to that of fuel handling apply. The flash point for Nitrogen dioxide is 125°F or 52 °C, which is the maximum temperature allowed for the container (Airgas, 2018). When storing propellant and oxidizer, there needs to be a detailed standard operation procedure (SOP), which all personnel working on propulsion testing should have a deep understanding of the document. The testing facility also needs to install explosion proof ventilation. The facility manager and the local fire-department should be notified when the material is delivered and being handled. In the same space where the material is being tested/handled, eye wash and emergency shower also needs to be installed and tested. Because of its reactivity and flammable nature, the surrounding is prohibited for any spark, open flames or ignition sources. All personnel on site should also be aware of the procedure to react to a potential leak or spill. Should any emergency occur, local authorities, the fire department, and medical care should be notified immediately.

Lander Testing

Depending on the circumstances, obstacles blocking the vision of the camera used for determining the safe zone will affect the computation. The way to reduce such risks is to implement subsequent algorithms to improve precision. Using additional instruments such as odometry will increase the accuracy of identifying the safest landing zones. To mitigate unknown or potentially overlooked hazards, a Non-Advocate Review should be in place before the testing. This will expose any danger posed to personnel as well as the environment, preparing the team to generate a more comprehensive mitigation procedure specific to the lander testing. Another method to avoid complex hazards, separated testings of each system and components are encouraged before the integrated testing. This way, any hazards specific to a system can be mitigated so that less hazards will accumulate exponentially, which could cause complex hazards that are more difficult to mitigate and react to on site.

Dust and Debris

Ways to reduce this hazard include regular cleaning, such as dusting and vacuuming, as well as air purifying and continuous air flow systems to blow the dust out of the way of the workspace, such as proper ventilation systems, which should comply with the need of each manufacturing machine or process. Hazards associated with debris can also be reduced by having a proper storage location for parts out of the way of the workspace, so that workers are prevented from tripping and falling over the debris. To assist with the hazard of flammability, there should be fire extinguishers located throughout the workplace, as well as smoke detectors and sprinklers to quickly put out any fires caused to prevent further damage (OSHA, 2005).

5.2. Lander/Payload Safety

5.2.1. Environmental Hazards

The south pole of Enceladus, also known as the Tiger Stripe Region, is characterized by 4 four subparallel, linear depressions. These are most likely tectonic fractures in the surface. The Tiger Stripes consist of large water jets or plumes of water, ice, and vapors. No impact craters have been found on or near the tiger stripes due to the, relatively, young age of the surface. Overall, Enceladus is considered to be covered in fine grained water ice, but the ridges surrounding the tiger stripes are covered in a coarse grained, crystalline water ice of higher density compared to other regions on Enceladus. Considering the required conditions for the formation of these crystalline water ice, which is relatively higher temperature compared to that of the surface (-330 °F or -201 °C) (NASA, 2019), likely caused by geological activities that also caused the cracks , flash freezing, rapid condensation, or irradiation of high energy particles , these water ice could have higher density compared to other amorphous crystalline ice (Newman, 2006). The high density of the water ice could imply larger forces should theses water ice fall on the lander, which could cause certain degrees of damage to the casing of the lander. As the ice layer on Enceladus is about 19 to 25 miles, or 30 to 40 kilometers thick, should the plumes or geysers start spewing in proximity to the lander, large pieces of the water ice could break from the surface layer and potentially land on Ensomnia; however, consider that the gravitational force is extremely low compared to that of the Earth (NASA, 2019), should any considerably large ice pieces been shot up into the sky, the acceleration of the pieces would be low, implying a low force apply to the casing of Ensomnia when the pieces land on Ensomnia.

Because of the earlier mentioned low surface and temperature, Ensomnia is also exposed to hazards such as freezing; this would pose significant risk to the mission because all systems require an operating condition that is higher than the surface temperature, especially the electronics on board.

