Navigating Regulatory and Ethical Hurdles with HexSat: A Detachable Net Casting Spider-Inspired Space Debris Removal Concept

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ABSTRACT

As the amount of space debris in orbit continues to increase, the need for methods of mitigating space debris becomes urgent. Drawing inspiration from nature, a net casting spider-inspired method of space debris removal has been proposed. This method, embodied in the HexSat design, features six separate wedges that can deploy to form a net for capturing debris. Once the target debris is captured, HexSat will intentionally reenter the atmosphere, where it will burn up. Any missions aimed at cleaning up space debris will face numerous challenges posed by international space regulations. To assess these challenges, a hypothetical scenario was constructed, envisioning NASA as the sole operator of a fully tested and operational HexSat. Compliance with both U.S. and international space exploration regulations was considered essential. Analysis revealed that Articles VI, VII, and VIII of the Outer Space Treaty present significant challenges due to their lack of detailed regulations. Long-term challenges include the need for new regulations and innovative designs to mitigate future space debris, such as the ongoing LignoSat satellite mission. Despite these obstacles, potential solutions are discussed and evaluated, emphasizing the importance of collaboration and proactive measures to ensure the sustainability of space exploration.

INTRODUCTION

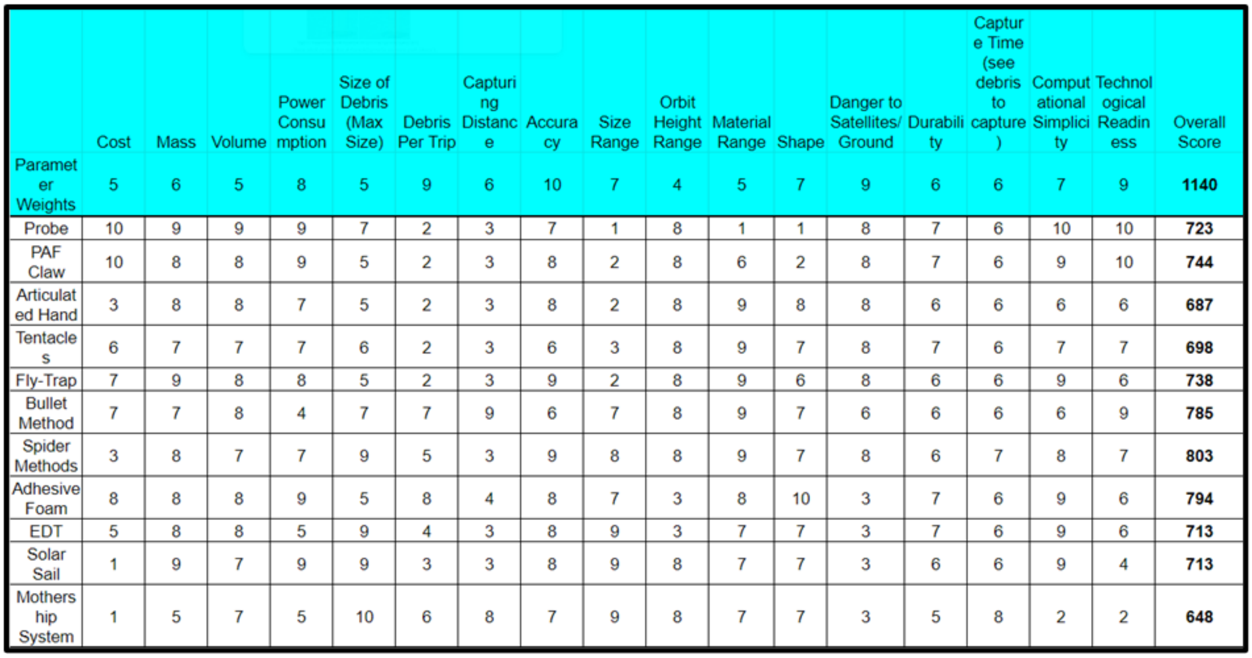
The Space Debris Mitigation Guidelines from the Inter-Agency Space Debris Coordination Committee (IADC) define space debris as "All man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere that are non-functional [7]." This covers everything from out-of-service satellites to shed-off boosters and debris resulting from orbital collisions or explosions. As of 2019, estimates suggest there are over 128 million pieces of space debris smaller than 1 cm, 900,000 pieces from 1 to 10 cm in size, and 34,000 pieces larger than 10 cm [1]. These estimates exclude untraceable space debris.

The first significant incident highlighting the problems posed by space debris occurred on February 10, 2007. Over Siberia, before noon in Washington, DC, a catastrophic collision between two complete satellites took place. The operational telephony satellite, Iridium 33, collided with an expired Russian communications satellite, Cosmos 2251, resulting in two debris clouds and increasing the trackable space debris count by at least several hundreds. The collision occurred at a closing speed estimated to be over 6.7 km/sec at an altitude of 790 km [14].

Kessler Syndrome is a scenario in which the density of objects in low Earth orbit becomes so high due to space pollution that collisions between objects generate more space debris, increasing the probability of consecutive collisions. The density of space debris is constantly increasing, making the threat of Kessler Syndrome more probable. Consequently, the need to remove debris from orbit becomes more urgent, as planning future space launches and avoiding interference from space debris in Low Earth Orbit would become exceedingly challenging. Moreover, Kessler Syndrome would significantly heighten the risk of destruction for daily-used space objects, such as all operational satellites, 63% of which were utilized for global communications in 2022 [13].

