Equinox Regolith Refinery

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In recent years, there has been an international push to develop in-space servicing, assembly, and manufacturing methods to assist current and facilitate new satellites. As such, team Equinox developed the Equinox Regolith Refinery payload, in direct response to the 2024 COSMIC Capstone Challenge. This payload is designed to semi-autonomously demonstrate the ability to turn lunar regolith into a usable material for 3D printing while in Low Earth Orbit (LEO). This is made possible through three sequential internal operations: crushing, sorting, and mixing. The microgravity environment aids the process, allowing the regolith to be moved throughout the system suspended in a gaseous fluid flow. The team used professional design engineering practices to ideate, design, and begin verification on the payload. In addition to the payload capabilities, the team has investigated the power, communication, thermal, structural, and orbital analysis of the payload. This work was extended to the Venus X-class satellite bus to ensure that it can support the needs of the mission. Initial verification has produced positive results, indicating that future work on this concept would produce a successful mission that advances In-space Servicing, Assembly, and Manufacturing (ISAM) capabilities.

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I. Introduction

In-space manufacturing has current applications in producing food and materials for astronauts aboard the ISS, or producing parts for on-orbit repair of active satellites. However, these manufacturing applications all rely on the materials for production being brought from Earth. A capability gap exists in the area of in space manufacturing from materials found off Earth. The reason for this capability gap can be summarized by considering that the availability of in-space materials is limited to locations accessible by space vehicles, such as the Moon, Mars, and asteroids. The Moon is the closest of these options, and has recently had a large increase in potential accessibility due to the successful landing of a commercial spacecraft. With this in mind, the ability to process regolith into a usable material for in-space manufacturing becomes a highly relevant capability gap, one that the Equinox mission seeks to fill by turning raw in-space materials into usable construction materials. To completely fulfill this gap, in-space material extraction and construction payloads would need further development as well.

II. Mission Overview

The goal of Equinox is to autonomously conduct a technology demonstration of in-situ regolith processing by turning lunar regolith simulant into 3D printer filament material in the microgravity environment of Low Earth Orbit (LEO). This is a particularly unique and useful way to fill the capability gap because there has been a large amount of research on earth of using 3D printers to print concrete structures on Earth, and research on processing on the Lunar surface, but there has not been as much exploration of resource processing in microgravity for use in-space. Utilizing in space materials like regolith from asteroids for the purpose of construction of space stations or other satellites in space would be very advantageous and efficient for the future of space exploration, travel, and habitation. As such, technology such as that of the Equinox payload plays a unique and crucial role in filling the gap of in-space construction material manufacturing.

The top level mission objective for the Equinox payload, the Equinox Regolith Refinery, is to process regolith simulant into 3D printer filament autonomously in microgravity. As such, the top level requirements are to crush the regolith simulant to uniform size, sort and sift the material into a fine and coarse size of desirable composition, mix the material into a concrete-like filament, and safely store and transport the products in microgravity.

Although most of the payload's actions to complete its mission are internal, it is still very important to consider the overall mission plan. This includes how the payload arrives at its orbit, how and when communication is sent between the satellite and the ground station, and the lifetime of the mission. As such, the overall mission architecture for the payload-satellite system is shown in Figure 1 below.

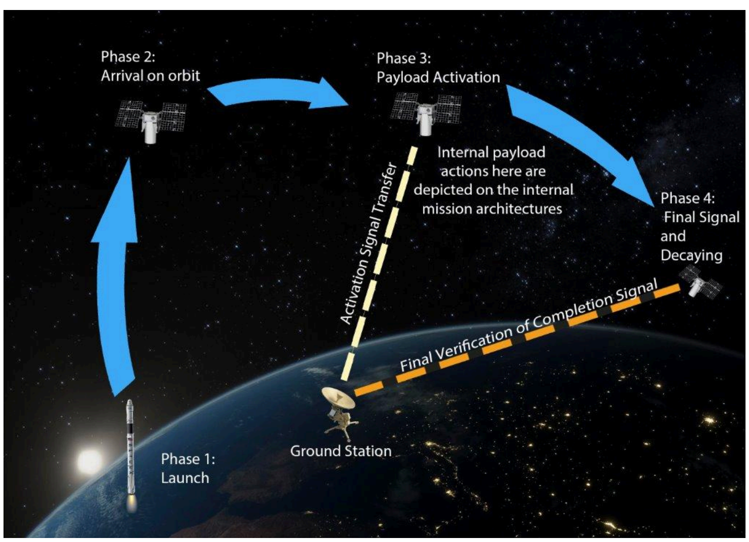

Figure 1. Overall Mission Architecture

The mission architecture consists of four key phases. The first phase is the launch, where the payload is securely placed inside a Falcon 9 rocket using SpaceX's rideshare program, and sent into space. In the second phase, the payload reaches its intended orbit and waits for the activation command. For the third phase, a command signal is sent from the ground station, which activates the pre-loaded command script in the on-board computer to begin autonomous operations. The final phase occurs after the operation of the payload is complete, where sensor data from the payload that has been stored on the payload's computer are sent back down to the ground station in order to verify that the mission has been completed successfully. If the sensors verify success, then a command is sent back to the payload to deorbit.

The maximum payload mass and the maximum power draw for the payload are defined by the competition's RFP, which were used to construct mass and power budgets for the mission. The payload mass is constrained to be no more than seventy kilograms. The mass budget for the payload is shown in Table 1 below.

Table 1. Payload and Venus X-Class Bus Mass Budget

Payload Subsystem	Payload Mass (kg)	Payload % Tot Mass	Venus Bus Subsystem	Venus Bus Mass (kg)
Structure	8.4	12%	Structure	44.6
Thermal	5.6	8%	Power	25
Power	10.5	15%	C&DH	10.9
C&DH	4.2	6%	ACDS	19.5
Storage	4.2	6%	Harness	5
Crushing	24.5	35%		
Sorting	5.6	8%		
Margin	7	10%		
Total Payload Mass	70	100%	Total Bus Mass	105
Total Mass with Venus X-Class	175			

A margin of 10% of the total payload mass was used in order to give a factor of safety to account for any extra masses or imperfections that the original design did not account for. The mass allocations are based on the payload design, and are divided by each subsystem. The mass of Venus X-Class bus was not given, and as such it was estimated based on a typical bus to payload ratio of 1.5, making the bus 105 kilograms in mass. The host spacecraft mass budget was determined using the overall assumed mass, and average values for spacecraft subsystems, as found in *Space Mission Engineering: The New SMAD*[5] . All host spacecraft assumptions used to estimate these values will be in the host spacecraft and future work sections.

