Cosmic Capstone Challenge Design Document

Starforge Team

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Abstract

Over two semesters a multidisciplinary team of engineering students collaborated with a NASA sponsor and other industry experts to research and develop a conceptual payload design for the COSMIC Capstone Challenge. The Challenge tasked teams to design a payload that demonstrates three In-Space Servicing, Assembly, and Manufacturing processes, hosted on a BCT X-Sat Venus Class bus. The management of space traffic and debris is critical to prevent the Kessler Effect and maintain safe low Earth orbit operations. The Kessler Effect describes the cascade of orbital collisions that exponentially increase the amount debris in orbit. These dense fields of debris must be avoided to maintain sustained activity in that orbit region. The primary objective of this payload is to detect and log debris fields within its orbit regime. Performing these operations in space will provide the ability to register and catalog smaller resident space objects than ground-based observatories. The conceptual design also includes the use of a laser to vaporize or de-orbit debris pieces. This paper summarizes the methods used to evaluate user needs, design a conceptual payload, and build a low-fidelity prototype to address the growing orbital debris issue. The results of this project will aid in the development of orbital regime infrastructure to support the growing space industry. As space commercializes, the risk of catastrophic collisions will increase unless proper collision avoidance strategies are employed.

Nomenclature

ISAM	In-Space Servicing, Assembly, and Manufacturing
COSMIC	Consortium for Space Mobility and ISAM Capabilities
C3	Cosmic Capstone Challenge
LEO	Low Earth Obit
STAR Levels	Space Trusted Autonomy Readiness Levels