PURPOSE

The purpose of this conceptual design is to provide a proof of concept for eliminating space debris from Earth’s orbit. The importance of this design comes from the increasing global concern of Kessler Syndrome. In order to tackle a problem of this magnitude, this research has implemented quality function deployment (QFD) charts, numerical analysis, and simulation software. After researching and compiling existing methods for sensing, targeting, acquiring and removing space debris, a QFD chart was used to quantitatively



	Cost	Mass	Volume	Power Consumption	Size of Debris (Max Size)	Debris Per Trip	Capturing Distance	Accuracy	Size Range	Orbit Height Range	Material Range	Shape	Danger to Satellites/ Ground	Durability	Capture Time (see debris to capture)	Computational Simplicity	Technological Readiness	Overall Score
Parameter Weights	5	6	5	8	5	9	6	10	7	4	5	7	9	6	6	7	9	**1140**
Probe	10	9	9	9	7	2	3	7	1	8	1	1	8	7	6	10	10	**723**
PAF Claw	10	8	8	9	5	2	3	8	2	8	6	2	8	7	6	9	10	**744**
Articulated Hand	3	8	8	7	5	2	3	8	2	8	9	8	8	6	6	6	6	**687**
Tentacles	6	7	7	7	6	2	3	6	3	8	9	7	8	7	6	7	7	**698**
Fly-Trap	7	9	8	8	5	2	3	9	2	8	9	6	8	6	6	9	6	**738**
Bullet Method	7	7	8	4	7	7	9	6	7	8	9	7	6	6	6	6	9	**785**
Spider Methods	3	8	7	7	9	5	3	9	8	8	9	7	8	6	7	8	7	**803**
Adhesive Foam	8	8	8	9	5	8	4	8	7	3	8	10	3	7	6	9	6	**794**
EDT	5	8	8	5	9	4	3	8	9	3	7	7	3	7	6	9	6	**713**
Solar Sail	1	9	7	9	9	3	3	8	9	8	7	7	3	6	6	9	4	**713**
Mothership System	1	5	7	5	10	6	8	7	9	8	7	7	3	5	8	2	2	**648**

Figure 1: The QFD for the studied space debris removal methods [9].

determine the most effective methods in each design category. The acquisition QFD measured 11 methods for debris capture against 17 parameters (Figure 1). Methods chosen for evaluation included net capture, robotic arm/hand capture, harpoon tethers, and many more. Performance parameters chosen to evaluate each of these methods included cost, mass, volume, power consumption, targetable debris size, debris collected per trip, capture distance, accuracy, size range, orbit height range, material range, shape, safety to other satellites, durability, capture time, computational simplicity, and technological readiness. Each performance parameter was weighted by importance. Each removal method was given 1-10 score (1 being poor and 10 excellent), which was multiplied by the category weight. The method that had the highest sum of performance parameter scores was the net casting spider inspired-design presented in this paper.

The net casting spider-inspired method combines features of existing techniques, including drone swarm technology and traditional net capture in a completely unique and original manner. Upon detecting space debris, the device, named HexSat, splits into six collaborative drones that direct a net around target debris. The HexSat then reattaches into a single pod and deorbits to burn up upon atmospheric reentry. The most significant strengths of this design include high fidelity for debris capture, high technology readiness level, and scalability for multiple debris acquisitions per mission.

BIOINSPIRATION OF HEXSAT

Bioinspiration was considered when designing the HexSat. The HexSat design was inspired by the family of spiders named Deinopidae, better known as net casting spiders. This family of spiders is unique because they actively use and manipulate their nets to capture prey. Deinopidae constructs square nets on vegetation before grasping the four corners with their front legs, testing it with a few stretches, and then waiting to catch their prey (Figure 2). When prey is detected, the spider propels itself forward, stretching the net further open and quickly releasing the tension on it without letting go of the net. The prey is trapped when the tension is released and the net contracts together. The same trapping process is applied to the HexSat. Each wedge will act as a spider leg and hold a corner of the net when approaching a piece of space debris. Once the debris has entered the net, the wedges will contract around it, and the leftover net will be reeled back into its compartment in each wedge to ensure that the debris does not convulse much as the HexSat de-orbits and returns to Earth.

Figure 2: An ogre faced spider stretching a web across its front legs to catch prey.

MISSION CYCLE

The mission cycle of the HexSat contains 5 parts; those parts are sensing, targeting, traveling/locomotion, acquisition, and removal. The aspects of the cycle are collectively known as ST^{2}AR (Figure 3).

The first part of the cycle is sensing; during the sensing phase, the HexSat uses its sensors to obtain raw data from its surroundings. With the raw data, the HexSat computes the orbit and size of objects that it has sensed. Using the computed orbits, the HexSat can avoid collisions with space debris. The computed orbits are also compared to orbits of active satellites; this allows the HexSat to differentiate between operational satellites and debris. At the end of the sensing phase, the HexSat will use the raw data that it has assembled to choose a specific piece of debris to target.

Once the HexSat has chosen a target, the targeting phase begins. The HexSat uses the orbital data of the target to begin calculating possible interception courses. The HexSat will then choose the most fuel-efficient interception course; if no valid interception courses can be found, the HexSat will return to the sensing phase and choose another target.

Once a valid interception course has been calculated for the target, the HexSat enters the travel/locomotion phase. During this phase, the HexSat uses its thrusters to enter the interception course with the debris. Once the HexSat is on an interception course with the target debris, the acquisition phase begins.

During the acquisition phase, the HexSat prepares to open and capture the debris. The main parameter of this phase is the distance to the target. Once the debris is within a set distance from the target, the thrusters that separate the wedges will activate, and the HexSat will expand. Once the debris has impacted the net and has been intercepted, the motors in the wedges will turn on, and the HexSat closes with the debris.

After the acquisition phase, the HexSat begins the removal phase. The removal phase involves calculating the best way to reenter the atmosphere with the fuel that is left. The HexSat will use spare fuel, to attempt to get into a low-risk reentry orbit. This orbit is designed to mitigate the risk of debris not entirely burning up in the atmosphere hitting populated areas on the ground. Equation 1 below will be used to determine the best inclination of the reentry orbit. Once the HexSat is at the best inclination, the deorbit thrusters will fire, and the HexSat will deorbit.

$$p_i = \varepsilon_i /(2\pi^2 R^2) * \int_0^{\pi/2} F'(sin(i)sin(\theta))d\theta \tag{1}$$

where p_i is casualty expectation per unit area, R is radius of Earth, ε_i is casualty area, i is orbital inclination, and $F'(sin(i)sin(\theta))$ is a function of population density.

