2024 COSMIC Capstone Challenge

Patcher-1: Fully Autonomous 3D Printing Patch Antennas for LEO Applications

Aida Chacon[1], Jimena Morales Perez[1], Diego Del Rio Reyes[1], Danna Martinez[1], Joanne Arellano[1], Joel Lujan[1], Joshua Servantez[1], Osmar Nolazco[1], Evan Griffin[1], Allison Kendrick[1], Andres Lepe[1], Bryan Sifuentes[1], Daniel Cruz-Nava[1]

[1]The University of Texas at El Paso, El Paso, TX

ABSTRACT

This report details the design, development, and implementation of a fully autonomous 3D printing payload for the on-demand fabrication of patch antennas in Low Earth Orbit (LEO). The purpose of the payload is to perform a sequence of three or more operations, in a mostly autonomous fashion to demonstrate in-space servicing, assembly, and manufacturing (ISAM) capabilities. The overall goals of the payload are to upgrade or repair existing satellites. The concept of direct manufacturing in space is convenient since it reduces the need to wait for resupply missions that can carry the essential parts such as the replacement antennas for the LEO satellites. By repairing and upgrading satellites while in orbit, the aim is to allow the satellites to finish their missions to reduce space debris by minimizing early mission decommissioning. It would also allow for the underutilized satellites to be repurposed for communication networking. To prove the feasibility of this concept multiple studies and decisions were conducted. By leveraging innovative manufacturing technologies, the payload considers key challenges of space environment operations, including microgravity, vacuum conditions, and extreme thermal cycling. The design ensures efficient energy usage, seamless automation, and robust performance of the antennas under space conditions.

Introduction

In-space servicing, assembly, and manufacturing (ISAM) missions are expanding the horizons of space. One of the increasing areas of development is on demand 3D printing. The fabrication of parts in Low Earth Orbit (LEO) facilitates the ability to sustain longer space missions and building structures directly in LEO. The team decided to focus on 3D printing patch antennas that may be used in LEO by various other satellites for a variety of purposes. The satellite will feature a robotic arm that will have dedicated printhead nozzles that manufacture multi-material prints. The design will be such that the robotic arm works as a printer and a manipulator capable of grabbing the finished 3D printed patch antennas to install them to other satellites. The 3D printing material will primarily consist of copper filaments for the patch and Polyetherimide ULTEM 1010 for structural purposes of the antenna.

The name given to the payload is Patcher-1. As explained later in the paper, the proposed payload is focused on printing patch antennas. Since the objective is to fix otherwise broken satellites it is essentially mending it like how a cloth patch would bring further use to an old pair of pants. Therefore, both for what the payload of producing and how it is being utilized the name patcher came to be. The additional hyphenated one is because this is the first iteration of the payload concept while also making it look most similar to a mission name.

METHODS

This section describes the methods used to develop the payload concept we are proposing which is meant to fulfill objectives guided by the 2024 COSMIC Capstone Challenge. Our process began by making very broad ideas for the payload concept to fulfill ISAM tasks. Some of these ideas included a type of scavenger that would collect parts from decommissioned satellites to create a new satellite. Another idea was to have a robotic arm that would connect special trusses with a vision system to autonomously create super structures. After much discussion with our professor and our mentor we saw we had more interest for on demand manufacturing in space using technology such as 3D printing.

After further discussion and inspiration from companies such as Space Monkey, which our mentor organized, we found that making antennas for satellites is a marketable and valuable idea. Limited information is found on satellite failure causes since the organizations that launch them report mission success on the basis that it was a learning tool for those who developed it. [18] However, in the few resources we did find that communication failures was one of the causes for mission incompletion and Patcher-1 seeks to remedy it. [18][19] We believe this project has a great technical impact on ISAM missions and will define them in the *technical impact of demonstrated capability* section.

One of the objectives recommended in the COSMIC Capstone Challenge packet was to create technical requirements and review them with our advisor and mentor. In doing so we gained a better understanding of the capabilities we want and need for our proposed payload. The technical requirements were a combination of requirements from the packet as well as ones made by us to ensure the mission's feasibility. The payload requirements [11] include some of the following such as environmental and operational specifications:

- Payload shall be no bigger than 17.0" x 16.4" x 27". [1]
- Electrical components shall not exceed 444 W of power and 10.2 Ah. [1]
- All 3D printed materials shall have a Total Mass Loss (TML) <1% and Collected Volatile Condensable Material (CVCM) <0.1%, minimizing contamination risk.
- The 3D printing system and materials shall operate in a vacuum environment and withstand thermal cycling from -100°C to 120°C.
- CubeSat shall demonstrate the following operations, printing, grasping and monitoring, and installing.
- The satellite mass shall not exceed 70 Kgs. [1]
- The robotic arm shall move and perform the 3D printing autonomously.
- Minimum EIRP for patch antennas (neglecting FSL) shall be 30 dbW

From the requirements we identified the key objectives and design considerations to have a successful payload for automation of the autonomous operations. For example, the printer arm would have to autonomously manage material switching, layer alignment, and quality control. To verify and monitor the progress integrated sensors measure thermal, pressure, and position feedback enabling real-time monitoring for accurate and reliable printing.

The requirements have considered the challenges the payload will endure given the space environment which includes microgravity compatibility. Additionally, vacuum and thermal resistance is accounted for in material selection for design and efficient performance under vacuum and extreme temperature variations (-100°C to 120°C).

Given that the packet outlines that the goal is to '… demonstrate a chain of three or more operations that provide an on-orbit, autonomous ISAM capability" [1] it is important that the payload is self-sufficient. Since we are using the dual cell solar array configuration, we must operate within the power generated from the panels to support continuous operations. Post-processing by the payload with mechanisms for localized heating allow in-situ sintering and stabilization, improving material properties to not require much external help. Further details will be provided in the *Antenna Design and Fabrication Process* section regarding the antenna manufacturing process.

TECHNICAL IMPACT OF DEMONSTRATED CAPABILITY

The predicted impact this concept presents for future space missions are identified and described here. Space grade printers enable the production of essential pieces such as antennas. Our proposed design integrates a manipulator to assemble and install the manufactured component. Patcher-1 seeks to repair satellites whose antenna is damaged or upgrade those whose signal requires improvement for a stable communication to complete their missions. Alternatively, for the satellites who have already completed their mission; they can be repurposed to create communication networks, rather than decommissioning a fully operational satellite. Furthermore, by providing this service to satellites directly in space there will be no dependency on mission resupply missions, meaning it will eliminate the cost and logistical challenges usually needed for such efforts to fix or replace the system entirely with brand new satellites. As a result of fixing and reusing existing satellites, space debris from decommissioned satellites would reduce. Mission lifespans would in turn be extended by replacing critical antennas needed for communication, reducing the need for early decommissioning to support long-term missions.

