Space Cyclone C3 Capstone Project

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I. Abstract

Space debris has become a significant concern, complicating space travel with objects ranging from micro debris to non-functional satellites. As technology advances, we aim to mitigate this issue by removing defunct satellites through In-Space Servicing, Assembly, and Manufacturing (ISAM). Our proposed solution, the **Space Cyclone**, involves a controlled net-based system to capture and deorbit target satellites. 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.

II. Introduction

To date, few ISAM-capable satellites reflect the emerging landscape of commercial space engineering. Engineers are creating innovative solutions to complex space and Earth-based problems by developing ISAM-capable satellites. For the C3: Cosmic Capstone Challenge, we designed a payload to be housed on the BCT X-Sat Venus Class bus and perform three continual ISAM tasks autonomously. Our solution must withstand the stress of the launch and successfully carry out its mission. Given the design constraints, our first semester of Iowa State University's participation in the C3 program focused on the fundamentals of space operations, identifying opportunity gaps, and assessing the current state of ISAM. Our solution was to design a low-cost approach to deorbit multiple debris objects using a reusable platform rather than sending one satellite to deorbit a single piece of debris.

Our design draws inspiration from previous net-launch satellites and conventional net launchers used on Earth like those used for animal capture. Our team has developed computer-aided design (CAD) models for the spring-based net-launching mechanism and the net capsules. The system includes an onboard housing unit capable of storing up to four net capsules, each equipped with thrusters, fuel, and onboard electronics for autonomous 1) navigation, 2) target capture, and 3) controlled deorbiting.

Once deployed in orbit, the platform identifies targets within the operational range of the net capsule's power budget. The spring-actuated launching mechanism propels the net capsule away from our platform and towards the target, where the capsule autonomously navigates to intercept and deploy a net to capture the target. The platform is designed for reusability—once the net capsules are depleted, future missions can reload the platform with additional capsules, enabling scalability and continued operation.

In the second semester of Iowa State University's participation in the C3: Cosmic Capstone Challenge, our team is progressing with physical testing of our device using resources available on campus, including 3D printing labs, vacuum chambers, and buoyancy tanks. Our team can accurately test and replicate our prototype implementation environment of lower earth orbit (LEO). Beyond the implementation of our device, we will conduct stress testing to assess the viability of our complete design, net capsule and launching mechanism as it undergoes the stress of launch.

III. Background

In Space Servicing, Assembly, and Manufacturing

In Space Servicing, Assembly, and Manufacturing (ISAM) describes an emerging field of engineering and platforms, products, and services centered around mobility, assembly, and manufacturing that is not on Earth. This includes near-earth orbits, lunar orbits, or asteroid belts. LEO is currently the primary target for launching small satellites ranging from CubeSats to Starlink and for new platforms to provide laboratory capabilities followed by fabrication capabilities, such as VAST Haven platforms, over the next decade. Current small satellites are focused chiefly on telecommunications and earth imaging. However, more ISAM-capable payloads to build infrastructure and deliver services such as refueling are being funded today. As more space agencies, commercial enterprises, and military organizations launch at a higher cadence and for more sustained periods, there will be an increased demand for existing infrastructure to support space operations. Therefore, to ensure safe and sustainable space operations, the problems caused by orbital debris—and the requirement for efficient recycling or removal solutions—will become more and more critical.

Material Manufacturing (Pharmaceutical and Metals): Operating in the vacuum of space allows manufacturers to create products with better crystal structures for metals, pharmaceuticals, proteins, etc. In the case of the pharmaceutical start-up Varda, the company can produce crystal structures in medicine made in space that are impossible on Earth.

Building Spacecraft: As previously mentioned, the increase in space travel corresponds to an increased need for supporting infrastructure in space. The International Space Station (ISS) is the best example of ISAM, it was assembled in space and today supports some basic research and manufacturing capabilities. Numerous space agencies came together to develop spacecraft capable of assisting astronauts in assembling the ISS. ISAM capable space payloads like the robotic Canadarm provided astronauts with the capabilities to move and assemble large ISS units and load and unload SpaceX and other shuttles from Earth.

In conclusion, the use of LEO and the emergence of ISAM is happening today at an accelerating pace.

Debris in Lower Earth Orbit

Currently, there are over 1.1 million pieces of debris in Earth's orbit between 1 cm to 10 cm in size that have been detected, previously limited by tracking capabilities [1]. As technology capable of detecting orbital debris advances, significantly more debris under 1 cm in size is being identified [2]. HUSIR at MIT has millimeter-wave radar capability that images and tracks various space objects. This radar system helps with national space security by keeping track of 100 million pieces of debris smaller than 1cm [3]. On the other hand, according to the European Space Agency (ESA) report, 34,000 space debris in the LEO environment are larger than 10cm [4].

Meanwhile Slingshot Aerospace estimates that 3500 of those debris are defunct satellites[5]. With continued satellite launches, the density of debris—particularly in low Earth orbit (LEO)—will keep rising. This debris poses serious risks to active satellites, space stations, and human spaceflight, with catastrophic debris collisions causing cascades of debris and potentially blocking orbits from being used, in what is known as Kessler Syndrome [6]. Some examples of collisions include the 2023 Russian Satellite being struck by fragments from an old Chinese weather satellite, generating even more space debris in orbit. In an incident in November 2021, a Russian anti-satellite missile test caused over 1500 pieces of debris that forced crew members aboard the International Space Station to seek shelter [7]. While the sizes of these fragments are very small, the velocities at which they travel pose a serious threat. Effective debris mitigation and disposal methods are essential to preserve the long-term sustainability of space operations.

Prototype Evolution

In December of 2024, our team began developing the initial prototype of the Space Cyclone, which focused on debris removal in LEO. Our team created numerous design iterations before a final prototype was established. With all of our design, our primary goal was to establish a sustainable method of capturing and de-orbiting debris. We wanted to create a craft capable of de-orbiting multiple pieces of debris. Our initial design consisted of a satellite launching a harpoon that would spear pieces of 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 had to be exact in striking its target. Our harpoon also had to have enough force to fully spear our target and allow it 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 lower earth orbit, which is much more prevalent.

In our second design interaction, we wanted to consider how to capture big and small pieces of debris effectively. The first solution we considered was using a net. We determined that a net would be the best alternative to a harpoon as it could be compacted into a spacecraft and expanded to cover the maximum area around a target. A net would require less accuracy for targeting as a net, when expanded, covers more target area. A harpoon has to be a precise shot and can capture finer debris particles.

Once we determined to utilize a net to capture debris, we had to choose the methods for storing and propelling our nets. The first round of designs we created for a net-launching satellite used a four-pronged net gun similar to the model shown in *Figure 1* below.

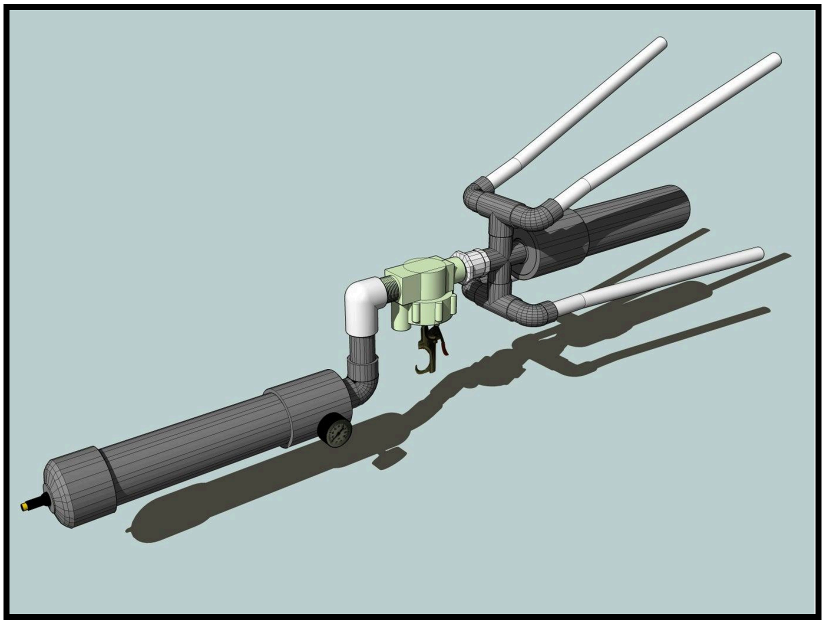

Figure 1: Four-Pronged Net Gun Prototype

We used the design shown above to inspire how we could launch nets from a satellite payload. While we initially liked having each net end point propelled outwards using a gas propulsion system, we recognized the additional complexity of designing a system to reload the net launcher. We were unable to determine a concrete method of reloading the system. Without reloading the net launcher, we could not satisfy one of our objectives of designing a reloadable/reusable product.

