C3: Cosmic Capstone Challenge

Design Document

Team
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Client
COSMIC - Consortium for Space Mobility and ISAM Capabilities

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Executive Summary

Currently, there is a lack of In-Space Servicing, Assembly, and Manufacturing (ISAM) capable satellites, which reflects the relatively new landscape of commercial space engineering. To address the deficit of ISAM capable satellites, the Cosmic Space Consortium for Space Mobility and ISAM Capabilities created the C3 capstone challenge where university teams from across the United State compete to create the best ISAM design.

For our submission to the competition, we designed a payload that can be housed on the BCT X-Sat Venus Class bus and perform three continual ISAM motions autonomously. Our solution is capable of withstanding the stress of launch and the course of its operation. Our solution uses a spring-based system to launch multiple nets stored in the net housing compartment. The net capsules have thrusters to navigate through, capture the target, and deorbit.

Our approach was heavily influenced by previous net-launched satellites and took inspiration from conventional net launchers used on Earth. At our current stage, our team has been able to develop computer-aided design (CAD) models to reflect our prototypes. The implementation we have created operates in three portions, each representing an ISAM action. The first action uses a spring powered launching mechanism to propel our net capsule away from the main craft. The second action is the autonomous piloting of the net capsule to the target debris. The third and final action is the deployment of the net to capture the target object, altering its orbit to hasten its re-entry into the atmosphere. This task decomposition comprises the way our project has successfully met the three continual ISAM actions requirement.

As we moved forward into our second semester with the C3 capstone challenge, our group worked to develop and create a prototype for the design, and to establish physical testing of our device using resources available to us on campus. This included validation of key prototype functions and the confirmation of feasibility and survivability through the launching process. During this we also developed our presentation and design documentation which were used to present our design and prototype to the C3 conference.

Learning Summary

Development Standards & Practices Used

- Standard Practices:
  - Hardware Practices:
    - Robust power design
    - Fuel efficiency
    - Minimizing heat dissipation
    - Effective material selection for space constraints
    - Modular components
  - Software Practices:
    - Testing CAD model for mission validation
    - Ensuring code is readable and robust
- Engineering Standards:
  - ISO 24113: Space Systems – Space Debris Mitigation Requirements
  - NASA-STD-5001: Structural Design and Test Factors of Safety for Spaceflight Hardware
  - ECSS-E-ST-31-01C: Thermal Control Engineering
  - ASTM F3309-19: Standard for Testing Capture Mechanisms in Microgravity

Summary of Requirements

- Analysis is required to sufficiently determine if a design is feasible, can survive launch, can operate successfully in a LEO environment, and can meet the BCT X-Sat Venus Class bus specifications
- The design needs to demonstrate three or more operations to demonstrate an orbital ISAM capable
- The payload should be designed to function autonomously with limited remote commands

Applicable Courses from Iowa State University Curriculum

- English 3140: Technical Communication
- Physics 2310: Introduction to Classical Physics I
- ME 1700: Engineering Graphics and Introductory Design
- ME 2700: Introduction to Mechanical Engineering Design
- EE 3030: Energy Systems and Power Electronics
- EE 3110: Electromagnetic Fields and Waves
- EE 3210: Communication Systems 1
- CPRE 2880: Embedded Systems I: Introduction

New Skills/Knowledge acquired that was not taught in courses

- CAD modeling
- Materials engineering and analysis
- Systems Engineering
- SWAP-C analysis

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1. Introduction

1.1. Problem Statement

The demand for In-Space Servicing, Assembly, and Manufacturing (ISAM) technologies is rapidly increasing, driven by both NASA and private sector interests. Historically, space endeavors have relied on single-use, non-recyclable systems, which hinder commercial viability. As part of the C3 competition, our project aims to address one of the pressing needs in this emerging field by designing a satellite payload to demonstrate and test innovative ISAM capabilities.

For our submission to the C3 design challenge we designed a satellite payload to mitigate in space debris by removing debris in the 10 cm to 1 meter size range in Low Earth Orbit (LEO). Our proposed solution, the Space Cyclone, involves a controlled net-based system to capture and deorbit target debris. The process begins with a soft launch from our payload, deploying a net capsule that remotely and accurately navigates to the target. The capsule deploys the net using spin mechanics and initiates deorbiting. Our prototype and various tests demonstrate that this solution is feasible and effective in addressing the growing threat of space debris.

1.2. Intended Users

NASA Employee

- **Wants:** Wants to reduce the cost of space travel so more funding is available for other projects and further funding is easier to obtain. This will help create new missions to send people back to space.
- **Sees/Hears:** Budgets shrinking, engineers complaining about satellite failures, deadlines.
- **Thinks:** There needs to be in-space servicing options to fix various issues.
- **Does:** Brainstorm solutions to current mission problems.

Industry Mentors

- **Wants:** Help the team succeed and foster new and innovative ideas.
- **Sees/Hears:** Ideas students come up with and weekly progress reports.
- **Thinks:** How to provide guidance to the student team on ideas to develop deliverables.
- **Does:** Provides industry experience and knowledge.

Private Industry

- **Wants:** Ideas that can be used to generate profits.
- **Sees/Hears:** Ideas for ISAM technologies and the potential market implications.
- **Thinks:** How to turn ISAM ideas into profitable business models.
- **Does:** Invests capital and other resources into ideas determined worthy of investment.

2. Requirements, Constraints, and Standards

2.1 Requirements and Constraints

2.1.1 Requirements

- Design
  - Accomplishes one of ISAM's main three goals: servicing, assembly, or manufacturing.
    - Servicing
      - Provide a specific service to satellites in orbit around Earth i.e. fueling, repair, etc.
    - Assembly
      - Support satellite/spacecraft assembly in some capacity.
      - This could also fall under the repair category somehow.
    - Manufacturing
      - Support or design some manufacturing capability.
  - The design should be autonomous with minimal remote control commands.
- Environmental
  - Does not create additional debris
  - Must be resistant to Radiation Single Event Effects/
- Resources
  - Weight: The solution should be as light as possible without sacrificing the functional integrity of the unit.
  - The unit should be reusable within its use case, not be single-use before retirement.
- Economic
  - Target Market: The solution should position itself as an economic solution to a problem facing NASA and other aeronautical companies investing in ISAM space technologies.

2.1.2 Constraints

- Design Constraints
  - The payload should be designed for the BCT X-Sat Venus Class bus.
    - Available volume: 20.5” x 16.4” x 27.0” (single solar array) or 17.0” x 16.4” x 27” (dual solar array)
    - Payload maximum mass capability: 70kg
    - Available Solar array power: 222W (single array) or 444W (dual array)

        - Energy storage: 10.2 Ah
    - The design should be autonomous with minimal remote control commands.
    - The design should fulfill ISAM (In space, servicing, assembly, and manufacturing)
- Environmental Factors
    - Near-Zero Gravity
    - Minimal Atmosphere
    - Radiation
    - LEO Temps –65 ºC to +125 ºC (cycling depended on orbit)
- Autonomy
    - The design should be autonomous with minimal intervention through commands.
- ISAM
    - The design must demonstrate three operations together, demonstrating an ISAM capability.

2.2. Engineering Standards

Engineering standards provided a set of common rules that helped create a foundation for our team's engineering practices. Standards primarily helped support safety, quality, and ethical compliance. Adherence to engineering standards can help manage and mitigate risks associated with our design. Another important aspect of engineering standards is interoperability. It is important to ensure that different components and systems work together effectively.

Examples of some standards are listed below:

- ***AIAA S-159 (202X)*** *– Best Practices, Functional Requirements, and Norms for In-space Servicing, Assembly, and Manufacturing (ISAM) Power and Data Interfaces (submitted to AIAA July 11, 2024):*

The standard outlines best practices for designing and implementing power and data interfaces for ISAM missions. This standard helps with the overall integration of ISAM capabilities across various platforms. It also describes multiple applications of ISAM capabilities that need to be satisfied with these power conditions, such as robotics, assembly, etc. This standard is important to drive advancement in space innovation.

- ***AIAA S-158 (202X)*** *– CONFERS Recommendations for Best Practices, Functional Requirements, and Norms for Prepared Free-Flyer Capture and Release (Approved by AIAA Standards Steering Committee, May 2023)*

The standard specifies the functions that systems involved in capture and release must support. It provides detailed descriptions of criteria such as performance, reliability, and safety.

This standard is applicable to satellites and other spacecraft in terms of service and assembly thereby supporting autonomy in space.

- ***IEEE/ISO/IEC 29119-2-2021 -*** *ISO/IEC/IEEE International Standard - Software and systems engineering - Software testing -- Part 2: Test processes (Last modified: 2 August 2024)*

The outlined document specifies test processes that can be used to govern, manage, and implement software testing for any organization, project, or testing activity. It comprises generic test process descriptions that define the software testing processes. Supporting informative diagrams describing the functions are also provided. This document applies to testing in all software development lifecycle models. This document is intended for, but not limited to, testers, test managers, developers, and project managers, particularly those responsible for governing, managing, and implementing software testing.

Using the above standards provided by space organizations like CONFERS, our team can utilize standard industry practices to build more effective designs. Implementing these designs will guarantee that we create a product compliant with standards and interoperable with other organizations. As an entry in a design competition, our project must adhere to industry standards for all performance metrics, and the best way to do this is to follow the best practices that the space industry also follows, allowing other organizations more ingrained in the field to understand our interpretation of the field easily.

While the enlisted standards apply to our project, our team members also picked IEEE/AIEE 750.1-1960, which outlines aircraft and missile guidance systems standards. The standard addresses the challenges of power systems in space using factors such as harsh environments, reliability requirements, and the need for lightweight components. This could apply to our project depending on whether the project will use a guidance system.

We plan to review the standards' best practices and recommendations and implement them into the project design as needed. The Standard for Software and Systems Engineering (IEEE 29119) will help design testing to ensure functionality. The Best Practices, Functional Requirements, and Norms for ISAM (AIAA S-159) will shape overall design decisions for materials and backups. Finally, the CONFERS Recommendations For Free-Flyer Capture and Release will be used to help shape the design of the net itself and the metrics used to measure its performance.

3. Project Plan

3.1 Project Management/Tracking Procedures

The project management style that our team is following is the Agile style. Our project deliverables are due at various times; the mid-check-in is due on December 9, and the final deliverables are due in April. As we have a flexible schedule and a lot of research work to do on how our design should function, we decided to follow the Agile management style.
Our team has two weekly joint meetings to discuss individual progress and how the team is progressing towards weekly goals. At these meetings, we break down tasks for the upcoming week and collaborate on the weekly lightning talk presentation. The progress is communicated through Discord if the team members cannot attend the meeting.

3.2 Task Decomposition

The design's mission cycle can be broken into several steps as follows: launching payload host into space from Earth, target acquisition, net deployment, target retrieval, deorbiting target, and reloading the net launcher. Due to the shortened timeline of our capstone project, several of our mission cycle steps are assumed to be completed or done by another outside party. Our design instead focuses on the completion of three key mission steps: 1) capsule deployment, 2) capsule piloting, and 3) net deployment.

These phases can be further broken down into actionable tasks. First, a spring powered launching mechanism propels the net capsule away from the magazine that houses and deploys the capsules. Second, the net capsule is automatically piloted towards the target debris using the onboard guidance to correct the path if misaligned. Third, the net is deployed to capture the target debris and alter its orbit using the thrusters onboard the capsule, facilitating faster re-entry and burn up in the Earth's atmosphere. After this operation has been completed, a reloading mechanism resets the launcher to its active position followed by the capsule taking the empty space left by the previous one and facilitates repeatability of the capture-deorbit cycle. This task decomposition demonstrates how our project successfully fulfills the challenge's requirement of implementing three continual ISAM actions.

3.3 Project Proposed Milestones, Metrics, and Evaluation Criteria

From a project timeline point of view, key milestones for this capstone challenge are listed below in section 3.3.1. In addition to the milestones, there are important metrics that the design will be evaluated on, such as demonstrating at least three consecutive ISAM steps, as discussed in section 3.3.2.

3.3.1 Milestones

- (02/09/2025) - Conceptual Design Review
- (03/14/2025) - Animation and Completion of 3D Printed Model
- (05/04/2025) - Final Presentation and Report
- (05/04/2025) - Prototype Complete

3.3.2 Metrics/Evaluation and Criteria

- Design executes 3 Operations, as defined by the C3 guidelines.
- CAD model animation demonstrates an ISAM application through 3 or more consecutive steps.
- The prototype can execute actions described in the CAD model animation within a neutrally buoyant environment.
- Energy Storage needs cannot exceed 10.2 Ah
- The design does not exceed a power draw of 444W
- Design is not larger than 20.5” x 16.4” x 27.0”
- Design does not exceed a power draw of 222W while larger than 17.0” x 16.4” x 27”
- The design does not exceed 70kg

3.4 Project Timeline and Schedule

The project tasks and milestones can be written into a timeline in the following Gantt Chart in Figure 1. To summarize the chart, it marks the dates each milestone should be started and finished in coincidence with the given deliverable due dates for our capstone course and the design competition. The initial brainstorming phase took about a month to discuss and choose an idea, of which nets were chosen as the idea. The next stage is the CAD model development for the net launcher, which was allotted about a month and a half. Not shown in this segment of the Gantt chart are the animation, final report and presentation, and prototype milestones. The CAD model animation was completed April 1st, 2025, starting after the CAD model was completed on the 23rd of February, 2025. After the CAD animation, the final presentation and report was completed on April 14th, 2025. Finally, after the animation, the design prototype continued development through May 4th, 2025.

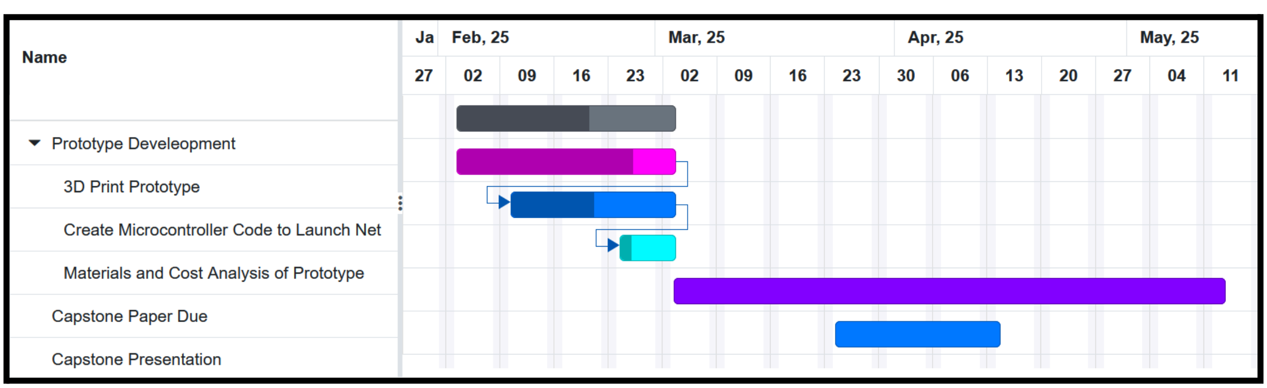

Figure 1: Milestone breakdown

3.5 Risks and Risk Management/Mitigation

Several key risks are posed by the operation of our payload which is a net-based deorbiting system in Low Earth Orbit (LEO). Our team has identified the three main categories of concern: deployment reliability, environmental reliance and platform reliability. Given below is the description of the mentioned categories.

Deployment Reliability

- Deployment failure
  - There is a possibility that the net may fail to deploy correctly due to mechanical issues or misalignment with the target.
- Misfire or Misalignment
  - Improper net trajectory or launch angle can prevent a successful capture from executing. To mitigate this our microcontroller calculates the expected position of the target when the net will capture it.
- Target Escape of Capture Failure
  - There is a risk that the net will not capture the target totally and the target escapes due to not being secured correctly.
- Deorbit Mechanism Failure
  - The net capsule should have enough fuel to deorbit successfully. Enough fuel on board will be planned to ensure the deorbiting is successful.
- Collision with Non-Target Objects
  - The net capsule can possibly collide with an unintended entity. To ensure that this does not happen we have on board sensors to monitor the surroundings till the completion of the event.

Environmental Resilience in LEO

- Microscopic Debris Impacts
  - The net must withstand potential impacts from small, fast moving particles. To ensure the small particles do not leave the net we have decided on designing our net to have a tighter mesh on the inside.
- Atmospheric Drag: Orbital stability and target positioning could be impacted.
- Thermal Extremes & Solar Radiation: Material selection and shielding strategies have been chosen wisely after testing to minimize issues.
- Radiation Infused Malfunctions: Use of components that can withstand radiation will be used in order to not compromise the system functionality.

Longevity and Sustainability

- System Longevity
  - Long term viability is ensured by using durable and reliable components. The system must sustain repeated operations, including multiple net deployments and reloading cycles.
- Reloading Mechanism Risks
  - Failure to reload the net capsule from the spring compressed magazine or jamming can occur hindering the reloading process.
- Minimizing Space Debris Contribution
  - Our solution is designed with sustainability in mind. Features such as reloading and housing multiple nets, efficient fuel and power consumption help avoiding the contribution to the LEO debris problem.
- Other Operational Risks
  - Unintended propellant outgassing: Proper sealing and venting mechanisms will be ensured to control unwanted leakage.
  - Invalid target designation: Verification with the ground communication as well as sensor data will be conducted to prevent targeting non-existent or non-debris objects.

