College of Engineering

Department of Mechanical and Aerospace Engineering

Technical Report

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Team # 32

ASTELAR

The 2024-25 COSMIC Capstone Challenge

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With approximately 580 satellites operating in GEO and an average replacement cost of $250 million, maintaining and upgrading these assets is both economically and operationally critical. The ASTELAR satellite servicing system will be central to the mission, focusing on life-extending operations for satellites in the GEO belt. ASTELAR’s proposed life-extension mission integrating the combination of autonomous repair and replacement of solar cells for satellites and debris management will enhance satellite reliability, contributing to sustainability goals while achieving commercial profitability, and setting a new standard for sustainable satellite operations in GEO. By utilizing robotic arms and advanced diagnostic systems, the mission autonomously identifies and replaces damaged solar cells extending their operational lifespan. Additionally, an orbital depot will be established supporting the mission aims to store spare parts, refuel servicing vehicles, and facilitate debris tracking. The mission will be to repair and maintain the 16 Intelsat Galaxy satellites, ensuring their continued operation and maximizing their commercial viability. Materials and components are selected to withstand extreme space conditions, with emphasis on the vacuum of space, microgravity, radiation, and thermal variations. CAD software will be employed to generate essential views that illustrate the operational workflows and structural integrity of the payload.

Table of Contents

Table of Figures

Table of Tables

1.0 Project Management

1.1 Project Description-Technical Impact of Demonstrated Capability

Consortium for Space Mobility and In-space Servicing, Assembly and Manufacturing Capabilities (COSMIC) Capabilities

The increasing congestion of Earth's orbits and the growing demand for sustainable space operations have underscored the necessity for advanced In-Space Assembly and Manufacturing (ISAM) technologies. This project focuses on a payload designed to autonomously demonstrate ISAM capabilities, through a series of interconnected operations. The goal is to prepare for complex ISAM missions that could potentially be ready for launch by the end of the decade, emphasizing the importance of self-sufficient systems in space and paving the way for advanced manufacturing processes beyond Earth. The proposed mission integrates autonomous repair and replacement of satellite components, specifically solar panels, to enhance the longevity of telecommunications satellites in geosynchronous orbit (GEO). By utilizing robotic arms and advanced diagnostic systems, the mission will autonomously identify and replace damaged solar cells, reducing the need for costly satellite replacements and extending their operational lifespan. Additionally, an orbital Depot will be established to store spare parts, refuel servicing vehicles, and facilitate debris tracking and management. A key aspect of this mission will be the repair and maintenance of 16 Intelsat Galaxy satellites, ensuring their continued operation and maximizing their commercial viability.

The ASTELAR satellite servicing system will be central to the mission, focusing on life-extending operations for satellites in the GEO belt. With approximately 580 satellites operating in GEO and an average replacement cost of $250 million, maintaining and upgrading these assets is both economically and operationally critical. The servicing vehicle will autonomously rendezvous and dock with client satellites, replace damaged solar panels, transport faulty components to the orbital Depot, and undergo periodic refueling to extend its capabilities. The mission lifecycle will be meticulously planned, covering all phases from launch to deorbiting while ensuring compliance with environmental and sustainability regulations. Materials and components will be selected to withstand extreme space conditions, such as the vacuum of space, microgravity, radiation, and thermal variations, ensuring the mission's longevity and effectiveness. To effectively visualize and communicate the design, CAD software will be employed to generate essential views that illustrate the operational workflows and structural integrity of the payload.

ASTELAR’s life-extension services sets a new standard for sustainable satellite operations in GEO. The combination of autonomous repair, in-orbit refueling, and debris management will enhance satellite reliability, extend operational lifespans, and reduce reliance on new satellite launches. Additionally, through international collaboration, this mission aims to promote responsible space traffic management, mitigate debris accumulation, and support the long-term viability of geostationary orbit, ensuring sustainable growth of the global space economy.

1.2 Prototype and Test Results

The robotic arm utilized for the COSMIC project prototype is the SES-V2 Robotic Arm, designed with five degrees of freedom for precise and versatile operation. With a maximum height of 21.92 inches, a maximum reach of 17.93 inches, and 360-degree rotation capability, the arm is compact yet highly functional. The prototype focuses on demonstrating the feasibility of a satellite payload equipped with In-Space Assembly and Manufacturing (ISAM) capabilities. Key operations simulated include satellite servicing tasks, such as recycling and repair processes, with a specific emphasis on solar panel replacement. This prototype highlights the potential of autonomous robotic solutions for satellite maintenance and operational longevity in space.

As demonstrated in the battery shown in Figure 1, it will be the power source that will allow the robotic arms to accomplish numerous movements and operations. The battery is intended to provide electrical power to the motors and actuators that operate the arms’ movements, the sensors, and computers that govern the fine movements of the arms during its tasks. This specific battery was chosen after a comparison of several batteries in terms of the reliability, efficiency and ability to integrate with the system. Interestingly, this battery was also suggested to us by the supplier of the robotic arms to guarantee compatibility and functionality in our design. Being a reliable device with all necessary characteristics that meet the mission requirement, it becomes an essential part of our system.

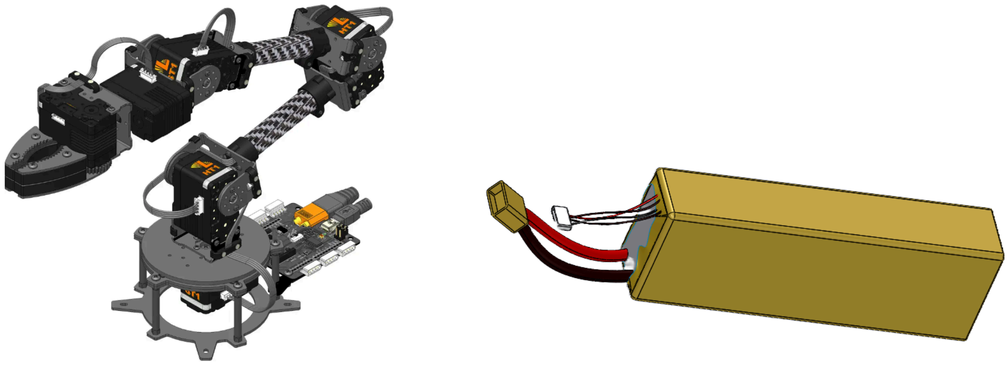

Figure 1: Robotic Arm CAD Model and Socokin Lipo Battery

The Venus VCT X-CLASS V-Sat bus is a strong and multi-mission satellite system for communication, observation, and science. This design has a modular payload accommodation system, innovative power and propulsion, and thermal control to address the harsh environments encountered in space. As shown in Figure 2, the V-Sat bus is used as the satellite vehicle in our design to offer the basic structure and systems that are essential to accommodate our payload and robotic arms. A high payload capacity, flexible interfaces, and dependable subsystems guarantee the implementation and functionality of all essential equipment to accomplish our goals.

1.2.1 Current Material Budget

The material budget is outlined below in Table 1. As of now, the current total budget remaining is $3,413.89, with $1,500 of that set aside for the team's travel and emergency fund. The $1,913.89 remaining has acted as a buffer for the testing period of the project, which has ensured that we remain within budget in case of emergencies.