Below the surface are large oceans of water. This has been best detected at the north and south poles of Enceladus where the ice is the thinnest. This must be taken into consideration when landing because the thickness, friction, and temperature of the surface can have a large impact on the lander. There is potentially a slope between the tiger stripes and normal surface of Enceladus which should be avoided when landing considering the surface could have low friction. Since the lander plans to settle near the tiger stripe named Baghdad, the fallen matter coming from the plumes could impact landing, but must be conscious of potential contamination.

5.2.2. Hazard Mitigation

To mitigate the hazard of high density water ice falling on the lander, the team considered this factor into the testing and validation plan for the structure of the lander. Because of the low gravity of Enceladus, the team determined that the risk of a piece of water ice crushing the lander and incapacitating the lander is low.

The lander will operate on a state-trigger model of hazard mitigation. Due to the large distance between the lander and ground control as well as the extended periods of time where communication with the lander is impossible as the sun blocks any communication, hazard mitigation will primarily autonomously. The state-trigger model creates 4 states that subsystems can be in during the mission; nominal, hazardous, failed, and recovered. The states of each subsystem are determined by the lander’s computer based on the data being recorded by instruments like pressure sensors, thermocouples, cameras, antennas, and strain gages. Should a disruption cause a subsystem to transition from nominal to hazardous, the computer will identify the disruption and trigger a predetermined set of safety controls to mitigate the hazard.

For example, should a thermocouple report data indicating that the lander is overheating or freezing due to the extremely low temperature on the surface, the onboard computer will identify that the lander is in a hazardous thermal state and reduce the power consumption to cool the lander or generate more power to heat up the components, especially the electronics. Given that communication to enceladus takes anywhere from 60 to 90 minutes, a thermal issue would likely kill the lander before ground control even identified the issue so this automated system is essential to mitigate any environmental risk.

Section 6: Activity Plan

6.1. Budget

Cost Breakdown

The following costs are approximate numbers and not fixed costs. These costs are the minimum amount required for the instrument to operate, however, the actual/final cost might differ, therefore, there will be some margin and a total budget that will be less than the allotted amount.

	# People on Team	FTE Year 1	FTE Year 2	FTE Year 3	FTE Year 4		
Science Team:	3	1	1	1	1		
Engineering Team:	3	1	1	1	1		
Administrative Team:	2	1	1	1	1		