With all materials and components selected for the mass budget, a basic bill of materials was drafted. The structure will require $2,500 total for basic framework rods and connective parts. The thermal subsystem needs $9,500 for its radiative cooling wrap and active heating system. Power requires $24,500 for general wiring and battery components. Command and data handling includes a wide variety of devices including an onboard processor, router, memory modules and supporting components, adding up to a cost of $56,000. Storage tanks inside of the payload will be purchased along with the other aluminum for the structure. The roll crusher being utilized can be purchased for $6,000 and the centrifugal sieve, $4,500. These are the general components that comprise the bulk of the payload cost. The predicted bill of materials, including 10% margin, will total $113,300.

The total power offered by the Venus X-Class bus, as constrained by the RFP, is 444 Watts for the dual solar array configuration. This power must be shared by both the bus and the payload. The power budget was determined first by using an average power usage estimation for spacecraft in LEO from *Space Mission Analysis* *and Design(SMAD)*[5], and then modified to account for the power drawn by the specific components of the payload. The payload's power budget is shown in Table 2 below, where maximum power output is shown in sunlight and in eclipse, assuming all subsystems are on at full power.

Table 2. Payload Power Budget

Subsystem	Power used in Sunlight(W)	Percent of Total Power in Sunlight(%)	Power used in Eclipse(W)	Percent of Total Power in Eclipse(%)
Structure	4.4	1	4.4	1
Thermal	0	0	48.3	10.8
Attitude Determination	0	0	0	0
Propulsion	0	0	0	0
C&DH	51.7	11.6	51.7	11.6
Payload-Crushing	116.5	26.3	104.9	23.7
Payload-Sorting	76.7	17.2	69	15.5
Payload-Mixing	48.4	10.9	29.1	6.5
Margin	55	12.5	55	12.5
TOTAL	**352.7**	**79.4**	**362.4**	**81.5**

The power usage is split between eclipse time and time in the sunlight, because the thermal power won't be used in the sunlight, and activates when in eclipse. Active thermal control is needed only in eclipse to keep temperature levels stable in order to prevent the regolith material from being unworkable. The structure (which refers to mechanical valves in the structure) and command and data handling (C&DH) also need to stay fully active in eclipse to ensure that the material stays in place and the computer can still control the payload during this time. During eclipse, the payload will operate with reduced power (at 90% power and efficency), in order to not drain the battery too much while more energy cannot be produced by the solar panels. The attitude determination and propulsion for the payload are at 0 Watts of power because the payload is not concerned with its attitude and there are no in-space maneuvers necessary for normal operation. There is a margin of 12.5 percent given in both situations, which allows for power fluctuations and other unexpected power draws without using too much power at any one time. There is also left over power not drawn, such that the Venus X-Class bus has enough power for its operation. This will be discussed in full in the Host Spacecraft section.

III. Payload Design

A. Payload Design Overview

The mission of Equinox is to provide a technology demonstration of regolith processing in LEO, where an initial regolith sample is crushed, sorted, and processed into a 3D-printer filament for construction purposes. The payload is fully autonomous and is sent up with a complete program on its on-board computer that launches each necessary process using a pre-planned series of timed actions, only needing a single command from the ground station to begin production. As such, the payload design focuses on efficiently processing raw material into a usable final product using a timed multi-step approach. For this technology demonstration, a simulated Lunar regolith is used, which is initially stored at the top of the payload, and is sent up with the payload. This simulant is pushed through the payload and processed in three separate steps: crushing, sorting, and mixing. A main challenge for processing in space is the microgravity environment, which this design gets around by utilizing a fluid pump that ensures a steady flow throughout the system. The first stage involves initial crushing, where large pieces are broken into smaller fragments using a roll wheel crusher. Next, the material passes through a rotating centrifugal sieve, which separates it into usable fine grain material, and waste large grain material, which is stored. The fine grain material then passes into the mixing chamber, where it is mixed with a binding agent thoroughly to form the final product. Finally the product is stored in a storage tank.

The model shown in figure 2 below is a three-view engineering drawing of the payload model. Each of the important components are labelled on the drawing. It portrays a half view, where parts of the structure and casings are cut away to show the internal operations of the payload. Also important to note is that the sieve screen on the centrifuge is removed for the engineering drawing, as to show the internal auger, and because the very small holes do not render well. Also missing from the three-view is the five millimeter thick silver teflon wrap for thermal insulation, which goes around the exterior of the structure. A fully rendered 3D CAD model of the payload half view is shown in Figure 3 as well.

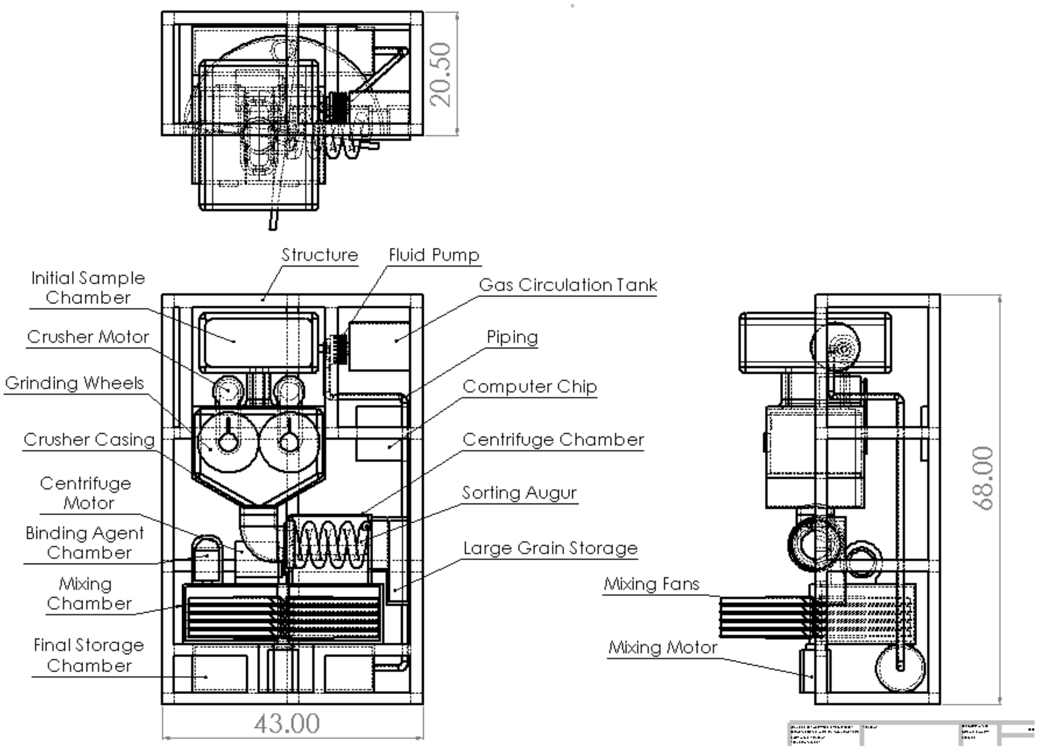

Figure 2. Payload 3-View Drawing Annotated (cm)