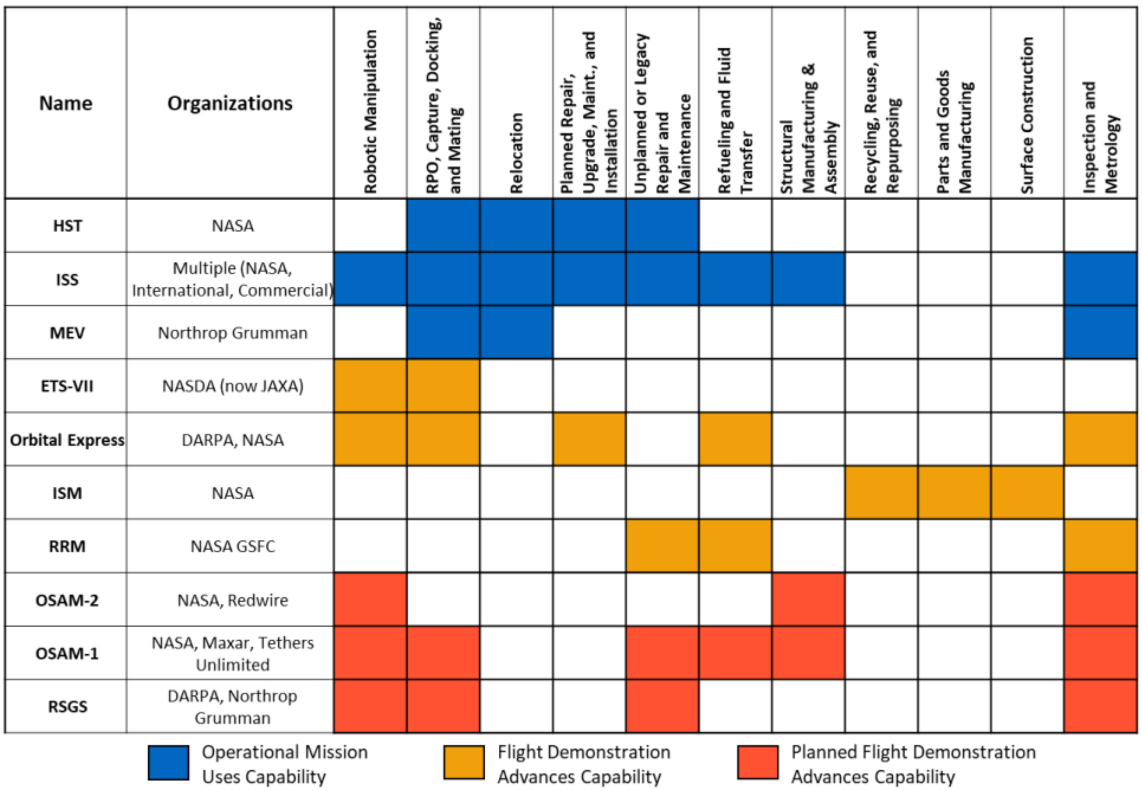
Introduction

Developing technology for space presents several environmental challenges in addition to creating the technology itself. Paramount to the development of the space industry includes the growing need for more efficient satellite management and repair due to the increasing number of satellites used for communication, navigation, and research.

With this concept in mind, it is imperative our team’s mission will both function in an LEO environment and remain primarily autonomous with the ability to be repaired or upgraded over its lifespan. Current satellite technology depends on ground-based operations, increasing costs when repairs or adjustments are needed after launch. Autonomous In-Space Servicing, Assembly, and Manufacturing (ISAM) systems aim to reduce these costs by enabling on-orbit tasks without significant human intervention. Designs must follow ISAM strategy and NASA standards. They must use modular, resilient, Low Size, Weight and Power technologies. Designs must comply with Interational Traffic and Arms Regulations and other standards relevant to the scope of operation.

Figure 1: *ISAM Capability Areas Map*

Note. Map of the ISAM capability areas investigated by government and private sector missions. Starforge has identified three areas of inquiry for the concept technology: recycling, parts manufacturing, and surface construction. Image source: *Arney, D., Mulvaney, J., Williams, C., Sutherland, R., & Stockdale, C. (2022). In-space servicing, Assembly, and Manufacturing (ISAM), p. 9*.



ISAM technology offers the unique ability to autonomously manage traffic in orbit regimes around Earth. When a satellite's mission ends, they are either deorbited to burn up in the atmosphere or moved to a graveyard orbit. As of May 2024, over 9,900 active satellites orbit Earth, aside from active satellites, there are over 670,000 pieces of debris larger than 1cm orbiting Earth. Debris of this size can disable operational spacecraft and create more debris. If the debris field continues to grow, so will the risks involved in space operations. The European Space Agency states that "doubling the number of objects will increase collision risk by approximately four times" (*About Space Debris*, 2016).

Commercial interest in space has been growing for decades. ISAM technology will play a pivotal role in facilitating this growth. Review of the ISAM "State of Play" document, the team has identified three areas of inquiry for developing a conceptual technology: relocation, inspection and metrology, and recycling, reuse, & repurposing (*National Aeronautics and Space Administration*, 2023). Development of ISAM infrastructure will reduce the cost of initializing, maintaining, and modifying operations in space. By reducing the associated risks, the private sector will be more likely to consider expansion into space.

User Needs and Design Requirement Metrics

Metrics Identification

Inspection serves as the foundation for detecting and addressing debris hazards, informing strategies for collision avoidance, and tracking changes in debris fields over time. The inspection process involves a combination of data gathering, analysis, and autonomous decision-making to assess the size, trajectory, and potential impact of debris. Effective data gathering is crucial for understanding the space environment and assessing debris locations and characteristics. This brings the need for energy-efficient sensors and systems that can operate for extended periods to collect comprehensive data, especially due to power and thermal limitations in space. The next step is to analyze this data accurately and quickly. An AI system will process data onboard autonomously, reducing the dependency on Earth-based systems. It is crucial for the system to operate independently. A common concern in space missions is delays in communication. Thus, a design factor that focuses on AI-guided autonomy that could handle a variety of situations without human input would ensure that the mission proceeds with minimal latency.