3.6 Personnel Effort Requirements

Table 1 below lists the personnel effort requirements with an estimated number of hours for completion. These essential tasks within the project will comprise the majority of the time spent on this project.

Task	Estimated Number of Hours
ISAM Research	50
Net Launcher Concept	30
Comparative Market Research	30
CAD Model	20
CAD Model Animation	20
Prototype Physical Construction	50
Prototype Electronics and Code	30
Electronic and Material Cost Calculation	5

Final Presentation, Report, and Paper	40

Table 1: Personnel Effort Requirements

3.7 Other Resource Requirements

- For details on BCT X-Sat Venus Class bus please see section 2.1

Our project is a payload that will be carried by the Venus Class Bus. As a result, we are limited in resources such as size, energy consumption, and weight.

- List of Viable Materials for use in space

Our project's operating environment is in the vacuum of space where factors such as high radiation and low temperatures will be experienced. Our material selection must comply with the unique aspects of the in-space environment. Beyond the use of our design in space, we must also consider materials that can handle the intense process of launching into orbit.

Through thorough research of materials, we determined the types of metals and alloys that could survive launch and be used safely in our operating environment. We used commercially available space-rated products when these were available and fit. We also performed a SWAP (Size, Weight, and Power) analysis for all of our components and materials in order to narrow down specific products that are currently offered in the market right now. This is due to the limited SWAP capacity of our payload as described in the *Design Constraints* section (Section 2.1.2) of this document. Below is a table summarizing all our selected components:

Component	Data Sheet Link	Power	Size	Weight
RP2040-LoRa	https://kamami.pl/en/lora-modules/1188994-rp2040-lora-development-board-integrates-sx1262-rf-chip-long-range-communication-options-for-freq-5906623428328.html	158.49 mW	21 x 41 mm	10-20 g
LIDAR Sensor (IR Sensor)	https://leddartech.com/app/uploads/dlm_uploads/2021/04/54A0028_V8.0_EN_Leddar-Vu8_User-Guide.pdf	2.2 W	70mm x 35.9mm x 71.2mm	107 – 128g
Ground com(transceiver generic)		30W		
servos/motors(for spring)		10 W(Part of the reloading mechanism)		
servos(for sensors) Parallax standard servo	https://docs.rs-online.com/0e85/0900766b8123f8d7.pdf	3 W	5.58 x 1.9 x 40.6 cm	44 g
Reloading mechanism		110W estimated	15" X 6" X 27"	
Total		~150 W		

Table 2: Components used for design

We researched materials that could survive the intense force, vibrations, and heat of launching into space. Through the material property data provided by ANSYS inc., we simulated the performance of numerous materials in different temperatures, modeling launch, and operational temperatures using MATLAB and NASTRAN. The results can be noted in *Section 6.2* of this document. Beyond surviving the environment, we tracked our payload weight to stay below 75 kg.

For the purposes of a prototype, we used the following components to show the functionality of the model. The list of components were narrowed down to:

Prototype Component	Description/Links

ARDUINO UNO Microcontroller	Used to demonstrate the primary microcontroller that commands the net launch https://docs.arduino.cc/hardware/uno-rev3/
SHARP GP2Y0A21YK0F IR Sensor	Used to detect objects and their speed of motion. https://global.sharp/products/device/lineup/data/pdf/datasheet/gp2y0a_gp2y0d_series_appl_e.pdf
Servo SG90	Used for compression or expansion of spring. http://www.ee.ic.ac.uk/pcheung/teaching/DE1_EE/stores/sg90_datasheet.pdf
100mF Capacitor	Used to improve the accuracy of the IR sensor. https://www.mouser.com/c/passive-components/capacitors/aluminum-electrolytic-capacitors/?capacitance=100%20uF&voltage%20rating%20dc=450%20VDC
Newark Breadboard	Used to connect all the components https://mexico.newark.com/en-MX/twin-industries/tw-e40-510/breadboard-solderless-400-tie/dp/56T0249
Conical Spring	Used to provide launching force (Max Outer Diameter 0.6 inches, Length 1.25 inches) https://www.grainger.com/product/Compression-Spring-302-Stainless-1NCY8
3D printed Net capsule, plunger, stand	Printed using Black PLA plastic.

Table 3: Components used for prototype

Our team selected an Arduino because it was readily available and members had experience with it. Additionally, it supports Digital and Analog I/O signals along with real time signal processing at low power. A SHARP IR sensor was selected due to its high accuracy and fast response time. Servos that were available on hand were also selected for the purposes of demonstration. When designing our prototype, we needed parts that were not commercially available, so we had to create these components ourselves. Using a 3D printer, we manufactured Net capsules, Plunger and Stand using PLA. We deemed that PLA had enough strength and dimensional accuracy for our purposes. To fit our printed model, a custom conical spring was ordered and selected.

4. Design

4.1 Design Context

There is a present and growing need for the removal of debris from space. There are currently over 1.1 million pieces of debris in Earth's orbit ranging in size from 1 cm to 10 cm. Meanwhile, it is estimated that there are 34,000 space debris objects larger than 10 cm in Low Earth Orbit (LEO) according to a report by the European Space Agency (ESA) [16]. With additional objects in space, more debris will likely be added into LEO. Rockets are losing components in launch, satellites die in orbit, and astronauts are even losing tools. Pieces of debris in space can cause collisions that could generate thousands of fragments of debris that could then collide into other objects in space. In what is known as Kessler Syndrome, catastrophic debris collisions pose serious risks to active satellites, space stations, and human spaceflight, resulting in cascades of debris and potentially blocking orbits [18].

Examples of this can be seen throughout the history of Space Exploration. An old Chinese weather satellite fragment hit a Russian satellite in 2023, creating even more space debris and halting operations. In November 2021, a Russian anti-satellite missile test caused over 1500 pieces of debris that caused the crew to seek shelter on the International Space Station [19]. In spite of their small sizes, these fragments travel at high speeds, posing serious threats. To maintain the long-term sustainability of space operations, it is necessary to mitigate and dispose of debris effectively.

The process of debris removal is an example of the service portion of ISAM. More specifically, the service provided by the design proposed in this section is the capture and removal of debris ranging from 10 cm to 1 m in size.

4.1.1 Broader Context

Our design will remove debris ranging in sizes from 10 cm to 1 m in size to create a clean space for future spacecraft to operate in LEO. We will accomplish this through remotely piloted net capsules that will envelope and deorbit debris. On a larger scale, our design will help preserve LEO for the continued use of communication, internet, and global positioning satellites. Societal areas affected by our design are categorized and explained in *Table 4*.

Area	Description
Public Health and Safety	The result of the design is the preservation of clean space for craft in LEO to operate. An

	additional benefit to manned missions in LEO, will be a reduced risk of a debris collision, which otherwise could pose a life-threatening harm.
Global, Cultural, and Social	Removal of debris provides a clear operating space for all nations with active LEO space programs to continue their operations unhindered by the threat of debris collisions.
Environmental	The removal of debris from LEO creates a cleaner environment that supports sustained operations in space and supports humankind's mission to pursue space travel.
Economic	Limiting debris in space would reduce risks of operating in space and allow for longer operating periods, lower risks, and higher likelihood for a return on investment.

Table 4: Design Solutions Impacts

4.1.2 Prior Work/Solutions

Our design is not the first net launching debris removal craft. One example of a previous project was the Remove Debris mission by the Research Executive Agency (REA) from the European Union. The project began in 2013 with the goal of demonstrating several experiments to catch self-launched targets representing space debris such as a CubeSat [11]. The net capture system design of the Remove Debris satellite is shown in Figure 2 below. The design used 5 masses attached to corners of a net that were spring-loaded and launched outward to expand the net. When the small satellite was ensnared in the expanded net, motors within each mass reeled in the remaining slack of the net to ensure the small satellite remained entangled in the net. The small satellite then began deorbiting due to the excess drag induced by the net.

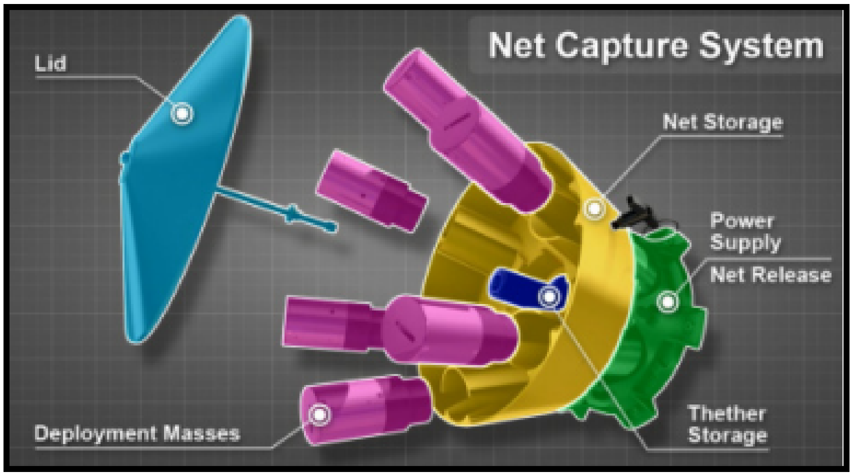

Figure 2: *Remove Debris Net Launcher Design[25]*

Another project was conducted at McGill University in Montreal, Canada, to create a simulation package for modeling a tethered net capture mechanism. This tethered net mechanism was designed to capture space debris such as rocket upper stages [12]. Publishing findings in 2018, the project results concluded the tethered net mechanism was successful and could also be used to capture small asteroids. Looking further into the project's details, the simulation model used a C++ program to model the vortex dynamics, which simulated the compressive and tensile stresses a net would face as it moves through space and wraps around a target object. Below in *Figure 3* is a schematic representation of the simulation process.

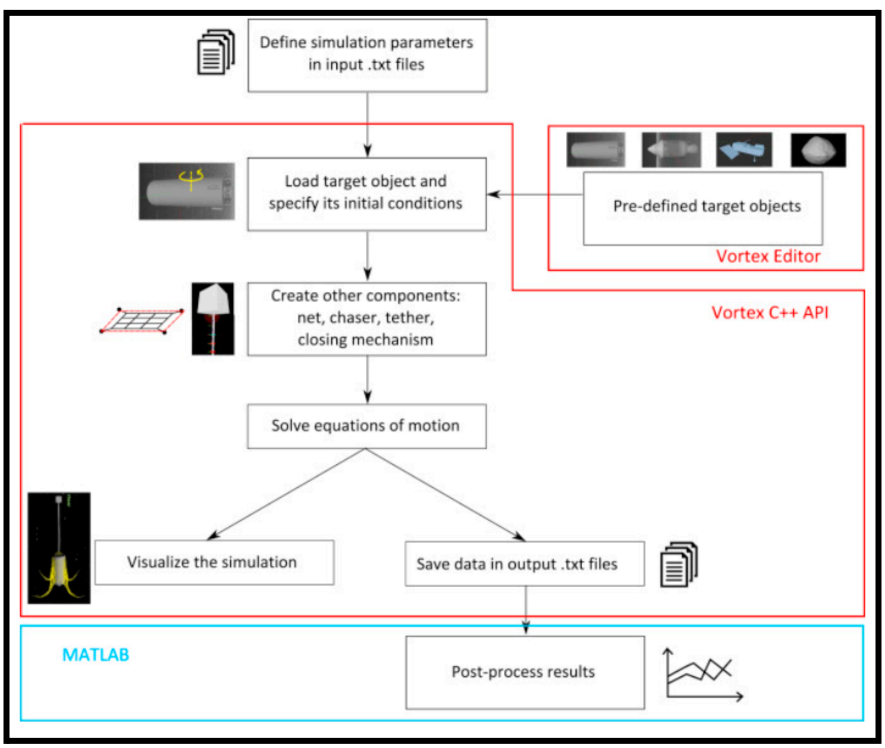

Figure 3: *Schematic representation of the tethered net simulation processes*

Finally, a third project that utilized a net capture mechanism designed for use in space was conducted by Tokyo Metropolitan University, Tokyo, Japan, and Royal Melbourne Institute of Technology (RMIT) University, Melbourne, Australia. The project proposed a tether-net release mechanism with unique design aspects. Similar to the design of the Remove Debris project, this project's design featured a circular net compartment with four attached masses arranged around the perimeter. When launched, the masses were to be ejected forward and outward, expanding the net while the net moved toward the targeted space debris [12]. An innovation of this design was combining the net lid and masses. This was accomplished by cutting the net storage compartment lid into 4 parts and attaching each part to a designated mass. A diagram showing the lids, mass tubes, and central net compartment is shown in Figure 4 below. The result was a reduction in the size of the net expansion masses as each of the 4 had a portion of the lid that was used as part of each mass.

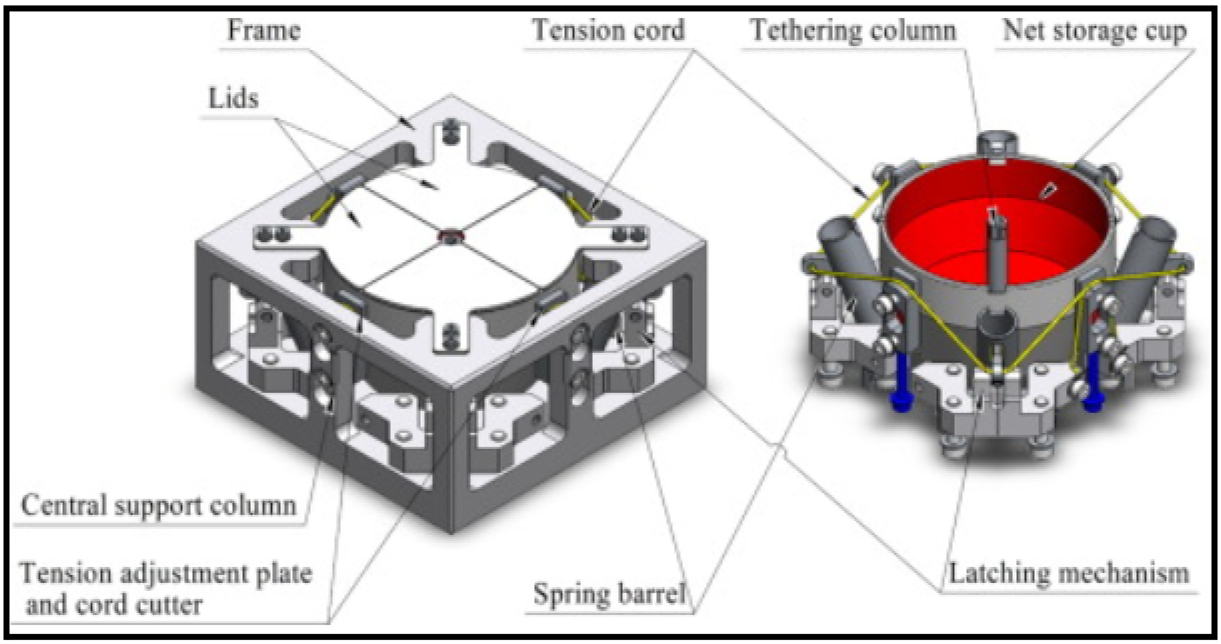

Figure 4: *Tethered-Net deployment mechanism design with 4 lids over the central net storage compartment[12]*

Our net launcher design combines features of the previous projects described and also adds further innovations. One innovation is the use of a net capsule, allowing a more compact net enclosure design. A second innovation is having a reloadable launching mechanism to launch multiple net capsules. Together, the compact net capsules and reloadable launcher allow an increased impact by removing multiple pieces of debris. A third innovation for our design is the expansion method of the net capsule. Once a net capsule is launched, it will use cold gas thrusters to initiate a rotational spin along the axis of travel. This will generate an outward centrifugal force, pushing the walls of the net capsule apart to expand the net that is enclosed inside. A smaller launching force is needed to get the capsule from the launcher to free space by having the thrusters on the net capsule. This is beneficial since there will be a reduced resultant launch force on the host satellite so smaller positioning corrections would be needed after a launch. The disadvantage of this design is the increased complexity of using cold gas thrusters and the increased cost of having thrusters on each net capsule.

4.1.3 Technical Complexity

Our payload design presents significant technical complexity due to two factors which are its physical design and the operating conditions in the space environment. At a high level, the system is based on a spring-launched net capsule mechanism intended to autonomously capture and deorbit orbital debris ranging from 10 cm to 1 meter in size. The three major subsystems of the net capsule are: the net capsule launcher, the net capsules, and the enclosure that houses the net capsules. Each subsystem involves intricate engineering considerations to ensure the reliability and functionality of the payload in space.

Operation in Lower Earth Orbit (LEO) introduces several environmental constraints that heavily influenced our team's design choices. The payload must be able to withstand harsh space conditions, including solar radiation, extreme temperature fluctuations, and the absence of gravity. These conditions not only complicate hardware durability but also affect the sensors, propulsion systems, and control mechanisms on board. Adding on to the complexity of our payload design, the aspects such as launching the net capsule and correctly deorbiting the debris require precise coordination of the systems.