We continued to develop ideas for how we could store the nets in a reloadable way. Developing capsules containing the nets and a storage mechanism to hold multiple capsules paved the way forward. We wanted to create a design for our net capsules that could expand and fully deploy a net once launched out of the payload. We first considered having the net capsule act similar to a shotgun cartridge. The net would be compacted into a hollow cylinder and have the endpoints of the net be attached to the base of the cylinder. When the net cartridge was fired out of the payload, the cylinder would press forward, force the net out of the capsule, and deploy it towards the target. 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 debris.

We adjusted our capsule design to make the entire system self-disposing. Our new idea was to create a capsule that would dispose of itself after making contact with the debris. We first identified the potential for having onboard capsule motors propel the net capsule. Our idea was to use small amounts of gas in the net capsule to steer the net toward the target to capture. Once impact with the target was made, the onboard thrusters would propel the captured debris into the atmosphere.

We still needed to determine how the net would be deployed. To do this, we looked into using centrifugal force to expand the capsule and deploy the net. Our first idea was to propel the net capsule through a rifled barrel to enact spin on the capsule as it left the craft. With the barrel idea, we faced numerous obstacles, 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 using a component on the payload to create spin, we examined using additional thrusters on the net capsule to spin the capsule. By placing angled thrusters on the sides of the capsule, we concluded that sufficient spin could be produced to deploy the net on the capsule. While it would be potentially increasing the size and weight of the capsule to account for more fuel, we determined that this would be a necessary tradeoff to produce full net deployment capabilities.

While we had considered the behavior of the net capsule post-deployment, we had 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. For the gas-based design, we had a system of interconnected pistons designed to use gas stored onboard the craft 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, preventing the storage of more nets and adding further complexity to the design. The alternative, spring-based design would compress a spring and release the tension to propel a net capsule out of the craft slowly. The "soft" deployment would reduce the launch displacement of our craft and help prevent damage to the net capsule.

For our storage mechanism, we took inspiration from two sources, a PEZ dispenser and a 6-shooter revolver, to create two very different methods of storing net capsules. Each net capsule would be stored in the PEZ dispenser design in a spring-loaded magazine. When a piece of 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 reload system would be more difficult to reload with more net capsules. We could support reloading more effectively with a box magazine approach. A supporting satellite could attach to the Venus bus on sustained operations and slot a replacement box magazine with an already primed spring. Attempting to swap the revolver barrels and having the new unit successfully interface with craft mechanically.

After determining that we wanted the net capsule to propel itself, we needed to determine how the capsule would approach a target and based on what information. We determined that for our design, we wanted our craft to receive coordinates for debris from ground-based communication. Once a piece of debris was located, our payload would change orbits to be on trajectory to meet the debris. We determined that we could use infrared sensors to identify the debris and assist in steering the net capsule toward its target. We determined that infrared would be used based on its relatively low cost and low difficulty to implement. The needs of our design also enabled us only to use infrared as we did not need to identify the 3-D characteristics of the target (by using 2D imaging).

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. We reasoned with our initial design that an optimal distance for the net to begin being unraveled 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 started CAD modeling for this design and established the concept of operations (CONOPS) that illustrated the process of the craft targeting a piece of debris, deploying a net capsule, and de-orbiting. We started tracking our mass, volume, and power requirements and researching space-rated commercial off-the-shelf products that could be used in our design. Our team completed the design phase of our prototype and prepared to implement our design starting in January 2025. Further discussion of our prototyping and final design selection is under Section VI.

IV. Risks

With the operation of a vehicle in the lower earth orbit environment, inherent risks are associated with product performance. We identified de-orbiting reliability, the operating environment, and device longevity as the three main concerns with our product design related to how our net launching design will perform sustainably and how to prevent adding more space debris into lower earth orbit.

De-orbiting Reliability

First, we needed to ensure our solution could deorbit LEO debris reliably over time without malfunction. We risk contributing more LEO debris if our platform malfunctions and becomes inoperable. Precise and accurate target acquisition is a significant priority for our net capsules. Our platform needs to reliably target and deorbit LEO debris while maintaining a stable orbit and avoiding obstacles. We need to maintain operational control of our platform. Otherwise, we risk losing operational control of the vehicle and exacerbating the debris problem we aim to fix.

Environmental Risks in LEO

Second, our prototype faces environmental risks operating in LEO and beyond. Our team is limited in what we can simulate here on Earth. Therefore, we took extra care to make our design more robust and reliable. Our solution will face LEO environmental factors, including debris, specifically microscopic pieces of debris that occupy LEO, atmospheric drag, exposure to radiation and solar flares, and thermal extremes—consideration of these factors influenced our design decisions regarding materials and components [8].

Longevity and Sustainability of the Platform

Finally, our team identified another central risk area: the longevity of our platform in LEO. And we wanted to develop a solution that would operate with as little waste as possible. For these reasons, our team selected reliable components when prototyping our solution. The electronic components must withstand different levels of solar and magnetic radiation that might be encountered in LEO. Also, refueling, reloading new net capsules, reusability of our platform, and the risks involved were considerations in our design process.

V. Data Handling and Communication

Our platform is intended to function with near-autonomous capabilities. We want to limit ground communication via radio to transmitting locations of debris to our craft. Onboard the Venus bus, we intend to use infrared sensors and LoRa radio transmission to have the craft act as an observer to steer its launched capsules towards its target.

Ground Communication

Our design aims to limit the need for ground communication, remaining autonomous where possible. One area that we cannot autonomously determine is target designation. As such, the design will receive instructions regarding designated targets, including, at a minimum, Target size, location, velocity, and designation. Any new assignment will be given a UUID and an estimated time of execution, which will be returned to the ground. If the estimated time of execution conflicts with an existing plan, information regarding the conflict will be communicated, and the new assignment will be rejected. In the case of cancelling an existing assignment, such as to make room for a new mission, the existing assignment can be canceled by referencing its UUID and updating the status of the assignment.

Target Designation

Using the input target size and mass, the Cyclone determines if it can capture the object and rejects it if it cannot do so. After this initial check, the next check ensures that the input target's mission would not interfere with another designated mission. Using the location and velocity of the target, a prediction for when the target is in range will be made; if this is included in an already assigned target's mission or is within a projected post-mission grace period, the assignment will be denied. If the mission is accepted, it is added to the list of current missions.

Mission Execution

Upon the approach of a target object, using LiDar, the system will detect its presence, verify the target validity using its size, and begin making iterative predictions as to the future location of the target. During this process, a projected launch schedule is created and updated After these position predictions are proven accurate by the object's motion, the launch schedule's angle and timing are finalized. When they are met, the net capsule projectile is launched and, using LiDar, is tracked and directed to steer toward the capture target. Upon reaching the range and the velocity differential required for net deployment, the signal is sent for the net to deploy. Using LiDar to determine if the object has been captured, the net then uses the propellant it has left as directed to expedite the deorbit of the target object. In the case of a mission aborted during execution, the capsule is directed to deorbit itself instead. After this process has been completed, the design will begin the reloading process.

VI. Systems Engineering Milestones

Pre-Phase A: Concept Studies

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 CubeSat-sized pieces of debris. 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[9]. 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 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 1: Overview Trade Study

Phase A: Concept and Technology Development

Once we finalized our concept, the next step was to validate the design. The concept development phase of our work involved extensive research. The goal was to prove the feasibility of every aspect of our design. We began with the launch mechanism. The soft launch was initially proposed via Bernoulli's principle using a pump chamber; however, we opted for a spring launch for simplicity. The reloading mechanism was designed as a magazine with a spring attached to reload the net capsules. Also this meant the spring could be engaged on the ground and not require power in LEO.