Currently all the technology used for the payload is based on existing products, materials, and systems, however there is room for improvement. One of the most relevant being in the raw material used to manufacture the patch antennas. The existing filaments we are looking into are described as space-grade yet, they can be further developed for an ins space printing and use environment to ensure their longevity justifying their manufacturing. Additionally, such an in the case of conductive material, the material properties desired to ensure that a stable signal is produced should be closer to that of a metal conductor than a polymer. As for the end effector, it can be outsourced to venders to create the hybrid between a gripper and a dual material hot end and extruder to create the robotic arm. Similarly, the structure, electronics, cooling system, communication etc. can be outsourced to existing companies specialized in creating these components.

FEASIBILITY OF PROTOTYPE MISSION

To accommodate the energy-intensive processes involved in the autonomous 3D printing and post-processing of patch antennas, the power system was upgraded from a single solar array to a double-array configuration. This change significantly enhances the energy capacity of the system, providing a total power output of 444 watts under optimal solar exposure conditions in low Earth orbit (LEO).

Using a daily sunlight exposure estimate of approximately 14.4 hours (60% of the orbital period), the total energy generated per day is calculated as follows:

$$E = \text{Power} \times \text{Time} = 0.444\ \text{kW} \times 14.4\ \text{hours} = 6.4\ \text{kWh/day.}\ [12]$$

This 6.4 kWh/day energy availability enables reliable support for continuous or repeated operation of high-power subsystems, including the heated print bed, extruders, sintering modules, and sensors. The system's energy capacity now supports the execution of complete print and installation cycles each orbit, ensuring the payload's operational feasibility.

Bill Of Materials

This Bill of Materials (BoM) outlines the estimated components and costs for a project focused on 3D printing patch antennas for LEO applications. Key materials include high-performance 3D printing filaments such as ULTEM 1010 and Electrifi conductive copper filament, which are essential for fabricating durable and electrically conductive antenna structures. The system integrates vacuum-rated stepper motors, a custom high-temperature build plate, and thermocouple sensors for precise thermal control during the printing process. It also features a motor controller, camera, and an electric power system, with solar cells for space-based power needs. Additional costs account for structural housing and miscellaneous components like relays and wiring.

The total estimated cost for the payloads main structure ranges from $22,000 to $25,000, excluding custom treatments and future enhancements. This setup supports the development and deployment of functional patch antennas tailored for the demands of LEO environments.

Item	Quantity	Estimate Cost	Source
(ULTEM 1010)	1 kg	$337.00	https://top3shop.com/product/intamsys-ultem-1010-1-75-mm-1-kg
Copper Filament (Electrifi-conductive filament from multi 3D)	1 kg	$205.99	https://shop.thevirtualfoundry.com/products/copper-filament?variant=12352925237331
Vacuum Rated Stepper Motors	6	$1,800.00 - $2,400.00	https://www.linengineering.com/products
Build Plate (McMaster-Carr (custom high-temp templates)	1	$500.00 - $800.00	https://www.mcmaster.com/silicon-
Sensors (Thermocouples)	4	$100.00	https://www.omega.com/en-
Motor Controller	1	$200.00	https://www.adafruit.com/product/3099
Camera	2	$60.00	https://www.omega.com/en-
Electric Power System	1	$15,000.00	https://www.customcells.org/en/space-
Solar Cell	2	$4,000.00	https://www.azurspace.com
Misc (relays, wiring, etc)	-	$500.00	-
Structural Housing	-	$500.00	-
Total		**$23,500.00 - $25,000.00**	

TABLE 1: Bill Of Materials for the Satellite Construction.

INNOVATION

To the best of our abilities we have confirmed that this design is original. After countless hours of research, it was established that individual elements have either been proposed or demonstrated to some degree but have not been integrated to propose what Patcher-1 seeks to accomplish.

Demonstrations

Several technologies have explored on-orbit manufacturing, particularly for antennas and spacecraft components.

- Robotic Arm Manufacturing (RAM) 3D Printing demonstrates the feasibility of robotic arms for additive manufacturing, but its application to antennas in space remains limited. [15]
- Fully 3D Printed Patch Antennas (Metal & Fused Filament) shows ground-based feasibility, but space-based execution is still an emerging area. [16]
- Mitsubishi Electric's In-Orbit FFF 3D Printer introduces high-temperature capabilities, addressing material constraints in space. [17]

Proposals

- OSAM-2 (On-Orbit Servicing, Assembly, and Manufacturing-2) focuses on in-space fabrication of spacecraft components, indicating the industry's shift towards additive manufacturing in space. [14]
- Mitsubishi Electric's Resin-Based Freeform Antenna Manufacturing proposes an alternative material for 3D printing antennas in orbit but has yet to be implemented.[17]

Novelty

While aspects of on-orbit 3D printing and robotic arms have been demonstrated, this approach introduces unique innovations by integrating:

- A combined gripper and 3D printing end effector on a robotic arm, allowing for both fabrication and manipulation in a single system, reducing complexity and mass.
- The capability to print and install directly onto existing orbiting satellites, enabling in-situ upgrades without requiring pre-fabricated spare parts or new launches.

This method enhances in-orbit operational efficiency by minimizing dependency on Earth-launched spare parts and allowing for real-time adaptations, making it a novel and pertinent advancement in space manufacturing.

COMPLETION OF REQUIRED ELEMENTS

Volume, Mass, and Power Requirements:

- The payload is designed to fit within 17.0" x 16.4" x 27", ensuring compliance with volume constraints. The total mass is less than 70 kg, staying within allowable launch limits. A power budget analysis confirms that the dual-array configuration meets operational power requirements. A complete CAD model was developed, integrating all components and verifying that everything fits correctly within the assigned volume. Additionally, materials were assigned to each component to ensure accurate mass calculations.

Operational Support from the Proposed Bus:

- The selected spacecraft bus is capable of supporting all mission operations. Key factors such as thermal management, data transmission, and power distribution have been considered. In cases where additional support is needed, modular power or thermal regulation solutions have been identified as potential mitigations.