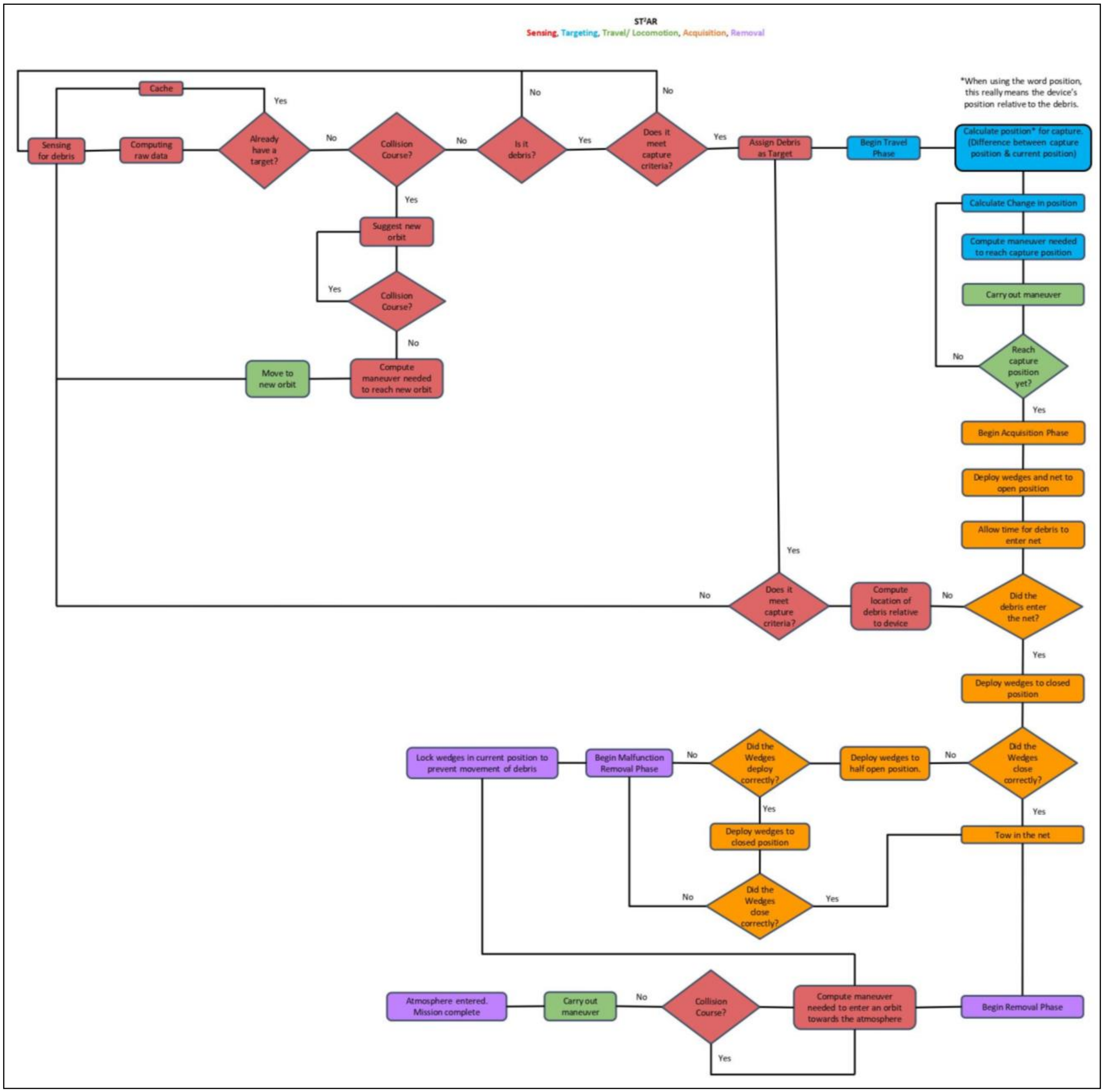


Figure 3: A flowchart of the ST^{2}AR mission cycle (sensing, targeting, travel, acquisition and removal).

DESIGN OF HEXSAT

Frame Dimensions

The frame of HexSat consists of six wedges with triangular cross sections, as indicated in Figure 4. During the optimization process, all physical dimensions of the frame were accounted for. The optimization process was initially geared toward finding the optimal frame dimensions for a set amount of fuel impulse (and, subsequently, lifespan). Because unit mass is largely a function of the frame dimensions, the idea was to find the ideal way to minimize mass while maximizing volume for fuel.

After beginning the study, it was decided that a better and ultimately safer approach to optimization would be to design the dimensions around predetermined wall thicknesses that are within the acceptable range of CubeSat-like satellites. Only wall thicknesses larger than 2mm were considered because CubeSats of similar size were found to require a wall thickness of at least 1mm [9], and we wanted a factor of safety of at least two. After calculating wedge mass for each frame at a span of wall thicknesses from 2mm to 10mm, the optimum thickness was determined to be 4mm. This allowed for a comfortable safety factor without causing the overall mass to skyrocket.

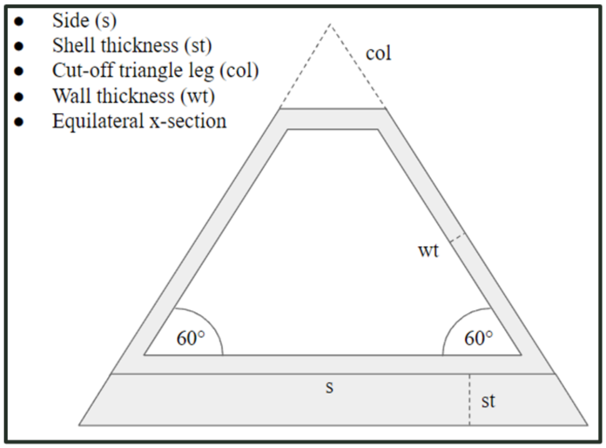


Figure 4: Cross-section of HexSat wedge with shorthand notation for dimensions, optimized and specified below (shorthand is consistent with MATLAB script used to optimize dimensions) [9].