Table 1: Current Material Budget - Prototype

Current Material Budget				
Total Budget Awarded	Total Budget Spent	Total Budget Remaining	Total Allowance Remaining	Travel/Emergency Fund
$ 6000	$ 2586.11	$ 3413.89	$ 1913.89	$ 1,500

1.2.2 Approach to Instrumentation and Manufacturing

In order to accomplish our technological goals, we established a test plan and the necessary instruments to fulfill our system requirements. The most crucial instruments for the close proximity operations, other than the robotic arm payload, are the cameras, sensor system, and attitude control systems. These allow the Servicer to safely approach the Depot or the client satellites for docking and solar repairs.

Table 2: Instrumentation and Test Facilities

Instrumentation	**Purpose**	**Test Facilities**	**Purpose**

Multimeter	Measure voltage, current and resistance	**Materials Testing Lab**	Conduct tensile, stress, and hardness tests
Tensile Testing Machine	Test material stress and strain	**Robotics Test Bench**	Test robotic arm for range of motion and load capacity
Stress Simulation Software (ANSYS)	Perform stress analysis on materials	**Electronics Lab**	Conduct battery testing, safety checks, and power output tests
Dynamometer	Load testing for robotic arms and battery testing		
Infrared Camera	Perform thermal analysis of batteries during tests		
Arduino	Test control system of robotic arms		

Table 3: Testing Plan

Test Plan	
Test 1	**Test 2**
Solar Cell Recognition & Damage Detection	Robotic Arm Motion Routine
Procedure: Camera Recognizes all solar cells, and determines damaged panels, sends information to robotic arms on what cell requires replacement. Success Criteria: Must detect solar cells and identify damage with high accuracy. Feedback/Improvement Plan: Enhance model training, refine detection logic.	Procedure: Robotic arms pick up, scan, and sort solar cells. Success Criteria: Must perform correct sorting without causing additional damage. Feedback/Improvement Plan: Improve motion stability, refine gripping technique.

1.3 Innovation

The Intelsat Galaxy satellites are a series of geostationary satellites that provide telecommunication and broadcasting services. Over time, their operational efficiency is impacted by the degradation of solar panel cells. Two clusters of Intelsat Galaxy satellites in GEO were identified as ideal targets due to the distances between satellites. A visualization of the client satellites can be seen in Figure 2. The mission involves a system of one Depot and a fleet of six Servicer satellites, designed to operate in GEO to service the two clusters of Intelsat Galaxy satellites. Figure 2 provides a visual representation of the ASTELAR system in conjunction with the O.R.I.O.N system.

During the initial stages of this project, several ideas were explored for how our ASTELAR Servicer could provide life extension services. When looking into current satellite servicing missions, it was found that there have been a few missions that have attempted to service existing satellites. For the ASTELAR mission, we explored refueling of other satellites, repairing damaged paneling, and performing battery replacements and electrical repairs. Currently, the most noTable in-space servicing mission is Northrop Grumman's Mission Extension Vehicle (MEV) mission, which successfully docked with its client in 2020. The MEV-1 operates as a life extension service by providing additional propulsion to its client satellite. This was one of the first successful demonstrations of in-space servicing, and several missions are currently attempting to follow suit. Our mission is unique in that we are performing life extension services through power systems repairs, which has not been demonstrated before.

The mission's primary objective is to extend the operational lifespans of 16 active Intelsat satellites by replacing their solar panel cells; this timeline can be seen in Figure 3. After being launched into GEO and strategically positioned within both Intelsat Galaxy satellite clusters, the Depot facilitates docking, refueling, and resupply operations, eliminating the need for costly resupply missions from Earth. The Depot will also be equipped with advanced debris tracking and identification systems to monitor the GEO environment.

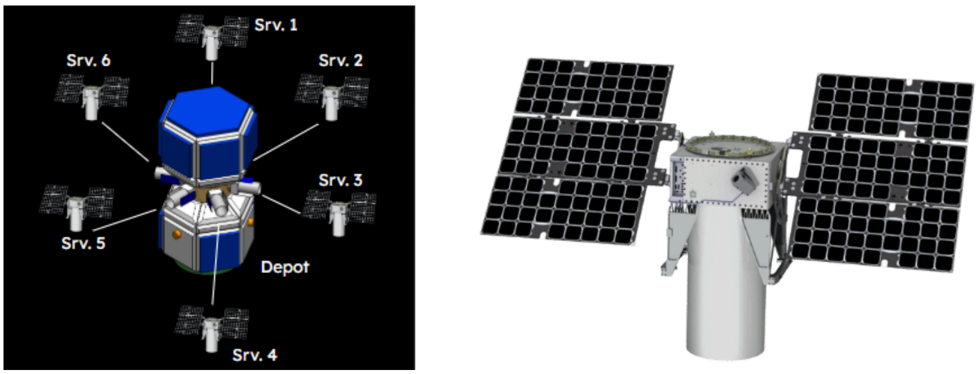

Figure 2: ORION System with all 6 ASTELAR Servicers & Venus Sat-Bus

Once in position, the Servicers detach from the Depot and begin their operations. Each Servicer semi-autonomously navigates to an active satellite, docks, and performs solar panel cell replacements using robotic arms. After completing its task, the Servicer returns to the Depot to unload old cells, refuel, and prepare to embark on its next mission. This process allows each Servicer to perform multiple missions ensuring that all the satellites in the cluster are serviced.

After servicing the first cluster, the Servicers will return to the Depot, and the entire system transitions to the second Intelsat Galaxy cluster to repeat the process. Upon mission completion of all satellites in both clusters, the entire system will be decommissioned and relocated to a graveyard orbit. The locations and exact coordinates of the proposed Intelsat galaxy satellites, along with cluster locations can be found in the appendix.