Beyond the physical and environmental constraints, our project also demands innovative technological solutions to fill existing capability gaps in space systems. For example, accurate sensors and LiDAR arrays are important in a space system to detect objects like debris in our system. Current LiDAR systems that are accurate are often bulky and power intensive and the lightweight ones are not feasible to operate in space and are less accurate. Addressing this complexity there is a need for LiDAR systems that balance size , power, efficiency, and spatial accuracy. They should also be able to operate in conditions suitable in space.

Another complexity that was identified was maneuvering the net capsule after it had been soft launched towards the target. Our system used adaptive thruster control to maneuver the capsule to its target. However, the traditional thruster systems lack real-time adaptability and error correction, which would have been helpful in our project and in dynamic orbital environments. Misfires or minor orbital deviations can lead to the capsule missing the target or not completely covering the target debris if not corrected automatically. This necessitates the development of intelligent thruster systems that are capable of real-time course correction to ensure accurate targeting and safe operation.

Finally, our mission envisions long-term space sustainability, which demands capabilities for autonomous on-orbit inspection and minor repairs. Current space systems rely on manual or Earth-based teleoperation, both of which are costly and slow. The absence of fully autonomous repair technologies limits mission lifespan and increases operational costs. Introducing intelligent, self-sufficient systems that are capable of conducting real-time corrections would be a transformative advancement for future systems.

Concluding, the technical complexity of this project arises from the integration of different systems, environmental resilience, autonomous navigation, and in-space propulsion control. It is further amplified by the need to address the technological gaps in the space systems that are present in today's world. Successfully implementing our payload not only pushes the boundaries of existing space technologies but also contributes to the broader vision of autonomous, sustainable, and cost-effective operations in orbit.

4.2 Design Exploration

4.2.1 Design Decisions

1. Net Launching Mechanism

Net materials are an important design decision we will face because this will impact our project's ISAM capabilities, weight, and size. The material of our net must be durable enough to capture and hold debris without tearing. Our net must also be light and flexible enough to comply with our weight and size requirements.

2. Propulsion System

We must consider primarily how our net propulsion will function. Our propulsion system will directly influence the overall weight of our final design. If we choose to utilize gas propulsion for our device, we can utilize a single large propulsion canister to launch our nets. Alternatively, we can use smaller, individual gas canisters each capable of launching a net.

3. Communication

Ensuring consistent and reliable communication between ground assets and our satellite will allow for safe in-orbit operations. Proper communication technology built into our net launcher will enable our design to receive relevant information about the location of potential pieces of debris.

4.2.2 Ideation

4.2.2.1 Brainstorming from Previous Semester:

In the brainstorming phase, we considered 6 potential ISAM problems to pursue: Refueling, Repairing, Upgrading, Space 3d-printing, Removing Space Debris, Communication Constellations

- **Refueling**: The idea here was to design a module that would allow for the refueling of satellites, however our biggest problem with refueling was establishing universal refueling plans. As we were unsure of the feasibility of such a process on older satellites, we abandoned this idea as we were looking for more of a catch-all at the time.
- **Upgrading**: Very similar to repairing, however, our ideas were in the field of making additions to existing satellites, and the challenge of not impacting existing functionality was too great for us to pursue the idea.
- **Space 3D-Printing**: After doing some research, we found that there is an existing grad team working on this, and felt that as a result the problem's scale was outside the feasible range for our team.
- **Removing Space Debris**: We were enamored by the idea of reducing the debris field, especially with some of us growing up hearing about it being a potential problem. Of our 2 ideas between robot arm and net, we were advised to stray away from an explicit robot arm in regards to the competition. Leading us to settle on a capture net idea.
- **Secure Communication Constellations**: The idea was to have a mesh network of satellites that used shorter range communications and the developing laser communication technology to drastically limit potential message interception in space. However as a concept built for a singular satellite it was impossible to rationalize within the project's scope.

4.2.2.2 Overview:

In December of 2024, our team began developing the initial prototype of the Space Cyclone which focused on debris removal in LEO. We explored multiple design iterations before finalizing a prototype, with the primary goal of establishing a sustainable method to capture and deorbit debris. Ideally, we wanted to create a craft capable of de-orbiting multiple pieces of debris per mission.

4.2.2.3 Determining Capture Method:

Our initial design consisted of a satellite launching a harpoon that would spear debris and attach a solar sail to drag the debris into the atmosphere. The harpoon and solar sail method of de-orbiting debris meant that our craft would require high precision to strike its target with enough force for the spear to penetrate through the material before it would be allowed to be dragged into the atmosphere. We determined that while the harpoon could be feasible for larger designs, our model could not handle the more significant issue of micro debris in LEO.

In our second design iteration, we aimed to capture both large and small debris more effectively. The first solution we considered was using a net, which could be compacted into a spacecraft and expanded to cover the maximum area around a target. Unlike the harpoon, a net requires less precision for targeting when expanded and is better suited to capturing smaller debris particles while still being effective for larger objects.

4.2.2.4 Reloading Mechanism:

We continued to develop ideas for how we could store and reload nets efficiently. This led to the concept of self-contained net capsules and a storage system capable of holding multiple capsules. Additionally, we wanted net capsules that could expand and fully deploy a net once launched from the payload. We first considered having the net capsule resemble a shotgun cartridge: the net would be compacted inside a hollow cylinder, with its endpoints attached to the base. When launched from the payload, the cylinder would press forward, force the net out of the capsule, and deploy it towards the target. However, a drawback to using the cartridge idea was that the cylinder would remain inside the payload after launch. We could not identify a simple method for safely disposing of the used cartridge without contributing to additional debris.

To address this, we revised the capsule design to make the entire system self-disposing. The new concept involved equipping the capsule with onboard thrusters that used small amounts of gas for steering. Once impact with the target was made, the onboard thrusters would propel the captured debris into the atmosphere for deorbiting.

4.2.2.5 Net Deployment Process:

We still needed to determine how the net would be deployed. One idea was to generate centrifugal force by launching the net capsule through a rifled barrel to induce spin as it exited the craft. However, we faced significant challenges, namely, generating enough force to propel the capsule through the barrel and overcoming friction in the barrel to produce spin. We could not determine a concrete method to resolve either of these issues, so we moved past the idea of relying upon spin from a rifled barrel.

Instead of relying on the payload to create spin, we examined using additional thrusters on the net capsule to achieve this. By placing angled thrusters on the sides of the capsule, we concluded that sufficient spin could be produced for the capsule to deploy the net. While this approach could potentially increase the size and weight of the capsule thus increasing fuel requirements, we determined that it was a worthwhile tradeoff to achieve full net deployment capabilities.

4.2.2.6 Net Capsule Launch Mechanism:

While we had considered the behavior of the net capsule post-deployment, we also needed to determine how our craft could launch a net capsule with limited offset to the host payload. We considered two initial designs for propelling our net capsules: a gas-based piston and a spring-based plunger. The gas-based design used a system of interconnected pistons powered by onboard gas to generate force to push a piston out and retract. Using a piston to strike the capsule and propel it out of the craft, we could create enough momentum to get the capsule to the target. The initial assessment of the piston design highlights that while the system could recycle gas and perform as intended, it would consume additional space on the bus, reducing net storage capacity and adding further design complexity. The alternative spring-based design involves compressing a spring and releasing the tension to propel a net capsule out of the craft slowly. The “soft” deployment would reduce the launch displacement of the craft and help prevent damage to the net capsule.

For our storage mechanism, we drew inspiration from two sources—a PEZ dispenser and a six-shooter revolver—to explore different methods of storing net capsules. In the PEZ-style design, each net capsule is stored in a spring-loaded magazine. When debris is identified, our payload will propel a net capsule out into space from the top of the magazine and deploy the net. Once the top net capsule has been fired, the spring force presses a new capsule into the firing mechanism. Alternatively, we considered using a revolver-style storage mechanism. Each capsule would be stored in a rotating barrel that would cycle in a new capsule into the chamber once a net capsule is launched. We determined that using a revolver-style mechanism to load net capsules would be more difficult for reloading due to the cylinder mechanism of the revolver having to be unscrewed or mechanically disengaged from the payload. The box magazine approach proved to be more practical, allowing for easier reloading. A supporting satellite could dock with the BCT X-Sat Venus Class bus and replace the magazine, which would come preloaded with a primed spring—something not easily achieved with a revolver barrel swap.

Once we decided the net capsule would be self-propelled, we had to determine how the capsule would approach a target and what data it would use. We wanted our craft to receive coordinates for debris from ground-based communications. Once a piece of debris was located, our payload would adjust its orbit to be on a path of trajectory to meet the debris. We chose infrared sensors to identify the debris and assist in steering the net capsule toward its target. Additionally, infrared is relatively low cost and low difficulty to implement as it enables us to use 2D detection as opposed to identifying the 3-D characteristics of the target.

4.2.2.7 Physical Model Creation:

We designed this initial model with the intent of the net capsule being steered autonomously using LoRa radio transmission and LiDar optics from the Venus bus. Based on early calculations, we found that an optimal distance for net deployment was approximately 10 meters, as this distance, coupled with the acceleration of the capsule, would provide ample time for the net to unravel before reaching its intended target.

We began CAD modeling for this design and established our concept of operations (CONOPS) that illustrated the process of the craft targeting a piece of debris, deploying a net capsule, and de-orbiting. We also started tracking mass, volume, and power requirements, and researching space-rated commercial off-the-shelf products that could be used in our design.

4.2.3 Decision-Making and Tradeoffs

The process used for determining pros and cons of each design came down to what had been tested previously and how successful they were from our research. The concept studies phase of our solution was the most time-demanding phase of our research. It first involved narrowing down a solution and a challenge to tackle. To aid in our efforts, we first addressed the following question: What type of service does the current Space industry require? Our team examined various challenges, including the concern of space debris, servicing needs of functional satellites, in-space manufacturing, etc. Solution concepts were then proposed for these different problems.

- Manufacturing: Our team brainstormed ways to 3D print in space or provide potential advancements in crystal growing for the medical industry. The benefit of doing so was that manufacturing in low-gravity environments could produce products or metal alloys with fewer defects. We also researched the medical advantage of space manufacturing through fluid dynamics and protein crystallization experiments.
- Servicing: A service we explored was in space photography. The goal of the payload on this project was to photograph any flaws and autonomously inspect satellites. This eliminates the problem of engineers going blind into a space service mission. Knowing about the defect before launch allows for better preparation. We also discussed a remote-controlled drone with arms to maximize access and reach for repair and maintenance applications.

After receiving guidance from multiple experts in the field, we decided that space debris would be the most pressing challenge to address currently. We cannot proceed to other advancements without cleaning up our current playing field. Of course, this meant many contestants would focus on dealing with debris, so we thought about ways to innovate.

We narrowed our focus to capturing pieces of debris 10 cm - 1 meter in size. We considered using a magnet that can attract the metal in dysfunctional satellites, but satellites are generally not made of magnetic materials. We then turned to using tethered nets, where we found a very extensive and intense research study[11]. Through research and mentor advice, we understood the problems of tumbling in space. This, combined with Newton's third law of reaction forces, eliminated the idea of using a tether and forced us to innovate further.

Our conclusion was to create a drone capable of capturing and deorbiting defunct CubeStats and orbital debris with a certain mass and volume. This solution would minimize the reaction forces and tumbling on our host satellite. The mechanism of a revolver inspired us. Initially, we thought our platform satellite would contain a launch tube with rifling to deploy our net capsule. However, we discovered this would have serious hostile reaction forces on our host. We thus opted for a soft launch and included thrusters on our net capsule for remote control of its trajectory. The final decision was to soft launch a net capsule, use spin dynamics to open the capsule, capture the object, and have a controlled deorbit of the dysfunctional satellite using the remaining fuel. This solution was the end of our prephase concept studies.

Concept	Time	Cost	Power	Reason for elimination
3D printing		Not Optimized	Not Optimized	Cost and Power are not optimized. Not innovative enough.
Pressurized vacuum chamber			Not Optimized	Power is not optimized
Remote Controlled Drone	Not Optimized	Not Optimized	Not Optimized	SWAP-C is not optimized.
Magnet for collection of Debris				Although it is SWAP-C efficient, it is not practical. Not all debris is magnetic.
Tethered Net				Although it is SWAP-C efficient, tumbling and reaction forces cannot be avoided
Rifled Net Launcher	Not Optimized		Not Optimized	Reaction forces cannot be avoided
Autonomous	Not			Although it uses extra fuel

Net Capsule (Drone)	Optimized			compared to tethered nets, it provides the most efficient way to counteract tumbling and reaction forces.

Table 5: Overview Trade Study

4.3 Final Design

4.3.1 Overview

Our prototyped design utilizes a piston/plunger-compressed spring and cold gas thrusters to propel a net capsule projectile toward targeted space debris. Once a net capsule projectile is launched, cold gas thrusters will generate rotational motion along the capsule's line of travel, generating a centrifugal force. This force will cause the capsule's cylindrical net compartment, made of 6 side pieces, to expand radially outward, deploying the net from within the compartment.

4.3.2 Detailed Design and Visuals

4.3.2.1 Conceptual Designs

The first net launcher design is shown in Figure 5, where the housing is shaped like a rectangular box. Centered in the box is a round bowl for the net. In a circular pattern around that are four cylinders for housing weighted masses. The masses are divided into two parts. One is the cylindrical portion that sits in the mass cylinder, as shown in Figure 5, and the second is the lid that covers the mass cylinder and a portion of the net's bowl-shaped container. This two-piece mass design allows the size of the cylindrical masses to be smaller by taking advantage of the mass of the lids.

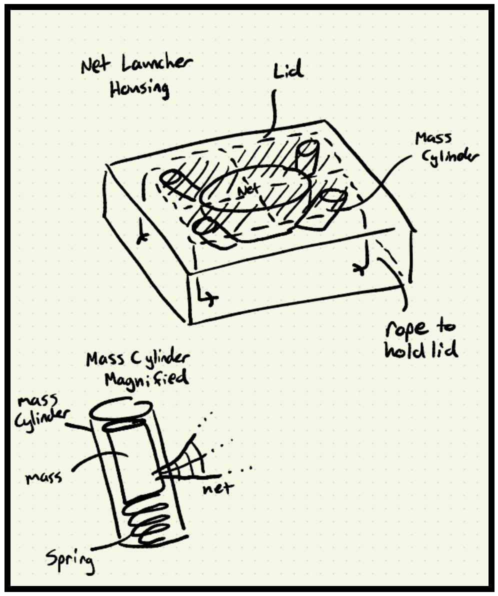

Figure 5: Net launcher housing and mass in the cylinder

Each mass is spring-loaded and attached to the net. A rope ties the masses down, securing them before launch. When ready to launch, the ropes are cut, releasing the spring-loaded masses and launching the net. As the masses are launched outward at an angle, they continue the forward momentum while simultaneously expanding the net, as shown in Figure 6.

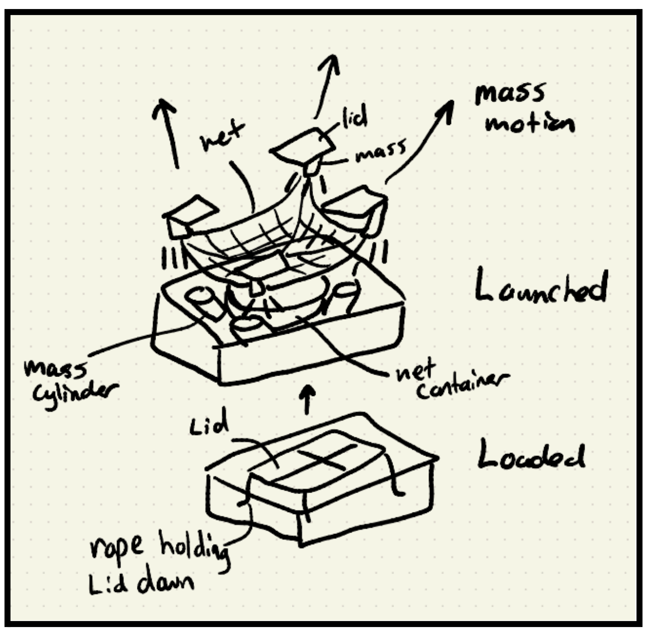

Figure 6: Net launching processes

Another deployment mechanism considered for this solution is shown in Figure 7. This mechanism utilizes the extension of collapsable linkages to push an object placed on the top plate rather than using spring-loaded masses.