The only dimension not to be optimized numerically was the cut-off triangle leg, which was chosen to be a constant of 2.5 cm regardless of other dimensions. This is because ample room was needed for internal thrusters used for the separation of the wedges. Before numerical optimization, the length of the HexSat wedges had to be addressed. While the average length was a value yet to be optimized, the ratio between the long length (on the inside) and the short length (on the outside) had to be determined. In order to not sacrifice too much volume, a ratio of 5:6 was chosen, which should allow enough space in the back of the HexSat for the net compartment without eating into the volume to be allocated for electronics and fuel. The final decision that was made before the numerical optimization was to eliminate the extruded shell of each wedge in favor of an overall thicker wall. The primary reason behind this decision was the fact that the interior of the HexSat, the walls which separated and reattached, would likely need as much or more armor than the outside of the overall satellite; it was deemed a waste of fuel life to have an extra layer of mass on the outside of each wedge.

Two dimensions were optimized numerically to provide the lowest frame mass possible for a specified internal volume. These dimensions, in accordance with Figure 5, were side width (s) and average length of the wedge. In order to optimize these dimensions, a range of set internal volumes was inputted, and the width and length were defined as a function of these volumes. The mass of each wedge was plotted against the width in order to find the optimal width values at each set volume (Figure 5). Although optimizations at all volumes seemed to yield very similar width values, the final design uses the set volume of 3,000 cubic centimeters of internal volume per wedge. This allows the final design to have a fuel volume of approximately 2.85 gallons. When defining mass during dimension optimization, only the masses of the wedge frames, solar panels, and fuel tanks were considered; this is because all other mass allocations are not determined by the dimensions. The final optimized average wedge length and wedge width were found to be 25.46 and 17.90 centimeters, respectively.

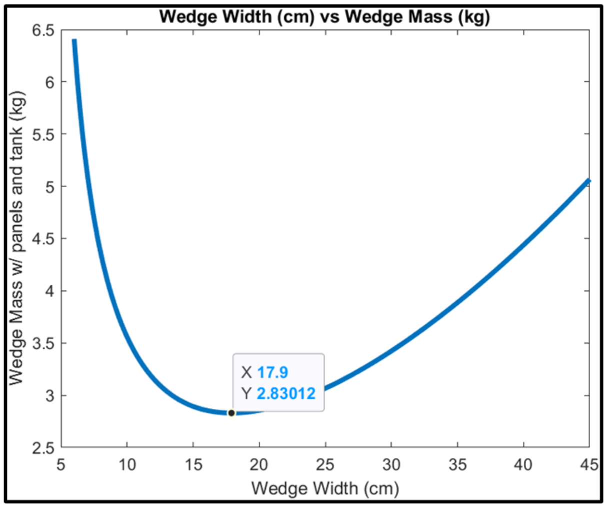


Figure 5: Mass of each wedge plotted against the width (s) at a set volume of 3000 cm^3 [9].

Frame Material

When selecting a material to use in the design of the frame, an assortment of materials already being used for satellite purposes was examined; these materials were 4 common aluminum alloys, and they were each examined for their material properties of density and yield strength. The material chosen for the design was to be the alloy that had the best strength-to-density ratio, and this material was 7075 aluminum.

Net Specifications

The net is custom-made to be optimized to maximize the distribution of stress. For this to happen, a quadrangular pattern was adjusted to fit into the hexagonal shape of the net (Figure 6). The material chosen for the net was the Ultra-high-molecular-weight polyethylene fiber, Dyneema, as it has an excellent ratio of strength to density. To ensure that the net has a high enough safety factor to eliminate the chance of failure, a two-millimeter weave was chosen for the net. The height of the net was made to be 2.5 meters as it maximizes the reach of the net while keeping a distance that is capable of maintaining communication between the Bluetooth modules within the HexSat wedges. The net span and weave decisions cause the total mass of the net to be 117.8 grams, which is ultimately a negligible fraction of the total mass.

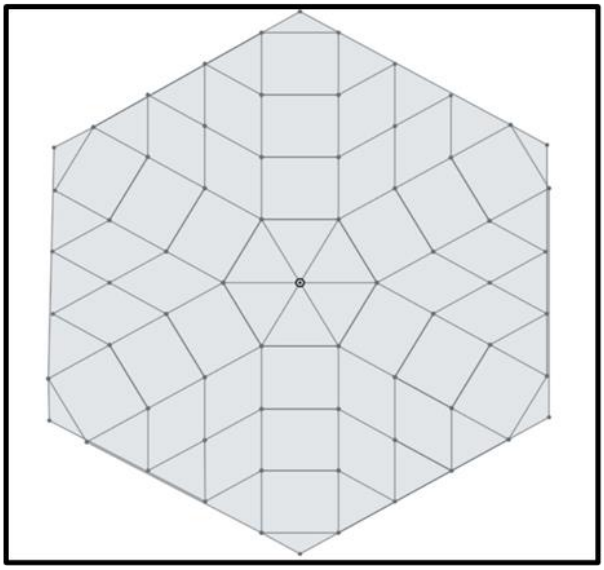
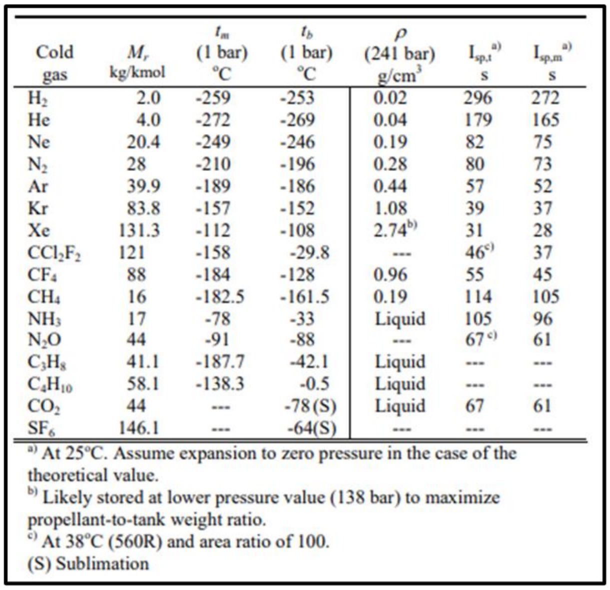