Year	Yr 1 Total	Yr 2 Total	Yr 3 Total	Yr 4 Total			Cumulative Total
PERSONNEL							
Science Team	$ 240,000.00	$ 246,000.00	$ 252,000.00	$ 264,000.00	$ -	$ -	$ 1,002,000.00
Engineering Team	$ 240,000.00	$ 246,000.00	$ 252,000.00	$ 264,000.00	$ -	$ -	$ 1,002,000.00
Administrative Team	$ 160,000.00	$ 164,000.00	$ 168,000.00	$ 176,000.00	$ -	$ -	$ 668,000.00
Total Salaries	$ 640,000.00	$ 656,000.00	$ 672,000.00	$ 704,000.00	$ -	$ -	$ 2,672,000.00
Total ERE	$ 178,624.00	$ 183,089.60	$ 187,555.20	$ 196,486.40	$ -	$ -	$ 745,755.20
TOTAL PERSONNEL	$ 818,624.00	$ 839,089.60	$ 859,555.20	$ 900,486.40	$ -	$ -	$ 3,417,755.20
TRAVEL							
Total Flights Cost	$ 800.00	$ 1,075.00	$ 1,075.00	$ 1,075.00		$ -	$ 4,025.00
Total Hotel Cost	$ 850.00	$ 800.00	$ 800.00	$ 800.00	$ -	$ -	$ 3,250.00
Total Transportation Cost	$ 320.00	$ 320.00	$ 320.00	$ 320.00	$ -	$ -	$ 1,280.00
Total Per Diem Cost	$ 150.00	$ 150.00	$ 151.00	$ 151.50		$ -	$ 602.50
Total Travel Costs	$ 2,120.00	$ 2,345.00	$ 2,346.00	$ 2,346.50	$ -	$ -	$ 9,157.50
OTHER DIRECT COSTS							
Total Outsourced Manufacturing Cos	$ -	$ -	$ -	$ -	$ -	$ -	$ -
|> Science Instrumentation	$ 2,526,583.00	$ 3,783,092.00	$ 5,019,283.00	$ 6,777,377.00	$ -	$ -	$ 18,106,335.00
|> Other COTS Components	$ -	$ -	$ -	$200,000,000.00	$ -	$ -	$200,000,000.00
Total In-House Manufacturing Cost	$ -	$ -	$ -	$ -	$ -	$ -	$ -
|> Materials and Supplies	$ -	$ -	$ -	$ 8,557.00	$ -	$ -	$ 8,557.00
Total Equipment Cost	$ -	$ -	$ -	$ -	$ -	$ -	$ -
|> Manufacturing Facility Cost	$ 60,000.00	$ 60,000.00	$ 60,000.00	$ 60,000.00	$ -	$ -	$ 240,000.00
|> Test Facility Cost	$ -	$ -	$ -	$ -	$ -	$ -	$ -
In-House Manufacturing Margin	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Direct Costs	$ 3,407,327.00	$ 4,684,526.60	$ 5,941,184.20	$207,748,766.90	$ -	$ -	#NAME?
Total MTDC	$ 3,407,327.00	$ 4,684,526.60	$ 5,941,184.20	$207,748,766.90	$ -	$ -	#NAME?
FINAL COST CALCULATIONS							
Total F&A	$ 340,732.70	$ 468,452.66	$ 594,118.42	$ 20,774,876.69	$ -	$ -	$ 22,178,180.47
Total Projected Cost	$ 3,748,059.70	$ 5,152,979.26	$ 6,535,302.62	$228,523,643.59	$ -	$ -	$243,959,985.17
Total Cost Margin	$ 1,124,417.91	$ 1,545,893.78	$ 1,960,590.79	$ 68,557,093.08	$ -	$ -	$ 73,187,995.55
Total Project Cost	$ 4,872,477.61	$ 6,698,873.04	$ 8,495,893.41	$297,080,736.67	$ -	$ -	##########

Figure 27: Budget

Themis

Chameleon Imager: The Chameleon is a compact CubeSat imager that provides:

- High resolution Multispectral or Hyperspectral linescan imaging or
- High frame rate RGB Bayer-pattern imaging
- Large integrated high-speed data storage
- Compact form factor that is optimised for integration with 3U or larger CubeSat frames

The Chameleon imager takes advantage of the space-qualified electronics of the Gecko imager and combines this with high-performance optics to maximize imaging capability in small form factor CubeSats. High capacity, high-performance mass storage is integrated into the compact design. The opto-mechanics have been optimized to fit within the available volume of CubeSat deployers thus providing maximum volume to accommodate the functionality required for the mission. Images are captured directly to the integrated mass storage. No need for additional payload data storage capacity on the satellite. Data can be streamed directly to a transmitter or to an onboard computer as required. Reliable operation is achieved by using a combination of proprietary hardware and ruggedized optics. This instrument would be crucial in determining and analyzing Enceladus's core surface and its atmosphere.

IR Camera Cost: €144,000 = $171,540 (CSS, 2020)

Integration Cost: $20,000 (SAC, 2020)

Visible Imager: $13,999 (Fluke, 2020)