Detecting space debris requires advanced sensor systems and imaging systems that can withstand harsh space conditions. Identifying environmental resistance, such as radiation resistant components, to maintain reliable detection capabilities over time. The next step after detection is mitigation. Mitigation strategies are to be ethical and safe, so it is essential to ensure that the actions taken to mitigate debris risks prioritize safe outcomes, especially in cases where human occupied orbits are affected. In addition, these systems need to be designed for modularity and reusability, allowing components to be upgraded and adapted for future missions and to reduce mission costs.

In space missions, inspection as it relates to debris is a critical function. Inspecting debris allows for the collection of space debris poses a serious threat to operational satellites and spacecrafts. As space activities increase, so does the need for advanced inspection systems capable of tracking and managing debris.

Table 1: *User Needs Table*

User Need	*Metric*	*Units (if Applicable)*	*Range*	*Ideal*	*Rank (1-5 most to least important)*
Must be more cost efficient then other supply chain options	Affordability	USD ($) and Mass(Kg)	-$1,000-$10,000(Prototype) -0-90Kg (payload)	$7,500	5
Must be capable of autonomously performing normal operations with limited input required from the user	Autonomous Control	Space Trusted Autonomy Readiness Levels (STAR)	STAR Level 1-9	STAR Level 4	2
Must be capable of future upgrades	Upgradibilty	Reserved Parameters (Mass, Volume, Power Available)	Mass: 5-15% Volume: 5-15% Power Available: 5-20%	Mass: 10% Volume: 10% Power Available: 15%	4
Must be able to collect species without creating more debris	Precision	Uncontained Fragments	0-1	0	1
Must be durable enough to handle small errors without comprising the mission	Durability	TBA	~	~	3

Table 2: *Design Specifications*

User Needs	*Design Spec/Req*
Affordability	Price
Autonomous Control	Automatic Processes
Upgradabilty	Mass
	Volume
	Power Available
Precision	Fragments Created
Durability	TBA
	~
	~

Design Spec/Req	*Units*	*Range*	*Ideal*
Price (Prototype)	USD ($)	$1,000-$10,000	$7,500
Space Trusted Autonomy Level	STAR Level	Level 1-9	4
Mass	kg	0-70kg	
Volume	cm^3	43.18x41.66x68.58cm	<Volume Constraints
Power Available	W	0-444W	66.6W
Fragments Created	Pieces	0-1	0
TBA	TBA	~	~
~	~	~	~
~	~	~	~

User Needs Rationale

The design specifications were chosen based on what the team determined to be key factors to keep in mind during the design phase. The main purpose and drive for our concept is to reduce the number of debris species orbiting Earth. It is crucial to achieve this without contributing to the problem.

Precision is critical to ensure that the mission tasks are performed without releasing any additional fragments into the environment. Autonomy is another key factor; the Space Trusted Autonomy Readiness Levels (STAR Levels) designed by NASA provide discreet levels of autonomous capability. For the scope of our mission, a STAR Level of 4 will be sufficient. Durability is a key factor in preventing the release of additional debris species. As the team develops the design, durability will be scored based on simulation and test data. Upgradability is important for ensuring the spacecraft can remain operational beyond its designed duration. By reserving capacity for future upgrades, the spacecraft may be modified to accommodate new mission requirements and technologies. Affordability is important to consider when designing a marketable product. The costs associated with building, launching, and operating the product must be less than the costs

Prototype Development

In developing a prototype, the team has decided on a few key design considerations: Energy efficiency, environmental resistance, latency tolerance, and ethical/safety protocols. The payload will need to have a sufficient power management system that allows it to survive long missions in outer space. The team will also need to incorporate both radiation and temperature resistant components to protect against the tough space environment. In addition to this, the design would ideally include upgradable systems that can be used for multiple missions. To allow for latency tolerance, there will be AI-guided autonomy that helps offset the problems with delayed communication from the crew on Earth. Lastly, there will be human oversight to ensure safety and ethical concerns are properly addressed.