Figure 6: Net design for HexSat [9].

Fuel Specifications

When determining the ideal fuel for the HexSat, several cold gas propellants were considered (Figure 7). The most important parameter for selecting the fuel type was a specific impulse, and Hydrogen gas turned out to have the highest by far (Figure 7). This will allow the HexSat to generate more thrust from less fuel, which is essential for a compact cube-sat with a high maneuverability expectation.



Cold gas	M_r kg/kmol	t_m (1 bar) °C	t_b (1 bar) °C	ρ (241 bar) g/cm^3	$I_{sp,t}$$^{a)}$ s	$I_{sp,m}$$^{a)}$ s
H_2	2.0	-259	-253	0.02	296	272
He	4.0	-272	-269	0.04	179	165
Ne	20.4	-249	-246	0.19	82	75
N_2	28	-210	-196	0.28	80	73
Ar	39.9	-189	-186	0.44	57	52
Kr	83.8	-157	-152	1.08	39	37
Xe	131.3	-112	-108	2.74$^{b)}$	31	28
CCl_2F_2	121	-158	-29.8	---	46$^{c)}$	37
CF_4	88	-184	-128	0.96	55	45
CH_4	16	-182.5	-161.5	0.19	114	105
NH_3	17	-78	-33	Liquid	105	96
N_2O	44	-91	-88	---	67$^{c)}$	61
C_3H_8	41.1	-187.7	-42.1	Liquid	---	---
C_4H_{10}	58.1	-138.3	-0.5	Liquid	---	---
CO_2	44	---	-78 (S)	Liquid	67	61
SF_6	146.1	---	-64(S)	---	---	---

a) At 25°C. Assume expansion to zero pressure in the case of the theoretical value.
b) Likely stored at lower pressure value (138 bar) to maximize propellant-to-tank weight ratio.
c) At 38°C (560R) and area ratio of 100.
(S) Sublimation

Figure 7: Specific impulses of a range of cold gas fuels [9].

Electronics

Each wedge of the HexSat will have its own independent onboard computer, two Jetson Nanos located in the 'lead' wedges, and four Raspberry Pis in the regular wedges. The six microcomputers will each have a Bluefruit LE Bluetooth chip, so that the command wedges can communicate with the other wedges to open and close the net. Each of these chips was chosen for their specifications, such as memory size and data rate after being compared to similar chips. The electronics for the HexSat also include an LSLiDAR MS C16 LiDAR sensor for detecting nearby debris, a BA01 High Energy Density Battery Array to power the chips, and an LS00041 High Torque motor that will operate the winch wheel to open and close the net system. Eventually, solar panels will also be implemented on the top of each wedge to allow the HexSat to charge its batteries.

Mass Allocations

The mass allocation for each wedge is shown in Figure 8. The main sources of mass for each wedge are the hull, fuel tank, and solar panels.

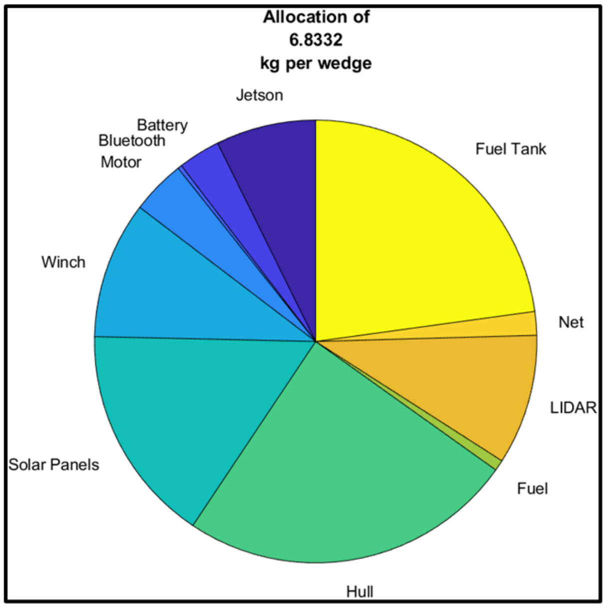


Figure 8: Mass allocation chart [9].

PROOF OF CONCEPT

Unity Simulation

In order to better visualize and understand the operation of the HexSat, a simulation was created with the use of the Unity engine. The simulation currently contains a model of the HexSat and a model of a piece of space debris; these models orbit a model Earth (Figure 9). The Unity simulation reflects the operation of the HexSat, catching up with and intercepting space debris. When the simulation calculates that the space debris is within range, it applies a force to each wedge; this is meant to simulate the thrusters firing. The wedges then fly apart and are stopped once they reach the maximum spread allowed by the net. After the space debris has been intercepted with the net, the simulation applies a force to each wedge to close the HexSat, and the HexSat begins slowing to deorbit. The simulation is designed to be easily modifiable, to allow for future expansion. The simulation also has the ability to interface with a virtual reality headset; this allows users to look around with an immersive view of the HexSat's operation.