Mastcam-Z

Mastcam-Z consists of an identical pair of zoom-lens cameras that provide images in broad-band Bayer red/green/blue (RGB), 11 unique narrow-band visible/near-infrared colors, and 4-color direct solar imaging, with fields of view (FOV) from ~5° to ~15°. The cameras will have the ability to resolve (across 4-5 pixels) features ~1 mm in size in the near field and ~3-4 cm in size at 100 m distance. Each Mastcam-Z camera consists of newly designed (compared to MSL) optics and associated focus, ~3:1 zoom, and 8-position filter wheel mechanisms, a CCD detector assembly that is identical to that used on MSL/Mastcam, and digital electronics cards (one per camera) and firmware that are nearly identical to those used on MSL. A newly-designed external passive color/grayscale calibration target, based on the MSL/Mastcam cal target design but enhanced based on lessons learned, will be mounted on the rover deck at a similar place as the MSL target. The two Mastcam-Z cameras will be separated by ~24.5 cm and mounted on the Mars 2020 rover's Remote Sensing Mast (RSM), which sits approximately 2 meters above the local surface.

Cost: $30,796 **Software and Integration Cost**: $30,000 (OPT, 2020)

LIDAR

A light detection and ranging sensor that uses a laser (light amplification by stimulated emission of radiation) radar to transmit a light pulse and a receiver with sensitive detectors to measure the back scattered or reflected light. Distance to the object is determined by recording the time between transmitted and backscattered pulses and by using the speed of light to calculate the distance traveled.

Cost: $2,000,000 suite of technologies (McCormick, 1994) (OPT, 2020) (Goddard, 2011)

Ptolemy

The cost has been adjusted because Ptolemy will perform various functions and provide chemical and isotopic data for a number of extant species, for atomic masses 10 Da to 140 Da, including the D/H, 13C/12C, 15N/14N and 18O/16O ratios, present in volatile and refractory materials of the surface.

Cost: Approximately $200,000 (BostonInd. 2020)

SELFI

Selfi is the main instrument that will be used in the mission to detect traces of life and analyze Enceladus's surface for organic minerals and study the composition of geysers spewing water vapor and icy particles from the south pole of Saturn's small moon.

Cost Breakdown:

- Phase A/B 2.0M
- Phase C/D 4.7M
- A-D Reserves 20% 1.2M
- NASA TOTAL A-D 6.9M
- Phase E 5.4M
- E Reserves 10% 0.5M
- **TOTAL** = $13.8M

The $13.8M is an estimated cost and the minimum required amount in order to build and test SELFI. Since SELFI is still a new instrument, most of the costs will be allocated towards the research and development and testing phase. The instruments equipped in SELFI will also be more advanced than previous missions and a maximum cost of $15M could very likely be the final approximate for the successful introduction of SELFI for the Enceladus Life Finder mission as well as missions that will be launched in the near future.

Robotic Arm

Cost: Approximately $60,000 with some adjustments (Shopcross, 2020)

Batteries

Cost: ~$2,000 (Chen, et al. 2018)

Thermocouples

Cost: $1,048 (Omega, 2020)

Comms

Cost: $4,000 - $6,000 (EnduroSat, 2020)

Power

Cost: $20,000 (Eaglepicher, 2019)

Project Management: $0.5M

Outreach: $3ML

Experiments:

- 2021: 20M
- 2022: 14M
- 2023: 15M
- 2024: 17M

Ground Operations:

- 2021: 10M
- 2022: 12M
- 2023: 13.5M
- 2024: 16M

Launch Vehicle: $170M - $230M (ULA, 2020)

Employees will be working around 40 hours per week in the first year with a minimum salary of $80,000 (base compensation without benefits included). The total base salary and hours will increase starting in year 2 and will keep increasing by a small percentage as roles change from lower level to senior managerial positions. Benefits will account for 28% of the employee salaries, years 1-4.

A salary of $80,000 per year would yield an hourly rate of around $38.46. The total salary with the ERE benefits added on comes out to be $102,400. The benefits/salary are subject to income tax withholding and employment taxes as well.