Specifications Update

To ensure the designs' specifications achieve the desired outcomes for the project, a requirements table has been developed. Each requirement represents a critical process the design implements.

Requirements Table
1. Detect - Shall detect debris
2. Catalog - Shall be able to catalog debris characteristics & ephemerides
3. Communicate - Shall communicate collected data to ground stations

4.	Redirect - Shall be able to alter the orbit of debris
5.	Update - Shall update debris characteristics & ephemerides when altered
6.	Validate - Shall be able to verify that debris ephemeris has been altered as intended
7.	Integrate - Shall fit within the payload volume of the host bus and integrate with its systems

Table 3: Requirements Table

The table is arranged in order of priority. The wording is altered to better represent the goals of the design.

Design Documentation

The design has two major components: inspection and collection of debris. To design for inspection, the Starforge team has further broken that category down into two more sections: software and hardware. The software will allow for real-time data integration from both mission and experiment databases, automatically interpret observations, and perform predictive analysis on debris using machine learning. The software will communicate between the space and ground stations. The design's hardware component would perform high-resolution imaging and multi-spectral sensing and failsafe communication for data transmission back to the payload would need to be able to predict collision paths, avoid said collisions autonomously, and send debris data to the ground crew.

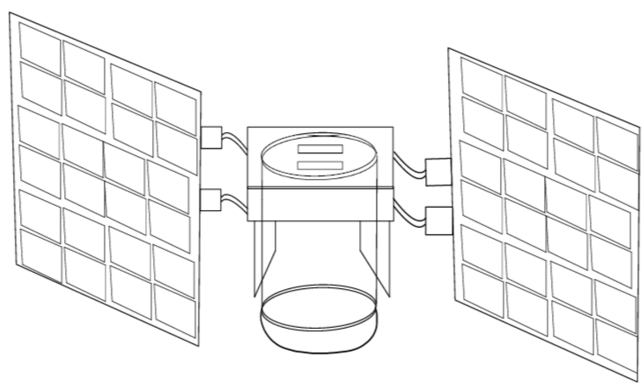


Figure 2: BCT X-Sat Venus Class Payload Sketch

Note. The finished design must fit within the 17 x 16.4 x 27 in. payload volume of the satellite, which is positioned between its two solar arrays.

Design Specifications and Overview

Design Documentation

In preparation for both the real-world satellite and in-class prototyping, the team developed several budgets and materials lists to properly document all available options.

Assumed to be built into host bus:					
System:	Component		Quantity	Cost per Unit	Total
Energy Storage	Battery		N/A	N/A	N/A
Energy Production	Solar Panels		N/A	N/A	N/A
Telemetry and Attitude Control	BCT Proprietary System		N/A	N/A	N/A

Table 4: Host Bus Features

The four systems listed in table 4 above are already integrated into the host bus. The designed payload will utilize these preexisting systems. The power system will need some modification to accommodate requirements for operating the laser. In this case, the existing system will be expanded on rather than replaced.

Item Description	**Vendor**	**Quantity**	**Price Per Unit**	**Total Price**
High Dynamic Range Light Sensor	Adafruit	1	$ 6.95	$ 6.95
Official Raspberry Pi 27W PD Power Supply 5.1V 5A w/ USBC	Adafruit	1	$ 12.00	$ 12.00
Official Raspberry Pi A2-Class microSD Card - 64GB Blank	Adafruit	1	$ 11.95	$ 11.95
Raspberry Pi 5 - 8GB RAM	Adafruit	1	$ 80.00	$ 80.00
Stepper Motor NEMA 17	Adafruit	2	$ 14.00	$ 28.00
Stepper Motor Driver	Adafruit	2	$ 5.95	$ 11.90
Laser Diode - 5mW 650nm Red	Adafruit	1	$ 5.95	$ 5.95
Pin Connector Cables (F/F)	Adafruit	1	$ 3.95	$ 3.95
Pin Connector Cables (M/M)	Adafruit	1	$ 3.95	$ 3.95
CyberTrack H4 Webcam 1080p	B&H Photo	1	$ 39.99	$ 39.99
			TOTAL	$ 204.64

Table 5: Prototype Bill of Materials

To reduce cost, the prototype used the basic off-the-shelf components. After testing basic functions and tweaking the design testing can be scaled up to a higher fidelity.