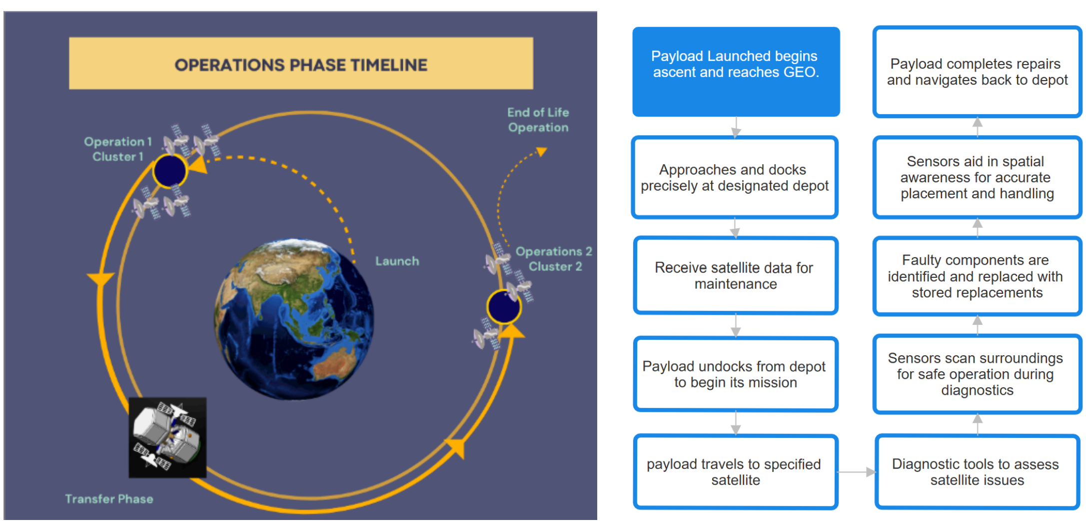

Figure 3: Mission Timeline for the O.R.I.O.N System & Process Flow

1. **Payload Launch and Insertion into GEO:**

The payload's journey begins with a powerful launch that propels it from Earth into Low Earth Orbit (LEO). From there, it transitions to geostationary orbit (GEO) using its onboard propulsion system, adhering to a meticulously planned trajectory. The Guidance, Navigation, and Control (GNC) system, supported by GPS receivers, continuously monitors and refines the payload’s position to maintain course accuracy. Reaching GEO demands precise maneuvering and sTable positioning to ensure the payload is optimally aligned and mission-ready upon arrival at the Depot.

2. **Docking with the Depot:**

Upon reaching orbit, the payload executes a precise approach toward the Depot. The GNC system, in conjunction with its LiDAR sensor, enables the payload to see the Depot in 3D, ensuring the spatial awareness necessary for secure docking. Utilizing small thrusters for controlled adjustments, the payload maneuvers toward the docking port while mitigating any risk of collision. This highly precise docking procedure is critical for acquiring the latest mission data and conducting final assessments before initiating repairs.

3. **Receiving Satellite Data for Maintenance:**

Upon successful docking, the payload receives critical data, including detailed information regarding the satellite requiring maintenance, its precise location, and the specific components or services needed. This data is processed and stored within the onboard computer to facilitate subsequent operations.

4. **Undocking and Departure from the Depot:**

With the satellite's data acquired, the payload initiates a controlled undocking sequence from the Depot. Utilizing precise thruster firings, it gradually disengages without inducing any disturbances, carefully orienting itself toward the designated satellite. The propulsion system executes minor trajectory adjustments to ensure optimal alignment for the upcoming transit, with each maneuver meticulously planned to maximize safety and operational efficiency.

5. **Navigating to the Damaged Satellite:**

The payload's propulsion system is activated, directing it along a precisely calculated trajectory toward the satellite requiring repairs. Rather than opting for the fastest route, the payload employs a Hohmann transfer maneuver, optimizing fuel efficiency through a more energy-conscious approach. As it approaches the target, Light Detection and Ranging (LiDAR) and radar sensors facilitate navigation by detecting and mitigating potential hazards, such as stray debris or nearby satellites. This phase necessitates continuous real-time adjustments; however, the advanced navigation systems seamlessly manage these corrections, ensuring a safe and controlled approach for servicing operations.

6. **Deploying Diagnostic Tools:**

Upon reaching proximity to the satellite, the payload deploys its robotic arms, which are equipped with advanced diagnostic tools to assess the satellite’s operational status. LiDAR mapping technology constructs a detailed 3D representation of the satellite’s structure, providing the payload with a comprehensive spatial understanding of its working environment. Utilizing high-resolution cameras and specialized sensors, the payload conducts a thorough inspection of the satellite’s systems, identifying potential issues such as structural damage, electrical malfunctions, or thermal anomalies.
The robotic arms operate with exceptional precision, guided by onboard sensors to prevent unintended contact that could compromise the satellite’s condition.

7. **Identifying Faults and Replacing Components:**

The payload's diagnostic tools systematically identify the necessary repairs, whether it be a damaged panel, a malfunctioning circuit, or a degraded battery. Upon determining the issue, the payload retrieves the appropriate replacement component from its onboard storage and precisely positions its robotic arms for the exchange. Advanced sensors provide continuous spatial feedback, ensuring meticulous handling of each component with precision and care. The payload carefully removes the defective part, installs the replacement, and conducts a thorough verification process to confirm proper integration and functionality before proceeding with the next phase of the mission.

8. **Returning to the Depot:**

With the repair successfully completed, the payload calculates its return trajectory to the Depot. The GNC system, in coordination with GPS, ensures a safe and fuel-efficient journey. As the payload approaches the Depot, it prepares for a precise docking maneuver, utilizing LiDAR and proximity sensors to facilitate a smooth and controlled arrival. Upon docking, the payload conducts a comprehensive system evaluation, verifying operational readiness for its next mission in the ongoing cycle of orbital maintenance.

2.0 Final Design

2.1 Operations

A. Trajectory

The trajectory subsystem is critical to mission success, ensuring the spacecraft can accurately reach its targets. For the Servicers, precise rendezvous with client satellites is essential, as failure to do so would render repairs impossible and the mission would fail. To travel between the Depot and client satellites, the Servicers must execute various maneuvers, including inclination changes, phasing maneuvers, and altitude adjustments. Most client satellites are in near-circular geostationary equatorial orbits with inclinations below 0.02 degrees and similar altitudes. It can be noted that the changes in velocity for the equatorial (non-inclined) orbits are much less than that of the inclined orbit, and due to this several Servicers will visit multiple client satellites before returning to the Depot. A detailed route plan for each Servicer can be found in the appendix.

For these transfers, each satellites change in velocity was found by calculating the change in velocities for the following phases: first, a Hohmann transfer to the orbital shape and altitude of the target satellite, inclination change if the target's orbit is inclined, and a phasing maneuver to match the location of the target satellite. From this series, the following changes in velocities for each Servicer were found. These values are well below the requirements for each ASTELAR Servicer in accordance with the limits set by the BCT Venus Sat-Bus of 7 km/s.

Table 4. Servicer Changes in Velocity

Servicer	1	2	3	4	5	6
ΔV Stops 1-3 (km/s)	1.218	1.0499	1.071	1.0934	1.2976	1.1194
ΔV Stops 4-6 (km/s)	1.3663	1.2403	1.2471	1.1863	1.0984	1.0502

B. Propulsions

Due to the use of the BCT Venus class Satellite bus, there is not much available data on the propulsion systems. According to the BCT website, the Venus X-Sat supports up to 6 chemical or electrical propulsion systems, with a maximum of 7000 m/s in velocity change available (15). This is well above the calculated values for the needed changes in velocity for the mission seen in table 4.. However, BCT does not offer any information on what these propulsion systems are, nor any of the specifications for them.

C. Structures

As a limitation from the COSMIC (C3) competition, the payload must be hosted by the Blue Canyon Technologies' Venus bus SmallSat platform. The Venus bus is made of two honeycomb aluminum panels for the top and bottom decks. The top deck has three unique bolting patterns that are used to integrate the payload onto the Venus Sat bus. Below is a Table depicting the bus's basic elements.