Figure 3. 3D CAD Model of Payload Half-View

Figure 4 shows the mission architecture for the Equinox payload, which demonstrates the chronological steps that the payload executes in order to complete its process.

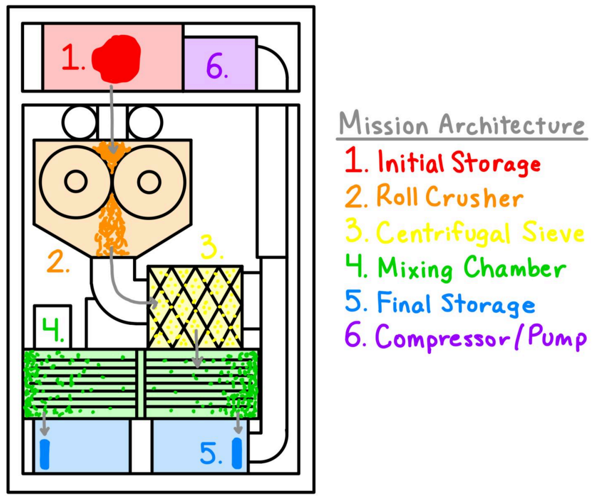

Figure 4. Payload Mission Architecture

The regolith simulant begins the initial storage container at the top of the payload, labeled as 1. The system sits dormant until it passes by the ground station for the first time, where a command is sent to the Venus X-Class bus and transmitted to the payload on-board computer to start the production process. This opens the valves of the system to have a continuous flow, and starts the pump to begin pushing the fluid and material through the system. At station 2, the material reaches the roll crushers, and is ground into fine grain sizes, as defined by the distance between the two roll wheels, and the initial grain size of the material. At station 3, the material reaches the centrifugal sieve, which has an external rotating sieve and an internal rotating auger at a different speed. This combines mechanical pushing, fluid force, and centrifugal forces to separate the material into fine grain material that is useful, and larger grain material that is stored away as waste. At station 4, the material moves into the mixing chamber. Here, the exit valve is screened such that no material can flow through at first, only the pumping fluid. The mixing fan then turns on and the binding agent valve opens, mixing the material together. After a set amount of mixing time, the valve opens to push the material into the storage container, station 5, while the pumping fluid goes through back to the pump to complete its cycle. The computer code then activates the sensor in the storage tank to determine if the material was successfully processed, and sends its data to be stored on the computer. When the payload is within the ground station's range again, it downlinks the sensor data.

B. Crushing

1. Regolith Processing

The crushing subsystem of the payload exists in order to take the raw sample material and crush it down into smaller more manageable pieces to work with. This is necessary when using regolith because collected samples from Lunar regolith consist of a wide range of grain sizes: anything from large rocks to fine sand. For almost every application of regolith for manufacturing, very small grain sizes are needed. In the case of creating filament paste used for 3D printing that Equinox is concerned with, the grain size needs to be within the order of 100 micrometers, which is very fine[6]. The simulant to be used is very important for the following process and there are a variety of regolith simulants available on the market that are commonly used. Each regolith sample has different grain sizes, and slightly different compositions, each of which are made to mimic lunar regolith from different regions. The regolith that will be used for the Equinox payload is BP-1, because it has been used extensively for similar research, has a composition very similar to that of actual lunar samples, and because it is cheap and readily available, at only \$15/ton. The approximate main composition of the simulant is shown on table 10 below[7].

Table 3. BP-1 Composition

Silicon Dioxide (SiO2)	Dialuminum Dioxide (Al2O2)	Calcium Oxide (CaO)	Ferric oxide (Fe2O3)	Iron Oxide (FeO)	Magnesium Oxide (MgO)
47%	17%	9.2	~6%	~6%	~6%

Furthermore, the approximate grain size of the simulant, which is very important to the crushing process, is shown below in figure 11. In this figure, it is comparing the BP-1 to one standard deviation above and below the mean of actual Lunar regolith, which demonstrates how good this simulant is at replicating actual lunar regolith.

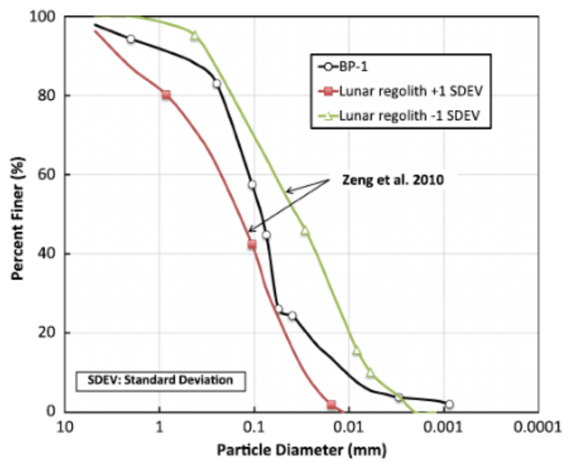

Figure 5. Particle-size distribution of BP-1 compared with 1 standard deviation of lunar regolith

Here, it is apparent that the grain size of the simulant is approximately between 10 and 0.001 millimeters, thus representing a wide spread that is very similar to that of true lunar samples. As such, it is a good choice of material to use for this mission.