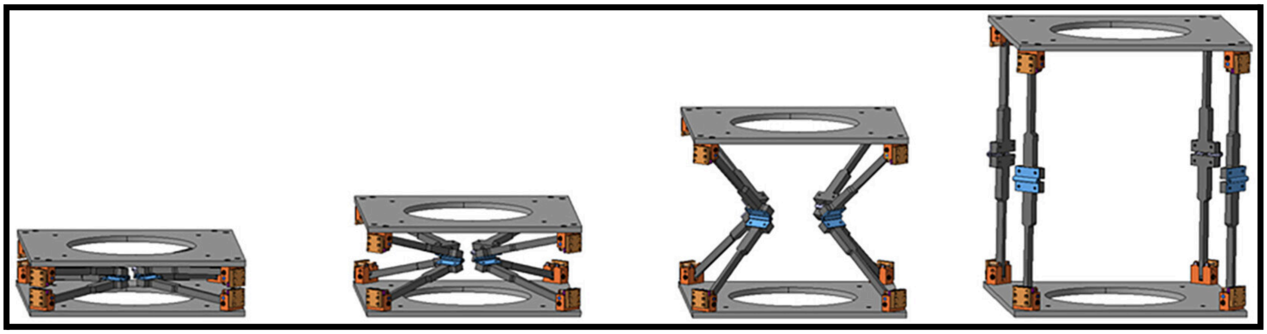

Figure 7: Collapsable linkage launching mechanism[6]

4.3.2.2 First Prototype

The first prototype design was built on the conceptual designs, having the same premise of a net enclosed in a container but now condensing the container down into a net capsule projectile. The first net capsule projectile design is shown in Figure 8 below.

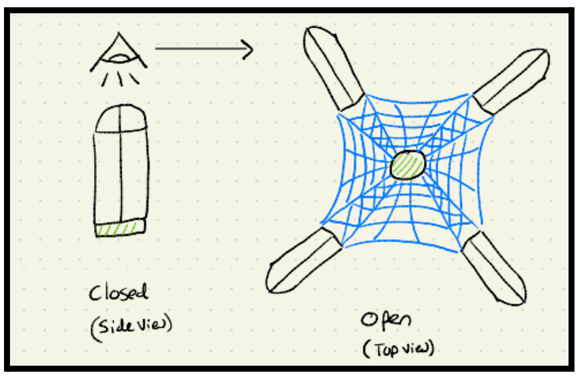

Figure 8: Net Capsule Projectile

The above net capsule projectile functions as a net deployment container. When stored, as shown on the left in Figure 8 above, the net capsule is a cylindrical shape. On the right in Figure 8 above is when the net (shown in blue) is deployed and fully expanded. The capsule design consists of five components. One is the circular, green-colored, plate that is the center point in the net and also the base of the net capsule projectile. The remaining four parts are rounded, hollowed-out side pieces attached to the net, and each holds a portion of the net inside when stored. Finally, centrifugal force would be used to expand the side pieces and the net.

With the net container design now a net capsule projectile, multiple projectiles could be stored on a launching device. Shown in Figure 9 below is the first net launcher prototype.

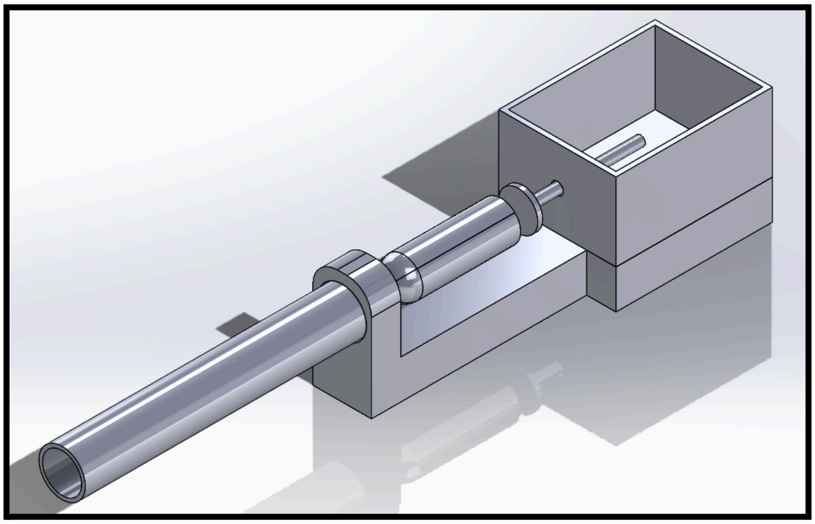

Figure 9: First prototype net launcher in CAD

Two propellant options were considered for launching the net capsules for the first design implementation. One used a gas propellant, and the other used a plunger/piston mechanism. In either case, once fired, the net capsule was designed to spin through a rifled, tubular barrel, generating the centrifugal force to open the capsule and deploy the net after leaving the barrel.

Elaborating further, Figure 9 above includes the net launching piston and enclosure (lid not shown) to house a piston mechanism. A gas-operated pump would pressurize the piston. When pressurized, the piston would push the net capsule projectile through the rifled barrel. A net capsule projectile is shown in the center in front of the piston (projectile holder not shown).

4.3.2.3 Second Prototype

The second prototype was built upon the first, revising both the net capsule design and the net capsule launcher design. The prototype assembly is shown in Figure 10 and can be broken down into three subsystems, which are the launcher, the net capsule enclosure, and the net capsules.

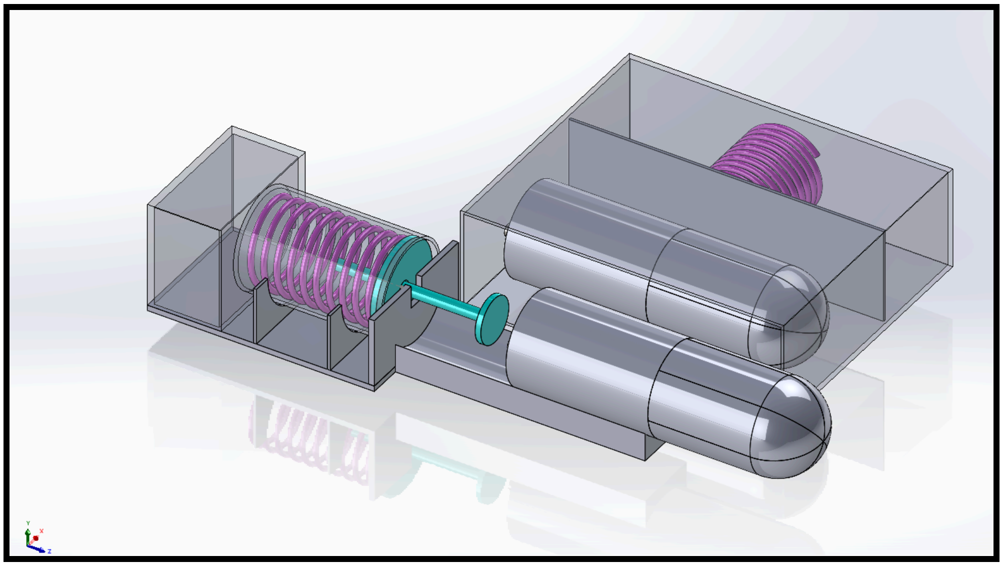

Figure 10: Second Prototype net launcher in CAD

Starting with the net capsule launcher subsystem, it utilizes a spring-loaded piston, shown in blue in Figure 10 above, to push loaded capsules into free space. The launcher only provides enough force to push the net capsule along and off the slot in front of the blue piston. This is by design as a “soft launch” to reduce the resultant forces of a net launch felt by the satellite from which the net launcher is mounted. After launching a net capsule, the piston is retracted to compress the pink-colored spring behind it, on the left in Figure 10 above. With the piston retracted, this allows a new net capsule to be placed on the slot in front of the blue-colored piston. The piston’s movement will be controlled by a winch and cable (not shown) attached to the piston’s rod in the center of the spring. The winch and a launcher control board (not shown) will be housed in the enclosed area on the left side of Figure 10 above, behind the piston and piston spring.

Next, the net capsule enclosure subsystem consists of a rectangular enclosure that houses net capsules to be launched. One end of the enclosure is open for net capsules to be pushed in front of the blue launcher piston in Figure 10 above. Then, on the other end, inside the enclosure, is a spring-loaded plate that can move linearly to feed net capsules from the enclosure to the curved slot in front of the blue launching piston.

Finally, a third subsystem is the net capsules. The net capsule design has two compartments. At the rounded tip is the net compartment. It’s made of six pieces magnetically held together, which are each used as masses to expand the net. In Figure 12 below is a cutaway showing two of these masses removed, revealing the net compartment. In the rear portion are cold gas thrusters, shown in Figure 11 below, and a cold gas pressure vessel (not shown). These are used to propel the net capsule to the targeted space debris after the net capsule is launched into free space by the piston on the net launcher. The thrusters will also induce a rotational spinning motion along the net capsule's axis of travel. The centrifugal force of the spinning motion will force the six masses enclosing the net to expand outward, opening the net to capture the targeted space debris.

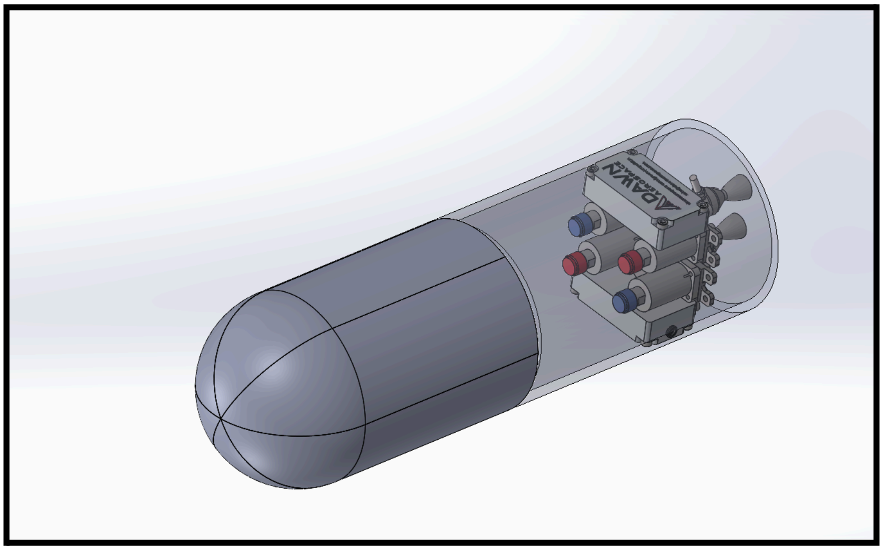

Figure 11: Net Capsule Boosters

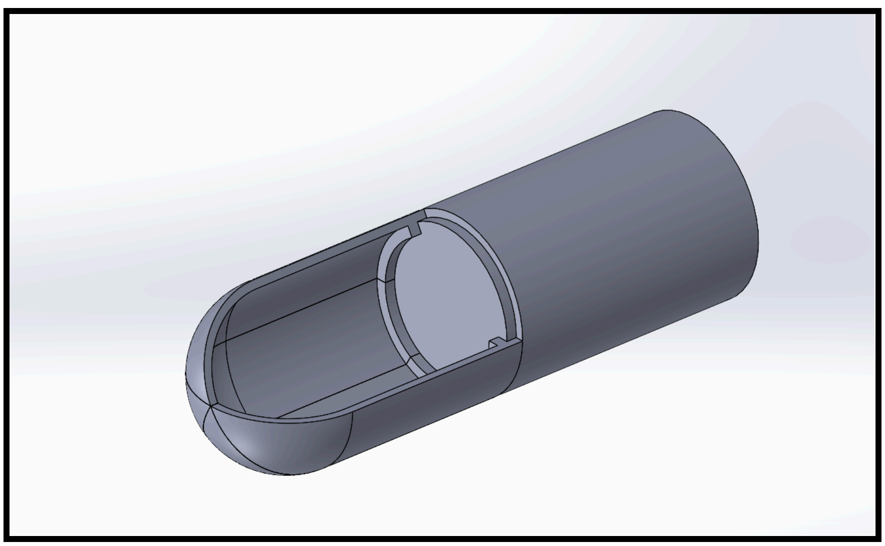

Figure 12: Net Capsule Payload Housing

4.3.2.4 Final Prototype

After further design revisions, the resulting prototype assembly is shown in Figure 13 below. This final prototype uses the identical net capsules as in the second prototype. Changes to this revision are the launcher and net capsule enclosure subsystems.

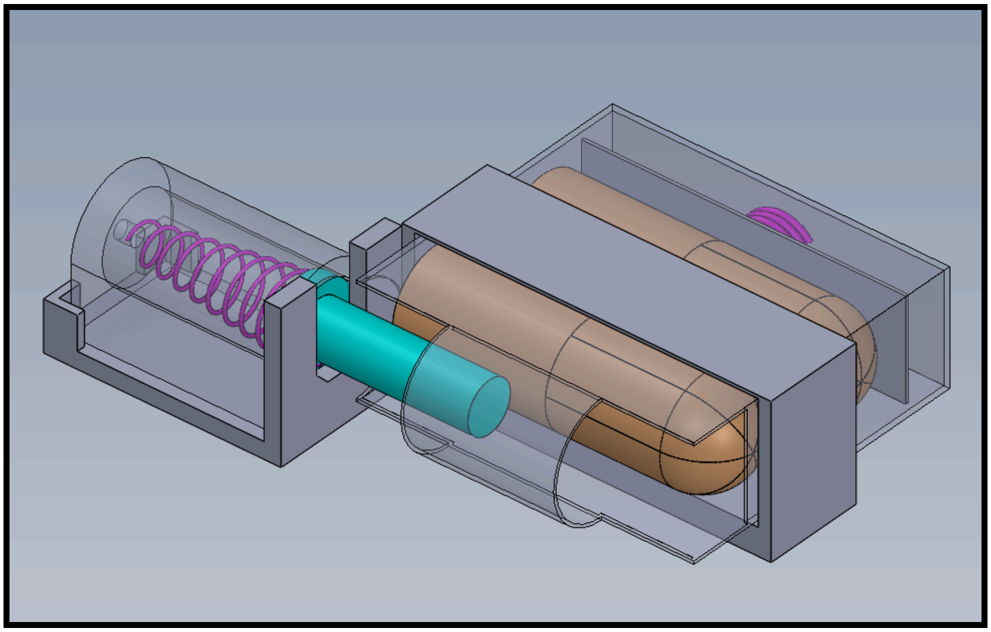

Figure 13: Spring Net Capsule Launch

First, looking at the launcher subsystem, the new design still utilizes a spring-loaded piston to "soft launch" the net capsules, pushing loaded capsules into free space. The piston, shown in blue in Figure 13 above, was reduced to one part rather than two. Next, the pink-colored spring on the left in Figure 13, used to push the blue-colored piston, was changed from a cylindrical to a conical spring due to the more compact size and greater spring force. Finally, the net launcher base, which holds the piston and piston spring, was reduced to two components.

The second subsystem that was revised was the net capsule enclosure. Previously, prototype two used a rounded slot in front of the blue piston on the launcher to hold the capsule to be launched in place before launch (as shown in Figure 10). This design revision removed the slot from the launcher and added a rounded portion to the open end of the net capsule enclosure. This change reduced the amount of material needed to hold the capsule to be launched in place before launch. The resulting net enclosure design is the semi-transparent part holding two orange colored net capsules shown in Figure 13 above.

4.3.3 Functionality

The net capture system uses target data to intercept, catch, and deorbit specific space debris automatically. The whole procedure, from targeting to system reloading, is broken down in detail below:

- Target Alignment and System Initialization:

    - After obtaining information on the target's position, orbit, and predicted intercept point, the system determines the best intercept trajectory based on its own orbital route.
    - After that, the soft launch from the spring-loaded piston occurs and the capsule uses cold gas thrusters to ensure proper alignment for net deployment.
- Target capture and net deployment:
    - With the cold gas thrusters active, they propel the capsule forward and generate rotation along the axis of travel.
    - The experienced centrifugal force generated by the cold gas thrusters causes the capsule to expand outward, expanding the enclosed net for catching that target upon impact.
    - To prevent escape during capture, the net securely entangles the target, even with little tumbling or rotating motion.
- The captured target's deorbiting:
    - Once the target is safely contained, the cold gas thrusters move the trapped item to a lower atmospheric reentry orbit through a controlled deorbit procedure. Upon reentry, the target will burn up.
    - This deorbiting procedure keeps orbital paths safer and reduces the possibility of more space junk.
- Reloading and Resetting the System:
    - The system autonomously repositions and resets itself when the capture and deorbit stages are finished, readying it for the subsequent target assignment.
    - Our spring launch mechanism is re-compressed to allow for a new deployment process for the subsequent mission, and a new net capsule is brought into the launcher via a reloading mechanism.

4.3.4 Areas of Consideration

The current design meets the basic requirements of launching a net at a 10 cm - 1 m piece of debris for capture and deorbiting. One concern for our design is ensuring once a piece of debris is entangled in the net it remains entangled and can be fully deorbited. When a net is wrapped around a piece of debris tumbling in orbit, a winching mechanism to ensure the net remains closed could be beneficial for future work. A potential solution is to have winches in the weighted masses to reduce the excess slack of the net to keep the net closed around the target CubeSat. Another concern is implementing a multiple/reloadable net feature to the design. This can make the design more complex as there are more moving components. One solution would be a revolving mechanism or spring loaded enclosure to guide the next net capsules into position for launch.