Table 5: Structures Mass, Power, and Control

X-Sat Venus Bus	Size (mm)	Mass (kg)	Power (W)	Pointing Control (degree)	Pointing Knowledge (degree)
	470 x 470 x 230	90	350	±0.002	±0.002

D. Power

The Servicer is powered by two components, solar arrays and batteries, embedded within the Venus Sat bus. Blue Canyon Technologies have designed this Sat bus to use the ESPA- Class Venus Solar Array that is made of carbon fiber and honeycomb structure. The solar panels require a power of 222-444 Watts and have an array voltage of 36.2 VDC. BCT also manufactures batteries for their Satellite buses. The Table below depicts the battery packs that are compatible with the Servicer. The 2P8S battery pack was selected in order to account for the Servicer's longer operational lifespan.

Tabel 6: BCT Battery Packs

Battery Packs	**1P8S**	**2P8S**
Mass (g)	<650	<1200
Height (in)	3.5	3.5
Footprint (in)	1.8 x 4.2	1.8 x 7.2
Nameplate Capacity (Ah)	3.4	6.8
Energy (Wh)	99	6.8
Nominal Voltage (V)	28	28
Voltage Range (V)	24 - 33.6	24 - 33.6

2.1.1 Data Handling and Communications

The primary objective of this subsection is to ensure that the data rate between the Satellite Servicer and Ground Stations is sufficient to support real-time operations. Additionally, it is essential to facilitate the bidirectional relay of information between serviced satellites, the Servicer, the Depot, and the respective Ground Stations. This encompasses, but is not limited to, the transmission of health data from the serviced Intelsat Satellite, as well as verifying the availability of necessary tooling and equipment on the Servicer. Furthermore, bandwidth compatibility with nearby satellites must be maintained to provide an additional layer of redundancy in the event of an antenna failure on the Servicer. In determining these values, the constraints were first identified and analyzed.

As previously stated, the Satellite bus, provided by Blue Canyon Technologies, is equipped with an integrated communication system that allows for operation in the L-band (1–2 GHz), S-band (2–4 GHz), and X-band (8–12 GHz). For efficiency and redundancy, both the Servicer and Depot will operate in the S- and X-bands. The S-band is used for telemetry, tracking, and command (TT&C) due to its reliability for lower data rates, while the X-band supports high-rate transmissions necessary for debris tracking and real-time data exchange. However, Ku-band remains a viable alternative for Depot-to-Ground communication, offering smaller antenna sizes and higher data transmission rates. Antenna sizing was based on Equation 1 (from Chapter 13, Eq. 13-19), where higher gain improves directional accuracy by narrowing the beamwidth.

Based on gain requirements, a high-gain phased array antenna (0.525–1.05 meters) will be mounted on the bottom of the Depot, continuously pointed toward Earth. To ensure redundancy and simplify communication with the Servicer, several low-gain patch antennas (0.088–0.175 meters) will be strategically placed around the Depot. The high-gain antenna will be a phased array system, selected for its reliability, compactness, and efficiency, while the patch antennas offer effective performance at lower frequencies in a compact form. A high level overview of the communication links for the mission are illustrated in Figure 4.

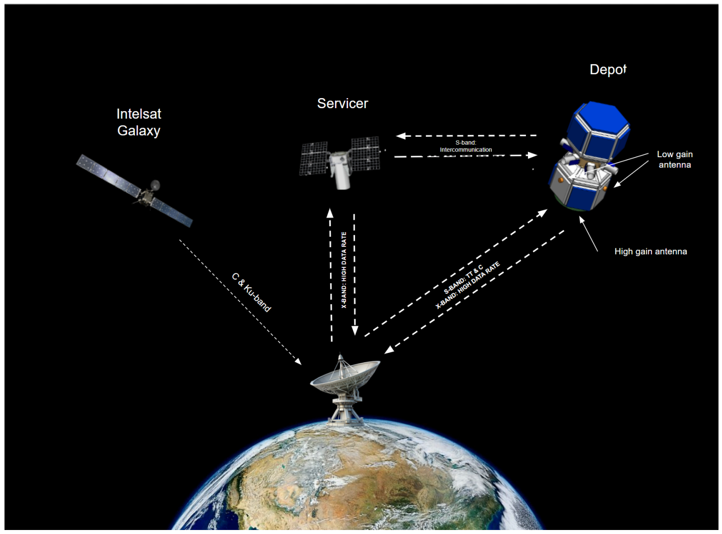

Figure 4: Communication Links for the ORION Mission

Ground station selection was critical for enabling both uplink and downlink communications for the Depot and Servicer, especially given the high data rates from debris-tracking systems, data processing was also a key concern. To reduce transmission volume and processing costs associated with ground-based processing, onboard filtering and compression were prioritized. Table 7 lists ground stations supporting S- and X-band communications, many of which also offer optional ground-based processing, which could serve as an alternative option for this mission. To maintain continuous coverage and accommodate servicing trajectories, multiple stations will be used, including those in Florida (USA), Weilheim (Germany), Bangalore (India), Katsuragi (Japan), and Hawaii (USA).

As previously stated, the mission supports servicing Intelsat Galaxy satellites, which communicate via ground stations rather than directly with each other. For this mission, when an Intelsat satellite requires solar panel servicing, it would send a request to a ground station, which forwards it to the Servicer. Upon receiving the request, the Servicer would assess whether it has the necessary tools, equipment, and sufficient fuel to complete the operation without requiring a visit to the Depot. During docking between the Satellite and Servicer, real-time video is streamed to the ground station. After servicing, a health report is sent to the Depot, compiled with other data, and transmitted in batch data weekly to the ground station—reducing latency and conserving power.

Table 7: Ground Station Information

<table>
<tr><th>Ground Station</th><th>Location</th><th>Size (m)</th><th>Bandwidth</th></tr>
<tr><td rowspan="2">KSAT - Kongsberg Satellite Services</td><td>Katsuragi, Japan</td><td>20, 13, 11, 10</td><td>S/X Band</td></tr>
<tr><td>Bangalore, India</td><td>7.5</td><td>X Band</td></tr>
<tr><td rowspan="3">SSC - Swedish Space Company</td><td>Clewiston, Florida, USA</td><td>3.5</td><td rowspan="3">S/X Band</td></tr>
<tr><td>Weilheim, Germany</td><td>30</td></tr>
<tr><td>South Point, Hawaii</td><td>70</td></tr>
</table>

To determine the required data rates, the most critical mission phase—docking—was prioritized. Key components for this phase are detailed in the GNC section (Tables 15–16), with supporting systems in the Payload section (Table 17). These systems collectively require an estimated total data rate of 0.5–2.5 Mbps. For real-time video transmissions during docking, both low-resolution (640p) and high-resolution (1080p) at 30–60 fps were evaluated, resulting in data rate estimates of 1–8 Mbps. To ensure continuous real-time communication, a minimum of 6–10 Mbps is necessary. Additionally, the passive debris-tracking mission, operating 24/7, generates approximately 3 TB of data per day. With advanced compression and filtering, this can be reduced by 50–90%, lowering daily volumes to 0.3–1.5 TB. Adequate onboard storage enables downlinking every 3–5 days, optimizing bandwidth usage and reducing communication costs. While processing, compression, and filtering systems significantly reduce operational costs and simplify communications, they may also increase the overall size of the satellite. Further analysis and optimization are required to refine these estimates and develop the most efficient data management strategy.