Next, we focused on selecting components that would fit the SWAP-C constraints of this design challenge. It was found that the European Space Agency (ESA) has an active database that keeps track of Space debris in the Lower Earth Orbit (LEO). Using ESA's data and tracking system, an incoming target can be identified before the start of the mission. A 2D-LiDAR array will also be provided on the payload to scan for relative velocity and predict orbit path for improved real-time accuracy.

For the net capsule, we also researched and selected thrusters that balanced lightweight design with optimal performance [10]. To enable remote operation, we shifted our focus to the microcontrollers. Our system was architectured such that a primary microcontroller on the host satellite would communicate with secondary microcontrollers on the net capsule. The primary microcontroller would be responsible for target detection, navigation, guidance and timing of the launch. In contrast, the secondary would handle the spin deployment and deorbit sequence upon receiving the command. The LoRa microcontroller was selected due to its long-range communication capabilities, low power consumption, and space-tested reliability. This completed our technology development and initial concept drafting phase.

Phase B: Preliminary Design and Technology Completion

As part of Phase B, we narrowed down mechanisms for implementation through various iterations. Our team began collecting materials for the prototype. An Arduino Uno was chosen to demonstrate the functionality of the primary microcontroller in our design. We then shifted gears and focused on selecting different servos that would help with the net capsule launch. Parallel to this, we developed a framework for a 3D CAD model of the mechanical structure. The process required many iterations. Our continuous research and development enabled us to agree on all the electrical system components and clearly understand how our final CAD model should be laid out.

Phase C: Final Design and Fabrication

Academic and industry mentors in Phase C finalized and reviewed the design to ensure feasibility. The prototype was fabricated as two separate systems: the mechanical and the electrical. The electrical prototype included the software component responsible for testing the predictive position and time of the space debris. Meanwhile, the mechanical prototype was 3D printed, as was a scaled-down version of the whole system. Final design review and fabrication completion marked the end of the conceptual and testing phase.

VII. Innovative Concepts

During the initial phases of the capstone project, our team focused on creating multiple conceptual designs and ideas from September through November. While our team ultimately decided to launch a net capsule to handle deorbiting debris, as shown in this paper, our team had numerous other ideas that could have met our requirements.

Satellite Weapon Defense

Today, satellites are the frontier of modern warfare as we rely on them for communication and surveillance, making them vital national security assets. With such a significant role, nations want to maintain their presence in space while also being able to counter their enemies' capabilities. In the late 1900s, countries like Russia and China began experimenting with anti-satellite technologies to destroy satellites in LEO from the ground. Recently, China has tested the capabilities of anti-satellite weapons, most notably when the Chinese could fire an anti-satellite gun at one of their satellites and successfully destroy it [11].

For our design, we looked into creating a satellite capable of shielding spacecraft and protecting them from anti-satellite weapons. Our platform could deploy a large Kevlar blanket that would mask a satellite. If an anti-satellite weapon were fired at the craft, the Kevlar shield would absorb the incoming blast, protecting the satellite behind it. Our ideal CONOPS was to offer satellite protection as a service for a large, more valuable satellite operating a mission over a known dangerous area. Our satellite would accompany the larger satellite into the area and act as a bodyguard.

Satellite Tug

Satellites operate within various orbits. For optimal performance, satellites must often adjust their positioning to receive cargo or payloads at different orbits. Providing a tug satellite feature, we can provide the service of maneuvering space payloads for use in orbit.

Our initial research phase for the tug design was based on the MOOG space tug. We wanted to create a design capable of deploying numerous cube satellites (CubeSats) at varying orbits. The bus of our design would have multiple housing units capable of storing, refueling, and deploying cube sats. We envisioned our tug design as an in-space gas station. Our tug could navigate to a CubeSat's orbit, provide refueling, or even adjust its orbit.

The primary constraint to creating a mobile space gas station was size. Onboard the Venus bus, we were limited by the operational size of our payload. Without the appropriate size to store CubeSats, fuel for refueling, and fuel for navigation, our payload would be incapable of providing complete services.

Materials Printing

The zero gravity environment of space provided unique manufacturing capabilities for various goods, including metals, fiber optic cables, and pharmaceuticals. To consider all aspects of ISAM, our team created design concepts for how we could make a payload capable of manufacturing metal components in lower earth orbit. Our initial research focused on 3D printers in space. While the idea of 3D printing in space has been approached before, our team wanted to investigate the possibilities of repurposing space debris to print new materials in space, i.e., sustainable recycling of materials in space.

Our initial conceptual design was of a craft that roamed lower earth orbit, looking for recyclable materials. When a viable piece of debris was identified, our craft would capture the materials and then melt the metals down through an internal process onboard the satellite to be used in a 3D printing process. By using debris to print, we could alleviate some debris in space and take advantage of the low gravity environment to capitalize off the unique 3D printing environment.

After carefully considering the design concept, we deemed the solution infeasible due to our platform's size and power constraints. Our analysis of the Venus Bus concluded that the power drawn from the bus itself would not create enough power onboard our craft to melt down our materials. We could not identify a viable method of capturing our debris samples in space. Our first idea was to implement a harpoon system capable of spearing debris and reeling it into the craft. We believed that the process of reeling the debris, melting it down, and repurposing it through 3D printing would not be feasible with the limited power capabilities of the craft.

VIII. Technology Gap Assessment

While designing our payload, our team had to conduct a detailed study of the components that needed consideration. This process identified several key technological gaps that present limitations in current space system designs. Addressing these gaps is essential for successfully implementing our payload and supporting future autonomous on-orbit operations. The identified gaps are as follows:

Low-Cost and Lightweight LiDAR/Camera Array

Accurate spatial awareness is critical for autonomous navigation and inspection tasks in space. Current LiDAR systems that are accurate and can be used in space environments are often bulky, expensive, and power-intensive, making them unsuitable for the payload required for our design idea. Conversely, compact and lightweight LiDAR or camera systems that meet size and power constraints often suffer from limited accuracy, reduced operational range, and poor performance in the harsh environmental conditions of space, such as extreme temperatures and radiation exposure. Developing a cost-effective, lightweight, and power-efficient LiDAR/camera array tailored for small-scale missions is essential to improve accessibility and functionality for autonomous operations in space.

Adaptive Thruster Control

Our mission concept involves precise capsule maneuvering toward target debris for inspection or servicing. Traditional thruster systems have limited adaptability and precision. Even minor misfires or unexpected orbital changes can severely impact the mission in dynamic orbital environments. Our system requires small thrusters on the capsule to navigate it towards the debris, and in case of misfire or change in orbit, it needs to adapt its direction automatically. Current propulsion technologies lack autonomous correction mechanisms for misfires, reducing their reliability in dynamic environments. Introducing an adaptive thruster control system with real-time correction capabilities would vastly improve maneuverability and operational safety.

Autonomous On-Orbit Repair and Inspection

Traditional approaches to spacecraft maintenance rely heavily on either preemptive redundancy, manual astronaut interventions, or Earth-based teleoperation. These methods are not only resource-intensive but also time-consuming. There is a lack of fully autonomous systems capable of conducting real-time repairs that increase mission and operation costs. The absence of such systems leads to shorter mission lifespans, increased operational costs, and missed opportunities for extending or salvaging missions that suffer unexpected failures. Developing an intelligent system capable of conducting inspections and minor repairs would revolutionize space sustainability. It would offer safety and more economical trips and lengthen the lifespan of spacecraft.

In conclusion, addressing the technology gaps above highlights the critical areas where innovation is needed to support our mission. Advancements in the above-listed technological areas are essential to ensure efficient, reliable, and sustainable operations in space. Addressing these gaps would lead to more effective autonomous missions and broaden the scope of small space systems, making the space more accessible and sustainable for all.

IX. Path to A Professional Design Review

Materials Research

By researching materials, we determined what types of metals and alloys could survive launch and be used safely in our operating environment. We used commercially available space-rated products when these were available and fit. When designing our prototype, we needed parts that were not commercially available, so we had to create these components ourselves. 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 [12]. The results can be noted in *Figure 2* and *Figure 3* below. Beyond surviving the environment, we tracked our payload weight to stay below 75 kg.