Launch Environment Considerations:

- The design accounts for the mechanical loads, vibrations, and thermal fluctuations expected during launch. Structural integrity and material selection have been evaluated through engineering calculations to ensure the payload can withstand launch conditions.

Integration of Multiple Technologies:

The payload demonstrates a useful capability by integrating and sequencing three key technologies:

- Printing: Additive manufacturing for on-orbit antenna fabrication.
- Gripping: Robotic manipulation to position and handle printed structures.
- Installing: Final integration of printed components onto existing satellite structures

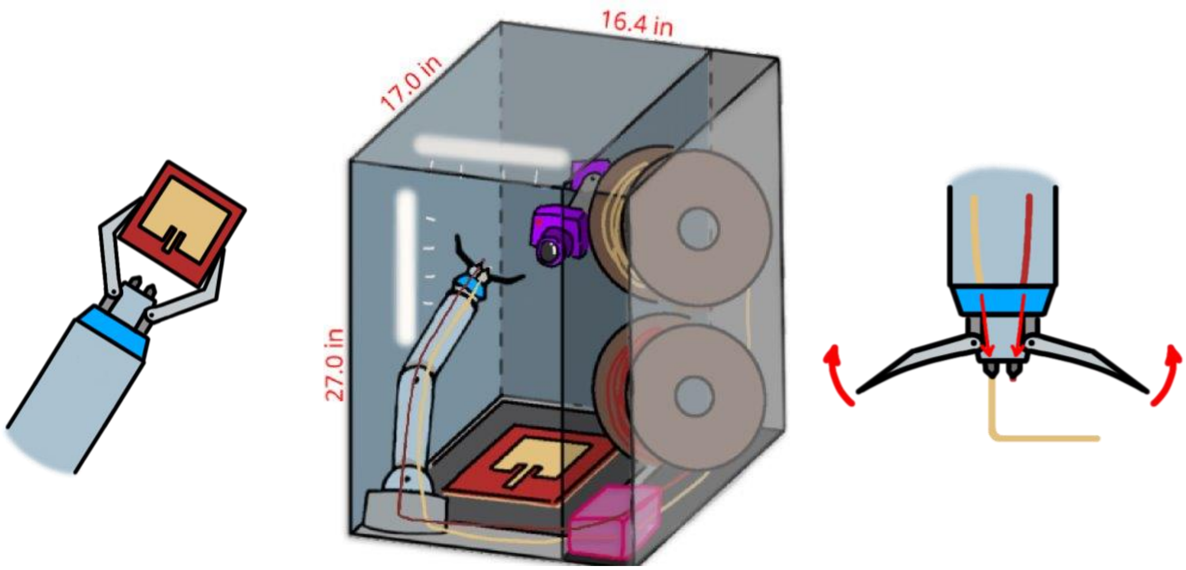

FIGURE 1: Patcher-1 Payload Layout Illustration & End Effector Functions of Printing & Gripping.

Antenna Design and Fabrication Process

To manufacture the 3D printed patch antennas, we need the development of a robotic arm manipulator. The manipulator is to have an end effector that both 3D prints multiple materials with dedicated print heads and also have some part of it that can handle and move the finished printed part. The following are the trade studies used to help us determine the materials and methods to follow for the payload.

The first study conducted was to determine the fabrication method. In the initial stages of the project we immediately designed to use Fused Filament Fabrication (FFF) [2] without considering other methods. Further down the line our mentor presented us to Dr. Salas who has expertise in multiple additive manufacturing methods. She introduced us to Nanojet Electrospray, a rather new technology with limited online resources, which proved to be extremely promising as illustrated in the table. However, since this idea was proposed into the ending stages of the project it was not feasible to redesign for the new configuration on a tight schedule.

FOMs	Weight	Nanojet Electrospray		Aerosol Jet Printing		Fused Filament Fabrication	
	1, 3, or 9	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Print Resolution & Feature Size	9	9	81	3	27	1	9
Material Compatibility	9	9	81	9	81	3	27
Print Speed	1	1	1	3	3	3	3
Ability to Layer Material	9	1	9	3	27	9	81
Energy Consumption	9	3	27	1	9	3	27
System Footprint & Integration	9	1	9	1	9	9	81
Robotic Arm Retrofit Capability	3	3	9	3	9	9	27
Weight Contribution	9	3	27	1	9	3	27
Vacuum & Thermal Stability	9	9	81	3	27	3	27
TOTAL			**325**		**201**		**309**

TABLE 2: Manufacturing Method Trade Study.

After determining the manufacturing method, to keep our concept simple and focused, it was necessary to pick the type of antenna to be manufactured. After researching the main types of antennas used for satellites in LEO it was settled to be between corrugated horn, helix, or patch antenna. The decision boiled down to ease of printing and material efficiency. Additionally, while researching there was a considerable amount of material pertaining to fully printed patch antennas and their performance backing up the concept's feasibility.

FoMs	Weight	Patch Antenna		Helix Antenna		Corrugated Horn Antenna	
		Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Ease of 3D Printing	9	9	81	3	27	1	9
Material Efficiency	9	9	81	3	27	1	9
Performance in Space Conditions	9	3	27	9	81	9	81
Structural Integrity	3	9	27	3	9	9	27
Ease of Assembly	3	9	27	3	9	3	9
Bandwidth and Frequency Range	3	3	9	9	27	3	9
Reusability	1	1	1	1	1	1	1
Manufacturing Time	1	9	9	3	3	1	1
TOTAL			**262**		**184**		**146**

TABLE 3: Antenna Trade Study.

For material selection, we focused on polymers already in use for space applications and identified three candidates: PEEK, PEKK, and ULTEM 1010. Each material was evaluated based on essential requirements for antenna performance under LEO conditions. Considering factors such as thermal stability, printability, mechanical strength, and other critical properties, ULTEM 1010 emerged as the most suitable choice. The trade study details these comparisons and findings.

FOMs	Weight	PEEK		PEKK		ULTEM 1010	
	1, 3, or 9	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Termal Stability	9	3	27	9	81	9	81
Printability	3	3	9	9	27	9	27
Mechanical Strength	9	9	81	3	27	9	81
Space Suitable	9	9	81	9	81	9	81
Dielectric constant (3)	3	9	27	3	9	9	27
Coefficient expansion	3	3	9	3	9	9	27
Cost	1	3	3	1	1	9	9
TOTAL			**237**		**235**		**333**

TABLE 4: Antenna Material Substrate Trade Study.