2. Trade Study Metric Justifications

Each design was evaluated based on the metrics of cost, GNC impact, mass flow, and power draw. Risk, as defined by the Technology Readiness level (TRL) is also a very important metric to consider, however it is left off as a metric of this particular trade study because all of the technology has the same readiness level for this type of mission. This is because all of these crushing technologies have been extensively used for resource processing on the surface of the Earth, but they have not been tested in the space environment or verified in a microgravity simulation extensively on Earth. In order to standardize the metrics used in this trade study, each of the crushing mechanisms that are being explored were defined for the same exit particle size, such that they can be fairly judged against one another. The quantitative values do not necessarily coincide with true values that will be used in the Equinox payload, as there are some extra power and size restrictions as previously described that will be accounted for when scaling these mechanisms down to size.

The first metric is cost, which is weighted at 10%. Cost is to be minimized, as it is desired to have the lowest cost for the payload overall. The weight is the lowest of the metrics, as it is the least important to the mission overall. The cost should always be considered, such that overly expensive equipment is not being used extraneously, but for the case of this study, cost is by far the least important. It is of the utmost importance that the technology works as desired more than how much said technology costs.

The second metric is the GNC impact that the mechanism will have on the payload overall. This metric is defined quantitatively by the rotations per minute (RPM) that the mechanism requires to crush the sample. As such, it is desired to minimize this metric such that there is not too much perturbation from the internal mechanisms that require lots of attitude control. This metric is weighted at 20%, because it is important that the entire payload is not sent into a vicious spin by the mechanism, as every design has some magnitude of rotational motion to crush the particles. It is not weighed higher because it is possible to have built in rotation dampers that stop any extraneous spin.

The third metric is the mass flow rate that the crushing mechanism processes at, which should be maximized such that the process completes as quickly as possible. The mass flow rate is quantitatively determined from the specifications at the set particle outlet size. It is weighted second highest, at 30%, because processing time is and continuous flow is very important for the design of the payload. There is only a limited window in the sunlight, and thus it is important that the process be completed as quickly as possible, which corresponds to a high mass flow rate.

The final and highest weighted metric is the power draw of the mechanism, sitting at 40%. This is the highest metric because the power restraints for the payload are relatively stringent, and crushing is a process that can draw large sums of power. Although each component of the payload will turn on and off at various times, it is important that the power draw from the crusher is not too high, as to sequester too much of the power and energy budget that is allotted to the payload as a whole. As such, it is desired that the power draw is minimized.

3. Trade Study

The table below shows the crushing mechanism trade study data for each weighted metric. Below each metric's raw data are the normalized and adjusted values, which means that they were scaled to between 0 and 1, where a higher score is more desirable.

Table 4. Crusher Trade Study

Metric	Weight	Goal	Blake Crusher	Cone	Roll Wheel	Impact Mills
Cost	0.1	Min	1000	1450	2250	7500
Normalized and Adjusted			1	0.930769	0.80769230	0
GNC Impact (RPM)	0.2	Min	1400	3000	200	375
Normalized and Adjusted			0.5714285714	0	1	0.9375
Flow (kg/hr)	0.3	Max	250	45	860	125
Normalized and Adjusted			0.2515337423	0	1	0.098159509
Power Draw (kW)	0.4	Min	1.5	4	1.5	9.7
Normalized and Adjusted			1	0.695121	1	0
Total			2.822962314	1.625891	3.80769230	1.035659509

4. Conclusions and Verification

As demonstrated in the Crusher Trade Study table above, the mechanism with the highest weighted total score is the roll wheel. These roll wheels work only for particles of a certain size, which is based on the geometry of the system. Figure 13 shows the geometry of the system, where theta is the nip angle, R is the roller radius, r is the particle radius, C is r plus R, and μ is the coefficient of friction[8].

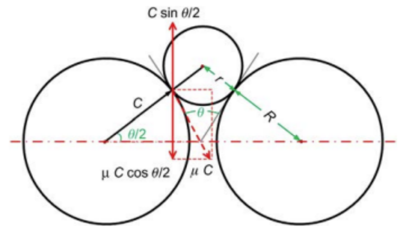

Figure 7. Roll Wheel Geometry

Assuming that the rollers are made of steel, and that the coefficient of friction between the simulant and the wheels is similar to that of typical ore particles, the angle of nip should never exceed 30 degrees[8]. In order to find maximum rock size, the following equation was utilized:

$$cos(\theta/2) = (R + a)/(R + r),$$

Therefore, using the angle of nip, the radius of the wheels, and a desired reduction ratio (r/a), the maximum rock size that can be processed can be found. Using the 30 degree assumption and 1000 millimeter rollers, the maximum rock size at multiple reduction ratios is shown in the table below:

Table 5. Maximum Diameter for Different Reduction Ratios

Reduction Ratio	2	3	4	5	6
Maximum Rock Size (mm)	30.9	23.0	20.4	19.1	18.3

As such, for 1000mm rollers, the roll wheels will work well, as the maximum sample size for the simulant material is only a few millimeters, and as such it can be effectively crushed at high reduction ratios to the desired size.

5. Specifications

The important specifications of the crushing wheel are the radius of each wheel, the area reduction ratio, the desired particle size, and the RPM of each wheel. Each of the characteristics are chosen and defined by normal operating conditions that allow for continuous crushing flow and the desired product size for 3D printing. A standard 3D printer spout has a diameter of 2 to 2.9 mm, with particle size of the filament greater than 50 μm[9]. As such, the particle size must be within this limit, with a reasonable size being 0.5 mm. This will be used as the spacing between the rolling wheels. The stimulant that is being used can have particles that are over 5 mm in diameter[5], and as such the inlet of the rolling wheels will be 2 mm, which defines a reduction ratio of 4. In order to provide the necessary crushing force, 1000 mm roll wheels operating at 200 RPM will be used. At this size and reduction ratio, table 12 shows that the maximum rock size that can be processed is 20.4 mm, which is much greater than what will be processed by the payload. As such, this design is feasible and will be capable of processing the regolith down to the desired size.

C. Sorting

1. Regolith Processing

The sorting subsystem is important in the processing of regolith in order to divide the material into more usable parts. The type of sorter system depends heavily on the desired final product, whereas it may be important to sort for material composition, particle size, or a number of other desirable properties. For the Equinox mission, the most important property is the size of each of the particles, whereas it is most desirable to have each particle to have a diameter smaller than one millimeter[6]. The composition of the material is slightly important too, where the desired final product needs to have a high composition of silicon. This is mainly taken care of by the fact that Lunar regolith (and thus the simulant used) has a high composition of silicate and other silicon oxide mixtures present, as demonstrated previously.