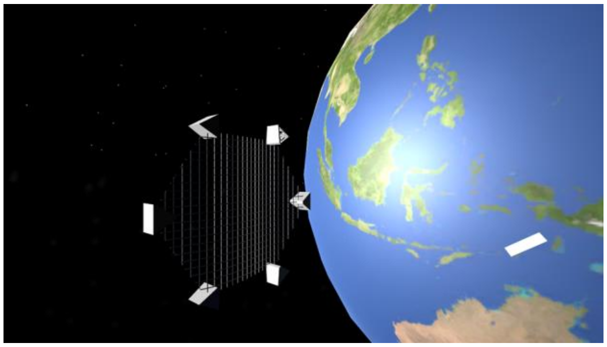


Figure 9: The HexSat intercepting space debris within the Unity simulation [9].

Model Production

OnShape computer-aided design (CAD) software was used to create models for the HexSat concept as can be seen in Figures 10 to 12.

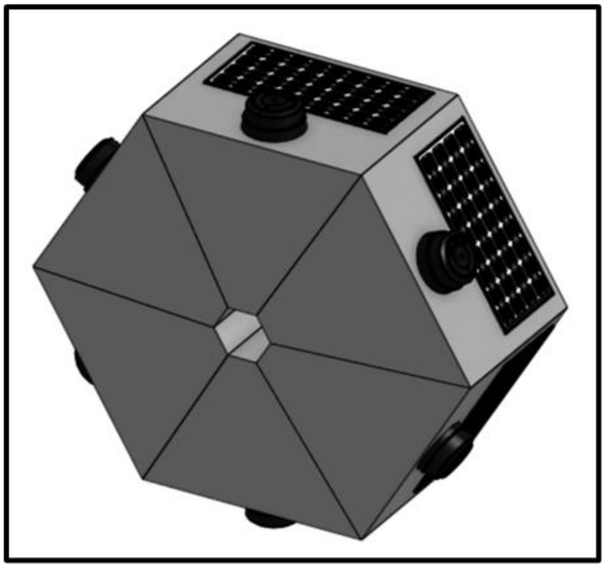


Figure 10: Final design CAD model with wedges closed [9].

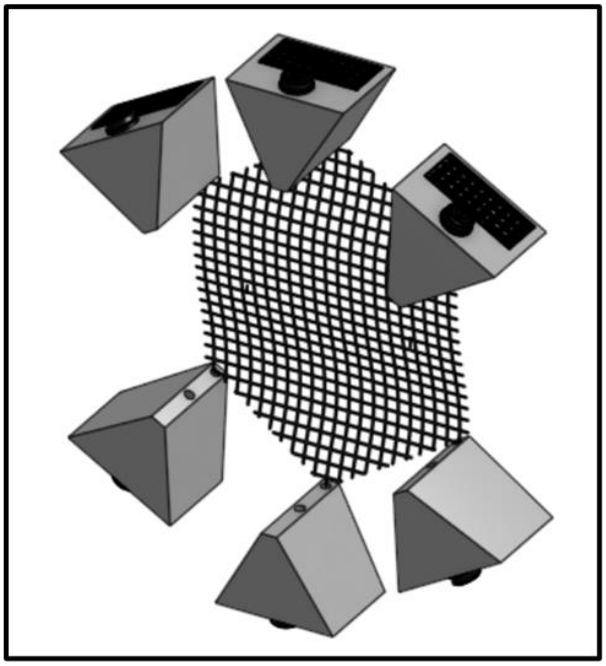


Figure 11: Final design CAD model with wedges separated and net deployed [9].

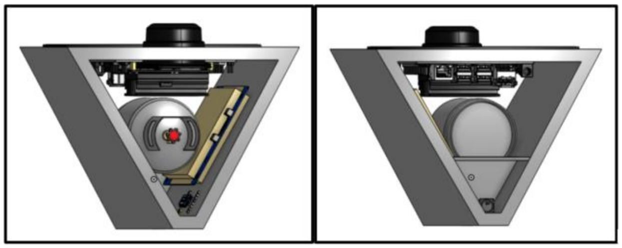


Figure 12: Front and rear views of the interior components in the final design of a "lead" wedge [9].

LIDAR Testing

One of the primary navigational sensors the HexSat will rely on is LiDAR (Light Detection and Ranging) which utilizes laser pulses to detect the distance of surrounding objects in a 2D or 3D radius, depending on the sensor. In order to maximize the visibility and debris detection potential of the HexSat, a 3D LiDAR mounted on the command wedge is the preferable sensor option. Due to budget constraints, a 2D LiDAR sensor by Slamtec was tested for definition and range, and a screen capture of sample data is shown below in Figure 13. This particular sensor was found to have 360 detections, 10m-40m range, a 9200 Hz sample rate, and an angular resolution of 0.31°to 0.59°. If this sensor were to be implemented in the HexSat, it would be able to detect pieces of debris that are an inch in diameter at ten feet away, which is not ideal for high-velocity orbital trajectories. A more expensive, higher resolution 3D LIDAR would be preferable for use in the HexSat's detection system.

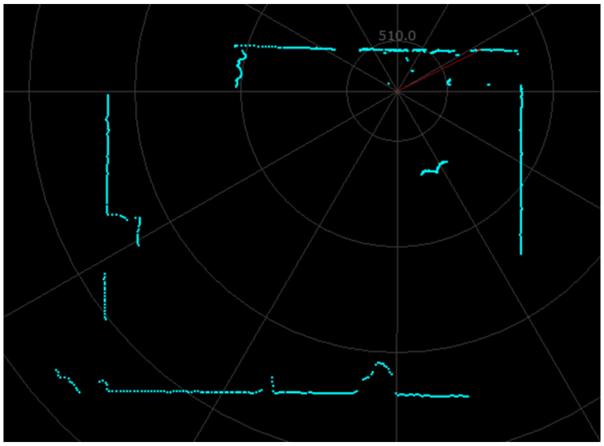


Figure 13: 2D LiDAR peripheral scan using RPLIDAR S1 [9].