For the conductive material selection, we compared copper, CNT-PEI, and graphene, evaluating key factors such as adhesion to ULTEM 1010, electrical conductivity, printability, and overall feasibility for the antenna application. Based on these criteria, copper emerged as the most suitable choice due to its superior conductivity, reliable adhesion, and manufacturability. The trade study outlines the detailed comparison and rationale behind this selection.

FOMs	Weight	Copper		CNT-PEI		Graphene	
	1, 3, or 9	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Electrical Conductivity	9	9	81	9	81	3	27
Adhesion to Material	3	3	9	9	27	3	9
Oxidation resistance	9	3	27	9	81	9	81
Printability	3	9	27	3	9	3	9
Radiation Resistance	9	9	81	1	9	1	9
Space Suitability (Long-Term Stability)	3	9	27	3	9	3	9
Cost	1	9	9	3	3	9	9
TOTAL			**261**		**219**		**153**

TABLE 5: Antenna Conductive Material Trade Study.

One of the final trade studies conducted was to determine the best end effector for the multi-purpose robotic arm. From the table it was determined that a two-finger gripper was the best choice since it most easily allows the hotend to print without being in the way. Integrated within the gripper are scraper like edges so that it can pry off the patch antenna from the bed after it is done printing.

FOMs	Weight	Two-Finger Gripper		Three-Finger Gripper		Flexible Robot Gripper (Pneumatic)	
	1, 3, or 9	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Dual Extrusion Capability	9	9	81	3	27	3	27
Object Removal Capability	3	3	9	9	27	1	3
Precision and Accuracy	3	3	9	9	27	2	6
Radiation Resistance	9	9	81	9	81	1	9
Lightweight Construction	3	3	9	1	3	3	9
Autonomous Operation	3	3	9	3	9	3	9
Strength-to-Weight Ratio	9	9	81	3	27	1	9
Robotic Arm Compatibility	3	3	9	3	9	3	9
Power Consumption Efficiency	1	9	9	1	1	9	9
TOTAL			**297**		**211**		**90**

TABLE 6: Gripper Configuration Trade Study.

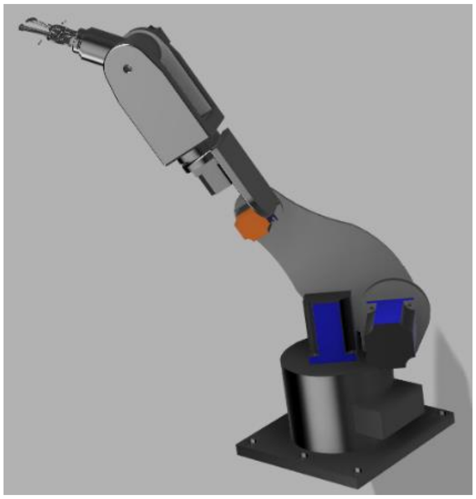

FIGURE 2: Robotic Arm CAD.

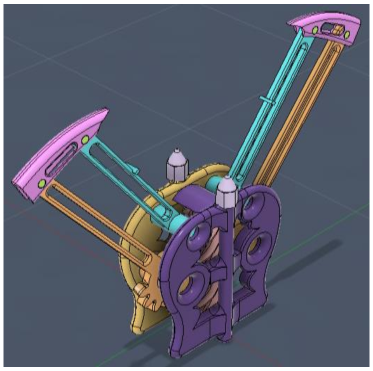

FIGURE 3: Gripper CAD End Effector (Gripping).

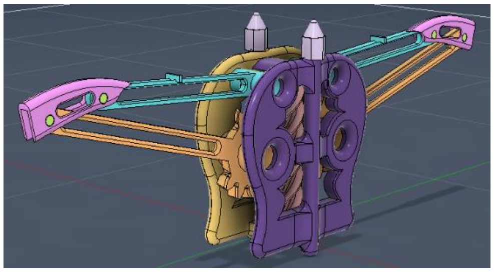

FIGURE 4: Gripper CAD end effector (Printing)

To recap the trade study selections, it resulted in the following:

- Printer setup: a multi-material FFF printer [2] with dual extruders supports processing of ULTEM 1010 and copper filaments for conductive elements. Vacuum-compatible elements: Includes heating components for extrusion and onboard post-processing.
- The materials considered are ULTEM 1010 and copper composite filaments such as Electrifi conductive filament. [2] However, we believe that further material development is needed to create a more robust and efficient patch antenna but for the purposes of our calculations we will use the proposed filaments.
    - ULTEM 1010 (structural material for antenna substrate):
        - Purpose: provides robust structural integrity of the antenna.
        - Advantages: lightweight, thermally stable, and radiation-resistant, making it suitable for LEO environments.
    - Copper Composite Filaments (conductive traces for the patch):
        - Purpose: enables radio frequency (RF) signal transmission.
        - Advantages: combines conductivity with reduced weight, making it ideal for space applications.
        - Disadvantages: requires high power draw from the satellite it is installed to have efficient data transmission.

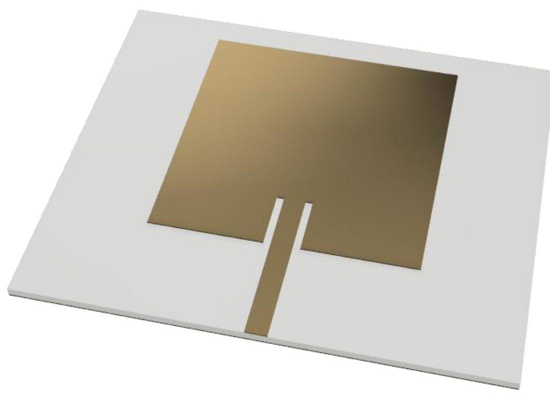

FIGURE 5: Fully 3D Printed Patch Antenna Design Made From Research Paper [2]