Table 8: Component Estimates

Component	Mass (kg)	Size (m^3)	Power (W)	Cost ($)
Antenna	0.09-1.3	0.088-1.05	2-15	$10,000-$500,000
Transponder (receiver, transmitter)	14-35	0.14 x 0.33 x 0.07 - 0.5 x 0.5 x 0.5	10-100	$2-$8M
Filters/switch diplexers	0.5-4	0.15 x 0.30 x 0.06 - 0.2 x 0.5 x 0.2	0	$1,000-$100,000
TT&C	9-15	0.013-0.015	15-50	$500,000-$2M
Onboard Filtering	5-13	0.02-0.15	10-45	$100,000-$2M
Ground	-	-	-	$3-$10M
Communications	-	-	-	8.8 - 25 M

2.2 Final Design- Completion of Required Elements

Through research found utilizing the textbook and Blue Canyon Technologies, the following physical requirements were calculated for the Servicer. These estimates take into account the individual components needed for each satellite system to fulfill the requirements outlined earlier.

Table 9: Determined Requirements

	Mass (kg)	Power (W)	Cost ($)
Total	76.5 - 199.4	362-513 W	9 million - 30 million

The last external of the COSMIC project payload is designed to address in-space servicing, assembly, and manufacturing (ISAM), focusing on satellite maintenance and repair. Constructed from Aluminum 6061, the payload is 27 inches long, 16.4 inches wide, 17 inches high, and 1/16 inch thick, ensuring durability and portability within the dimensions of the BCT X-Sat Venus Bus. It houses critical subsystems, including robotic arms, a communication module, batteries, and solar panel compartments.

The payload features two 5-degree-of-freedom (DOF) robotic arms capable of lifting up to 0.5 lbs in orbit, facilitating operations like solar panel replacement. Encased in an aluminum box welded using TIG or MIG techniques, it includes a hinged, actuated access panel. Inside, the system accommodates a battery secured in a fabricated or procured bracket, replacement solar cells, and storage for damaged cells. The design prioritizes CAD modeling and conceptual representation, with fabrication and assembly efforts focused on prototype realization.

This payload is intended to increase the operational life of in-orbit satellites and significantly decrease the frequency of space debris-generating repair space missions from Earth. The design allows for at least two repair operations, making it possible to have multiple, non-tire repair operations throughout the year. The prototype follows the specifications provided in the C3 information packet, and COSMIC constraints are within a specification range set by the BCT X-Sat Venus Bus. In addition to its specific goals, the payload is a means of proving the efficiency of ISAM technologies and setting out a framework for the development of subsequent generations of satellites and tools for their servicing, thus promoting the use of such tools and practices to ensure the long-term operation of space facilities.

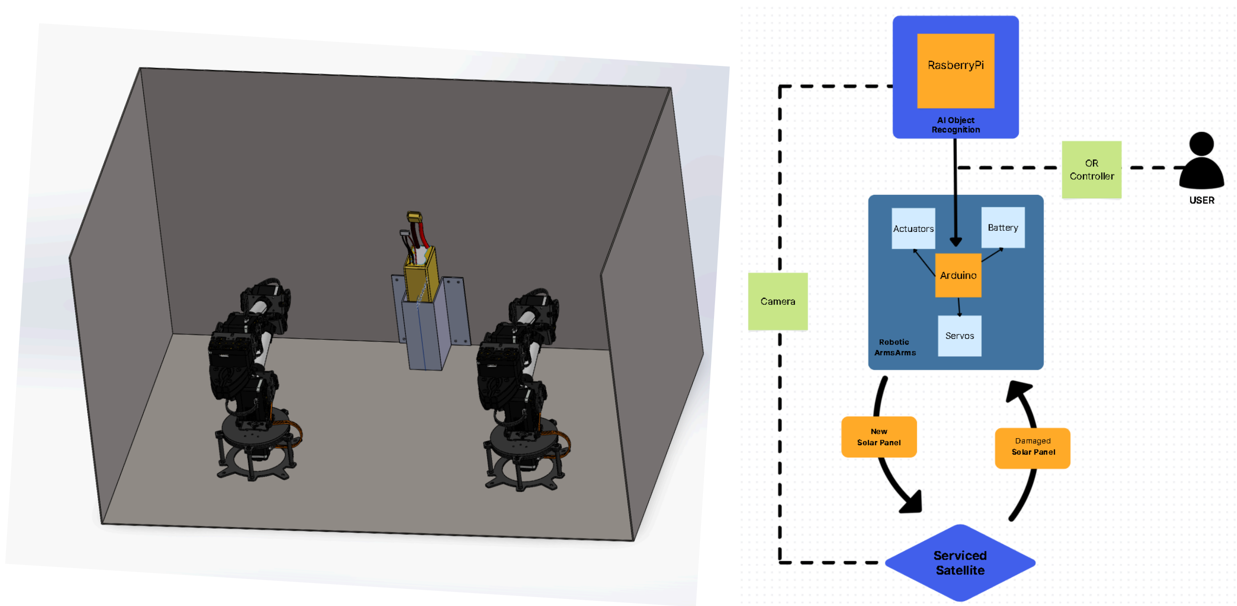

Figure 5: Payload Layout Design & System Level Diagram

This diagram illustrates an automated satellite servicing system designed to replace damaged solar panels with new ones using a combination of AI, robotics, and human oversight. A Raspberry Pi serves as the central processor, utilizing AI-based object recognition to identify components such as damaged and new solar panels. It receives visual data from a camera and sends control commands to an Arduino microcontroller. The Arduino operates robotic arms, actuators, and servos to execute precise physical tasks like removing the damaged panel and attaching the new one. Powered by a battery, the system ensures operational reliability in remote environments, such as space. A user can oversee the process or intervene using a QR-based controller interface. The workflow seamlessly integrates AI, robotics, and manual monitoring to deliver a serviced satellite with a fully functional solar panel.

2.2.1 Design for Manufacturing and Assembly

Scope

The manufacturing plan primarily supports the conceptual CAD design, which represents the payload's functional and visual aspects. The plan also addresses the prototype, ensuring practical representation while adhering to the conceptual framework.

Key highlights of the scope:

- Conceptual CAD Focus:
    - Detailed models of components such as the aluminum box, battery bracket, robotic arms, and storage mechanisms.
    - Pending additions include actuators, hinges, solar cells, and their storage container.
- Procurement vs. Fabrication:
    - The prototype integrates numerous procured components (e.g., robotic arms, batteries, actuators, and hinges) to minimize fabrication requirements.

  - Fabricated components include the aluminum box and potentially the battery bracket and solar cell container, depending on practicality.
- Assembly:
  - Prototype assembly will utilize a bolt-and-nut system to secure components to the aluminum box.
  - Assembly will be visualized through CAD layouts and imagery, supplemented by a physical prototype.
- Quality Checks:
  - Emphasis on safety, including smooth finishes on fabricated parts and elimination of burrs.
  - Ensuring no mechanical interference between components.