HYPOTHETICAL SCENARIO

To examine the regulatory and ethical challenges a mission to remove space debris using HexSat would encounter a hypothetical scenario will be constructed. In this scenario we will assume that the National Aeronautics and Space Administration (NASA) is the sole creator and thereby owner of a fully tested and operational HexSat. The scenario will follow the five-part mission cycle named ST^{2}AR (Figure 3).

Since NASA is an independent agency of the U.S. federal government, all of NASA's missions must comply with regulation for space exploration enforced by the U.S. as well as regulations enforced by international organizations the U.S. is a member of. Currently the U.S. is a member of The North Atlantic Treaty (NATO), The Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (COPUOS) written by the United Nations Office for Outer Space Affairs (UNOOSA), the Outer Space Treaty (OST) enforced by UNOOSA, and the Space Debris Mitigation Guidelines written by the Inter-Agency Space Debris Coordination Committee (IADC).

CURRENT REGULATIONS

Currently there are more international guidelines and goals to help reduce space debris than there are regulations.

NATO has no regulations of their own, but vows to remain in line with international regulations; no specifics are provided. For the thirteen nations who are members of the IADC and the one hundred and two members of UNOOSA's COPUOS, the following seven non-enforced guidelines for mitigating space debris are provided:

1. Limit the debris released during normal operations.
2. Minimize the potential for break-up during operational phases.
3. Limit the probability of accidental collision in orbit.
4. Avoid intentional destruction and other harmful activities.
5. Minimize potential for post-mission break-ups resulting from stored energy.
6. Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit region after the end of their mission.
7. Limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous Earth orbit (GEO) region after the end of their mission [17].

The Outer Space Treaty put into action by the United Nations Office for Outer Space Affairs on October 10, 1967 consists of seventeen articles. Of the seventeen articles, articles VI, VII, and VIII seem to most impact any attempts at space debris removal. In simple terms, the articles state as follows:

- Article VI: Signatory countries are accountable for the actions of their government agencies and private entities in space. Each country must ensure that the activities conducted by its entities comply with the provisions of the treaty. For private companies seeking to engage in space activities, they must obtain permission from their respective country, which is responsible for overseeing their operations. In the case of international collaborations in space, both the collaborating group and the treaty member countries involved bear responsibility for adhering to the treaty's regulations.

- Article VII: A country that launches or assists in launching an object into space from its territory is held responsible if that object causes harm to another country or its inhabitants, whether on Earth or in space.

- Article VIII: When a country launches an object into space and registers it under its jurisdiction, that country maintains authority over both the object and the personnel associated with it while it remains in space or on another celestial body. Ownership of the object does not alter upon its placement in space or on another celestial body. If components of these objects are discovered beyond the borders of the launching country, they should be returned to that country upon request, and the country claiming ownership must provide evidence to establish their ownership.

The U.S. itself has not put into effect any regulations that would negatively affect attempts at space debris removal whom NASA or private companies must follow. But various documents, such as the National Space Policy of the United States of America published on Dec 9, 2020 and the National Orbital Debris Implementation Plan published in July 2022, have detailed multiple research and development topics the U.S wishes to pursue along with space guidelines for commercial, civil, and national security usage. Many of the guidelines overlap with those of the Outer Space Treaty.

IMMEDIATE CHALLENGES AND POSSIBLE SOLUTIONS

When planning the mission for HexSat, four questions immediately surface. Each of these questions are left unanswered by any of the current international space regulations. The questions that pose an immediate challenge to removing space debris are:

1. Can HexSat only collect debris belonging to the same nation as itself?
2. Who owns debris from collaborative missions?
3. How do we decide who is the rightful owner of debris that has broken off from larger pieces and is no longer identifiable?
4. Who is responsible for unidentifiable debris?

Challenge 1

As HexSat is programmed, the number one question to be asked is: what debris can it catch without breaking any regulations? All objects launched into space are registered with UNOOSA as property of the nation from which they originate. Article VIII of the outer space treaty states that when in space the ownership of an object does not change. As a consequence, one must now ask whether HexSat, which will be registered as property of the U.S., catching a piece of debris registered as property of another nation, would violate Article VIII? Nowhere in the treaty is a definitive yes or no answer provided. The IADC guidelines do not hint towards any answer either.

For the hypothetical scenario there are three paths to take, the first is for HexSat to play it safe and only be used to catch debris registered as property of the U.S., the second is for HexSat to take a risk and catch any debris while assuming that doing so does not break article VIII, and the last option is to take a chance at negotiations with other nations about working together to catch debris belonging to both nations.

If the second path is pursued and HexSat catches a piece of debris not registered as property of the U.S., it is possible for the nation whose debris was caught to claim article VIII was violated while at the same time invoke another section of the same article to reclaim their debris. This possibility creates a new issue: what is to happen to a nation who breaks the regulation imposed by any article? Nowhere in the outer space treaty are consequences stated.

While it will be time consuming and involve many political and ethical negotiations between nations, option three would be the most productive choice to pursue. Not only does it eliminate the risk of breaking any regulation, but it provides the opportunity for nations to support each other with resources to build and improve HexSat to be more efficient in removing space debris from Low Earth Orbit.

Challenge 2

To simplify how regulations would apply to HexSat's mission it was made a sole nation project, something not true for most space research nowadays. Expanding on the discussion from challenge 1, the question becomes: can HexSat collect debris which resulted from previous joint missions between the U.S. and other nations without invoking article VIII's wrath? It can be assumed that when launched the object, now debris, was registered as property of both nations. As a result, HexSat should not be accused of breaking any regulation by catching said debris. But until a regulation specifically states how ownership of objects from joint missions is determined, arguments can be made that HexSat did violate article VIII.