2. Trade Study Metric Justifications

Each of the designs was judged on the metrics of GNC impact, risk (as defined by the TRL of the technology), and the power drawn from the mechanism. The quantitative data used in this study comes from the academic research documents that discuss each method of sorting.

The first metric is GNC impact, which is defined as the RPM of the device. This is weighted at 30 percent, which is the middle weighted metric. This metric is important for the same reasons that it was in the crusher trade study, whereas it is important that the payload is not sent into spin by the internal working components, as that will bring up the weight and cost by needing more propellant or other stabilizing devices.

The second metric is the risk factor, as defined by the TRL of the method. This metric is weighted the least, because each of the technologies is untested in the space environment, and a big part of the Equinox mission is to conduct in-space testing on novel technologies to prove their efficacy for in-situ resource utilization. As such, the TRL is still a necessary factor when judging the methods, but it is weighted the lowest. The TRL is judged based on the experiments conducted on the designs, as discussed in academic journals.

The third metric is power draw, which is weighed the highest, at 40 percent. This is the most important metric for much of the same reason as it was in the crusher trade study. There is a very limited amount of power generation and energy storage on the Venus X-Class Bus and in the payload, and as such it is important that any one system not use too much power for its normal cycle. The sorting mechanism was allotted a moderate amount of power, and should be activated independently of most of the other systems, and as such the power drawn is of great concern.

Table 6. Sorter Trade Study

Metric	Weight	Goal	Spiral Mesh	Centrifugal Sieve	Electrostatic Sorting
GNC Impact (RPM)	0.3	Min	150	250	0
Normalized and Adjusted			0.4	0	1
TRL	0.2	Max	4	5	3
Normalized and Adjusted			0.5	1	0
Power Draw (kW)	0.4	Min	1.5	2	24
Normalized and Adjusted			1	0.9777777778	0
Total			1.9	1.977777778	1

3. Conclusions and Verification

As shown in the table, the centrifugal sieve is the most feasible design for the sorting mechanism. Figure 8 below shows the 2D schematic of the patented design.

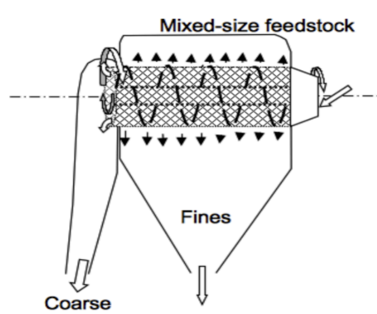

Figure 8. Centrifugal Sieve Schematic

As stated previously, this design is patented and has been tested in multiple levels of gravity, including microgravity. Furthermore, the design has been tested for multiple granular sieve sizes, and multiple regolith simulants: Lunar, Martian, and Phobos regolith simulants. For the Equinox mission, the most important test by the prototype of this design was using a screen size of 100 µm on Lunar simulant JSC-1A, which was able to successfully separate material into fine and coarse particles[6]. As such, these tests can be used as verification that the technology can perform its intended function on Lunar regolith simulant with a desired grain size of the same order of magnitude as desired by the Equinox payload.

4. Specifications

Coming from the crushing wheel exit distance, the desired particle size is 0.5 mm in diameter, and as such the sieve will be using 0.5 mm holes such that all material of that size and less passes through and is used. The sieve drum is 1000 mm in diameter, with the 0.5 mm holes radially distributed with a distance of 0.75 mm between the centers of each hole. A very helpful study on sorting regolith in-situ is "Low-Gravity Size-Sorting, Conveying, Storage, and Delivery of Regolith for ISRU"[8], which can be used to determine different sizes and speeds of the sorting mechanism. This study focuses on an auger encapsulated in a cylindrical sieve, much the same as the sorting system for the Equinox payload. The internal round auger is positioned with a gap of 1.5 mm between the sieve and the outer auger edge, which research has shown that this gap increases the performance of the sorting. As such, the auger has a diameter of 997 mm with a wire diameter of 175 mm. The wire diameter was derived from the same study, where it is demonstrated to be advantageous to have an auger with a large central gap of this proportion. This study also explored the RPM necessary for the mechanism, where it concludes that in a Lunar environment, 100 to 200 RPM is suitable, and since the Equinox payload is focused on Lunar regolith, it makes sense to use these as limiting values. As such, the outer sieve will be rotated at 100 RPM, with the internal auger being rotated at 150 RPM.

D. Mixing

1. Regolith processing

The mixing system is important for creating a smooth and consistent filament used for 3D printing. After crushing and sorting the regolith to get the right particle size, it is needed to be mixed evenly to form the paste. Even mixing is essential because uneven paste can cause weak spots and problems in the final 3D-printed object. The mixing system uses a mixing fan which is rotated using the mixing motors to ensure all particles blend well with the binding agent. The mixer is designed to handle the rough nature of regolith without quickly wearing down. Mixing speed, time, and blade design will be tested and optimized to produce a paste that's perfect for 3D printing, making a strong and dependable filament.

2. Trade study

Each of the designs is compared based on power consumption, efficiency, and cost. The quantitative data used in this study comes from scholarly research reports that analyze each method.

The first metric is cost, weighted at 10 percent, making it the least significant factor in this study. While cost is always an important aspect of system design, it holds less weight than efficiency and power consumption in this evaluation. Cost is measured in dollars and reflects the estimated total expense of implementing each method. Since lower costs are preferable, this metric follows a minimization objective.

The second metric is efficiency, which carries a weight of 40 percent. It plays a crucial role in determining how effectively each method performs its intended function. Greater efficiency leads to better overall performance and resource utilization. Efficiency is measured as a percentage, and since higher efficiency is desirable, this metric follows a maximization objective.

The third and most critical metric is power draw, which has the highest weight at 50 percent. Given power limitations, minimizing energy consumption is essential. Power draw is measured in kilowatts, and lower values are preferred to maintain energy efficiency. The sorting mechanism must operate within strict power constraints to prevent disruptions to other essential systems.

Each method was assessed based on these three factors, and the normalized and adjusted scores were calculated accordingly. The final scores highlight the most balanced method, considering cost, efficiency, and power consumption. The table below shows the mixing mechanism trade study data for each of the three different types. Below each of the raw data are the normalized and adjusted values.