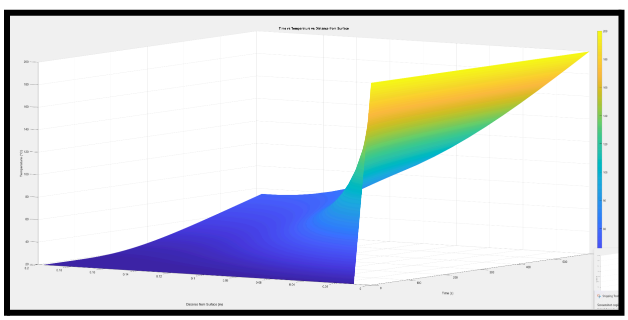

Figure 2: Distance vs Temperature vs Time graph for Steel Payload

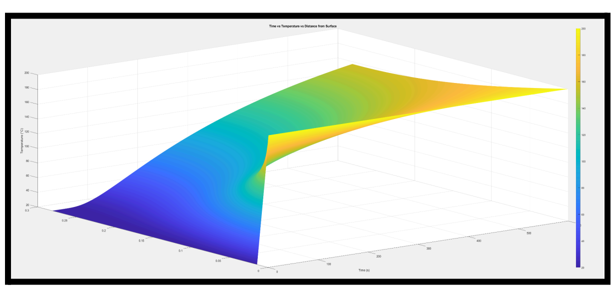

Figure 3: Distance vs Temperature vs Time graph for Aluminium Payload

Power Consumption and Budget

Our prototyped design had power constraints to maintain compliance with the provided satellite bus package. We used numerous electronic components to provide complete functionality for our platform and the on-board net capsules. With each added element of our design, we faced costs and benefits regarding price and weight. The tab below includes the overall power consumption of different components and the cost of the components we used in our design.

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: Power Estimation

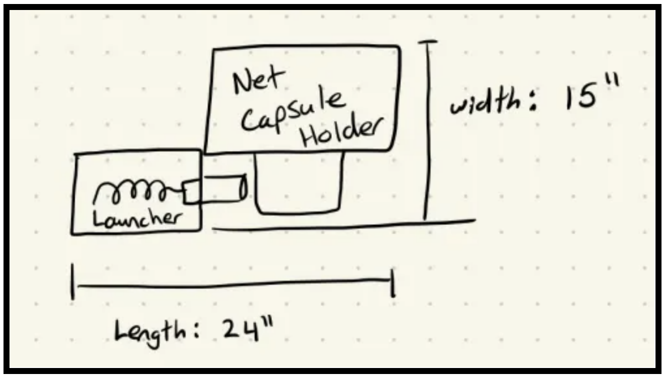

Figure 4: Space Cyclone Dimensions (Height: 6")

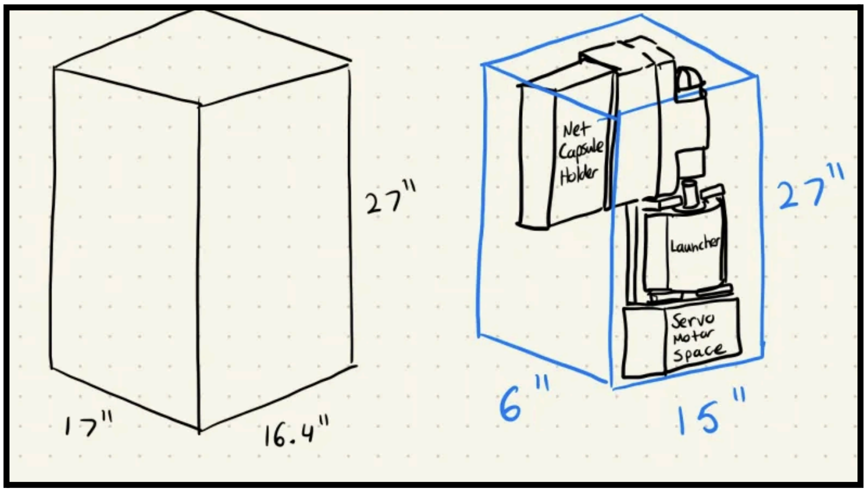

Figure 5: Left, Venus Bus Payload Maximum Dimensions. Right, Space Cyclone Payload Dimensions

Material/Component	Low Estimate ($)	High Estimate ($)
Aluminium	80	1400
Microcontroller	7	17.9
PCB	5.99	29.99
Thrusters	1000	10000
LIDAR	129	3800
Servos	4.37	69.99
Spring	0.05	1
Net	6.95	345
Total Cost	1233.36	15663.88

Table 3: Estimation of Cost

Material/Component	Low Estimate (kg)	High Estimate (kg)
Aluminium	0.27	2.7
Microcontroller	0.2	0.7
PCB	0.3	0.9
Thrusters	7.5	11.7
LIDAR	1.2	3.7
Servos	0.7	3
Spring	0.1	0.3
Net	1.5	4
Total Weight	11.77	27

Table 4: Estimation of Weight

Command and Control

During our research, we developed our platform's command, control, communications hardware, and software. The first idea we pursued was performing all calculations on the ground using existing information to calculate what actions should be taken and directing the Space Cyclone to launch a net capsule towards a specific target. We liked the idea of offloading the computing resources to the ground. However, when analyzing the system process for error correction during execution, we determined that we should focus on performing and adapting autonomously to avoid communication delays and conserve power. This thought process led us to split the command and control factors into two general pools. Events can be handled preemptively on the ground and those that need to be managed locally, in space. This determination is primarily based on response time requirements, specifically the challenge posed by the round-trip communication delay. Due to limited computing resources in orbit, we will use a simplified formula for object pathing. Although a sanity check is performed when being assigned a target, actual target viability should be determined on the ground, using a more accurate formula to predict the future location of the target object. We determined the speed benefit of a simplified formula to be worthwhile for mission operation due to the decreased range of actual error when operating within the closer distances seen during operational execution.

As the mission execution is time-sensitive, we determined that we should design the system to handle itself autonomously. As an essential preemptive command, target designation is directed by ground control, as we determined that it was not feasible to make this determination on our platform in LEO. Specifically, this targeting determination should be manually triggered to avoid any such instance of an active, functioning satellite being mistakenly targeted. The resulting command configuration is to have commands to designate a target or remove a designated target by using ground control. The Cyclone assigns each target a Universally Unique Identifier (UUID), and all ground communications contain a UUID, with id zero used to tag the initial Cyclone platform. The designation requires the object's Size, Mass, Location, Velocity, and Rotation, used for target identification and determining if the target is viable due to factors such as being outside of the operating range, conflicting with an existing mission, being too large, or with too extreme a tumble.

After target validation, the UUID is returned to the ground along with the status of the mission, either standby or rejected. There are five stages to a mission, and each stage will result in a communication to ground updating the status of that mission at each step of execution (Tracking, Launching, Net-Deploy, Capture, Deorbiting) as well as the potential Abort status in which the mission is abandoned due to autonomous determinations about the possible failure of the mission.