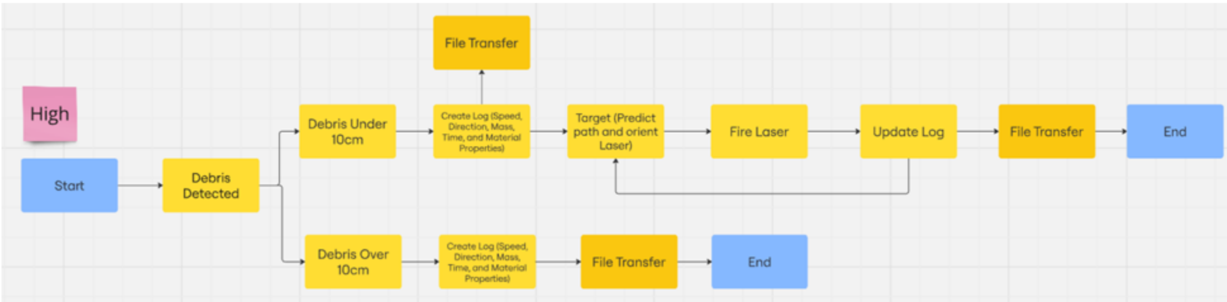


Figure 3: *System Process Flowchart*

As shown in Figure 3, the first step is to detect space debris. The payload will then determine if the debris is over or under 10cm. in diameter. If over 10cm. a data log of speed, direction, mass, time, and basic material properties will be created. This data will next be transferred back to a centralized system and the interaction will end. If the debris is found to be under 10cm in diameter, it is selected for mitigation. In this case, the satellite will once again create a data log of speed, direction, mass, time, and material properties then transfer this data to a centralized system. Next, instead of ending the interaction, the system will maneuver itself, to be in line with the debris: considering the speed, direction, and distance of the debris. From here, the laser fires, vaporizing the debris. The satellite will now rescan to determine if the debris was appropriately eliminated and update the data log based on this information. If necessary, the satellite will retrack and refire on the debris, continuing until the debris is destroyed.

Prototype Development

The plan was to leverage SolidWorks API and utilize potential options for programming languages that are compatible such as VB.Net, C# and VBA with the current preference from the team being C#. From there, the team has broken the process down into five subcategories: Setup and Environment, Accessing the Model, Coding and Bug Testing, Parametric Design, and Simulation and Analysis. In the setup and environment phase the team will install SolidWorks having the API SDK set up and then use development tools like Microsoft Visual Studio or the built-in VBA editor. Next, the team will open a SolidWorks file and use AOI calls to interact with features, sketches, and parameters. In this case, inputs from the CAD designer assisted in making it compatible. When coding and debugging, the team will develop code to perform repetitive tasks such as generating drawings, exporting files to various formats, or modifying assembly configurations. Once established, during the parametric design the team can use code to link part dimensions or features to external data sources to account for changing design requirements. Finally, during simulation and analysis, the team automated analysis processes, extracted results, and integrated the model with external software for further computation using SolidWorks Simulation API.