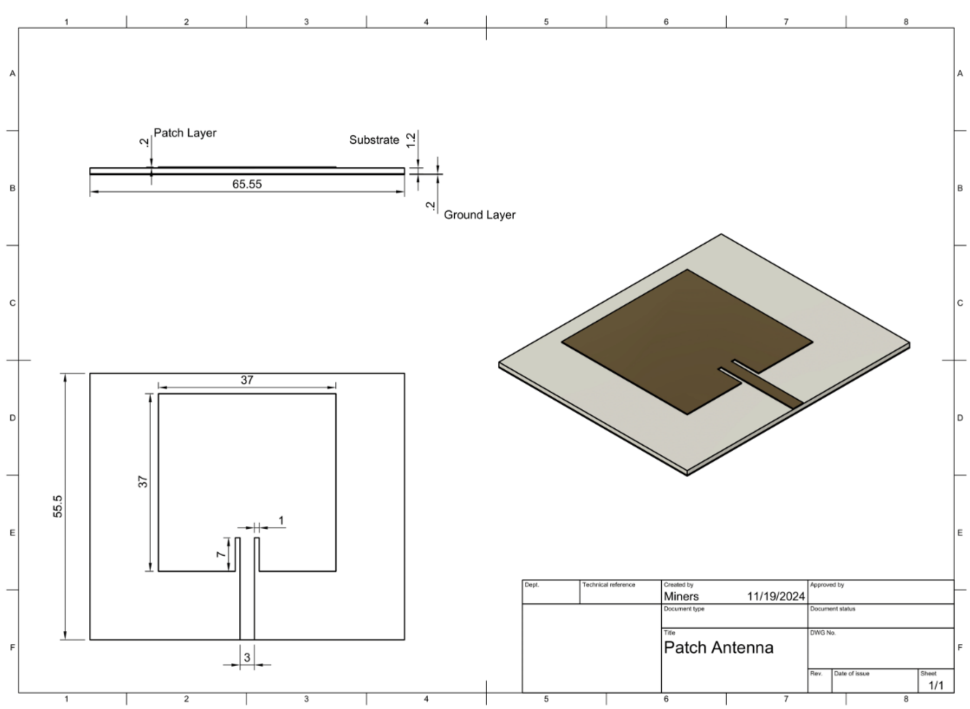

FIGURE 6: Drawings Of The Fully 3D Printed Patch Antenna Design [2]

As for the process, we are inspired from the work done by Dipankar Mitra, where they manufactured a patch antenna entirely using FFF [2]. From their work, we understand that a patch antenna can be fabricated from two filaments. One filament is conductive while the other is not to serve as the substrate needed to separate the ground layer from the patch layer of the antenna. The printing workflow is as follows:

- The ground layer would first be deposited creating a solid rectangle of conductive filament.
- The ULTEM 1010 is then deposited over the same surface area and serves as a structural foundation since it is the thickest material layer. It also creates the separation between the conductive layers to make the patch antenna functional.
- Finally, another thin layer of conductive filament in the shape of the patch is added. This layer also includes the trace that will be used later for the installation of the antenna. Localized heat during deposition can enhance the bonding and conductivity of the traces.
- Real-Time monitoring from sensors checks material alignment, temperature, and deposition quality. Additionally, strategically placed cameras provide further monitoring and verification of the success of the antennas.

We are considering post processing, as mentioned above, to make the result be durable and of high quality. These standards supplement our goals of repairing and upgrading antennas to ensure the longevity of orbiting satellites. Such processes we are considering are in-situ sintering and annealing [3][4]. In-situ sintering is a heat-based process where the copper composite material is strengthened, and its particles fused below the melting point. We can achieve this in the payload by using the printer itself with localized heating elements to sinter the conductive traces immediately after deposition. This improves the conductivity of the traces, ensuring efficient RF performance. This step ensures the antenna’s conductive elements are robust and functional for signal transmission in LEO. Annealing is another heat treatment process. This process relieves internal stress, stabilizes the material structure, and improves mechanical properties. Similarly, the printer can also do this by applying controlled, localized heating to anneal the ULTEM 1010 substrate after printing. This step enhances the material's dimensional stability and resistance to thermal and mechanical stresses encountered in space. This step provides the 3D printed antenna with the structural integrity for long-term operation in space.

ANIMATE KEY OPERATING SEQUENCE

To visualize our payload’s mission, we utilized two software tools: Fusion 360 for creating the CAD models of each component, and Blender for developing the animation. The animation illustrates the full mission sequence of our payload—from approaching the target satellite, to installing a patch antenna. Once the payload reaches a predefined distance, the robotic arm initiates the 3D printing of the patch antenna. Upon completion, the payload’s hatch opens, allowing the robotic arm to install the antenna onto the satellite that requires it.

To achieve a realistic and visually engaging animation, we made use of Blender’s Shader Editor to create the space environment and added lighting to highlight the satellite and payload. For animating the robotic arm, we constructed an armature using joints, enabling us to simulate the motion that would be driven by stepper motors in a real-world scenario. These techniques helped us accurately represent both the mechanical functionality and the operational sequence of our payload.

STORYBOARD OF COMPLETE OPERATION

The storyboard was created to visually illustrate the step-by-step mission of a payload designed for in-space manufacturing and satellite servicing. Using a storyboard helps clearly communicate complex processes in a simplified and structured manner, allowing team members, stakeholders, and reviewers to understand the sequence of operations at a glance. It serves as a visual guide to align technical objectives with the actual deployment plan, from initial launch preparations to the final execution of the mission. This storyboard in particular showcases the importance of coordination, communication, and precision in space missions involving autonomous payload operations.

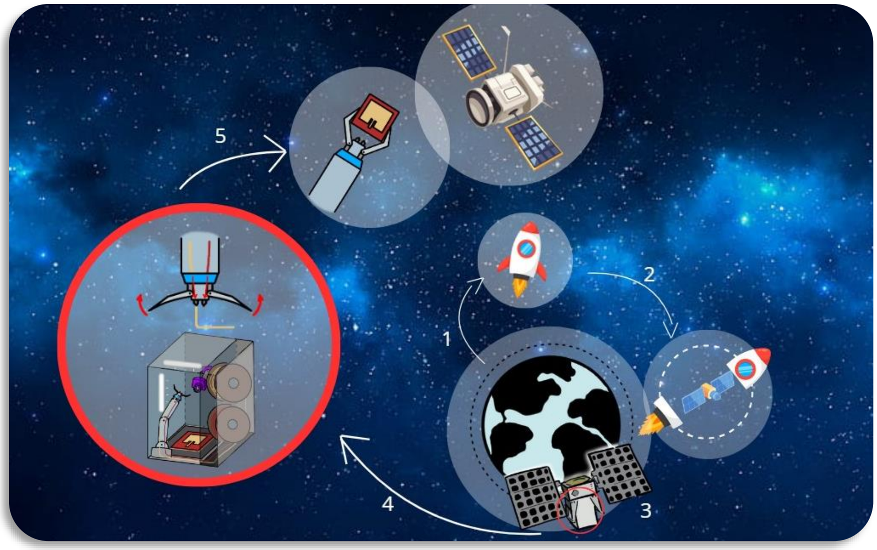

FIGURE 7: Concept of operations from describing operation from launch to LEO.