Table 7. Mixing Trade Study

Metric	Weight	Goal	Extrusion based mixing	Fluidization	Electromagnetic Stirring
Cost ($)	0.1	Min	5000	250	60000
Normalized and Adjusted			0.6	1	0.2
Efficiency (%)	0.4	Max	96	92	85
Normalized and Adjusted			1	0.833333	0.666667
Power Draw (kW)	0.5	Min	1.2	0.05	0.2
Normalized and Adjusted			0	1	0.8
Total			1.6	2.833333	1.666667

3. Specifications

Based on table 7, the best choice would be to mix using fluidization for the regolith. The sorted regolith from the sorting section will go inside the mixing chamber. While the mixing chamber is rotating from the mixing fan, the hydrogen gas would be inserted into the chamber causing the reaction to form the metals and silica rich particles and water. Once the mixing is complete, having a determined time decided or based on consistency, the filament will enter the final storage container at the bottom of the 3D printer, easily to be removed and reinserted for the next use of the payload.

E. Fluid Processing

The fluid processing subsystem utilized a closed loop system of gaseous nitrogen flowing throughout the payload with a mass flow rate of 0.5 g/s, resulting in velocity of suspended regolith of 0.32m/s. The design is intended for a small radial turbo compressor to be attached to a nitrogen storage tank, where the loop will be prefilled with a gauge pressure of 15 psi to allow the pump to begin operation. This design takes advantage of the microgravity environment to suspend the regolith in the gas and allow for ease of movement throughout the payload. Based on a trade study, the Celetron 15-150 was selected as the ideal pump that can deliver this mass flow with optimal power consumption.

F. Structure

The structural design of the payload began with the given dimensional and mass constraints of 27.0” × 17.0” × 16.4” and 70 kilograms. Considerations were made for internal structural demands such as vibration from components like a centrifugal sieve and fluid dynamics within a closed system, but the dominant stress factors are from launch and ascent. The payload will be carried by an X-Sat Venus Class satellite aboard a SpaceX Falcon 9 rocket. Launch conditions pose axial and lateral loads of up to 6g and 2g respectively[1], which were verified to meet safety requirements using Finite Element Analysis, shown in Figure 9. This is the simple payload structure under launch loads seeing some deformation. However, because the team is assuming a rigid connection within the X-Sat Venus Class, the bus will absorb the entire launch load.

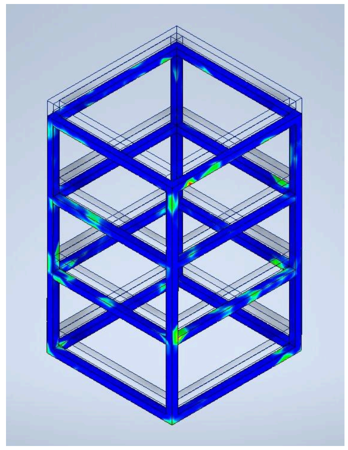

Figure 9.Finite Element Analysis of the payload structure

The frame is composed of 2 cm thick vertical struts and four evenly spaced horizontal cross members made of Carbon Fiber Reinforced Polymer. This material was chosen through a trade study for its exceptional strength-to-weight ratio, compatibility, and low density, despite a higher cost. The design itself was created based on C3S' 3U Structural Framework[3]. For the spacecraft-to-launch vehicle interface, a 15-inch circular aluminum plate compatible with the standard ESPA-ring was chosen[4], secured with twenty-four ¼-inch fasteners. This ensures secure and standardized integration with Falcon 9.

G. Power

The power subsystem is based on the components provided from the Venus X-Class to power the bus and the payload. This would include the dual-array providing 444W of power and 10.2 Ah battery for energy storage. As previously discussed in the mission overview's payload power budget, the payload will operate differently based on eclipse versus sunlight conditions, and will (in both cases) operate safely within the host spacecraft's power and battery limits, with a margin of error and left over power for the bus. The power budget demonstrates the maximum power that could potentially be drawn at any time, but in reality not all of the components will be active at one time, which will give an even larger safety cushion. The crusher, sorter, and mixer will be activated in their respective orders, with no overlap between the activation of each component. The host vehicle power integration is discussed later, detailing more on its requirements.

H. Thermal

The goal of the thermal subsystem is to keep the payload's internal temperature within the desirable range for onboard electronics and regolith processing. The target overall temperature was set for -10 degrees celsius. Initial hand calculations proved a necessary passive thermal control method of 5-mm thick silver Teflon wrapping. In addition, SolidWorks thermal simulation (Figure 10) was done to calculate the heat generated by the onboard electronics to determine the need for active thermal processing. Simulating the heat transfer through the payload showed that a maximum temperature of 47.85 degrees celsius of the payload is possible with all electronics running at maximum power, without any active heating methods.

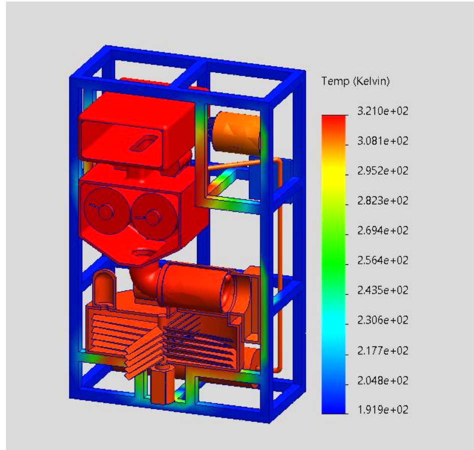

Figure 10. SolidWorks thermal model of the payload cross-section

The heat transfer from the fluid pumping through the system to the rest of the payload was considered in the thermal model. Though convective heat transfer does occur, other methods of active heating are still necessary. Given that the payload operation sequence does not require every component at once, it was determined that 40W of active thermal control is necessary to keep all electronics in target range when not in use. The choice and placement of these heaters remains as a place of future research and work for the payload's development.

I. Payload C&DH/Communications

Reliable onboard data processing, data storage, command execution and system parameters monitoring are the main focus of this subsystem.. To capitalize on the benefits of autonomy, minimal contact will occur between the spacecraft and ground station. The spacecraft will only receive an initial activation signal that commands it to carry out its internal process. Upon successfully carrying out all onboard processes, the spacecraft will then send a confirmation signal back down to the ground control station indicating whether that iteration was successful or failed. This level of autonomy minimizes the power necessary for data transmission and allows the payload to operate with more availability throughout its orbit.

Onboard processing greatly reduces the dependency on ground station availability and demonstrates the possibility for future design iterations to fully automate the Equinox payload with various other means of this activation signal being sent to the payload. This design feature would allow future Equinox payloads to operate with zero dependency on Earth after being placed in its intended orbit. Larger computing hardware is required to internalize these communication processes, but the departure from continuous or frequent communication greatly decreases the risk of mission failure due to loss of communication.