A	B	C	D	E	F	G	H	I
Type of Debris	***Name/Code***	**Volume (m^3)**	**Length (m)**	**Width (m)**	**Mass (kg)**	**Speed (km/s)**	**Main Contents**	***Manageable?***
Natural Debris								
Meteroids	NAT1	0.001–100	0.01–10	0.01–10	0.1–100,000	11–72	Iron, rock, silicate materials	No
Dust Particles	NAT2	0.000001–0.01	<0.001	<0.001	<0.001	11–72	Mineral and organic compounds	No
Boulders	NAT3	10–50	2–50	2–50	10,000–100,000	11–72	Rock, iron	No
Artificial Debris								
Satellites	ART1	1–50	1–15	1–5	500–10,000	7–10	Aluminum, electronics, fuel tanks	Yes
Rocket stages	ART2	10–200	10–30	3–10	5,000–20,000	7–10	Aluminum, steel, residual propellants	Yes
Fragments	ART3	0.0001–0.1	0.01–1	0.01–1	<10	7–10	Metal, composite materials	Partially
Mission-Related Objects	ART4	0.1–5	0.1–2	0.1–2	1–100	7–10	Experimental devices, fuel tanks	Yes
Paint Flecks	ART5	<0.000001	<0.001	<0.001	<0.001	7–10	Polymer coating from satellites	No
Solidified Liquids	ART6	<0.01	0.01–0.1	0.01–0.1	<1	7–10	Frozen propellants, water	No
Unburned Particles	ART7	<0.001	<0.01	<0.01	<0.1	7–10	Metal oxides, fuel particles	No

Figure 4: Debris Analysis

Figure 4 shows the classification of different kinds of space debris according to whether they are naturally occurring or artificial. Additionally, an initial analysis included dimensions and size of debris and the viability of removal of the type of debris. It was discovered that ART1, ART2, ART4 and ART3 (partially) were manageable to safely remove due to their lower speed, types of materials and generally smaller dimensions.

Results

Prototype Testing

The prototype validation phase tested the Starforge payload concept at low cost. The team spent $204.64 on a low-fidelity model built with both off-the-shelf parts and parts fabricated in-house. Initial tests using a standard webcam and a high dynamic range sensor verified that the system could detect small objects. The Raspberry Pi processed sensor data and logged information such as size, speed, and trajectory with minimal delay. The system logged data that matched expected values and simulated data transfer to a central system. The prototype code supports future integration of high-speed data communication protocols. For debris mitigation, a low power 5mW laser diode engaged debris under 10 centimeters. The test showed that the system could re-scan and re-engage as needed. The tests did not replicate space conditions, but assessments indicate that the methods and materials can be scaled for space. A structured test plan evaluated core functions such as frame capture, object detection, and data processing.

Overall, the validation phase confirmed that the system detects debris accurately, logs data in real time, and shows potential for active debris mitigation. Future models will use higher-resolution sensors and improved processing to support autonomous decision-making.

Design Refinements

The early prototype featured PLA brackets and laser cut plywood to serve as support columns for a small camera and laser package. One drawback to this design was the potential for stress fractures since the bulky stepper motors pressed down onto the thin plywood sheets. There was also a problem with scale and empty space, so the team planned ways to optimize each part in the prototype. Using CAD software, a team member designed custom fit parts that were 3D printed in ABS plastic. These proved much more durable than the PLA and wooden parts used previously. Additionally, metal bearings were introduced to the design, as well as a sturdy plastic base to house the Raspberry PI motherboard. To address camera balancing issues, the team swapped out a long axis running through two columns for a shorter axis directly mounted to a single stepper motor.

Future Work

Further testing and validation of the prototype functions must still be completed. Parts of the prototype would be switched with space-ready options. A higher resolution camera will be required along with more computing power to reduce uncertainty. Material testing needs to be conducted to determine which materials are suitable to mitigate. The software would need to fully incorporate all working functions of the design. For testing, look to utilize space-like environments such as vacuum chambers, neutral buoyancy pools, and solar radiation labs to simulate space conditions and further develop the prototype.

Conclusion

Space debris poses a threat to any satellite that is sent into space. Collisions with satellites will result in spending money, time, and materials to restore operations. Our product will allow companies to be more confident investing in space by reducing the risk of these collisions. As space operations expand, so will the need for infrastructure to manage space traffic and waste streams. Designing technology to reduce orbital debris will make space operations safer. Without proper management and regulation, debris will continue to build up and increase risk to current and future space operations.

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