The storyboard begins with securing the payload inside the rocket fairings, followed by its integration into the launch vehicle. Once launched into LEO, the payload is deployed, and communication is established with the operations center. Upon confirmation, the payload receives commands to heat the extruders and print bed, reaching the required temperature to begin fabricating a patch antenna using a preloaded STL file. After printing, the antenna is allowed to cool before being picked up by a robotic arm. The payload then opens a sealed compartment door, allowing the arm—guided by an internal camera—to place the patch antenna onto the target satellite. This storyboard illustrates not only the payload's advanced in-space capabilities but also the careful planning and automation needed to carry out such a sophisticated mission.

DATA HANDLING AND COMMS

The communication architecture of the COSMIC payload is designed to support its fully autonomous operational model. Real-time downlink capability is essential for transmitting telemetry, sensor data, and visual feedback from onboard cameras during fabrication tasks. This ensures that ground operators can verify process integrity and intervene, if necessary, through scheduled uplinks.

Due to the system's autonomous functionality, no human observer is required onboard or in constant contact. Monitoring is handled by integrated sensors and cameras, with decision-making executed by onboard control logic. Similarly, no continuous operator presence is required; operator intervention is limited to pre-mission programing and post-event response.

The estimated data transmission requirements are as follows:

- Sensor telemetry: ~1.6 kbps
- Compressed video feeds: up to 500 kbps per camera
- System logs and status updated: 10-50 kbps

The combined peak downlink demand during active print phases is estimated at approximately 1 Mbps. [13]

The payload's communication system must fulfill several operational and environmental requirements to ensure mission success. Key requirements include support for real-time downlink of video and sensor telemetry, as well as low-latency uplink of command sequences. Given the LEO operational environment, the system must be capable of buffering data during blackout periods where communication is unavailable.

Additionally, a persistent beaconing system is necessary to transmit health and status updates, even when full data transfer is not possible. The communication subsystem must be integrated within the payload's constrained volume (17.0" x 16.4" x 27") and must operate reliably within the overall 444-watt power budget. It must also be capable of functioning in the extreme thermal conditions encountered in space, ranging from −100°C to +120°C.

POWER AND ENERGY REQUIREMENTS

The power system for the payload must meet the substantial energy demands of 3D printing operations while staying within the constraints of the 444 W solar array. This section outlines the energy requirements, strategies to manage power, and how the payload ensures operational feasibility in LEO.

Printing Operations

The energy-intensive nature of high-temperature printing and conductive material deposition drives the following requirements:

- ULTEM 1010 Extrusion: Requires approximately 444 W for high-temperature heating. [5]
- Copper Composite Deposition: Demands about 50-120 W for conductive material processing.[6]
- Total Printing Energy: A full antenna fabrication cycle consumes an estimated 3–5 kWh.[6]

Post-Processing

- Post-fabrication processes are necessary for material stabilization:
- Sintering and Annealing: These thermal treatments consume 0.2–2 kWh.[6]
- Total Post-Processing Energy: The combined post-processing phases require 1.96 kWh per patch.

Additional Power Consumption

- Sensors and Control Systems: Continuous operation requires 0.25-0.6 kWh.[6]
- Overall Energy Use: The cumulative energy requirement for antenna production, including printing and post-processing, totals 1.96 kWh.[6][7]

Addressing Solar Array Constraints

Solar arrays in LEO generate power only during sunlight exposure, typically 60% of each orbit, as Earth's shadow blocks sunlight during the remaining time. The solar array on this payload operates at 30–38% efficiency, typical for multi-junction cells in LEO. This efficiency determines the maximum power output and affects the overall energy available for operations. [7][8][9]

Energy Storage System

To address power limitations and accommodate the energy spikes of high-demand operations:

- Battery Integration: A 15–20 kWh lithium-ion battery system is included to store energy during sunlight periods for use during shadowed phases or peak power requirements.[7][8]
- Capacity Design: This ensures sufficient energy for at least one antenna fabrication cycle, considering inefficiencies and power management overhead.

Power Management Strategies

Duty Cycling

- High-energy tasks, such as extrusion and post-processing, are scheduled during sunlight exposure or when battery reserves are sufficient.
- Low-power operations (e.g., sensors and controls) are maintained continuously, as their power consumption remains within the real-time output of the solar array (50–100 W).[9]

Optimized Solar Panel Design

- Expandable Arrays: Deployable solar arrays maximize available surface area without significantly increasing the payload mass.[9][10]
- Advanced Solar Cell Materials: Lightweight, high-efficiency thin-film solar cells (efficiency >20%) are employed to enhance energy output.[10][7]

Energy Optimization Techniques

Preheat Optimization

- Preheating of the printer's hot-end and heated bed is optimized to reduce standby energy consumption. Material Efficiency.[5]
- Material usage is minimized through precise extrusion and reduced energy density for non-critical layers, conserving power without compromising print quality. [6]

Feasibility Analysis

The 444 W solar array can generate approximately 6.4 kWh per day under optimal sunlight exposure (60% of orbit time in LEO). [8] This energy is sufficient to recharge the batteries and support:

- One antenna fabrication every 1–2 days, depending on the operational schedule and specific energy consumption of the printing cycle.[9]
- STK simulations shown that a LEO orbit with a single array may be capable of producing 2.25kW per day, however, if paired with power management, the power production of the satellite will increase.

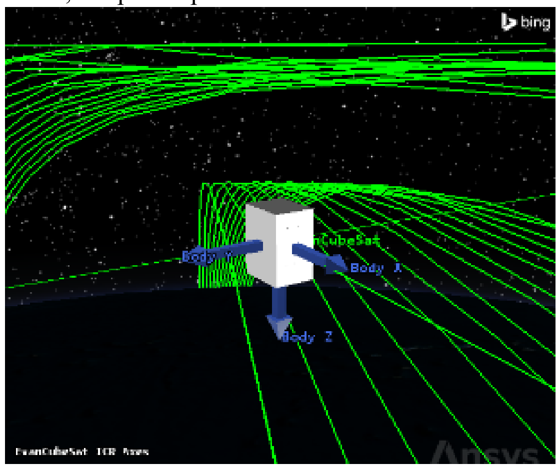

FIGURE 8: STK Analysis For Power Generation (Conducted With The Single Array Configuration)

Identify & Mitigate Risk

The risk identification and mitigation process is a key component of systems engineering, ensuring that potential threats to a project's success are systematically recognized and addressed. This structured process involves determining what could go wrong, evaluating the severity and likelihood of each risk, and implementing measures to reduce their impact on the project. The higher the risk, the more important the system, or component, needs to be reinforced. The purpose of any risk identification and mitigation process is to be improved, reconstructed, referenced, and developed for any possible scenario throughout any possible outlying factor as the project develops further; this process is never-ending.