Cost of travel for annual meetings and other expenses are detailed as follows:

A return ticket from Indiana to Cape Canaveral would cost about:

12/21/2020 - 12/23/2020

Year 1: $115*3 = $345 (JFK to Orlando Melbourne International Airport)
$185 = (Dulles International Airport to Orlando Melbourne International Airport)
$150*3 = $450 (Indianapolis International Airport to Orlando Melbourne International Airport)

Travel cost from airport to Cape Canaveral: $320. It will cost $160 to travel from the airport to Kennedy Center in two separate rides and then another $160 to return to the airport on the last day.

Hotel Stay: 2 nights

$850 for 8 adults staying 2 nights**.**

Year 2: $120*3 = $360 (JFK to Orlando Melbourne International Airport)
$190 = (Dulles International Airport to Orlando Melbourne International Airport)
$175*3 = $525 (Indianapolis International Airport to Orlando Melbourne International Airport)

Hotel Stay: 2 nights

$800 for 8 adults staying 2 nights**;** Booking the hotel in advance would reduce cost

Year 3: Too early to predict travel costs
$120*3 = $360 (JFK to Orlando Melbourne International Airport)
$190 = (Dulles International Airport to Orlando Melbourne International Airport)
$175*3 = $525 (Indianapolis International Airport to Orlando Melbourne International Airport)

Hotel Stay: 2 nights

$800 for 8 adults staying 2 nights

Year 4: $120*3 = $360 (JFK to Orlando Melbourne International Airport)
$190 = (Dulles International Airport to Orlando Melbourne International Airport)
$175*3 = $525 (Indianapolis International Airport to Orlando Melbourne International Airport)

Hotel Stay: 2 nights

$800 for 8 adults staying 2 nights

Estimated manufacturing facilities cost:

*Year 1-4: $60,000*4 = $240,000*

Total Projected Cost = $342,322,935

Margin $400,000,000 - $342,322,935 = $57,677,065

6.2. Schedule

Table 12: Mission Schedule

Team/Category	Milestone	Start Date	End Date
Science, Engineering, Admin	1.1 - Project Start	09/04/2020	5/1/2030
Admin	1.1.1 - Mission Proposal Initial Summary	10/05/2020	10/20/2020
Engineering	1.2 - Design Requirements Planning	11/05/2020	4/1/2021
Engineering	1.2.1 - Minimum Criteria Requirements	12/06/2020	12/21/2020
Science	1.2.2 - Major Operational Phases/surface operations plan	01/06/2021	1/21/2021
Admin	1.2.3 - Concept Studies Completion	02/06/2021	2/21/2021
Admin	1.2.4 - Mission Concept Review (MCR)	03/09/2021	3/24/2021
Engineering	1.3 - Descent Maneuver and Lander Summary	04/09/2021	11/1/2021
Science	1.3.1 - Conduct research on Enceladus atmosphere/surface	05/10/2021	5/25/2021
Science	1.3.2 - Analyze Cassini's findings on Enceladus	06/10/2021	6/25/2021
Science	1.3.3 - Research possible landing sites	07/11/2021	7/26/2021
Science	1.3.4 - Update/Change Concept Review Requirements	08/11/2021	8/26/2021
Engineering	1.3.3 - Research science/engineering instruments	09/11/2021	9/26/2021
Engineering	1.3.4 - Systems Requirements Review	10/12/2021	10/27/2021
Admin	5.1 - Activity Plan	11/12/2021	4/1/2022
Engineering	5.1.1 - Design and Fabrication Review/Pre-launch review	12/13/2021	12/28/2021
Admin	5.1.2 - Budget Plan	01/13/2022	1/28/2022
Admin	5.1.3 - Outreach Summary	02/13/2022	2/28/2022
Admin	5.1.4 - Team Meeting to review final design and submit proposal	03/16/2022	3/31/2022
Science, Engineering	2.1 - Evolution of Project	04/16/2022	10/1/2022
Engineering	2.1.1 - Choose a landing site with the help of the JMARS software	05/17/2022	6/1/2022
Science	2.1.2 - Science deliverables	06/17/2022	7/2/2022
Engineering	2.1.3 - Brainstorm different design iterations for lander	07/18/2022	8/2/2022
Science	2.1.4 - Brainstorm different payload and science instrumentations	08/18/2022	9/2/2022
Admin	2.1.5 - Evolution of the mission plan/updated review	09/18/2022	10/3/2022
Science, Engineering	3.1 - Finalize Scientific and Engineering Instruments	10/19/2022	3/1/2023