Note: Timeline and budget details are covered in a separate section of the project documentation.

2.3 Risk Management Cube

Technical risks are problems that plague any design project, and reveal many potential problems during, and after the design of such a project. This risk Table provides a structured analysis of potential risks that could impact the operations and mission success of a Servicer satellite. The identified risks cover various scenarios—such as docking failures, propulsion system issues, fuel transfer malfunctions, communication losses, orbital debris impacts, power depletion, and navigation inaccuracies—that could hinder or prevent the satellite from performing critical tasks like servicing client satellites, refueling, and returning to its Depot. The Table is crucial as it prioritizes risks by assessing their likelihood and impact. This allows us to find major problems that could hinder our design, and how we can mitigate them.

Table 10: If/Then Technical Risks Matrix

ID	IF (Risk Event)	THEN (Consequence)	Likeli-hood	Impact	Risk Level	Post Mitigation
1	IF robotic arms fail to actuate	THEN Satellite will not be serviced (mission failure)	Low	High	Medium	Low
2	IF battery fails/Dies	THEN robotic arms can not function to service satellite (mission failure)	Medium	High	Medium	Low
3	IF opening door mechanism fails	THEN robotic arms cannot engage satellite to service (mission failure)	Low	High	Medium	Low
4	IF wiring notices a fault	THEN may cause loss of power to arms/door (mission failure)	Low	High	Medium	Low
5	IF collision occurs	THEN may cause failure in arms/electronics (mission failure)	Low	Medium	Medium	Low

Mitigation Steps

Mitigation Steps are very important in assessing not only what can go wrong with a design project, but what action can be taken to prevent these failures. These preemptive and corrective measures are essential for reducing mission risks, enhancing system reliability, and protecting both the Servicer satellite and client satellites. By outlining a combination of autonomous responses and manual interventions, the team can ensure the satellite has versatile, robust protocols to address unexpected scenarios. These mitigation steps allow us to identify and correct any weaknesses or defects in our design. Table 11 also ensures flexibility in our design, in order to optimize mission success and safety.

Table 11: Mitigation Steps Matrix

Scenario	Pre-Mission Testing	Software-Based Analysis	Manual Overrides	Mission Abort
R1	Perform extensive actuator performance and redundancy tests	Implement fault detection algorithms to diagnose issues in real time	Activate backup systems or apply manual control	Abort mission if no redundancy works
R2	Conduct stress tests and life-cycle analysis on batteries	Monitor battery health and predict failure using telemetry data	Switch to backup battery or solar power	Abort if critical power systems fail
R3	Test mechanical door components for wear and tear	Analyze motor and sensor feedback for anomalies	Trigger manual override for door mechanism	Abort if access to payload is impossible
R4	Inspect all wiring connections for integrity and shielding	Use fault isolation routines to identify issues	Reroute power/signals via alternative wiring paths	Abort if the fault impacts critical functions
R5	Simulate collision scenarios during pre-mission testing	Use onboard sensors to assess damage and functionality	Assess recovery feasibility manually	Abort if the collision causes irreparable damage

A risk cube matrix, such as the one presented in Table 12, is a simple but efficient way to compare different technical risks based on the likelihood of them occurring, and the impact of what would happen if these were to occur. It resembles a grid pattern, where these risks are ranked from high likelihood to low likelihood and high impact to low impact. Where a cube is red, the risk is defined as high, where a cube is yellow, the risk is defined as moderate, and where a cube is green, the risk is defined as low. Based on Tables 11 and 12, where the risks are defined, each risk is designated a cube number based on likelihood and impact. Then, after mitigation steps are implemented, the risks are reevaluated. In the risk cube matrix below, the bold and underlined numbers represent the updated risks after mitigation steps were taken into consideration.

Table 12: Risk Cube Matrix for ASTELAR/ORION Joint Mission (underlining represents risks post mitigation)

Risk Matrix						
Likelihood	5					
	4					
	3					
	2					R1, R2
	1	**R3, R4, R5**		R3, R5	**R1, R2**	R4
Impact		1	2	3	4	5

2.4 Supporting Trade Studies

The trade study presented in Table 13 compares four metals commonly used in aerospace applications—cold-rolled low-carbon steel, 6061 aluminum, 4130 alloy steel, and 304 stainless steel. Key factors such as weight and cost were evaluated to determine the most suitable material for constructing the payload walls and battery bracket of the satellite. The weight estimates are based on sheet metal dimensions of 27 inches in length, 17 inches in width, and 1/16 inch thickness, while cost data reflects quotes for ten sheets of each material from a local supplier, Metal Supermarkets. Among the options, cold-rolled low-carbon steel is the most cost-effective and offers a respectable yield strength. However, its high density results in a significantly heavier structure—nearly three times the weight of an equivalent 6061 aluminum design. Given the Servicer satellite's emphasis on efficiency and minimizing mass, 6061 aluminum was selected for its superior strength-to-weight ratio and relatively lower cost compared to 4130 alloy and 304 stainless steels. With the payload constructed from 6061 aluminum, the estimated total weight—fully loaded with robotic arms, a LiPo battery, and replacement solar cells—is approximately 25 to 30 pounds. In contrast, using any of the three steel options would raise the total weight to 60–70 pounds. In aerospace applications like this, reducing weight is critical to lowering fuel consumption, decreasing launch costs, and improving overall system performance.

Table 13: Payload Wall/Battery Bracket Trade Study

Material	Weight (lb, kg)	Thermal Conductivity ($\frac{W}{m \cdot k}$)	Weldability	Yield Strength (MPa, Kpsi)	Cost ($)
Cold Rolled Low Carbon Steel	8.13 (3.69)	51	Excellent	250 (36)	236.40
6061 T6 Aluminum	2.80 (1.27)	167	Moderate	276 (40)	366.10
4130 Alloy Steel	8.13 (3.69)	42	Very Good	435 (63)	890.40
304 Stainless Steel	8.28 (3.76)	16	Moderate	215 (31)	443.40

The trade study presented in Table 14 outlines the robotic arm options considered for our senior design project. Each entry details the number of degrees of freedom (DoF) and associated costs. Initially, the team focused on robotic arms with three DoF; however, further research revealed that a five DoF arm would better suit our needs—enabling the manipulation of objects in both horizontal and vertical orientations. All robotic arm models were sourced from Robotshop.com. Among the candidates, the **Lynxmotion SES V2** stood out, featuring five servo motors dedicated to arm articulation and an additional motor for the gripper. Its design includes a base rotation servo (360°), as well as servos for shoulder, elbow, wrist joint movement, wrist rotation (360°), and claw actuation. In comparison, the **Hiwonder XArm 2.0** lacked the desired wrist rotation, limiting its range of motion for our application. The **Yahboom DOFBOT Pro** offered greater DoF and included wrist rotation capabilities, but its significantly higher cost—nearly double that of the Lynxmotion—posed budget concerns. Ultimately, the **Lynxmotion SES V2** was selected for its balanced combination of functionality and affordability. It provides the required wrist rotation and meets our performance criteria within budget constraints.