Risk Identification Process

The identification process begins by analyzing the project's mission objectives and constraints to identify potential risks. For the COSMIC Capstone Project, the first and most important study is the payload's survivability through various mission phases—launch, operation in the LEO environment for three years, and deorbiting.

The following steps were applied:

1. **Categorization of Risks**: Risks were divided into three main categories based on the mission lifecycle:
   - **Launch Survivability**: Risks related to structural or functional failures during the high-stress launch phase.
   - **LEO Operations**: Risks concerning payload degradation or failures due to the harsh space environment, including radiation, thermal cycling, and microgravity effects.
   - **Deorbit Capability**: Risks associated with the failure of deorbit mechanisms, leading to non-compliance with reentry requirements.
2. **Brainstorming and Data Gathering**: Inputs were gathered from team discussions, mentor concerns, research on similar space missions, and historical data on satellite payload failures to identify potential issues in each category.
3. **Risk Documentation**: Identified risks were systematically documented in a Risk Register. Each entry included:
   - A detailed description of the risk.
   - The conditions or events that could trigger it.
   - The mission phase it would affect.

Matrix Template

Risk ID	Risk Description	Likelihood	Impact	Risk Score	Category	Mitigation Strategy	Owner
A	High G-forces during launch may damage payload.	Medium	High	9	Launch	Conduct vibration tests; use shock absorbers.	Structural Engineer
B	Thermal fluctuations in LEO may affect electronics.	High	Critical	20	LEO Environment	Design thermal insulation; incorporate active cooling.	Thermal Systems
C	Micrometeoroid or debris impact in LEO.	Medium	High	9	LEO Environment	Use shielding (e.g., Whipple shield); monitor debris.	Systems Engineer
D	Radiation exposure may degrade payload materials.	Medium	High	9	LEO Environment	Use radiation-hardened components; test materials.	Materials Team
E	Failure of deorbit mechanism could leave debris in orbit.	Low	Critical	4	Deorbit-ability	Design redundant deorbit system; verify reliability.	Propulsion Team
F	Communication loss during deorbit phase.	Medium	Moderate	6	Deorbit-ability	Develop robust telemetry systems; test during simulation.	Avionics Team
G	Payload functionality may degrade due to combined stressors from launch, LEO environment, and deorbit phases.	Medium	Critical	12	Cross-phase (Launch, LEO, Deorbit)	Perform integrated system testing under simulated conditions for all mission phases; build redundancies into critical subsystems.	Systems Integration Team

TABLE 7: Risk Analysis of General Satellite Survivability.

Mitigation Planning Process

Mitigation involves devising strategies to reduce the likelihood of a risk or its impact. For the COSMIC Capstone Project, specific mitigation plans were tailored to each risk category:

1. **Launch Survivability**:
   - **Identified Risk:** Structural failure during launch vibrations.
   - **Mitigation Strategy:** Strengthening payload housing using reinforced materials and shock-absorbing mounts. Testing with vibration simulators was proposed to validate the design.
2. **LEO Operations**:
   - **Identified Risk**: Degradation of sensitive components due to radiation exposure.
   - **Mitigation Strategy**: Selection of radiation-hardened materials and protective coatings. Incorporating redundant systems for critical functions to ensure reliability.
3. **Deorbit Capability**:
   - **Identified Risk**: Failure of the deorbit mechanism, resulting in prolonged orbital debris.
   - **Mitigation Strategy**: Designing a robust deorbit propulsion system or passive drag mechanism. Conducting simulations to ensure reliability under worst-case scenarios.

Each mitigation plan was documented in the Risk Register, outlining the action steps, responsible team members, and expected timelines for implementation.

Risk Assessment Process

Once identified, each risk was evaluated to determine its severity using a **Likelihood × Impact (L × I)** scoring method:

1. **Likelihood (L)**: Defined as the probability of the risk occurring, ranging from Low (e.g., 1) to High (e.g., 5).
2. **Impact (I)**: Defined as the severity of consequences if the risk occurs, ranging from Minor (e.g., 1) to Critical (e.g., 5).
3. **Risk Score**: The product of Likelihood and Impact (L × I), used to rank and prioritize risks on a Risk Assessment Matrix.

   The matrix visually categorized risks into tiers:
   - **Low Risk (Green)**: Risks with minimal impact or low likelihood, requiring periodic monitoring.
   - **Medium Risk (Yellow)**: Risks that might disrupt mission objectives but can be managed.

- **High Risk (Orange)**: Risks with significant potential for mission failure, requiring immediate attention.
- **Critical Risk (Red)**: Risks with catastrophic impact, demanding urgent mitigation or contingency plans.

Likelihood	Description
Low	Rare occurrence, less than 10% more
Medium	Possible occurrence, 10-50% chance.
High	Likely to occur, over 50% chance.

	Impact	Minor	Mode-rate	High	Critical
Likelihood	Low	1	2	3	4
	Medium	3	6	9	12
	High	5	10	15	20

Impact	Description
Minor	Minimal effect on mission success.
Moderate	Partial loss of functionality or delays.
High	Significant effect; requires major mitigation.
Critical	Total mission failure if not addressed.

Iterative Review and Refinement

The risk identification and mitigation process is not static. Periodic reviews were conducted to:

- Add new risks as the project evolved.
- Update risk likelihood and impact scores based on design changes or new test data.
- Verify the effectiveness of implemented mitigation strategies through simulations and analyses.

The risk identification and mitigation process ensure that potential issues are addressed proactively, reducing the likelihood of mission failure. By prioritizing risks based on severity and implementing targeted mitigation strategies, the COSMIC Capstone Project is better positioned to achieve its objectives of payload survivability through launch, extended LEO operation, and controlled deorbiting. This framework is a critical foundation for ensuring mission success.

INNOVATIVE CONCEPTS

Throughout the development of the payload, several ideas were explored, many of which we integrated while others were not. In this section we highlight the most innovative concepts we thought would bring about advancements and novel ideas to future ISAM missions.