Science, Engineering	3.1.1 - Plan on the overall descent system	11/19/2022	12/4/2022
Engineering	3.1.2 - Analyze subsystems and describe design in detail	12/20/2022	1/4/2023
Science	3.1.3 - Change any instruments based on new findings/ PDR review	01/20/2023	2/4/2023
Engineering	3.1.4 - Systems Design Review	02/20/2023	3/7/2023
Engineering	3.2 - Design CAD Models and engineering drawings	03/23/2023	7/1/2023
Engineering	3.2.1 - Design CAD Model for delivering system	04/23/2023	5/8/2023
Engineering	3.2.2 - Design CAD models for lander	05/24/2023	6/8/2023
Engineering	3.2.3 - Test and integrate models with lander design	06/24/2023	7/9/2023
Science, Engineering, Admin	3.3 - PDR/Critical Design Review	07/25/2023	8/9/2023
Engineering	3.4 - Recovery/Redundancy System Review	08/25/2023	12/1/2023
Engineering	3.4.1 - Define out mission failure alternatives/design review	09/25/2023	10/10/2023
Science	3.4.2 - Find out safety risks and measures	10/26/2023	11/10/2023
Science	3.4.3 - Research potential hazards and mitigation approaches	11/26/2023	12/11/2023
Science, Engineering	4.1 - Testing Phase	12/27/2023	5/1/2024
Science, Engineering	4.1.2 - Establish testing requirements on Enceladus	01/27/2024	2/11/2024
Science, Engineering	4.1.3 - Review instrument and design structure	02/27/2024	3/13/2024
Science	4.1.4 - Payload success criteria of scientific instruments	03/29/2024	4/13/2024
Science, Engineering	4.1.5 - Research on how to analyze collected samples, data, & images	04/29/2024	5/14/2024
Science, Engineering, Admin	6.1 - Launch/Completion	5/23/2024	5/1/2030
Science, Engineering, Admin	6.1.1 - Post Launch Review	6/23/2024	9/23/2024
Science	6.1.2 - Mission exploration/analyze findings	11/9/2030	12/30/2031
Science, Engineering, Admin	6.1.3 - Project Completion Review	1/1/2031	1/14/2031
Science, Engineering, Admin	6.1.4 - Decommissioning Review	2/1/2031	3/14/2031
Science, Engineering, Admin	6.1.5 - Mission end	4/1/2031	5/1/2030

6.3. Outreach Summary

Social Media:
Upload posts and blogs on social media sites such as Instagram, Twitter, Facebook, Reddit, and a custom, interactive website detailing the mission. Make the audience aware of the mission and post regular updates regarding milestone completions and progress. Answer any questions that the audience might have on live streaming channels and post findings and facts of Enceladus and provide opportunities for students to engage in the mission through online activities.

Media Events:
Through scheduling media events, the Enceladus Life Finder mission will gain the public trust, invite reporters to press conferences to answer questions related to the mission and present the team's proposal. Broadcast launching, landing, and a real time view of the spacecraft as it leaves space to keep people interested throughout the journey of the spacecraft.

STEM Education:
Inform, engage, and inspire the public by sharing the project's mission, challenges, and results. Involve the student body in experiences that inspire their interest and achievement in STEM disciplines and assure that students participating in the ELF programs consist of a diverse body, help out underrepresented groups, and increase the number of women in STEM.