4.4 Technology Considerations

Our distinct technologies include

- The net
  - Materials: Lightweight, durable, flexible that can be compactly packed in a space
  - Packing Form: A hexagonal net shape that will be folded into a cylindrical capsule
- The launching mechanism
  - Pushing Force (Compressed Gas / Spring)
  - Destructive Tension Release (cut rope / cable-winch)
- The reloading mechanism
  - Net Capsule Enclosure: Loads the next net into the launcher
  - Primer: Preps the piston for the following launch

Concept	Time	Cost	Power	Reason for elimination
3D printing		Not Optimized	Not Optimized	Cost and Power are not optimized. Not innovative enough.
Pressurized vacuum chamber			Not Optimized	Power is not optimized
Remote Controlled Drone	Not Optimized	Not Optimized	Not Optimized	SWAP-C is not optimized.
Magnet for collection of Debris				Although it is SWAP-C efficient, it is not practical. Not all debris is magnetic.
Tethered Net				Although it is SWAP-C efficient, tumbling and reaction forces cannot be avoided
Rifled Net Launcher	Not Optimized		Not Optimized	Reaction forces cannot be avoided
Autonomous Net Capsule (Drone)	Not Optimized			Although it uses extra fuel compared to tethered nets, it provides the most efficient way to counteract tumbling and reaction forces.

Table 6: Overview Trade Study

There are three categories of the design that need to be tested to ensure desired operation. The first is component testing. The most important component of the design is the net. It will be what wraps around the targeted space debris which will likely be rotating arbitrarily in space. To ensure secure capture of the target, the net material will need to be temperature tested, tensile tested, and abrasion tested.

The second category is testing the three subsystems of the proposed design to ensure proper physical operation. First, the net launcher subsystem will need to test the physical operations of priming the launch piston, launching a net capsule, and reloading another net capsule. For the net capsule reloading system, the movement of reloading net capsules will need to be tested. Then for the net capsule subsystem, it will need to complete propulsion tests and net expansion testing.

Finally, the third category is the design as a whole and its ability to survive being launched into space, operating in space, and surviving re-entry. For this, several simulations and physical tests such as vibration testing, temperature testing, and finite element analysis will need to be conducted. From the results, it can be determined if the proposed design can successfully survive the extremes of space launch and operation.

5. Testing

5.1 Unit Testing

The first unit that was tested was the net. The net was designed to be stored in the front portion of the net capsule, so it needed to be tested for proper storage and expansion. As shown in the implementation section of this report, the net would fold to save space when stored in the net capsule. Then, when the net was expanded, it was successfully expanded to the desired six-sided shape.

The second unit tested was the conical spring. This was a purchased part for a scale model of the net capsule launcher and is discussed in detail in the implementation section of this report. The conical spring fit well in the 3D-printed launcher housing and successfully provided enough force to launch scaled-down net capsules. The net capsules used for launcher testing were 3D printed, Nerf dart-sized capsules.

Finally, the third unit to be tested was the IR sensor for target detection. As discussed in the implementation section of this report, the IR sensor successfully detected target objects. For the object detection testing, a suspended pen cap was used. When moved along a linear path, the IR sensor detected the pen cap and calculated the anticipated position. This successfully demonstrated the target detection and position calculations, which are critical to determining when to launch a net capsule.

5.2 Interface Testing

An important interface is the net and net capsule. A 3D-printed net capsule was made to test the net for proper storage and expansion and is discussed further in the implementation section of this report. The first test was to ensure the net could be folded and packed into the net capsule's net storage compartment. The net compartment was made of six side pieces to form a cylindrical shape for the net to be packed into. Unfortunately, the net was slightly too large to fit in the capsule but this was due to the capsule and net not being exactly to scale. Additionally, the purchased net was made of cotton rather than a Dyneema fiber material, so the net didn't pack as tightly. The second test was the net expansion test. Since the 3D-printed net capsule prototype didn't have actual cold gas thrusters to generate the centrifugal expansion force, the net couldn't automatically expand but could be expanded by hand. As shown later in the implementation section, the net was successfully fully expanded by hand.

Another interface was the launching spring, launcher base components, and launching piston. As shown in the implementation section, the launcher base had two parts that contained the conical spring within a cylindrical space. The launching piston was also partially contained within the same cylindrical space but could move linearly when the spring was compressed or expanded. It was placed in the 3D-printed launcher base parts, and then the fishing line was tied to the launcher piston. The fishing line was then fed through the center of the spring and one of the launcher base components. Then, when the fishing line was pulled, the launching piston moved linearly, compressing the conical spring. Once released, the conical spring expanded and pushed the launcher position, which then, in turn, launched 3D-printed Nerf dart-sized capsules.

A third interface was the electrical prototype's IR sensor and Arduino microcontroller. For this prototype, discussed in detail in the implementation section, the IR sensor was wired to the Arduino and a small breadboard circuit. A program was written and uploaded to the Arduino microcontroller to test the IR's object detection and predicted position calculation. The software Arduino IDE was used to create the program and view the target current and predicted position. As discussed in the implementation section of this report, a pen cap suspended on the fishing line was used as the target object. When moved in front of the IR sensor, the sensor successfully detected the target, calculated the predicted position, and displayed both on the output window in Arduino IDE.

5.3 Integration Testing

The critical integration paths of the net capsule and net launcher designs are object detection, net capsule launch, and net capsule expansion. These three paths were considered essential to achieve the primary objective of capturing space debris for deorbiting.

For object detection, the integration path was tested using the Arduino IDE software, as just discussed. Further details about this critical path's electrical prototype are discussed in the implementation section. Overall, the object detection integration was essential since no space debris could be captured if it was not detected.

The net capsule launch is the second integration path. This step of the space debris capture is important since the capsule needed to be soft launched. Since the net capsule launcher would be attached to a larger host satellite, any capsule launched would have an opposite reaction force on the host satellite. Therefore, a spring-powered soft launch was used to minimize the effect of the launch reaction force on the host satellite. This integration path was tested by a 3D-printed scale model of the launcher, as discussed in detail in the implementation section.

Finally, the net capsule expansion is a third critical integration path. If a net capsule were to partially open or not open, the space debris could be missed, meaning a mission failure. Since the 3D-printed net capsule didn't have cold gas thrusters, the expansion couldn't be tested for automatic net expansion as designed. Instead, the net capsule was manually expanded by hand to ensure that the capsule mechanically functioned as desired. The net capsule was successfully expanded, as shown in the implementation section.

5.4 System Testing

The goal of this project was to deorbit space debris as a service. So, the system-level testing strategy was to individually focus on the three main integrations and then put them together. After testing each of the three integrations individually, the target object detection and net capsule launch were tested together.

When combined, the net capsule launcher and target object detection integrations were successful. As discussed further in the implementation section, the prototype successfully detected a moving suspended pen cap, representing the targeted space debris. Then, a Nerf-dart-sized capsule was successfully launched when the target's position was confirmed.

The third integration, net capsule expansion, was not tested with the others due to the net capsule prototype having a different scale than the launcher prototype. Secondly, the net capsule did not have cold gas thrusters in it for testing the centrifugal force generation and automatic net expansion. This was due to the complexity and cost of designing and adding cold gas thrusters to the net capsule. However, as discussed in the previous integration testing section the net capsule expansion was successfully done by hand.

5.5 Regression Testing

One critical feature that was implemented in the prototype was the use of a fishing line and a servo motor to compress and release the launcher's conical spring. The fishing line provided a linkage between the electrical and mechanical systems of the net capsule launcher prototype. This allowed the net capsule launcher prototype to launch a net capsule only when a target object was detected and confirmed. To ensure that this addition did not break the previously established motion tracking functions. They were first tested independently of each other while all components were connected. After testing determined that they did not interfere with each other while inert, we performed a test in which they worked in conjunction with each other, while maintaining the previous motion tracking functions.

One feature addition that initially failed our regression testing was that of the reloading mechanism. Due to the increased friction force upon launch due to the next shot, the prototype system failed to uphold its previously functioning ability to launch a capsule. This then required us to go back and increase the tensile force used to prime the launching mechanism. After increasing the tensile force used to prime the launching mechanism, we were able to once again fire the projectile with a capsule ready to reload.

5.6 Acceptance Testing

The functional design requirements were demonstrated through the prototype net capsule launcher, electrical prototype for object detection, and net capsule prototype, as discussed in the implementation section. The prototype successfully detected target objects, calculated predicted position coordinates, and launched Nerf-dart-sized net capsules.

Looking at the environmental requirements, the design is intended to remove space debris without adding more debris to space. The cold gas thrusters on the capsules will enable the capsules to be mobile after the soft launch. This will allow the capsule to have more mobility when approaching a target object and provide a means of self-deorbiting of the net capsule in the event of a failed net expansion.

The prototype design was made to fit within the specified size, weight, and power consumption parameters of the host satellite. With the design being reloadable, the net capsule launcher can remove an increased amount of space debris. Offering an economic solution to the space debris problem faced by NASA and other aeronautical companies looking to continue and expand in space operations.

5.7 User Testing

In the creation of our design we had limited interaction with intended users outside of our NASA and industry advisor. We informed our advisors of our design changes and progress through bi-weekly meetings that functioned as miniature design reviews of our final product. In each review session we gathered new insights and ideas to incorporate into our design.

5.8 Other Types of Testing

Material testing was used to verify that components used in our design could survive launch into space. The two kinds of testing considered were structural and thermal testing. Structural testing was done using MATLAB as the simulation environment, where the prototype design materials were modeled to estimate displacement during launch. Thermal testing was also done using MATLAB as the simulation environment. The simulations were done to analyze the impacts of heat throughout the payload, helping to understand how heat affects the functionality of the capsule. Material analysis softwares was used and discussed in further detail in the material analysis section.

5.9 Results

In the prototype, the primary microcontroller on board the payload was successfully demonstrated. A LiDAR array detects incoming debris, predicts its position at a certain time, and passes that information to a net capsule. Due to the lack of a secondary microcontroller, this is "done" through the display monitor in our prototype. In the next step, the conical spring recoils and launches the 3D printed capsule that contains the net. The results presented here demonstrate the most complex aspect of our project requirements: predicting the incoming debris and accurately launching a capsule there using a spring "soft" launch. Thus, the user's needs for ISAM capability in space are also met.

6. Implementation

To implement our solution, we conducted design and materials analyses to verify our solution's likelihood of success.

6.1 Design Analysis

To test our solution's functionality, we designed and constructed a scale model of our net capsule soft launching mechanism. Shown in Figure 14 below is the assembled launcher which featured an object detection/targeting system and the mechanical launcher assembly.

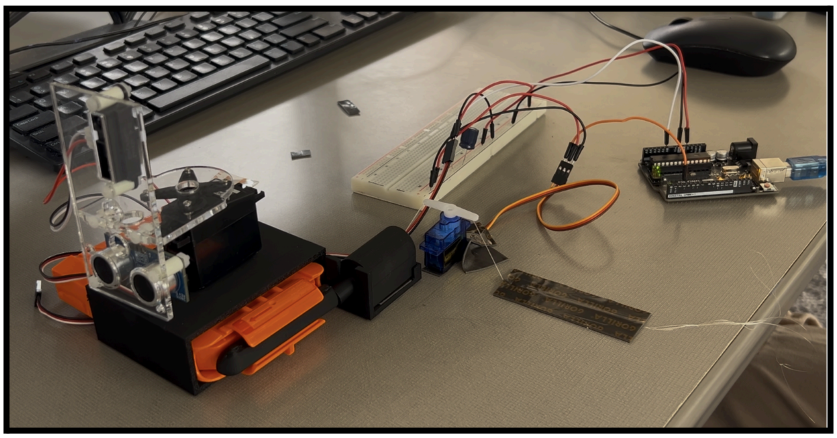

Figure 14: Assembled Prototype During Testing

For the mechanical portion of our prototype, all manufactured parts were 3D printed using black PLA plastic. The remaining components were purchased, such as a conical spring and an orange Nerf dart magazine, as shown in the exploded view in Figure 15. When assembled, as shown in Figure 16, the net launcher could hold six Nerf dart-sized projectiles, which represented net capsules. These 3D-printed capsules were solid, so they did not contain a net to expand like would be done for the full-size capsules. Instead, they were used as a scaled-down representation of our soft launching mechanism.

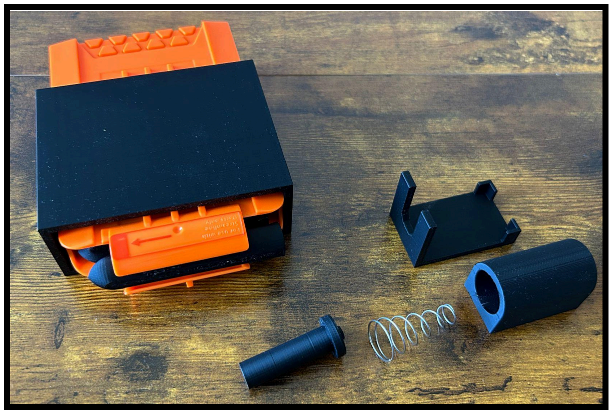

Figure 15: Exploded View of Prototype Mechanical Components

Figure 16: Assembled View of Prototype Mechanical Components

The second part of the soft launching prototype was the electrical system. The electrical prototype was used for target object detection, tracking, and control of net capsule launching. In Figure 17, the electrical hardware consisted of five main parts, which were the following:

1. An Arduino Uno Microcontroller
2. A SHARP 2Y0A21YK IR Sensor
3. An SG90 Servo Motor
4. A 100 mF Capacitor
5. A Newark Breadboard

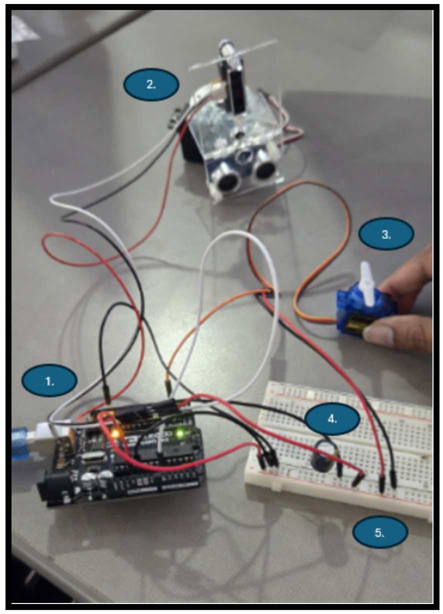

Figure 17: *Arduino Circuit Prototype With a Servo Motor and LiDAR Sensor*

A LiDAR sensor would be used in the design for target identification. For simplification and ease of integration, this prototype used a SHARP IR sensor (numbered 2 in the Figure above). Our IR sensor was mounted on a servo motor, which enabled the sensor to move in sync with the target object. For predictive modeling simplification, it was assumed the target object moved along a linear path. The IR sensor operated by emitting an infrared pulse and measuring the time it took for the signal to bounce off the target object and return to the sensor. The sensor then outputs a voltage, which is converted into a distance measurement (in centimeters). The IR sensor emitted subsequent pulses at regular time intervals to track the changing position of the target object. Then, using the two distance-time readings, the Arduino Uno microcontroller used a programmed predictive position model to estimate the future position of the target object. Once the target object's position was determined, a servo motor connected to the net capsule launcher via fishing line released the spring propulsion mechanism and launched a net capsule. To launch the net capsule, the Arduino activated the servo motor by sending a PWM pulse, triggering the retraction and release of the launcher's plunger. The retraction and release of the spring allowed a net capsule to be loaded and launched only after the target object had been detected and the predicted location determined, ensuring efficient power usage. After launch, the predicted position of the target object would then be transmitted to a hypothetical secondary microcontroller on board the net capsule to continue to guide it to intercept the target object.

A net capsule prototype was also 3D printed and is shown with the net fully expanded in Figure 18 and then partially packed with a net (not to scale) in Figure 19. There are two sections to the net capsule prototype. One was a rear section for housing cold gas thrusters. For this prototype, the rear section was solid, only showing the locations of the cold gas thruster nozzles.