The trade study presented in Table 14 outlines the selection process for a 3S LiPo battery suitable for the senior design project. This comparison focuses on battery capacity and cost across three options available on Amazon.com. All batteries evaluated offer the same capacity; however, the **Socokin 3S battery** was selected due to its lower price point relative to the **Zeee** and **Hoovo** alternatives. Although the Zeee and Hoovo batteries provide identical capacities, their pricing reflects a set of two, and it remains undecided whether the final design will require one battery to power both robotic arms or a dedicated battery for each. In the spring semester, the team purchased redundant components in case of any failures. This included LiPo batteries as well, and with product links already cataloged by SSF, reordering these parts was straightforward. Additional spare components, such as wire connectors, were also procured to support continued success for future teams.

Table 14: Robotic Arm and Lipo Battery Trade Study

Robotic Arms	Degrees of Freedom (#)	Cost ($)	Battery	Capacity (mAh)	Cost ($)
Lynxmotion SES V2	5	769.94	Socokin	10,000	73.99
Hiwonder XArm 2.0	5	329.99	Zeee	10,000	159.99
Yahboom DOFBOT Pro	6	1,339.00	Hoovo	10,000	159.99

3.0 Technology Gap Assessment

Guidance, Navigation, and Control

For the Servicer, some of the guidance and navigation components are already embedded within the X-Sat Venus Class bus. This includes an attitude control system, reaction wheels, gyroscope, and star tracker. However, since the Servicer handles the close-proximity operations, such as docking with the Depot to be refueled and resupplied or docking with the client vehicles for solar cell repairs, additional instruments are required. This section will discuss the components within the Venus bus and establish the GNC requirements for these operations, the varying components, mass, size, power, cost estimates, and the justifications.

In order to successfully and safely operate within close proximity of the Depot and Intelsat satellites, there must be a degree of accuracy, precision, and range that must align from the Servicer to its target. Firstly, the GNC components must be able to detect and track the target vehicles from 50 km for long range navigation. For close range inspections, the components must be able to maintain a range from 400 to 900 nanometers. Both of these requirements were inspired by the Mission Extension Mission 1 that had a unique docking system that allowed them to rendezvous and dock with approximately 80% of all GEO satellites. Since that mission operated on similar satellites, the requirements and components established for the Servicer were generated from the MEV 1 and 2 mission as compared to the Servicer's objectives.

The Blue Canyon Technologies (BCT) X-Sat Venus Class bus is a compact yet capable satellite platform that aligns well with the Servicer's mission objectives. For the purposes of the COSMIC (C3) competition, it is advantageous that key Guidance, Navigation, and Control (GNC) components are already integrated into the satellite bus.A critical element of the GNC system is the Attitude Control System (ACS). BCT offers a wide range of ACS units—nearly a hundred models—so it is essential to select one that is both compatible with the Venus Class bus and capable of operating in geostationary orbit (GEO). After evaluating both the XCAT and FleXcore product lines, the FleXcore ACS emerged as the most suitable option. Designed for minisatellites like the Servicer, it supports GEO operations and offers compact dimensions of 12.1 × 11.4 × 4.9 cm. The FleXcore system includes two star trackers with a pointing accuracy of ±7 arcseconds and operates with a 28 V power supply. However, one limitation is its design life of under five years in GEO, which may require incorporating redundant units onboard the Servicer to extend its operational lifespan and ensure mission continuity.

Table 15: BCT Reaction Wheels

Reaction Wheel	RWP015	RWP050	RWP100	RWP500	RW1	RW4	RW8
Mass (kg)	0.13	0.24	0.33	0.86	1.1	3.2	4.4
Dimensions (mm)	42x42x19	58x58x25	70x70x25	110x110x38	110x110x54	170x170x 170	190x190x 190

Max momentum (Nms)	0.015	0.050	0.10	0.50	1.0	4.0	8.0
Max Torque (Nm)	0.004	0.007	0.007	0.025	0.06	0.25	0.25
Power (W)	<1	<1	<1	<6	<14	<10	<10
Design Life (year)	5	5	5	10	10	10	10

The second critical component required is the reaction wheel system, which provides attitude control by adjusting the satellite's orientation to align with its target. These reaction wheels must be capable of operating in geostationary orbit (GEO) and must be compatible with the Venus Sat bus. Blue Canyon Technologies (BCT) offers several models suitable for this application, including the RWP015, RWP050, RW1, RW4, and RW8. Key specifications—such as mass, dimensions, maximum momentum, maximum torque, power consumption, and design life—are summarized in Table 15. As the Venus Sat bus documentation does not specify which reaction wheels are included, it is assumed that one of the seven listed models will be integrated.

The third component needed is the gyroscope which maintains the orientation of the satellite and determines its direction and pointing. The gyroscope is fully integrated into the Sat bus and therefore fulfills its compatibility and ability to operate in GEO. The two Control Moment Gyroscopes (CMG) are listed in Table 16. They have an unlimited gimbal axis angular range, over two million gimbal maneuvers, and have a design life of 10 years.

The fourth essential component is the **star tracker**, which enables long-range navigation by analyzing the positions of surrounding stars relative to the satellite. As it plays a critical role in fulfilling the Servicer's primary navigation requirement, careful consideration was given to its selection. Three star trackers manufactured by Blue Canyon Technologies (BCT) were evaluated. Each model offers a 10° × 12° field of view, peak power consumption of 3.5 W, and attitude knowledge accuracies of 6 arcseconds across the cross-boresight and 40 arcseconds around the boresight. Among the options, the **Mid Extension NST** was selected for its compact form factor and lower cost compared to the Full Extension variant, while still meeting mission performance requirements.

Table 16: BCT Control Moment Gyroscopes and Star Trackers

Gyroscope	CMG-8	CMG-12	Star Tracker	Standard Extension	Mid Extension	Full Extension
Torque (Nm)	8	12	**Mass (kg)**	0.35	0.45	0.85
Power, Full Momentum (W)	25	20	**Dimensions (cm)**	10 x 5.5 x 5	12 x 8.5 x 7	25 x 10 x 10
Power, Maneuver (W)	30	35	**Baffle Sun Exclusion Angle**	45°	22°	17.5°
Mass (kg)	13	18				
Volume (cm)	22x22x30	34x43x38				
Momentum (Nms)	8	12				

The next two components, sensors and cameras, are utilized specifically for the Servicer's close proximity operations when docking to refuel or repair. They must fulfil the second requirement which is to maintain a spectral range of 400 to 900 nanometers for close range inspection. These components were identified based on the Northrop Grumman MEV-1 mission during their refueling operations. In Table 17, are different sensors or sensor systems that are used in similar satellite missions. When selecting the best sensor, the LiDAR sensors were chosen because it has a larger field of view compared to the other sensors. Although it may cost and weigh more than the sun and infrared sensor, the LiDAR sensor has been successfully used in the MEV-1 mission which is evidence that it would perform well with the Servicer. The LiDAR sensor must also be able to be used with the Servicer's payload, specifically the two robotic arms to conduct solar cell repairs.