Collaborating with Schools and Colleges:
Host events at schools and colleges and invite special guests from NASA to give a presentation on the mission and talk about what past missions have discovered on Enceladus or other planets. This will help promote the program and garner more support for the Latitude Learning Initiative with the help of professional scientists and engineers. This will also lead to hiring more volunteer researchers and interns coming directly out of these schools and colleges to help out with the mission and present their own designs and ideas.

Hitting the Road:
Travel to museums, space events, and informational sessions to share the details of our project. This can help in a way that the team will be able to inform the public of the benefits of investing in space flight and inspire the next generation of scientists, engineers, and explorers. The team will also have the opportunity to share the design of the spacecraft with others.

Attend Networking Events:
Attending networking events and meeting with students, researchers, industry professionals, and the general audience is a great way to interact with others and learn more about what projects they are working on or what they are interested in. Sharing ideas and making a personal connection with others will be beneficial in a way that it will significantly increase the impact of outreach efforts and increase the transparency of the mission design.

Partnership:
Partnering up with private and public aerospace companies such as SpaceX, Boeing, North Grumman, and Lockheed Martin to hold events in different parts of the country would also expand outreach efforts and gain interest.

6.4. Program Management Approach

Latitude operates with a three tiered hierarchy consisting of project management, team leads, and technical experts. Team leads also operate as technical experts in teams which they do not lead in order to maintain clear and effective communication between teams. Involving team leads in other subteams ensures that even when subteams begin to work independently, members will still have a good idea of the operations of other teams. As the mission progressed, it became apparent that scheduling conflicts would continue to become more frequent so project managers addressed the issue by encouraging members to work independently and use the meeting times as a weekly progress update rather than a group work session. Areas of study which require contributions from multiple members simultaneously will still warrant group work sessions and are scheduled on a case by case basis.

Section 7: Conclusion

This preliminary design review outlines a high level plan of the Ensomnia mission: the search for signs of life on Enceladus. The Ensomnia mission will explore and determine the presence of organic compounds on the Damascus Sulcus tiger stripe on the south pole of Enceladus by using THEMIS, Mastcam-Z, Ptolemy, SELFI, and LIDAR to analyze the compositions of surface materials and map the topology of Enceladus. These specific goals will advance the understanding of the presence organic material of Enceladus, revealing clues to natural phenomena and potential biosignatures of the past.

The Ensomnia mission features advanced technology which will expand upon the discoveries made by Cassini. Ensomnia's payload features five primary technologies which investigate the conditions of the plumes within the tiger stripes and the fallen matter, including the chemistry, physical conditions, and potential biological activities, investigate how Enceladus interacts with its surroundings and how this affects the tidal forces and recreation of its own surface, and prepares for follow up missions by establishing characteristics of life along with mapping Enceladus and identifying future landing sites**.**

LIDAR will use light pulses to determine the altitude of the lander and map the topology of the surface during descent. Mastcam-Z will be used to investigate points of interest in high resolution to assist in the topological mapping of the surface. THEMIS will investigate the thermal properties of the tiger stripes. SELFI will determine the chemical composition of Enceladus' interior ocean. Finally, Ptolemy will determine the chemical and stable light isotopic composition of the surface materials. With these instruments, a high fidelity model of the Damascus Sulcus tiger stripe can be developed and used to further understand potential building blocks for life on Enceladus.

Ensomnia will ensure a safe landing by employing the state and trigger model to autonomously manage disruptions to the mission. The descent profile is optimized to conserve mass and the engineering features of the lander are inspired by previous missions to similar environments.

Team Latitude plans to conduct a critical design review for the Ensomnia lander by July 25th, 2023 and continue developing the concept for its eventual launch on March 23rd, 2024. To ensure that the project stays on schedule, a Mission Concept Review, Systems Requirements Review, and Systems Design Review will be conducted across the development cycle of the concept. After launch, a launch review will be conducted to ensure that the subsystems are in good condition for the transfer to Enceladus. Finally, after the mission has been completed, the full mission review will be conducted along with the public release of all data collected during the mission.

Section 9: References

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