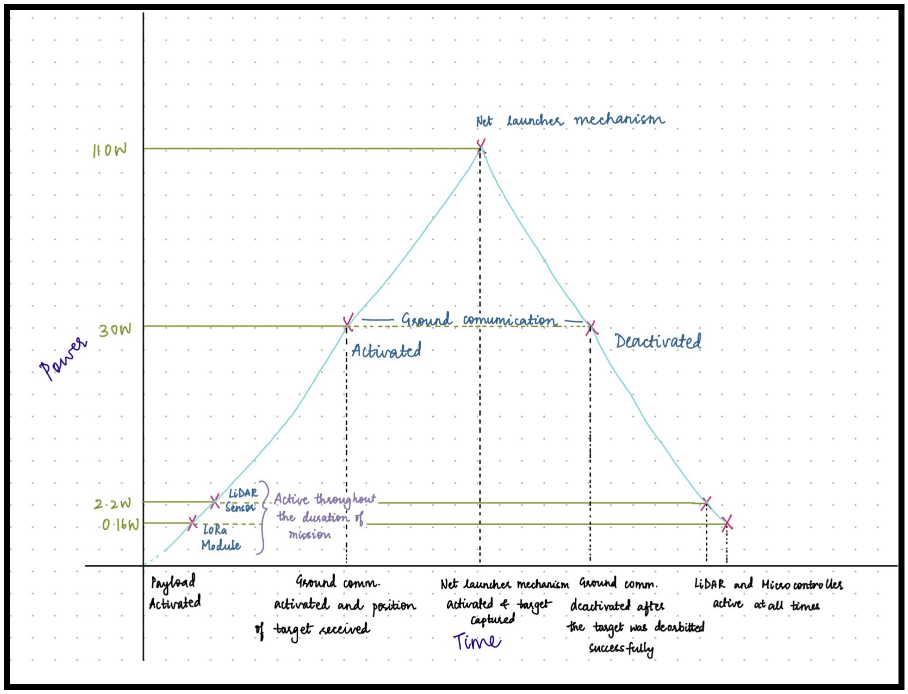

Figure 6: Power vs Time Graph for payload

X. Animation

Two animations were created using SolidWorks to demonstrate two phases of the "Space Cyclone" operation. In each animation, some simplifications were made and are discussed. The first animation was a soft launch of two net capsules, as shown in *Figure 7*.

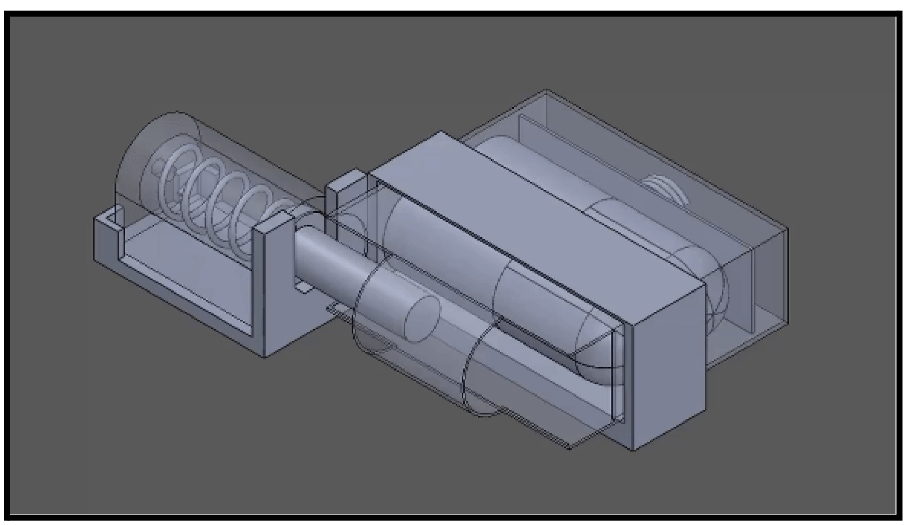

Figure 7: Space Cyclone Soft Launch Animation

Going step-by-step, the soft launch began when a plunger was drawn back to compress a spring. Once retracted, another spring located in a net capsule holder pushed a net capsule from the holder into the firing position in front of the plunger. With the net capsule loaded, the plunger was released, and the net capsule was pushed out from the holder. This process was then repeated to launch the second capsule in the animation. Not shown in this animation was the retraction method for the plunger. A servo motor with a reel and cable would be attached to the plunger to retract the plunger and compress the launching spring. A microcontroller would be used to control the plunger retraction and release timing for launching net capsules. Another design note is instead of using regular springs, conical springs would be used. Finally, the Venus Bus and how the launcher would be attached to the Venus Bus were not shown. The second animation was the net capsule expansion after launch, as shown in *Figure 8*.

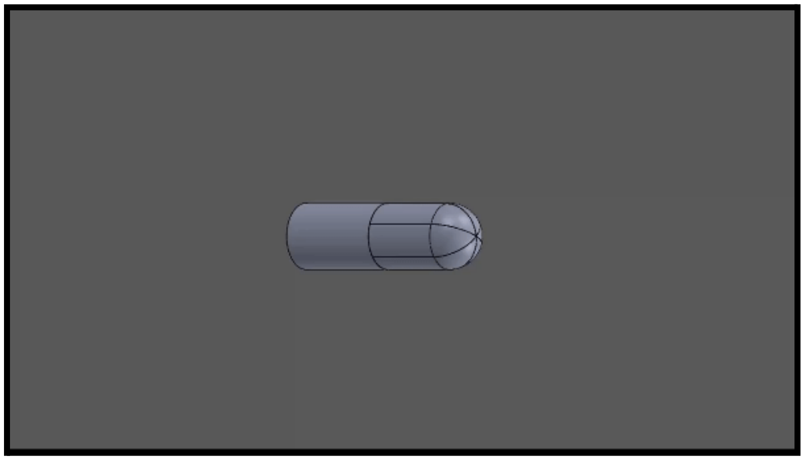

Figure 8: Space Cyclone Net Capsule Expansion Animation

In this animation, the net capsule’s six-sided front portion, the net compartment, expanded outward. Not shown in this animation was the capsule's direction of travel, which would be moving left to right. Also not shown is the rotational motion along the axis of travel, generated by cold gas thrusters in the rear portion of the capsule. This rotation would generate the centrifugal force needed to expand the six-sided net compartment outward, thus expanding the folded net inside (also not shown).