Table 17: Possible Sensor Systems and Cameras

Sensor	**Sun Sensor**	**LiDAR**	**Infrared**	**Cameras**	**Spacecam 5MP**	**Astro CL**	**ASTRO head Cam**
Alternate Component	SITAEL Sun	MEV-1 Sensors	Infrared Earth Sensor	**Mass (kg)**	1-2.5	0.305	0.9
Mass (kg)	0.24	12.4 - 15.3	2.5	**Dimension (mm)**	107x84x 238	60x60 x110	80x80x80
Dimension (mm)	92x68x33	350x275 x220	170x164 x156	**Power (W)**	5.5-6	1	<25
Accuracy	0.5 deg°	0.5-1°	-	**Field of View**	14°, 12°, 20°, 31°, 65°, 89°	25	19, 68
Field of View	140 °	160°	5.5°				
Power (W)	0.05	71 - 97	4				

For the Servicer, the selected camera must support close-range imaging and offer multiple fields of view to accommodate potential operational challenges. Table 17 outlines several camera options suitable for geostationary orbit (GEO) operations. While the ASTROhead camera has a higher power requirement compared to the other candidates, it was chosen due to its dual field-of-view capability, which meets the mission's adaptability requirements. In alignment with the MEV-1 mission configuration, a total of six cameras will be integrated: two with a narrow field of view (19°), two with a wide field of view (68°), and two dedicated docking cameras positioned alongside the LiDAR sensor. This configuration ensures full redundancy between the visual and sensor systems, enhancing reliability during docking and servicing operations.

4.0 Knowledge Management

4.1 Systems Engineering Milestones

The systems engineering milestones for this project are the review of the mission concept, system definition, prototyping, a preliminary design review followed by a critical design review and a final review before manufacturing and eventually launch. Currently, we have finished the prototyping, and identified the steps necessary to get to a PDR in the next 6 months. For the first four months of this project, the ASTELAR team identified our mission concept, refined system requirements, costs, and feasibility to complete a system design review in December, along with acquiring the necessary materials to begin prototyping in January. From January to April, the team has focused on building a functional prototype as discussed earlier, creating high fidelity animations of essential mission aspects, and performing more in depth analysis to justify the requirements identified in the system design review.

4.1.1 Path to PDR

To make sure the COSMIC project is implemented successfully, a detailed quality assurance and safety plan will guide the project moving forward. This plan focuses on thorough analysis of each system, inspecting materials, ensuring precise manufacturing, thoroughly testing the system, and managing risks to maintain high standards of functionality and safety while preparing our project for a PDR. From the success and analysis results of the prototype, improvements on the current design will be implemented. These changes will be supported by in depth engineering analysis, to ensure all modifications meet the requirements of the mission. Along with this, any gaps found in the Technology Gap Assessment (Section 3.0) will be addressed in order to ensure that the project could be feasibly launched in the next ten years.

4.2 Biggest Challenges

Group projects always consist of difficulties in communication, workload management, and overall coherency on the project matter. Our project, named The 2024-25 COSMIC Capstone Challenge, was tasked with creating a conceptual design for a Servicer satellite that would operate in space. We encountered several challenges during the project, including communication issues, issues with the robotic arms not functioning, and having very little information on docking and rendezvous procedures. Towards the beginning of the project, many changes were made in requirements, and receivables, which halted progress. Due to this project being a joint effort amongst AE's and ME's, information was handed down the ladder. The overall project was a AE focused project, with the ME's focused on designing and building the Servicer payload. When changes were made on the AE side, this caused major changes, and temporary halts in progress on the ME side. Later on as the semester progressed, communication between the AE's and ME's vastly improved, which led to seamless communication, and changes if need be. Communication in the beginning was rough, but became effective and essential in our project's success. We consistently engaged in short, focused discussions that gave each team member time and space to share personal insights on what worked, highlight challenges we encountered, suggest improvements, and reflect on how we could learn and grow as a team. These meetings fostered open communication and helped us adapt week-to-week.

The challenges with the robotic arms not functioning was solved through very carefully troubleshooting of individual parts and precise reassembly. This taught us both the importance of high quality assembly and gave us a better understanding of the function of the arms, which was invaluable later in the project. The issues with the lack of information on docking, specifically docking with satellites not initially designed for docking caused several issues. During the fall semester, lots of time was put into trying to understand the current state of docking procedures with very little luck. Due to this, it was determined that a specific docking mechanism would be beyond the scope of the current project.

5.0 Summary

The development of the payload with ISAM capabilities represents a big step toward space debris reduction and improvement in in-orbit satellite maintenance. ASTELAR uses part replacement for extending satellite life; it utilizes a design that accommodates a pair of robotic arms able to work autonomously within its volume constraints of the BCT X-Sat Venus Bus. Primary resources included COSMIC and NASA materials that were provided along with the project package, supplemented with information from previous projects, influential case studies, such as the NASA Robotic Refueling Mission and DARPA's RSGS program, gave extensive insights into autonomous and robotic servicing technologies. Key design decisions were based on feasibility, ease of operation, and efficiency; therefore, more complicated options such as refueling and detailed electrical repairs were out of the question. The design was developed with a high level of detail, incorporating sketches and CAD models to effectively visualize and optimize the available space. Materials were carefully chosen for their performance in the extreme environment of space. AI-enhanced object recognition was also incorporated for autonomous operation with a workable and reliable manual override. By supporting reusable servicer vehicles and a centralized depot for logistics and refueling, this design reduces the frequency and cost of replacement satellites and helps mitigate space debris caused by nonfunctional satellites. This final design provides a scalable framework for future orbital repair and upgrade missions, reinforcing the long-term sustainability of GEO infrastructure and setting a precedent for robotic ISAM operations moving forward.

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Appendix

Cluster 1				
Intelsat Galaxy ID	Longitude (west)	Inclination	Apogee	Perigee
17	85	1.42	35808	35765
28	89	1.73	35811	35763
36	89	0.01	35794	35779
32	91	0.01	35793	35782
35	93	0.01	35796	35777
15	95	2.17	35800	35774
19	97	0.02	35,799	35,774
16	99	0.02	35,798	35,775
Cluster 2				
Intelsat Galaxy ID	Longitude (west)	Inclination	Apogee	Perigee
23	121	1.62	35,798	35,775
31	121	0.01	35,793	35,779
18	123	0.01	35,800	35,773
30	125	0.02	35,799	35,775
37	127	0.01	35796	35777
34	129	0.02	35793	35781
33	133	0.02	35795	35779

Cluster 1				Cluster 2		
Servicer	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6
1	galaxy 33	galaxy 34	Depot	galaxy 3 (10)	Depot	-
2	galaxy 37	Depot	-	galaxy 28 (13)	Depot	-
3	galaxy 30	Depot	-	galaxy 17 (15)	Depot	-
4	galaxy 18	Depot	-	galaxy 16 (8)	galaxy 19 (9)	Depot
5	galaxy 23	Depot	-	galaxy 35 (11)	galaxy 32 (12)	-
6	galaxy 31	Depot	-	galaxy 36 (14)	Depot	-