The multipurpose 3D printing and gripping robotic arm is an idea we found to be very innovative and useful. While investigating, no resources came up for this particular combination. Although RAM robots exist, they tend to have only one function leveraging the multiple degrees of freedom that robotic arms have to offer. For example, some RAM robots will only focus on welding parts, while others focus on aligning the pieces, but one arm never does all functions. This is why the combination of FFF 3D printing with an integrated gripping mechanism on a robotic arm stands out to us. Facilitating in-situ manufacturing and installation of patch antennas without human intervention, reducing mission complexity and mass.

As for the concepts that were not integrated into the payload, two main ideas stood out. The first was to harness the solar heat to facilitate the sintering processes. The sintering process is important because it enhances material properties for higher-quality signal performance, which is essential for the goal of Patcher-1. Solar sintering would cut the energy consumption needed from the solar panels to complete the manufacturing process while in LEO. It would reduce or eliminate the need for traditional heating elements, requiring less components, which in turn makes the payload lighter and more cost-effective. This idea came about when Dr. Salas inquired about how the nozzles would be capable of providing the temperature levels to sinter the antenna.

The other integrated concept was mentioned earlier in the manufacturing selection trade study. Overall, this manufacturing method was a new discovery to everyone on the team and has extremely promising features. Such as the high precision printing compared to an FFF printer and the material it deposits to create the 3D structures. The material extruded through a nozzle similar to that of an airbrush is nano particles suspended in a liquid. It can print on any surface shape and can print without contacting the build plate. Since the material is pure and not a composite it reduces the off-gassing significantly. Additionally, this method does not require a constantly heated nozzle or bed, only sintering the end print potentially offering better durability for space applications.

Unfortunately, since these last two ideas we developed by the end, most of the calculations had already been completed and would not allow enough time to integrate the idea.

TECHNOLOGY GAP ASSESSMENT

- Advanced space-grade filaments
  - Challenge: Current filaments have significant off-gassing that can pose a risk to spacecraft operations and the overall quality of 3D-printed components.
  - Development Need: New materials with low off-gassing to improve print quality and reliability in the harsh conditions of space.
- Power & Thermal Management for On-Orbit 3D Printing

- Challenge: High-power 3D printing systems may disrupt CubeSat operations, and excessive heat buildup can damage sensitive electronics.
    - Development Need: Efficient power regulation systems and thermal control strategies to ensure stable operation without exceeding spacecraft energy budgets or overheating components.
- In-Situ Antenna Performance Validation
    - Challenge: 3D-printed antennas in space require real-time performance verification to address RF behavior, electromagnetic interference (EMI), and frequency tuning challenges.
    - Development Need: On-orbit testing and calibration techniques to standardize integration with CubeSats and small satellites, ensuring reliable communication performance post-fabrication.

PATH TO PDR

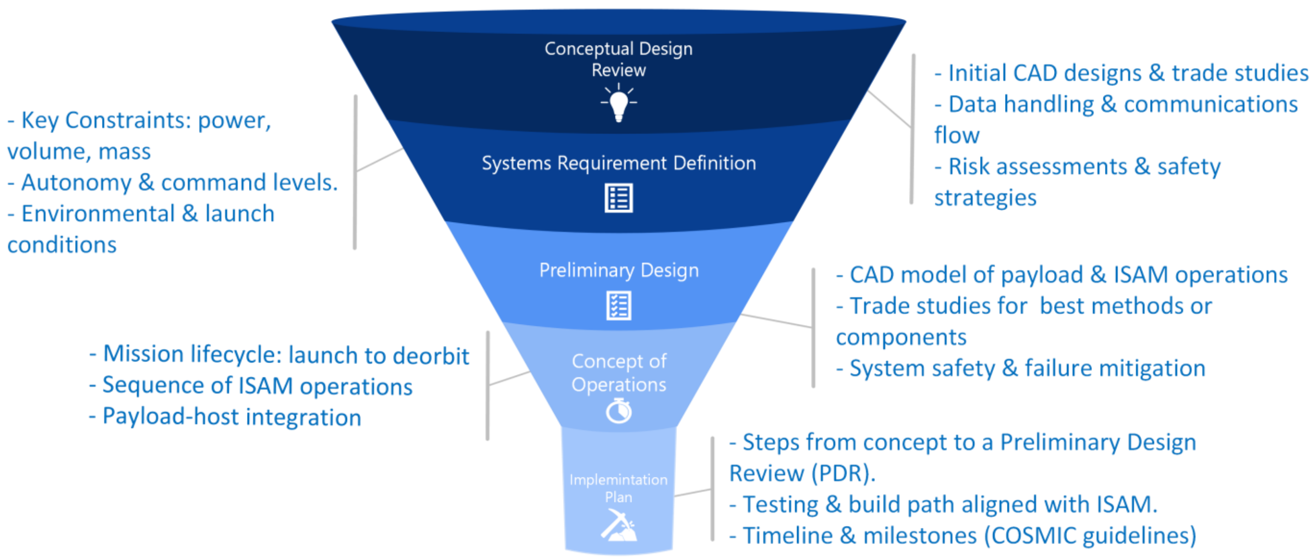

FIGURE 9: Preliminary Design Review Diagram.

CONCLUSION

The Patcher-1 payload presents a novel and practical approach to in-space servicing assembling and manufacturing by enabling the autonomous fabrication and installation of patch antennas in LEO.

Challenges were faced especially with the initial concept decision. As a team we were going between a handful of ideas such as a scavenging robot or a super structure manufacturer. However, we did not become engaged in the ideas until we got more focused on a more specific additive manufacturing purpose. The next challenge after deciding that we wanted to print antennas for satellites was how to make it an innovative idea. Initially we thought of a robotic arm and a 3D printer working separately to complete the task. After much debate we concluded on creating a multi use robotic arm that can both 3D print and manipulate the finished antennas to then install them. The last challenging aspect was balancing all the energy demands of the system. At first this was difficult because we were using the single array configuration that provided 222W but later we were able to transition to the dual array providing us with 444W.

Additional challenges such as microgravity, vacuum conditions, and thermal cycling, must be considered for the system to enable the efficient, on-demand production of high-performance antennas. Integration of innovative materials like ULTEM 1010 and copper composite filaments, combined with advanced post-processing techniques such as in-situ sintering and annealing, ensures structural and functional reliability under space conditions. Furthermore, the payload's energy-efficient design, using solar arrays and battery systems, aligns with the power constraints of space operations. The successful development of this concept lays the foundation for sustainable, adaptive manufacturing in LEO, contributing to establishing a foundation for further refinement and deployment in future missions.

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