XI. Storyboard

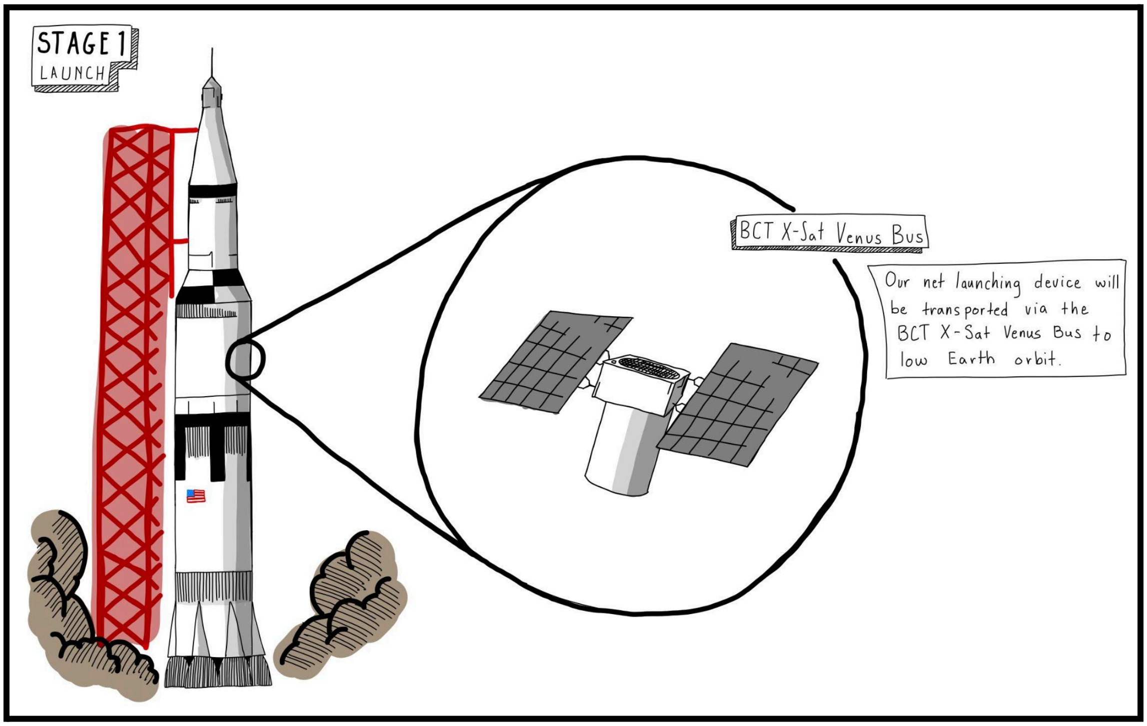

Figure 9: Stage 1-Launch

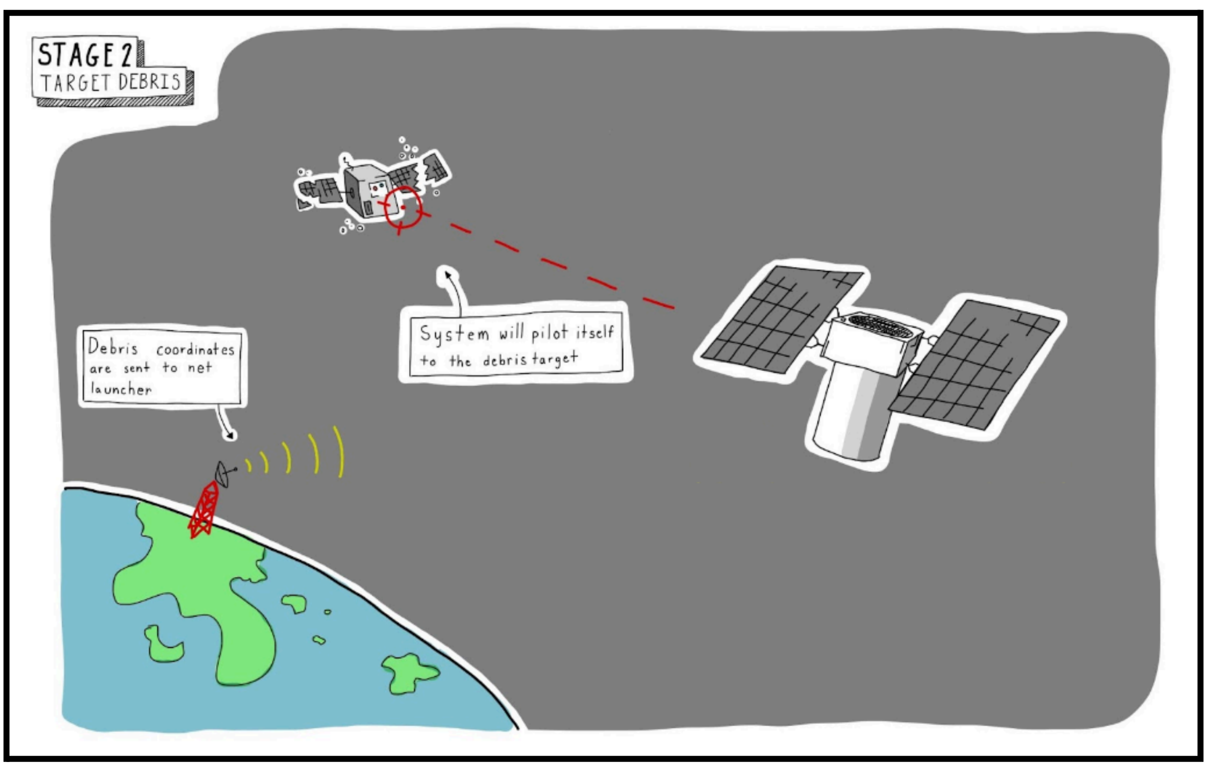

Figure 10: Stage 2-Target Debris

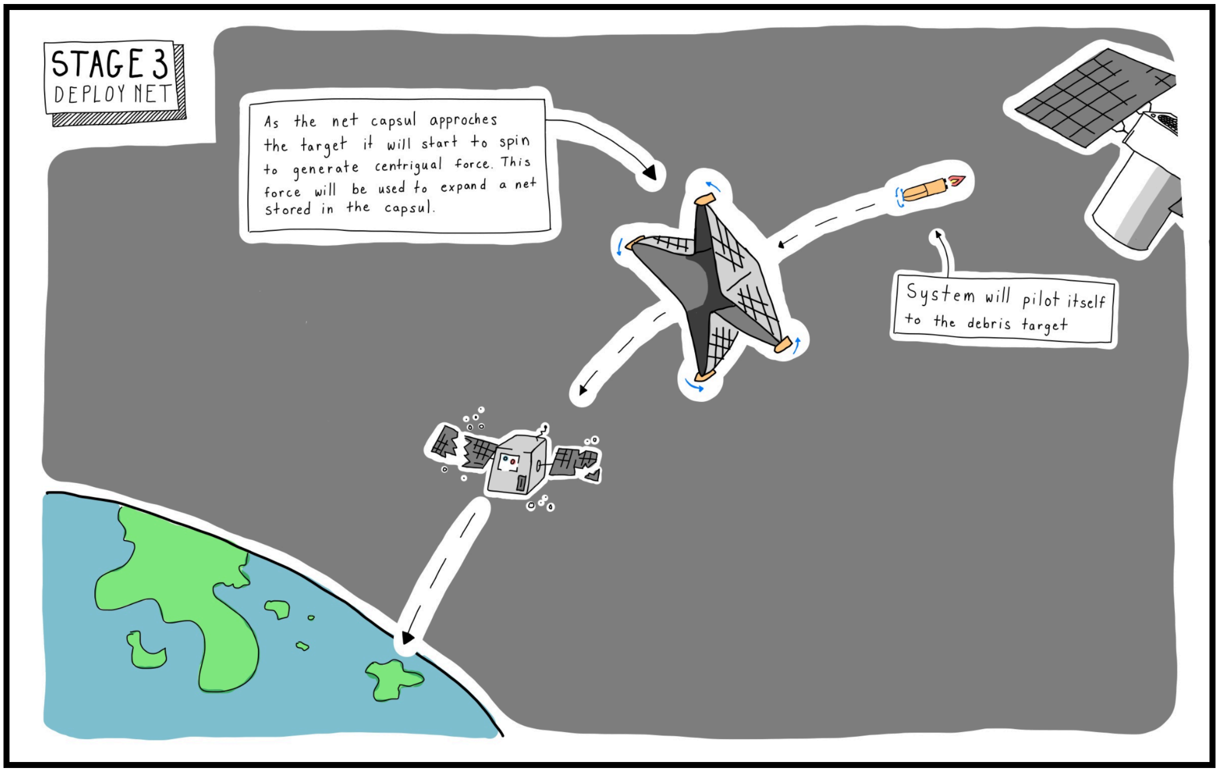

Figure 11: Stage 3-Deploy Net

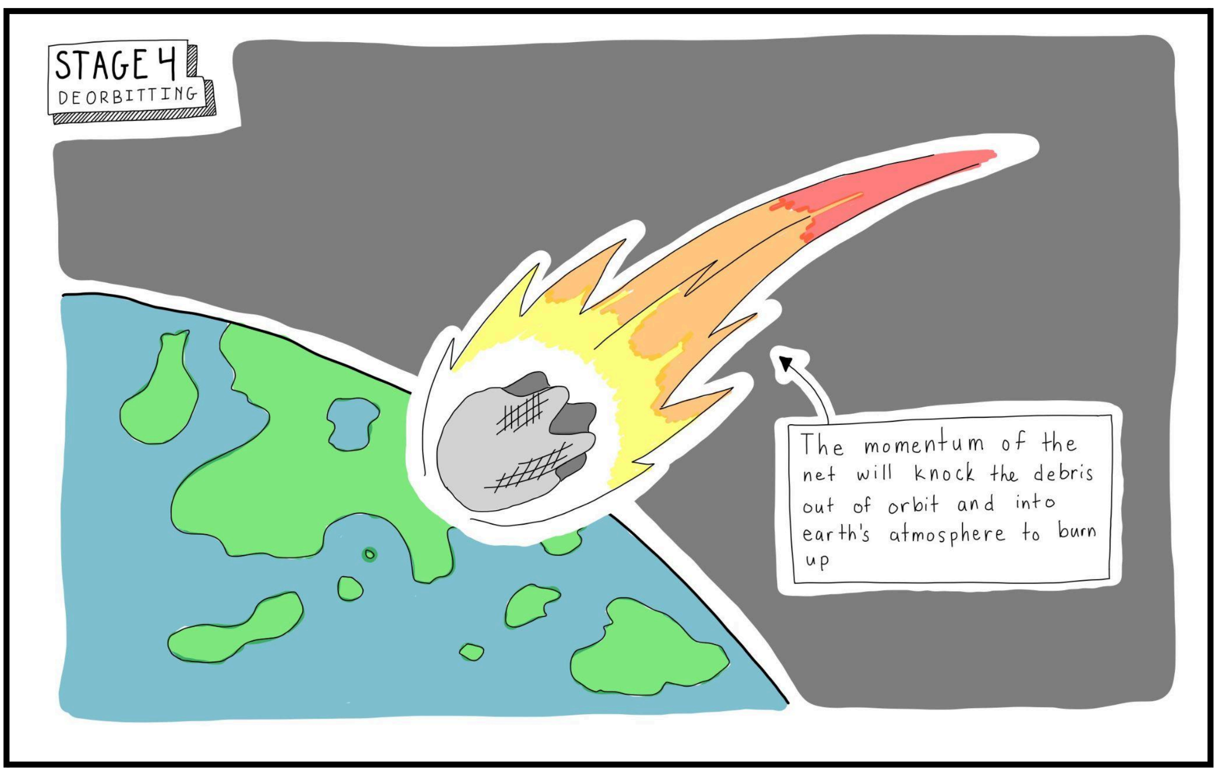

Figure 12: Stage 4-Deorbiting

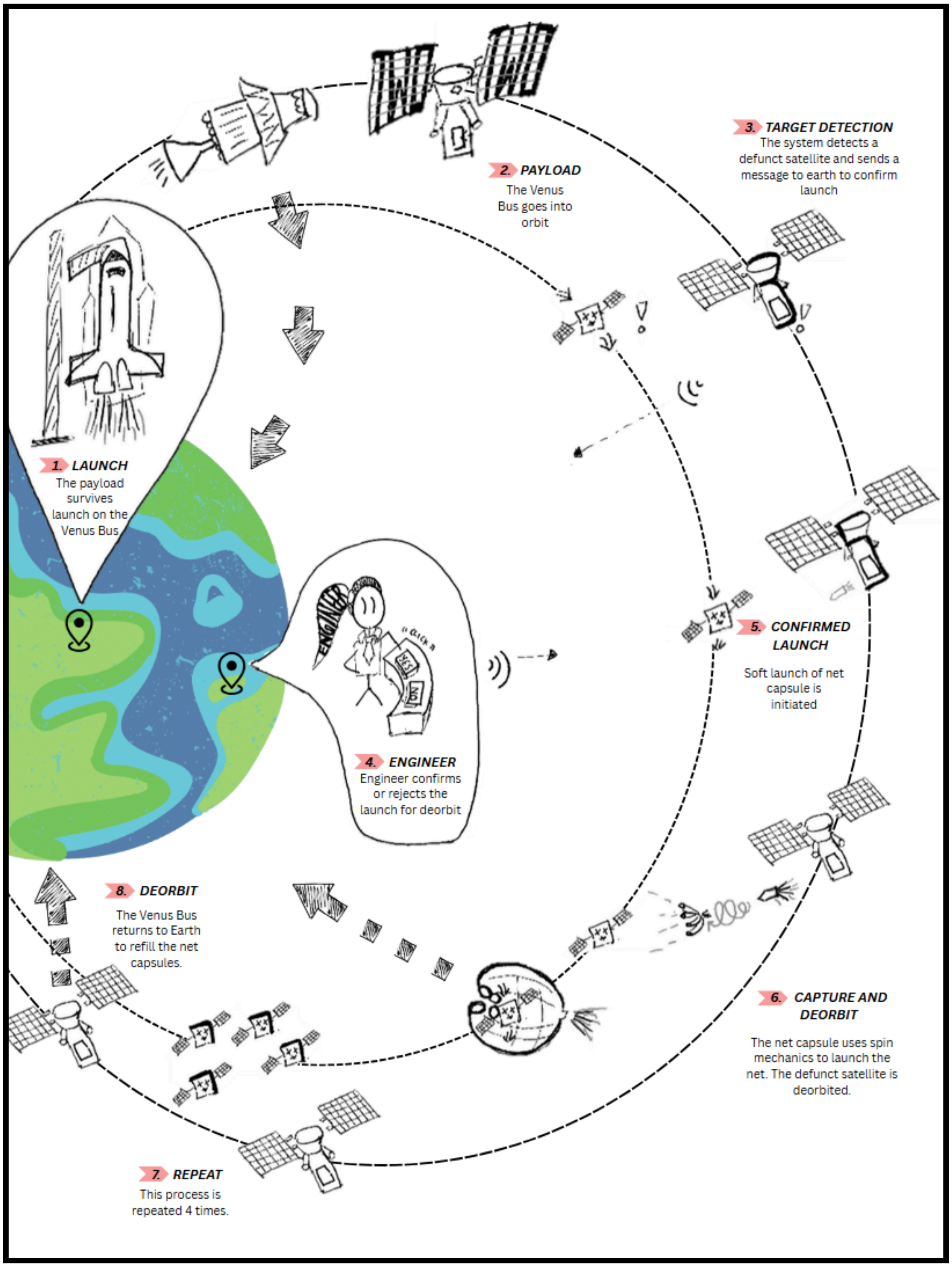

Figure 13: Concept of Operations

XII. Challenges Faced

While developing the prototype, many challenges emerged that heavily influenced the design decisions, system architecture, and performance. The following outlines the challenges that we faced:

Field familiarity

As a team without any formal learning background in aerospace engineering, we faced a steep learning curve in understanding space systems' design concepts and requirements. We had to conduct extensive research in propulsion control, thermal dynamics, and space-related materials to develop a feasible design and Concept of Operations. This knowledge gap posed a challenge at the start of the project to align our initial ideas with the constraints we had to follow. Still, it also drove us to research innovative ISAM concepts and deeply study the design concepts and existing architectures in detail to build a solid foundation for our payload.

Weight and Power Constraints

The weight and power budgets heavily influenced the selection of the components, such as the LiDAR array. We had to ensure that all the components stayed within the weight limit and that our main design allocated sufficient weight. These constraints significantly impacted the overall system design and performance metrics and required trade-off analysis.

Design Complexity