The hardware selected for this payload is as follows. The primary onboard computer needs to be radiation-hardened for better reliability in the harsh environment of LEO. The GR740, radiation hardened system-on-chip will be used, which features a quad-core fault-tolerant LEON4FT SPARC V8 processor, an eight port SpaceWire router, a PCI initiator/target interface, and CAN and Gbit Ethernet interfaces. The data bus will be SpaceWire, which is a computer network designed to connect together high data-rate sensors, processing units, memory devices and telemetry/telecommand sub-systems onboard spacecraft. It provides high-speed, bi directional, full-duplex data links up to 200 Mbit/s. For redundancy and error detection, the payload will include non-volatile memory to store telemetry and payload component parameters until transmission back to ground control station occurs. Integrated fault software will have triple modular redundancy in place for each major component carrying out a key mission objective. S-band will be utilized for lower power command signals with high reliability[22]. The payload success signal will be formatted as a checksum-based verification. If a confirmation signal is not received within the intended orbit revolution, a retransmission sequence will be sent to reinitiate the process. Each individual internal process will have its own verification requirements to ensure duplicate actions are not taken during a retransmission signal processing.

IV. Host Spacecraft Integration and Mission Analysis

A. Launch Vehicle, Ground Station, and Orbital Analysis

Due to its extreme cost effectiveness, high reliability, and frequent launches, the SpaceX Falcon 9 Rideshare Program was selected to launch the Equinox payload and Venus X-Class Bus into LEO. A trade study compared various common options for CubeSat sized missions and the results are outlined in Table 9 below.

Table 9. Launch Vehicle Trade Study

Launch Vehicle	Payload Capacity	Cost per kg	Frequency	Other
SpaceX Falcon 9 Rideshare	22,800 kg	$6500	Monthly	441 completed missions
Rocket Lab Electron	300 kg	$20,000	Quarterly	Dedicated system only launching one payload
Arianespace Vega-C	2,200 kg	$12,000	Quarterly	Would cost much more due to difficulty “ridesharing”
ISRO PSLV	1,750 kg	$10,000	Semi-Annual	Not frequent launching, difficult “ridesharing”

With the ability to purchase a portion of the total payload capacity, the Falcon 9 vastly became the most cost effective option which was the main deciding factor for the selection as Equinox’s launch vehicle choice. The reliability of this particular launch vehicle drastically lowers the overall mission risk as the frequency of launching gives great flexibility for time of departure. This low price is largely due to the ability of the Falcon 9 to be reusable with over 396 landings and 369 reflights of rocket boosters. The mass and volume constraints of the SpaceX Falcon 9 accommodate the set parameters of the Venus X-Class Bus.

The spacecraft will be inserted into a low earth orbit (LEO) with desired orbit properties listed below.

Table 10. Orbit parameters

Parameter	Value
Semimajor axis	6678 km
Altitude	307 km
Eccentricity	0
Inclination	40°
Argument of perigee	50°
Period	90 min

It is important to note that the simulated date for launch was February 13th, 2026. The Right Ascension of the Ascending Node (RAAN) for this time, such that the payload will pass directly over the designated ground station is -30 degrees. A low earth orbit was chosen as it would provide the required microgravity environment and because it is more cost effective than a higher altitude orbit, as achieving such a higher altitude would not make a difference for the mission. Additionally, the low altitude allows for orbital decay due to atmospheric drag.

The selected ground station is in Alice Springs, Australia and operated by Geoscience Australia. Only two communications will go through the ground station, one to start the mission when in space, and one to assess success criteria. This station was chosen for its position in comparison to the intended launch site of Cape Canaveral, FL, whereas the Alice Springs Ground Station allows the Equinox payload to launch directly into its desired orbit and communicate with the station without needing an inclination change maneuver. Alice Springs has two 9 meter antennas, one 3 meter antenna, and one 2.3 meter antenna. It is one of three stations outside of the United States that forms the global Landsat network, which is a mission set of satellites that have similar requirements as the Equinox payload in terms of communication. This ground station is capable of handling S-band signals, which is the chosen form of up and down link for payload communication. This mid-latitude location allows for multiple daily passes in LEO. A 9 meter parabolic dish will be utilized that has an antenna gain of roughly 45 dBi at S-band. As such, the Alice Springs ground station is perfect for this mission, and can easily handle the communication needs.

B. Communications

In order to properly communicate with the ground system, the following up and down link budget was constructed. Because the hardware, locations, and relative signal size are the same, it is assumed that the up-link and down-link will have the same characteristics. In reality, there may be slight variations between the up and down links, but this simplifying assumption is acceptable for primary analysis and verification. The values found for the Equinox mission link budget are highlighted below in table 8.

Table 8. Uplink and Downlink Budget Parameters

Parameter	Value
Transmit Power	40 dBm
Transmitter Antenna Gain	8.3 dBi
Receiver Antenna Gain	45 dBi
Free - Space Path Loss	148.86 dB
Miscellaneous Losses	2.5 dB
Atmospheric Attenuation	0.5 dB
Additional Atmospheric Effects	1 dB
Received Power [dBm]	-59.56 dB
Received Power [W]	1.107e-9

Based on this link budget, it was determined that the host spacecraft shall have an EnduroSat S-band Antenna ISM, which has a frequency of 2400-2450 MHz, a gain of 8.3 dB, an HPBW of 71 degrees, and a mass of 64g[22]. This antenna is a patch antenna and was chosen for its low profile and fixed gain. Helical antennas have higher gain and are directional, and parabolic reflectors have high gains and require precision pointing. The simplicity of the mission communications allowed for a simple and reliable S-band patch antenna. Furthermore, the host spacecraft must be able to interface with the payload to relay all communications. The payload uses a GR740 radiation-hardened onboard computer, which features an 8-port SpaceWire router for internal and external data transfer. To interface with the payload, the host spacecraft needs to have a compatible SpaceWire interface, enabling direct data link connectivity for command relay and telemetry data. With this communication system, the host spacecraft will be able to successfully communicate to the ground system and interface with the payload.