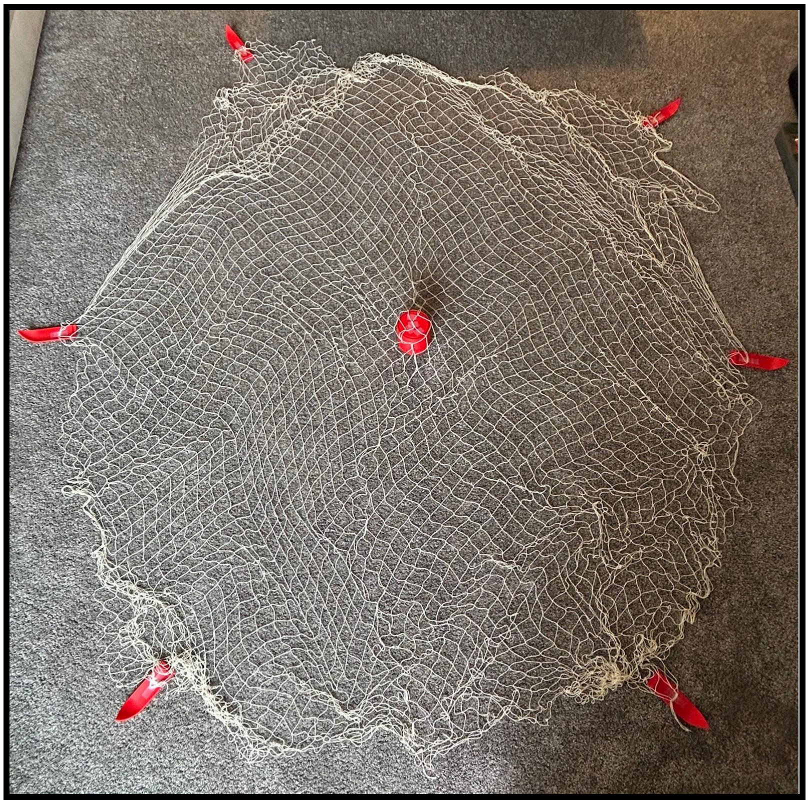

Figure 18: Net Capsule Prototype With Net Compartment Expanded

Figure 19: Net Capsule Prototype With Net Compartment Partially Packed (Note: Net is not to scale)

Then, the other portion of the net capsule prototype was a net compartment made of six side pieces in the front of the capsule. As shown in Figure 19, one of the side pieces was removed to show the net compartment. The cold gas thruster section and the net compartment side pieces were connected to the net.

Overall, the implementation of our solution was successful. During testing, the 3D-printed Nerf darts, representing net capsules, were successfully launched when a target object was detected. The deployment of the Nerf darts demonstrated the successful implementation of target identification and net capsule launch.

One feature we were unable to demonstrate was the net expansion after launch. We could not implement full net deployment due to the complexity and budget required to add cold gas thrusters to net capsules. Instead, as discussed above, a prototype net capsule was 3D printed with a net inside the net compartment to demonstrate how the net would be enclosed in the actual design.

6.2 Materials Analysis:

The materials analysis consisted of two phases which considered the material structural behavior and thermodynamic behavior.

6.2.1. Structural Analysis:

Structural analysis tests the displacement of the payload during launch conditions. Our goal in conducting structural analysis was to understand how the payload performs under gravitational and vibrational forces and confirm that our design would survive the process of launching into orbit, as is required by the C3 challenge.

Considerations for the structural analysis:

a. With limited information about the Blue Canyon X-Sat Venus Bus, we assumed the craft was mostly made out of aluminum, which is lightweight, durable, and can be produced in space-grade.
b. Other assumptions made regarding the Venus Bus:
    i. Payload Mass: 60 kg
    ii. Overall Satellite Volume: 28 inches (710 mm) × 28 inches (710 mm) × 38 inches (970 mm)
    iii. The solar panel is considered to be the length of the spacecraft's longest dimension, which is 28.0 inches (approximately 71.0 cm). The width of each panel would be proportional to the other dimensions of the spacecraft.
c. For our payload, analysis was done for two different types of metal: Steel and Aluminium Alloy 2024. While steel is durable and resistant to wear and tear,

aluminium 2024 is lightweight, making it optimal for reducing the payload weight without sacrificing functionality.

```
% Masses of Payload and Satellite
mass_payload = rho_payload * L_payload * W_payload * H_payload; % kg
mass_satellite = rho_sat * L_sat * W_sat * H_sat; % kg

% Launch Acceleration (in g's)
g = 9.81; % Acceleration due to gravity (m/s^2)
accel_launch = 15 * g; % Launch acceleration (g-forces converted to m/s^2)

% Force due to launch acceleration (F = ma)
force_payload = mass_payload * accel_launch; % Newtons (N)
force_satellite = mass_satellite * accel_launch; % Newtons (N)

% Number of nodes for a more realistic analysis
num_nodes_payload = 30; % 30 nodes for the payload structure (finer mesh)
num_nodes_satellite = 50; % 50 nodes for the satellite structure (finer mesh)
```

Figure 20: Snippet of Code

The mass and payload of the satellite were calculated through Young's modulus, Poisson's ratio, and material density. The gravitational force during launch was calculated at an average of 15g, and the force on the loads was correspondingly calculated. The number of nodes, or the number of "critical" points the payload is split into, such as joints and edges was factored into our calculations.

Results for Steel:

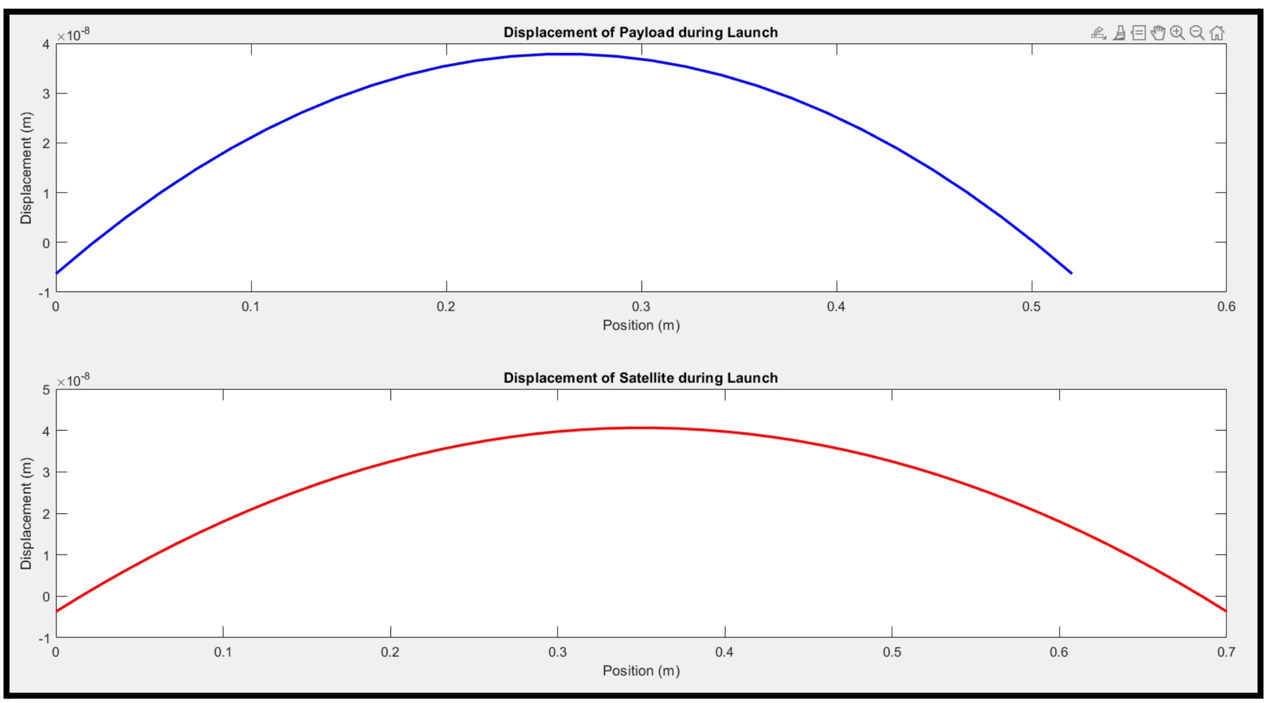

Figure 21: Displacement vs Position graph for Steel Payload

Results for Aluminium:

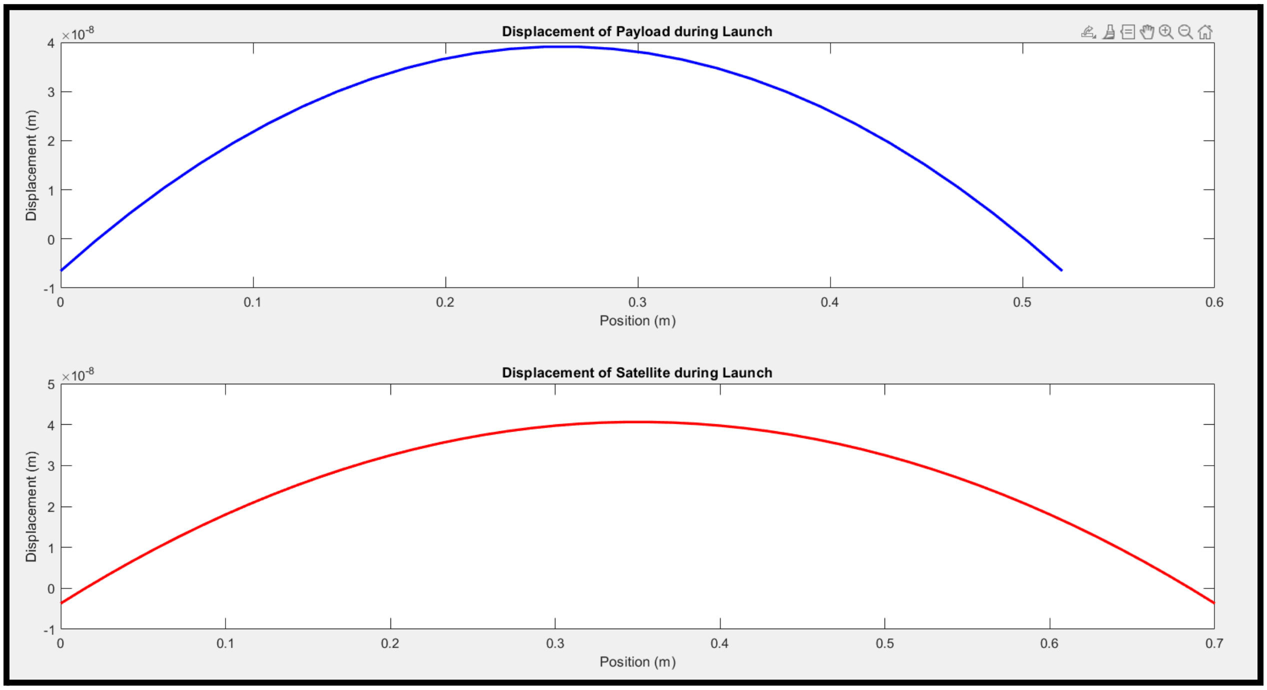

Figure 22: Displacement vs Position graph for Aluminium Payload

The above plots generate the displacement of the payload and satellite by considering the position from one end of the structure. This implies that at positions 0m and 0.7m (for satellites), we would be at the edge of the structure, and 0.35m would indicate the center of the structure.

As can be seen by the above plots, the maximum displacement occurs at the center of the structure for both the payload and the satellite during launch. The difference between the aluminium and steel plots is most observable in the peaks of the charts. As expected, the steel payload has slightly less displacement than the aluminium one. Modal analysis must be performed to understand the vibrational impacts of this as well fully.

6.2.2. Thermal Analysis:

Thermal Analysis considers understanding temperature fluctuations experienced due to the following factors:

I. Thermal load
II. Internal heat generation
III. Thermal stress
IV. Conduction

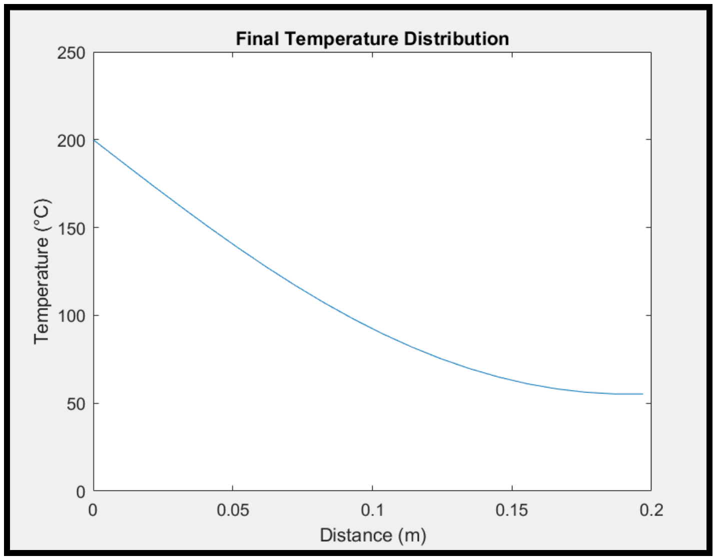

Figure 23: Distance vs Temperature graph for Steel Payload

It is assumed that the surface of the load experiences 200 celsius during launch. The above temperature vs distance graph measures the temperatures that the payload experiences as we go further into the payload from the surface.

In order to better understand the effects of thermal stress on the payload, time is also an essential factor to consider. Thus a 3d graph of time vs distance from the surface of the payload vs temperature was considered.

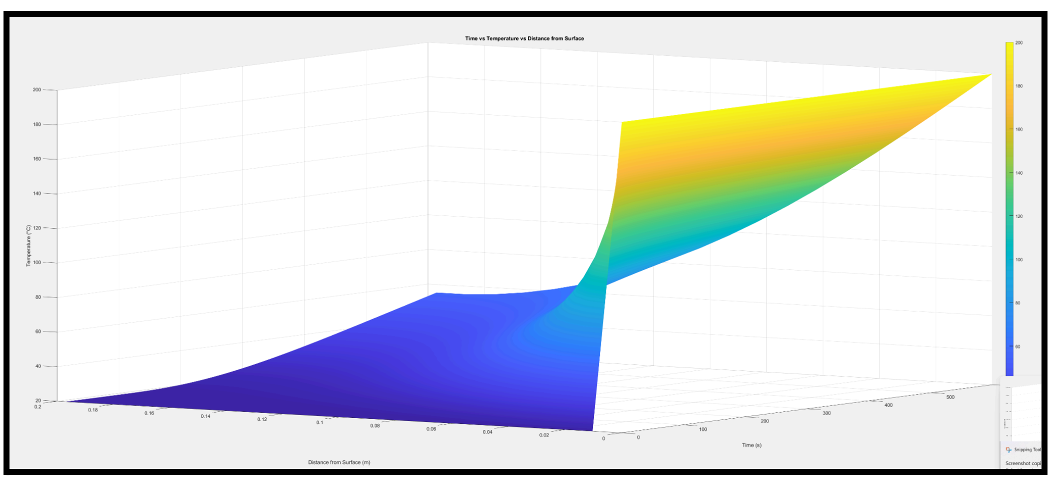

Figure 24: Distance vs Temperature vs Time graph for Steel Payload

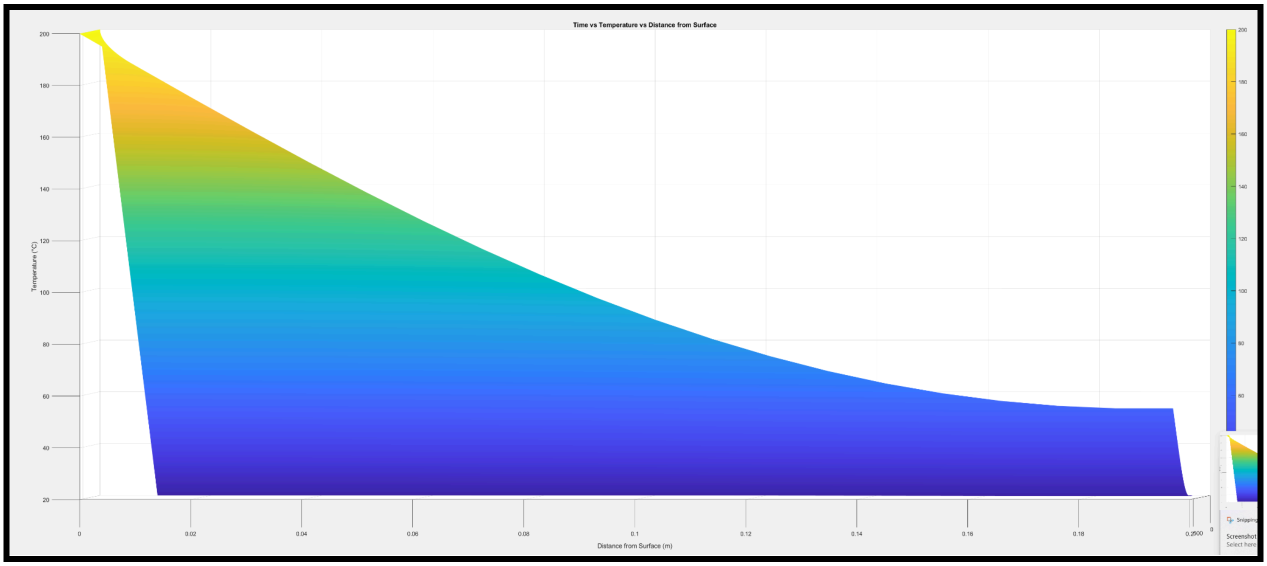

Figure 25: Distance vs Temperature graph for Steel Payload

From the above graph we can see that there is a gradual decrease in temperature as we go further into the center payload due to conduction. The temperature range is from 55 celsius to 200 celsius.