Integrating multiple subsystems presented significant challenges in ensuring seamless compatibility and functionality. A substantial amount of time was required to properly align, attach, and integrate components while maintaining modularity and reusability. Achieving an efficient balance between these factors and mission feasibility was a complex process requiring careful planning and iterative testing.

Thermal Management

The extreme temperature fluctuations in space necessitated the selection of materials capable of withstanding harsh conditions without excessive reliance on insulation or active cooling systems. The limited experience in material science and thermal management posed a challenge in identifying and implementing practical solutions. Addressing these issues required extensive research into passive thermal management techniques and high-performance materials suitable for space applications.

The above-listed challenges we encountered played a crucial role in shaping our system architecture and component selection. Overcoming these challenges required clever trade-offs and iterative refinement to ensure that the final design met the requirements and proved efficient in space.

XIII. Results

Physical Prototype

After developing the “Space Cyclone” concept and creating the CAD design using SolidWorks, the next step was constructing a physical prototype. To simplify the prototyping process, a scaled-down launcher mechanism was manufactured using 3D printing and is shown in *Figure 14*.

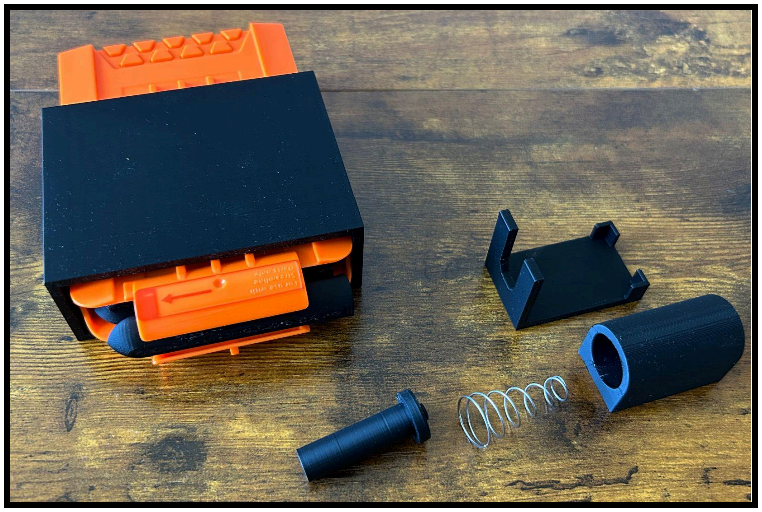

Figure 14: Exploded View of The Launcher Prototype

Two simplifications were made using 3D-printed Nerf darts as net capsules and a Nerf gun magazine (shown in orange) as the net capsule holder. A plunger-compressed conical spring provided the soft launch force to push the net capsules out of the holder. A servo motor with a small fishing line reel (not shown) was used to draw the plunger back and compress the spring.