C. Structural

While the X-Sat Venus Class is being provided as the mission's bus, standard assumptions had to be made to ensure accommodation and accomplishment of the mission. It is assumed that the payload will be rigidly connected inside the lower segment of the bus, where the structure of the payload is attached to the structure of the bus. As previously stated, a secondary FEA was conducted with a simplified version of the spacecraft bus during launch loads, and it successfully endured the Falcon 9's ascent. The same mathematical analyses were conducted for vibration as well, which demonstrated that the bus and payload could handle the largest stress condition. The team's assumed primary material for the bus is aluminum-6061, which is a commonly used aluminum alloy for spacecraft.

There is not any available information online about the dimensions of the X-Sat Venus Class bus. The team had to make estimates in order to properly calculate surface areas and moments of inertia, those being approximately 1m x 0.5m x 0.5m for the central bus structure and 1m x 1m x 0.01m for the solar panels, based on the image found on SatCatalog [2]. These assumptions were not perfect but were the only means of ascertaining proper estimates for other components of the mission.

Based on the volume and mass of the payload, the Venus X-Class bus will allow for mission success without any need for modification. The payload requires a rigid connection to the bus before launch

D. Power

Based on the power requirements of the payload, it is necessary to use the dual solar array configuration, which has 444 Watts of generated power. As shown in the power budget, the maximum power draw is less than that generated by the solar panels, such that the battery will not be depleted when in the sunlight. It was also determined in the power subsystem that when in eclipse, the battery will not be fully depleted, so continuous operation is possible with this configuration. As such, the Venus X-Class Bus will enable a successful mission.

When in sunlight, the payload shall receive 352.7 Watts of power, while in eclipse the payload shall receive 362.4 Watts of power from the host spacecraft. Through estimation based on other SmallSats, it was determined that the internal operations of the Venus X-Class bus will not exceed about 20 percent of the total available power. As such, the host spacecraft shall not draw over 81.6 Watts of power for normal operation. It is important here to note that the host spacecraft will also be drawing power for its operations, which is why this requirement is set on the bus, and why extra power is left over from the payload power budget.

E. Propulsion

As previously stated, it is not necessary for the Venus X-Class Bus to have a propulsion system for the mission to be successful. This is because the mission timeline is very short, and it will not require any attitude adjustment or orbit transfers, which is by design. This means that the host spacecraft does not need to waste mass or space on propulsion for this demonstration. For future expansion of this technology, propulsion systems could be useful, which will be explored further in the Future Work section.

V. Risk and Fault Recovery

As previously stated, the Equinox Regolith Refinery's mission is to demonstrate the technology of regolith processing autonomously in microgravity. Because the payload is autonomous, there cannot be any manual fixes in the process. As such, all risk mitigations must be built into the command code prior to launch, with any problems autonomously detected and corrected. The identified risks are demonstrated in Table 9 below.

Table 9. Risks and Mitigation Strategies

Risks	Pre-mitigation	Mitigation Strategy
1. Sequential Operation	Failure in one step would cause mission failure	Sensors at each step, manual overrides
2. Power Draw Fluctuation	Sunlight/shade prevents continuous operation	Activation in sunlight
3. Flow Choking	Material build-up could cause choking in pipes	Sensors at ends of pipes, attempt fluid recycling

Because of its sequential processes that each must occur, there are multiple points of potential faults that could cause mission failure. Each component is a potential point of failure, where the risk level can be mitigated by having sensors before and after each component that scan the passing material for important properties. This can then send information back to the control system to halt, continue, or restart the component process. This risk applies to the crusher, sorter, mixer, and pump. Another risk is potential power fluctuations, which could drain the battery. To mitigate this risk, the operations will only occur in the sunlight, as previously discussed. A third potential risk is flow choking, where the material blocks the passageways. The sensors before and after each component can detect material flow, and if it stops at a component the code will recycle the fluid and restart the component to attempt to unchoke the flow. A color-coded risk matrix showing the risks and mitigations is shown in Table 10 below.

Table 10. Risk Matrix

Very Likely					
Likely			2		
Possible			1	3	1
Unlikely					
Very Unlikely			2	3	
	Negligible	Minor	Moderate	Significant	Severe

In the table above, red indicates a severe and likely failure of the mission. Yellow indicates a significant risk that should be avoided if possible. Green indicates a general level of safety. The team has used the above analysis to ensure that the mission would succeed and be prepared for any risks that may crop up. Mitigations have been shown above, but in the case that the mitigations fail, there isn't much room for descoping due to the nature of the Equinox mission. In the worst case scenario, the team will only be able to prove the technology that was used up until the point of failure.

VI. Future Work

The Equinox Regolith Refinery is near the end of its conceptual stage, whereas most future work focuses on refining designs before moving into the prototyping and testing stage. For the payload, it is still necessary to choose driving motors for the payload that will work in the space environment to use in the crushing, sorting, and mixing sections. The current analysis and design uses feasible RPM and power use based on a variety of on the market motors, but the exact design must still be chosen by way of a trade study. For the thermal component, the locations of the radiative heaters still need to be explored, which can be analyzed and determined using simulations. By refining the design, a more accurate model can be created and tested in simulations, before moving on to the physical prototype. The command code package that litigates the activation and operation of each component in the payload also needs to be developed, which will lead to real testing and accurate data storage requirements.

In terms of host spacecraft analysis, future work would consist of analyzing the mass budget, thermal requirements, structural limits, and internal power usage of the Venus X-Class bus more accurately, with fewer assumptions. This can be accomplished by attaining realistic models of the spacecraft and its inner components from Blue Canyon Technologies, or by attaining helpful data directly from the company. This structural and thermal analysis would be useful to verify mission success and could also allow for the host spacecraft to be modified to better meet the needs of the mission.

In terms of enabling technologies, the Equinox payload is assumed to be part of a larger process. First, others should begin looking at ways of collecting regolith and preparing it for our payload. This requires collection, transportation, and docking mechanisms, and would also require the Equinox Regolith Refinery to be modified to accept material from other spacecraft. Once others have designed and applied autonomous methods of regolith collection, tests could be conducted to interface material between the two spacecraft. After the material is processed, there are many areas for potential expansion, whereas spacecraft that utilize the construction material could be made. Any form of in-space 3D printer would be capable of harnessing the product for use in manufacturing. This would be done in collaboration with Equinox, as the final product of the team's design would be specified to meet criteria for others' printers. If different material compositions were desired, the Equinox payload could be modified to fit those requirements. Finally, future in-space manufacturing plants may require propulsion capabilities for the Equinox Regolith Refinery, such that future work could entail modification to the host spacecraft to allow for precise motion and interaction with other spacecraft.

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