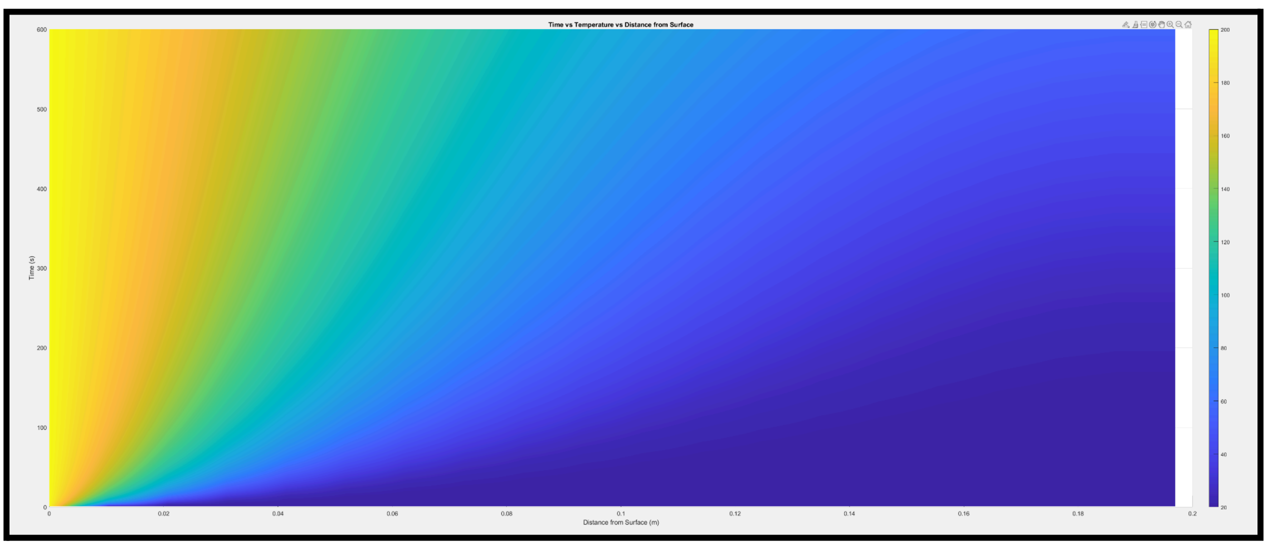

Figure 26: Distance vs Time graph for Steel Payload

The time vs distance graph shows the temperature gradient of the payload with time. The time is marked up until 600s and thus accounts for the first 10 min of launch time. It can be concluded that during this time the surface temperature of the payload doesn't experience much fluctuation. Based on this information we can choose to strategically place our net capsules away from the corners of the payload container.

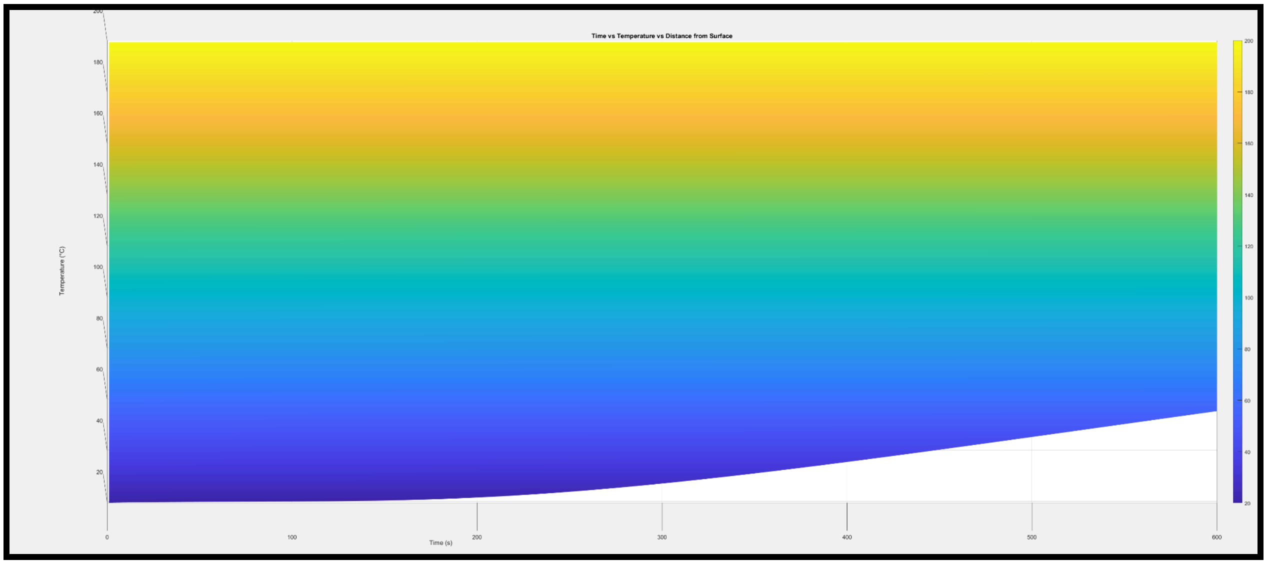

Figure 27: Temperature vs Time graph for Steel Payload

The time vs temperature graph describes the change in temperature range over time. It is observed that the range decreases gradually and more heat enters the payload.

Results for Aluminum:

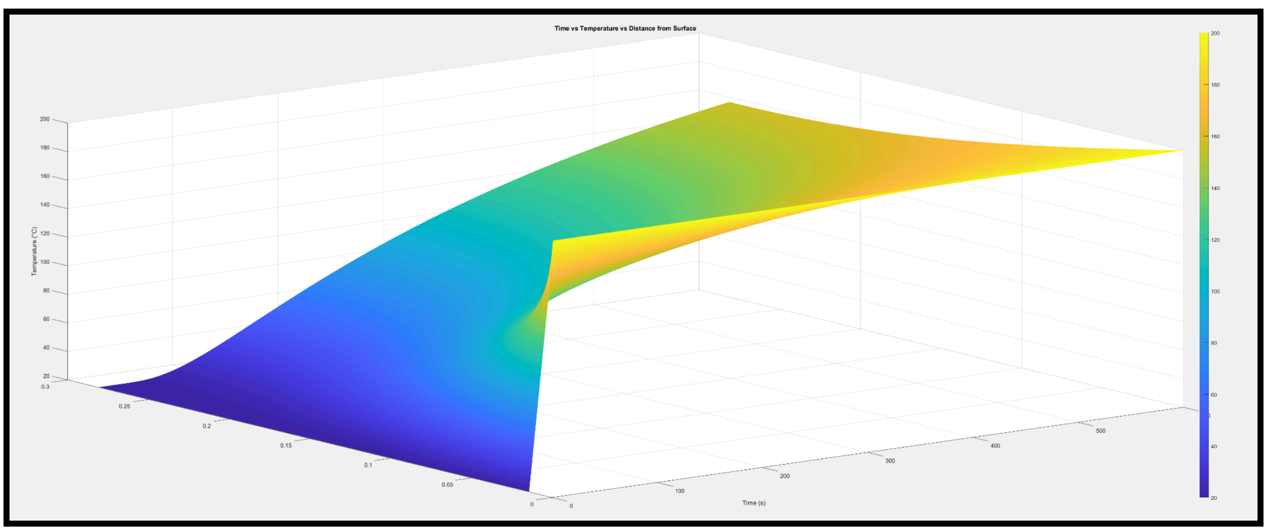

Figure 28: Distance vs Temperature vs Time graph for Aluminium Payload

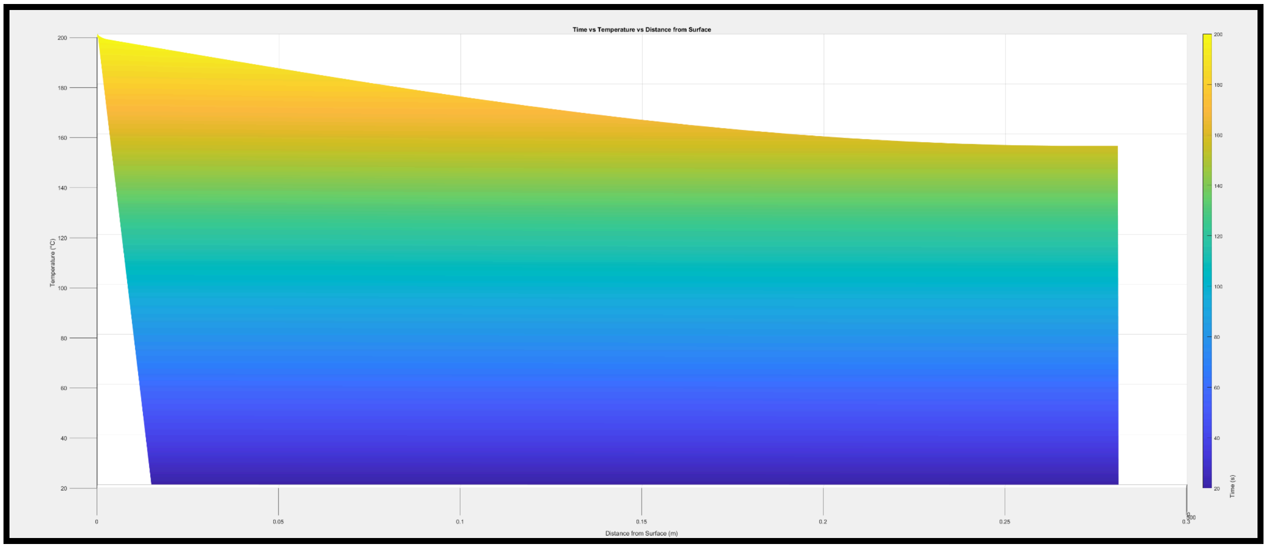

Figure 29: Distance vs Temperature graph for Aluminium Payload

Figure 30: Distance vs Time graph for Aluminium Payload

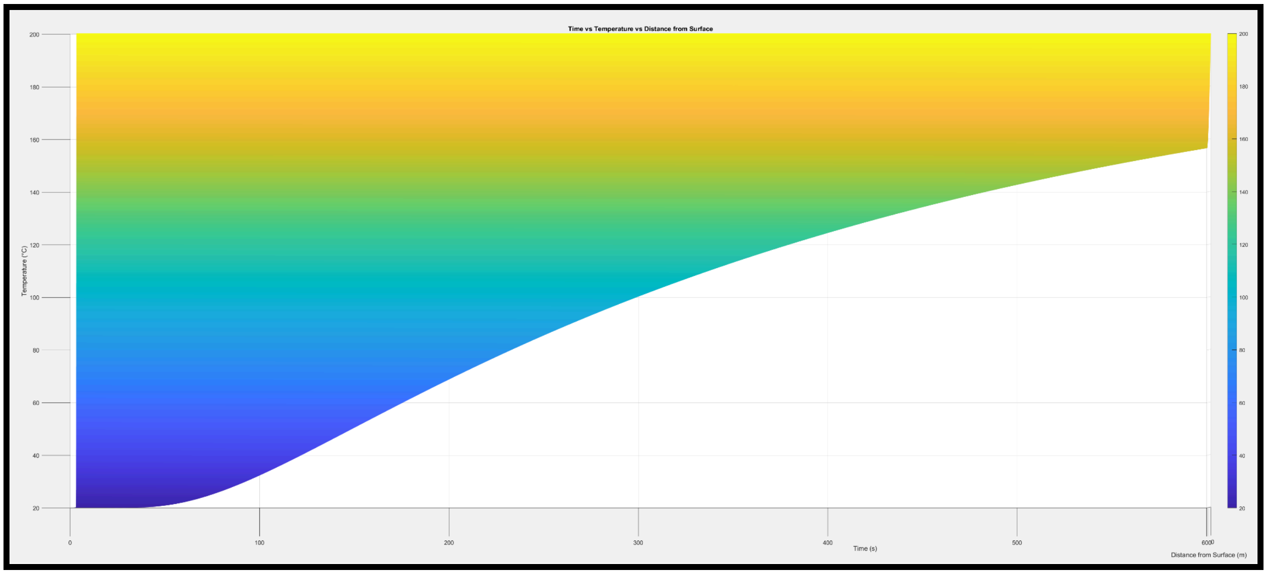

Figure 31: Temperature vs Time graph for Aluminium Payload

Aluminium is much less resistant to heat. As can be seen by the time vs temperature graph, aluminium rapidly loses the varied range in temperature, which causes it to heat up very quickly. Heat spreads much faster toward the center of the payload as we advance. In conclusion, steel is much better for handling thermal stress than aluminium.

7. Ethics and Professional Responsibilities

7.1 Areas of Professional Responsibility and Code of Ethics

Area of Responsibility	Definition	Relevant Item from ACM Code of Ethics	How Our Team Has Interacted/Adhered
Work competence	Completing tasks in which one is competent and informed while avoiding deception.	2.2 Maintain high standards of professional competence, conduct, and ethical practice.	Team members have actively researched various ISAM technologies, worked on prototype and improved their skills.
Financial Responsibility	Managing resources and ensuring transparency in financial matters.	1.3 Be honest and trustworthy.	The team has focused more on managing the estimated cost and financial responsibility. The cost analysis has been done in depth.
Communication Honesty	Sharing accurate, clear and truthful information between the team and the stakeholders.	1.2 Avoid Harm 1.3 Be honest and trustworthy	Team members discuss progress and provide inputs weekly to be up-to-date.
Health, safety and well-being	Putting the security and well-being of everyone involved first in all choices and activities.	1.1 Contribute to society and to human well-being, acknowledging that all people are stakeholders in computing.	The ISAM payload design minimizes risks during on-orbit deployment and operational phases.
Property Ownership	Respecting others' intellectual property, ideas, and information.	1.5 Respect the work required to produce new ideas, inventions, creative works, and computing artifacts.	The team makes sure that all creative work is properly credited and that shared resources are properly attributed.
Sustainability	Ensuring environmental and societal sustainability in designs and implementations.	1.1 Contribute to society and to human well-being, acknowledging that all people are stakeholders in computing. 2.3 Know and respect existing rules pertaining to	The design considers environmental impacts and prioritizes to minimize harm.

		professional work.	
Social Responsibility	To act ethically and responsibly to benefit society and uphold professional integrity.	3.1 Ensure that the public good is the central concern during all professional computing work.	Team has followed ethical practices and has worked on a solution designed to serve societal needs.

Table 7: Areas of Professional Responsibility

Performance Analysis:

- Strengths:
  - Communication Honesty

  The team has demonstrated exceptional communication skills throughout the semester. The team ensures to convey any progress towards the solution weekly during the team meetings. We assign tasks and ensure the team is aware of them and working towards the same shared goal for the week. Any disagreements or concerns are addressed in a professional manner where the team discusses them collectively.

- Weakness:
  - Limited Emphasis on Stakeholder Feedback

  The team should have put more emphasis on gathering feedback from potential users or stakeholders throughout the design process. To bridge this gap to a particular extent the team did hold meetings with the industry mentors provided by the C3 competition organization, but lacked direct feedback from potential stakeholders. Engaging with representatives from different companies could have been a good way to approach this issue.

The team can guarantee that the project is both technically sound and commercially sustainable, in accordance with professional ethical standards, by enhancing financial responsibility and preserving communication and competency strengths.

7.2 Four Principles

	Beneficence	Nonmaleficence	Respect for Autonomy	Justice
Economic	Our designs allow for economic growth in space.	Our design does not negatively impact economic growth and development.	No economic hindrance is caused by our design, and it enables all groups to benefit.	Our solution provides equal economic benefits to all.
Environmental	The design promotes clean-up of LEO.	Our design does not actively contribute additional waste to the environment	We do not hinder any company or organization from being able to operate in the environment of space successfully	Our design would provide all of mankind with a debris-free space
Societal	The design will help society continue space exploration	Our design does not negatively impact society's functions	Our designs do not prevent any barriers to societal autonomy	Implementation would equally benefit all of society

Table 8: Four principles

Important Pair:

- Environmental - Beneficence

Our project seeks to enhance the orbital environment by promoting debris removal and control of possibly harmful objects in the Low Earth Orbit(LEO). Since our team is encouraging environmental well-being and guarantees sustainable use of space for future satellites and space stations, which aligns with beneficence. To ensure this we are incorporating debris removal through net deployment, minimizing risks associated with it and prioritizing long-term environmental preservation.

Lacking Pair:

- Economic - Justice

Equal financial gains for all stakeholders involved may be difficult to guarantee regarding our project, particularly for smaller aerospace companies or nations with limited access to space technologies. This disparity may result in uneven access to the financial benefits of our project. To make progress regarding the project, our team will concentrate on producing the best outcome while minimizing the cost of our solution. We will look for affordable components while keeping the quality intact so that our project can benefit the entire world.

7.3 Virtues

Compassion: Treating everyone with the respect and kindness they deserve and need. Our team has demonstrated this virtue through open and respectful communication during the team meeting. Feedback is provided constructively and a safe environment is created so that everyone feels included, valued and supported.

Competence: To be knowledgeable and understanding of technical aspects of our design to ensure smooth development of the project. Weekly meetings ensure that our team is progressing at a steady pace and every team member is aware of the technical aspects of the design. Tasks are assigned based on each member's strengths and peer reviews help maintain standards of work.

Commitment: Willingness to see the job through, ensuring the tasks are completed with diligence and integrity. All tasks are completed within the deadlines and team members take accountability for the tasks. We ensure that all the members' hard work is appreciated and motivation is consistent.