For a net capsule prototype, a 3D-printed version was manufactured. For simplification, the net capsule cold gas thrusters were printed as a solid piece in the rear section of the net capsule, as shown in *Figure 15*.

Figure 15: Net Capsule Prototype Showing The Net Compartment Without a Net

Then, the front portion of the net capsule was made of six side pieces, just like in the “Space Cyclone” CAD design. These six side pieces created the net compartment that, after launch, would expand outward and open the net. This prototype net capsule was used as a visual aid to demonstrate how the net would be packed in the net compartment.

Electrical Prototype

The electrical prototype focused on testing the functionality of the primary microcontroller used in the payload system. For the purpose of this prototype, an Arduino Uno was used as the main microcontroller. Instead of the LiDAR sensor intended for use in an actual mission, the SHARP 2Y0A21YK IR sensor was selected due to its simplicity and ease of integration. The IR sensor was mounted on a servo motor, which moves in sync with the detected target object. In our prototype, we assumed that the object moves along a straight, linear path to simplify the predictive modeling. The sensor operates by emitting an infrared pulse and measuring the time it takes for the signal to bounce off the object and return. This results in a voltage output, which is then converted into a distance measurement in centimeters. At regular time intervals, the IR sensor emits subsequent pulses to track the changing position of the object. Using two distance-time readings, the predictive model developed estimates the future position of the moving object. This predicted location at a given time is displayed on a screen and is assumed to be transmitted to a hypothetical secondary microcontroller on board the net capsule.

Finally, based on the predicted destination, another servo (*labeled as 3 in Figure 16)* is activated to release the plunger of the launcher, which then initiates the launch of the “net capsule.” The Arduino activates the servo motor by sending the appropriate PWM pulse, triggering the retraction that releases the plunger. Once the release is complete, the servo extends, allowing the plunger to return to its original position, ready for the next reload. Thus, the PWM signal is only sent after the debris has been detected and confirmed for launch, ensuring efficient power usage on the payload. The electrical prototype setup can be seen in *Figure 16*.

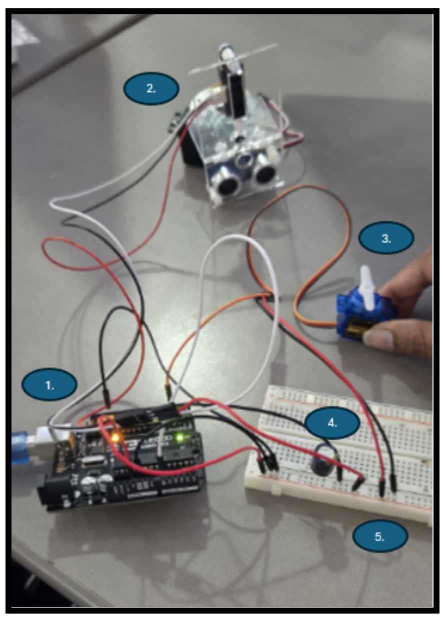

Figure 16: Arduino Circuit Prototype With a Servo Motor and LIDAR Sensor

ELECTRICAL KEY:

PART NUMBER	*PART DESCRIPTION*
1	Arduino UNO
2	SHARP GP2Y0A21YK0F
3	Servo SG90
4	100mF Capacitor
5	Newark Breadboard

Table 5: Electrical Prototype Key

Shown in *Figure 17* is an electrical schematic of the Arduino prototype.

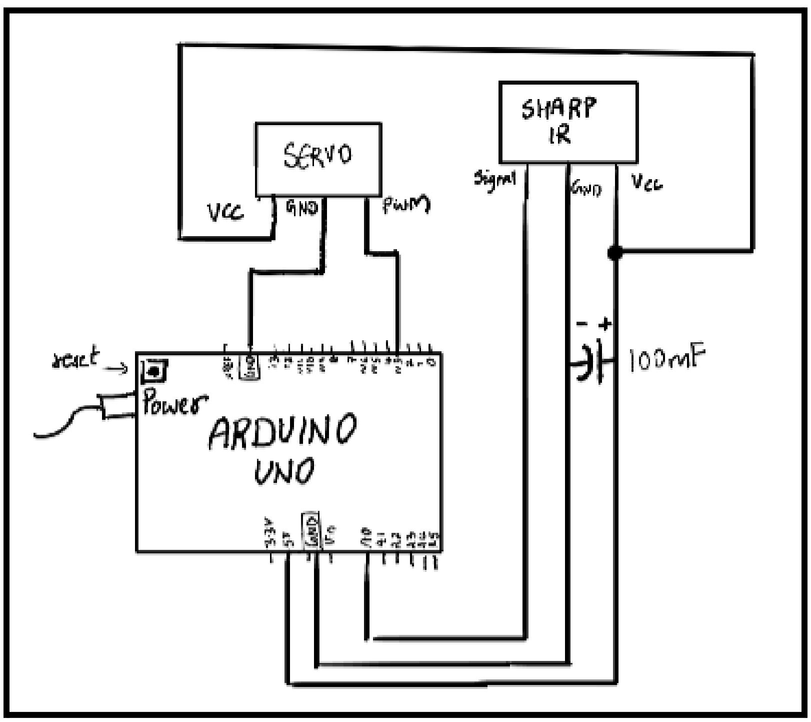

Figure 17: Arduino Electrical Prototype Schematic

XIV. Future Work

Given the initial time frame and limited manpower, we faced certain product limitations in our design. We could not incorporate a LiDar array into our design, a remote capsule control system, or a system for balancing the force of launching our net capsule. With additional funding and time, we plan to adjust our current prototype to include a LiDar instead of the current IR sensor. Using a 2D LiDar array, our prototype could more accurately and precisely identify a target. More accurate detection would allow for increased performance in de-orbiting in space debris.

With more time we can additionally continue development of the net capsule itself. Creating the logic and underlying control systems to provide autonomous functionality of our crafts net capsule. While we could develop code capable of identifying and targeting debris, we did not integrate the logic into the physical prototype due to time constraints. Our team initially researched integrating a LoRa module into our design but could not work with the components and create software to interface with a LoRa module. If allotted more time for research and development, our team could enhance our prototype to include a LoRa module that could control simulated motors on the net capsule.

More calculations are needed to consider the viability of our design's capture mechanics. As previously mentioned, our team could not test our design in a low-gravity environment. Without testing and adequate calculations, we cannot guarantee that our design will be able to capture a piece of debris in orbit successfully. Our primary concern is that our net will deploy around the target but not close around the target to ensure the full capture required to de-orbit the debris.

XV. Conclusion

We designed the Space Cyclone, a device designed to deploy autonomous net capsules fired at defunct CubeSats that uses spin dynamics on approach to unravel the net and capture the debris. The debris is proposed to be contained within a net and is deorbited using propellant onboard the net capsule. Our team created a limited prototype design throughout the engineering development cycle showcasing the spring-based net launching mechanism and net capsule unit. Our design intends to deploy and capture debris items in lower earth orbit between 10 cm and 1 m. Our team used material research and cost-benefit analysis to determine our design's best components and parts. Beyond our physical model, we designed code capable of identifying targets using ultrasonic waves to enable our net capsules to intercept and de-orbit pieces of debris. With the creation of a rudimentary physical design and underlying software-based logic to control our devices, our team is ready to proceed with testing our design to continue research into orbital mechanics and perform the necessary net capture calculations to ensure the proper functioning of our design.

XVI. Appendix

Senior Design Website: https://sdmay25-09.sd.ece.iastate.edu/
GitHub Repo: https://github.com/dmaheeka/Space-Cyclones

XVII. Acknowledgment

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