John:

One virtue that I have demonstrated throughout senior design has been commitment. Throughout the semester I organized meetings with our advisors and team to produce quality work and revise our design continually. I contributed extra hours revising documentation and providing feedback to help the team achieve its goals. Commitment enables the efficient movement of the team towards the completion of its objectives. Without commitment from all team members the team struggles to accomplish its objectives.

A virtue that I am looking to improve upon going forward is compassion. Practicing empathy and compassion allows me to form more menacing relationships with my team members and produce more quality work. Without being a compassionate team member, resentment gets built up in the team and people stop recognizing the work that others are contributing. Taking a step back at times and putting myself in the shoes of others is very beneficial to the overall strength of the team.

Maheeka:

A virtue that I believe I have demonstrated is curiosity. I believe that by being curious to learn new information and develop new skills it can not only help me improve myself but also help the team progress. By being eager to challenge myself, I am able to contribute more effectively to the team. Whether it be learning how to operate CAD for the first time or jumping at the opportunity to think outside the box, I feel that I have demonstrated this virtue throughout the project. In the second semester I continued to tackle new aspects of the projects that are unfamiliar to me. Curiosity has enabled me to develop the electrical prototype, gain research experience and some video editing skills as well. This virtue has helped me aid in the success and growth of our project.

One virtue I recognize I need to develop further is persistence. Throughout the course of this project, there were moments when I allowed it to take the back seat and set my focus elsewhere. Looking back, I realize that I could have contributed much more had I maintained a more consistent level of commitment. Balancing the demands of senior year with such a unique design project has been challenging, and staying persistent wasn't always easy. My contributions to the project were varied in consistency. Some weeks I was highly engaged, while others not so much. Persistence is a virtue that can help ensure the team has a steady pace of progress. Going forward, I hope to cultivate this virtue in order to support the success of any team that I am a part of.

Tanvi:

One virtue that I feel I have demonstrated during this semester of senior design would be flexibility. As the project went on and became more technical focused, a lot of additions had to be made. During my task of estimating the power consumption, I remained open to changes concerning the components and looked for options that would better suit our design. When the deadline for the final paper was preponed, I did not panic and collaborated with my teammates to deliver a finished and polished work. Flexibility not only helped me to be on track but also helped me overcome the challenges.

One virtue that I felt I lacked was consistency. Throughout the course of this project, there were instances where I was unable to contribute a lot to the project as much as I would have liked due to other academic and personal commitments. As a result, my level of involvement sometimes fluctuated, and there were periods when I had very little progress to show for my part of the work. While researching for components, I was not able to finalize them due to the lack of time on my part. I recognize that being a reliable and steady contributor is essential in a team-oriented environment, and I regret not being able to maintain a more balanced and consistent presence throughout the project.

Daniel:

One virtue I feel I represented in the second semester of senior design was precision. One of the key things I worked on was the predictive model, in which I derived a formula to compute a predicted distance for the next scan angle. I strived to ensure the accuracy of this system and therefore along with our testing, also created a model in which I could input any given linear path and ensure that the prediction was accurate for that path. This adherence to precision made sure that the path prediction was accurate within the models parameters.

The virtue I need to improve upon the most is my diligence. I feel as though this semester I caught the senioritis bug and failed to adhere to a persistent work ethic. Instead of methodically chipping away at my work for this project, it feels as if most of the productivity came in the form of short high energy bursts rather than as the result of persistent effort. This also resulted in less time for the team to see and interact with my work before deadlines, potentially slowing down the pace of the group's development as a whole. In the future I plan on creating a much more fleshed out guideline for myself and my work, as well as creating a less abstract schedule for myself so that I have something more concrete to follow through on.

Ben:

A virtue I have demonstrated during semester two of senior design is thoroughness. Specifically, in the design area, I’ve had increased thoroughness by making more detailed CAD models and animations. Additionally, I had two prototypes 3D printed to provide visual aids for presentations and for testing. One was a scaled down version of the mechanical portion of our net launching mechanism. This allowed the team to test our launching concept on a small scale. The other was a model of a net capsule that provided a visual aid showing where the net is stored in the capsule. Through the CAD models, animations, and 3D printed prototypes, our team was able to more thoroughly explain our design during presentations and in our documentation.

One virtue I could have improved upon was perseverance. There were several aspects of the project that were difficult to achieve or could not be fully achieved. Since I spent a larger portion of time on the technical design using CAD and animations, those were the areas of difficulty. Particularly with the CAD animations, the net capsule expansion animation only showed the net compartment expanding and no other movement or rotation to explain how the compartment expansion was generated. There was also no net shown in that animation which made it somewhat unclear what the animation was showing. To improve in perseverance, more time would need to have been dedicated to continue learning how aspects like a net or capsule rotation could be added. Another option would have been to use another animation software that could more easily implement the net and rotational motion desired. Overall, having increased perseverance would be shown by creating better, more clear CAD animations.

Riley:

A virtue that I have demonstrated throughout this semester is perseverance. This semester thoroughly challenged me in many ways. One of the biggest challenges was being able to balance all of the commitments that I had and having the perseverance to fulfill my commitments to the fullest of my ability. Whether that commitment be class work, club work, or senior design tasks, I had to push myself to make sure that I completed all my assignments on time and to the best of my ability. I believe that this virtue will serve me well in the future. In a job, there may be situations and opportunities that I encounter that require me to push myself again to achieve a goal and fortunately I have the tools to do that now.

One virtue that I senior design has shown me that I could work on is curiosity. I found that often when I was delegated tasks to complete for our senior design project I was more concerned with getting them done on time and in a presentable way that I missed out on opportunities to learn and grow in my engineering skills. Our team's senior design project had a lot of aspects that were new to every member of our team and presented opportunities to learn about a new field of engineering. In my case, I had the opportunity to speak with several graduate students who were studying materials engineering and got to ask them questions about different materials that they suggested using for our design. In reflection, I was too concerned with making sure I just got the information that I needed on time so that I didn't take advantage of an opportunity that I had to learn about a completely new field of engineering. There are many other questions that I wish I would've asked those grad students that could've led to other ideas that I could've explored.

8. Conclusions

8.1 Summary of Progress

In October of 2024, we focus on market research to determine what aspects of ISAM were currently being developed, or have already been developed. By November 2025, we made the decision to focus on 'Deorbiting as a Service' for our design. After this, we designed a multitude of initial concepts, but after discussion with our mentors, decided to focus on specifically net-based designs. After narrowing the design space, we worked to develop a couple concept candidates with a focus on 'reusability' of which were once again analysed and reduced to our final net capsule concept. After determining this concept we developed designs specific to this implementation. On December 9th we presented our preliminary design to the C3 Midpoint Showcase, after which we began to focus on creating a physical prototype. This included 3D printing structural parts, obtaining electronic components and software development. These were done separately at first and then later combined. In this process we worked to establish a operation execution plan as well. Due to delays in acquiring hardware and prints, we had to shift focus to creating the documents and presentation required for the C3 Showcase. On April 15th we presented the current design and future plans to the COSMIC C3 Final Showcase. After which we have continued working on the development of our prototype.

8.2 Value Provided

Due to the intended operating environment this is designed for it is difficult for us to determine a realized value brought by our design. As we cannot make the determination with our limited resources and limited experience as to whether this will successfully aid in the removal of existing LEO space debris. However, as part of the C3 ISAM design competition we can look to the experts in the field who have analyzed our design and provided feedback. As of now the only thing we know is that we did not place in the top 10 out of the 23 teams that made it to the Final Presentation. However, based on our knowledge and results from prototype testing, our design has promise in achieving its goal of providing a debris deorbiting service. If effective the design should allow for the deorbiting of objects between 10 cm and 100 cm in size, which can be used to decrease the amount of debris within LEO. The reduction in debris would reduce collision risks and increase the potential operation space for new LEO missions. The simplistic design focused on reusability should allow for cost efficient removal of debris, which is more economically viable than existing single-use methods. While this is limited to 10-100cm sized debris objects, our design should serve as an integral part of the mitigation of existing debris. Larger existing debris objects likely will need dedicated single use solutions to deorbit them. An example for our designs use would be for a research or surveillance mission with a specific orbit requirement. While looking for potential orbits, the designed debris removal service could allow for the removal of one or multiple debris objects creating too much risk for operation to proceed. The ability to remove those objects would therefore decrease the potential risk of that orbit and allow the mission to take place. Another example is debris predicted to have an eventual collision event, in which its removal would eliminate that potential collision event, eliminating the proliferation of debris.

8.3 Next Steps

In our design, we have created a prototype for a net launcher that will deploy a net capsule to capture and deorbit debris in space ranging from the size of 10 cm to 1 meter

Our goals laid out in the design competition are specified as follows:

- Analysis is required to sufficiently determine if a design is feasible, can survive launch, can operate successfully in LEO, and can meet the BCT X-Sat Venus Class bus specifications
- The design needs to demonstrate three or more operations to demonstrate an orbital ISAM capable
- The payload should be designed to function autonomously with limited remote commands

The primary goal of our team during this semester was to develop a CAD model and on board electronics for our design. For our project we implemented a waterfall workflow design to prioritize research and development of a net launching prototype. With our design phase we prioritized rapid prototyping and redesigning based on feedback from our industry advisors. Following this development structure we were able to accomplish our goal of developing a CAD model and create a scale model of our design.

Our group was hindered at times by the volume of design considerations that we had to make for our design. Operating in space is an incredibly difficult task especially for novices in aerospace engineering. During our project, we would create prototype mock ups and designs only to receive feedback from our industry advisors that our design would not function properly in space. Beyond the difficulty of the operation environment, our group had to act on limited information pertaining to the platform we would be designing a payload for. Without full modeling of the satellite, it was difficult for our team to make accurate assessments about the capabilities of the satellite bus.

Going forward, if future teams were composed of more engineers with mechanical or aerospace engineering backgrounds, it would accelerate the development of prototypes and the creation of more viable designs. Our group experienced numerous delays related to developing ideas and conducting research that would be previous academic knowledge for mechanical and aerospace engineers. The main next developmental steps would be scaling up from our more limited proof of concept prototype to one that begins to implement more properties needed for space operation. These include updating the software to handle orbital paths in 3 dimensions, wireless target assignment, as well as the addition of hardware to allow for wireless target assignment instead of the wired currently used, and the upgrade from the IR scanner used in the prototype to the LIDAR specified in the design.

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10. Appendices

Appendix 1 - Future Testing Manual

As discussed in section 6.1, Design Analysis, a prototype net capsule launcher and object detection system were made and tested. During testing, these systems had the basic functionality desired but didn't function well. For the net capsule launcher, the parts fit loosely together, and it could launch the Nerf-dart-sized capsules, but when using the servo motor and fishing line to retract the launcher piston, it didn't work well. The reason for this was the servo motor and fishing line connecting the launcher piston to the servo motor weren't strong enough to fully compress the launcher spring. These factors resulted in a couple of semi-successful launches. When the launcher piston was moved by hand to fully compress the launcher spring, the launcher worked successfully. So, if a stronger servo motor with a pulley and a stronger fishing line were used, the prototype would see better test results.

Future work for the Space Cyclone design net capsule and launcher would include constructing a scaled prototype with space-grade materials such as Aluminum, as discussed in section 6.2, Material Analysis. With an Aluminum prototype, more testing could be done for functionality by testing in a microgravity environment. Then, updates on the software side would include handling orbital paths in 3 dimensions and wireless target assignment. Finally, another upgrade to be implemented would be switching the IR sensor out to replace it with the LiDAR sensor. Overall, future work would provide better testing results and a more refined Space Cyclone net capsule and launcher design.

Appendix 2 - Alternative/Initial Version of Design

Prior to the selection of removing space debris as a service, which led to the net capsule and net launcher designs, other areas within In-Space Servicing, Assembly, and Manufacturing (ISAM) were considered for project ideas. These were discussed in section 4.2.2, Ideation, where the following ideas were considered: Refueling, Repairing, Upgrading, Space 3d-printing, Removing Space Debris, and Communication Constellations. After researching each idea, learning more about the project, and defining the specifications, removing space debris was selected.

With a project idea selected, the next consideration was what method to use for debris removal. The two considered were a robot arm and a net. We were advised to stray away from an explicit robot arm in regard to the competition, so we chose the capture net idea. From there, each iteration of our net launcher design was discussed in section 4.3.2, Detailed Design and Visuals. There, each of the designs' details and revisions were discussed, leading to the final design, the Space Cyclone net capsule and launcher.

Appendix 3 - Other Considerations

All necessary information about our design can be found in the sections of the design document. From our project we were able to gain numerous new experiences related to the application of engineering to the aerospace industry and practice our understanding of physics. Design are great but they must adhere to the laws of physics.

Appendix 4 - Code

The link below is to the GitHub repository with this project's code. The code files used were discussed previously in sections 6.1, Design Analysis, and 6.2, Materials Analysis. In section 6.1, the detection and predicted location of target objects was discussed using an Arduino microcontroller and IR sensor. In section 6.2, the structural and thermal analysis were discussed for Aluminum and Steel.

GitHub Repository: https://github.com/dmaheeka/Space-Cyclones

Appendix 5 - Team Contract

A5.1 Team Members

John Beuter - Cyber Security Engineer
Tanvi Mehetre - Computer Engineer
Daniel Sprout - Software Engineer
Maheeka Devarakonda - Electrical Engineer
Ben Swegle - Mechanical and Electrical Engineer
Riley Heeren - Electrical Engineer

A5.2 Required Skill Sets for Your Project

Technical Skills

- Engineering problem solving
- Circuit design and analysis
- Power system design and analysis
- Mechanical system design and analysis
- CAD modeling

- Cybersecurity systems design and analysis
- Proficiency in one or more coding languages

Intrapersonal
- Communication
- Idea presentation
- Conflict resolution
- Resource management

A5.3 Skillsets Covered by the Team

John Beuter
- Cybersecurity systems design and analysis
- Project management and leadership
- Public speaking
- All intrapersonal skills listed

Tanvi Mehetre
- Circuit design and analysis
- Proficiency in one or more coding language
- All intrapersonal skills listed

Daniel Sprout
- Proficiency in one or more coding languages
- All intrapersonal skills listed

Maheeka Devarakonda
- Circuit design and analysis
- Power systems design and analysis
- Proficiency in one or more coding languages
- All intrapersonal skills listed

Ben Swegle
- CAD modeling
- Circuit design and analysis
- Power systems design and analysis
- Proficiency in one or more coding languages
- Mechanical systems design and analysis
- All intrapersonal skills listed

Riley Heeren - Electrical Engineer

- Circuit design and analysis
- Power systems design and analysis
- Proficiency in one or more coding languages
- All intrapersonal skills listed

A5.4 Project Management Style Adopted by the Team

Our team opted for a hybrid management style that incorporated elements of an agile system and a waterfall system. Due to the nature of our project we were able tackle some tasks using an agile management style while other tasks that were linearly constrained required a waterfall approach.

A5.5 Project Roles

Team Lead/Advisor Contact: John
Materials Researcher: Riley
Documentation Lead: Tanvi
Event Manager/Schedule Planner: Daniel
Lead CAD Design Manager: Ben
Systems Engineer: Maheeka

A5.6 Team Contract

https://drive.google.com/file/d/1jpA_ii_m0QT4qt7RIo6P0cOGYYHd-nsV/view?usp=drive_link

A5.7 Team Procedures

The team met twice a week, both remotely and in person. Given the goal-oriented nature of our project, it allowed our team to meet asynchronously. In the previous semester, we outlined the work we needed to complete and could then divide and conquer. At any point a decision in the design had to be made, a vote was held by the team in which the idea with the majority of votes won. Records for each of our meetings were kept in the team's Discord channel and used to dictate the future work the team needed to complete.

A5.8 Participation Expectations

The team was expected to participate hands on when able to and communicate with the team otherwise.

A5.9 Leadership

Maheeka was the electronics team lead, Ben was the CAD lead, and Tanvi led the documentation efforts. For our leadership, we prioritized the development of independent leadership where each team member took responsibility for and accountability of their section of the project, becoming their own expert and managing their efforts appropriately. Through transparent and honest communication, we were able to remediate any issues.

A5.9.1 Collaboration and Inclusion

Our team contains a representation of all majors in the department of electrical and computer engineering. From this diverse composition, we have a broad collection of ideas to pull from. To encourage full participation amongst the team, we established communication policies as a team that were conducive to creating a healthy work atmosphere that allowed each person to contribute effectively. Through one-on-one conversations and check-ins, we enable the team to resolve conflicts as they arise.

A5.9.2 Goal Setting

We established weekly goals for our team to progress towards. At the end of the week our bi-weekly we checked in with our progress to verify that we were accomplishing our objectives. Through open communication about our upcoming deadlines, we were able to establish effective goals to approach our objectives.

A5.9.3 Consequences for Not Adhering to Team Contract

In the event of continued infractions, the team will meet with the faculty advisor to discuss appropriate action with the offending team member.

1) John Beuter Date: 5/7/2025
2) Tanvi Mehetre Date: 5/7/2025
3) Maheeka Devarakonda: 5/7/2025
4) Riley Heeren: 5/7/2025
5) Daniel Sprout Date: 5/7/2025
6) Ben Swegle Date: 5/7/2025