Challenge 3

Millions of pieces of space debris are estimated to be smaller than 1 cm and not all of them are large enough to be identified by any current technology. There is no answer to who becomes the owner of these pieces of debris now that it is unknown what space object they originated from. If HexSat is assumed to be capable of catching these very small pieces of debris, it can proceed under the assumption that the pieces will not have an owner. Given their tiny size it is almost a guarantee that nothing will survive reentry into the atmosphere and the rightful owner will never be found, leaving no evidence for any nation to claim article VIII was broken. Should any large unidentifiable debris survive reentry, an attempt to discover what object the debris originated from can be made in order to return the debris to the proper owner.

Challenge 4

In Challenge 3, the scenario for what could happen if HexSat was used to remove unidentifiable debris was discussed. But would HexSat ever be used for such a scenario? Why should the U.S. or any other nation devote its resources to catching ownerless debris? Such a scenario would only likely occur if a piece of ownerless debris severely threatened a very important space object, be it a satellite or a space station. If ownerless space debris remains in space unaccounted for, sooner or later an answer to who becomes responsible for this debris will be needed. Discussions to create a just and fair answer to this question will need to take place between all nations in the future.

LONG-TERM CHALLENGES AND POSSIBLE SOLUTIONS

As HexSat and other debris-cleaning devices are deployed, three questions that will impact the future arise. They are as follows:

1. What if only a few nations help clean debris and others keep creating? At what point do they need to be held accountable as well?
2. Where to store any debris if it survives reentry? Could it be reused?
3. What can be done about negative effects on the Earth's environment caused by reentry?

Challenge 1

Cleaning Low Earth Orbit of space debris is not a one nation job. Should HexSat be successful and remove space debris created by the U.S. continuously for years, it will make very little difference if other nations continue to create large amounts of debris. When will it be time to hold nations only creating debris and not helping clean accountable? A possible solution to mitigate debris could be enforcing limits for how much space debris a nation can risk making per an allotted amount of time. An example is limiting or completely prohibiting anti-satellite (ASAT) weapons test. The 2007 Chinese ASAT test alone produced over 3000 pieces of trackable debris, along with a much larger number of smaller, untraceable fragments. Similarly, the Russian ASAT test in 2021 resulted in the creation of over 1500 pieces of trackable debris and more untraceable fragments.

Currently only mitigation guidelines, and not regulations for mitigating space debris exist; these guidelines would need to be enforced and nations must agree to follow them.

Challenge 2

Should any debris HexSat captures survive reentry, the U.S. would need to find a safe area to store the debris as well as establish procedures for reusing any parts. With space on Earth overall being a precious resource, this challenge is very important. All electronic parts to survive must be tested to determine whether they still provide correct results. Material parts such as metals, must be tested for residual weaknesses in strength and durability due to their long time in space, and any completely unusable parts to survive must be disposed of safely.

Challenge 3

HexSat's mission ends by it reentering the Earth's atmosphere with the piece of debris it has caught. The caught debris would no longer be a danger in space, but has now possibly become a danger to life on Earth. Recent research from the National Oceanic and Atmospheric Administration (NOAA) found that 10% of atmospheric aerosol in the stratosphere contained metallic particles from spacecraft, including satellites [12]. The long-term impacts these fragments could cause are unknown, but there is great concern of them causing damage to the Earth's already fragile ozone layer. Should this suspicion be true, HexSat's method of removing space debris from Low Earth Orbit becomes extremely unwise and dangerous, as it would continue to increase the percentage of atmospheric aerosol in the stratosphere with each piece of debris that burns up upon reentry. Studies on the long-term effects of metallic fragments in the stratosphere must be pursued in order to ensure HexSat is using a safe method for the disposal of space debris.

CONCLUSION

After careful examination of the various proposed methods of space debris removal, a clever variant of net-based capture was decided upon as ideal for space debris capture and removal. The design, which is focused on enveloping the debris with individually controllable net anchors, was heavily inspired by the prey capture mechanism of the net casting spider. The

HexSat, so called due to the six wedges which combine to form the hexagonal hull, was designed to be a novel but effective approach to the growing concern of space debris. The capture approach was arrived at after careful evaluation of 17 parameters related to the mission of space debris capture. Several design parameters associated with the design of the HexSat have been numerically optimized for the mission at hand, and CAD models and simulations have been developed for the optimized design.

As technology has improved exponentially over the last few years so has the amount of space debris in Low Earth Orbit. With every new piece created humanity becomes one step closer to causing the Kessler syndrome and putting at risk the future of space exploration and satellites used daily worldwide. A simple scenario for a mission to remove space debris was described and analyzed for immediate and long-term challenges it would face from current space regulations. The majority of immediate challenges come from regulations not having enough details while the long-term challenges revolve around reducing future space debris and removing the existing debris in the best way possible.

Some steps have already been taken to mitigate future debris. For example, on September 29, 2022 the Federal Communications Commission (FCC) of the U.S. put into effect a regulation stating that spacecraft that end their lives in orbits at altitudes of 2,000 kilometers or below will have to deorbit as soon as practicable and no more than five years after the end of their mission [6]. This regulation replaced the previous, whom allowed spacecraft to remain in orbit up to 25 years, and is set to apply to satellites launched in 2024 and beyond.

Innovative designs are another way the mitigation of future space debris has begun. It is not the first material one thinks of when creating objects for space, but wood has many qualities that could make it advantageous for space use: it has the same strength – to – weight ratio as aluminum, can be penetrated by electromagnetic waves, and would not leave metallic particles in the stratosphere as it would completely burn up upon reentry [2]. Mitigating any risk posed by the metallic particles to the ozone layer, as outlined in long-term challenge 3. In 2020, a team of Japanese researchers launched the LignoStella Space Wood Project to test the durability of three different types of wood in space: Erman's birch, Japanese cherry and magnolia bovate. After exposure tests for more than 290 days on the ISS, the wood showed no signs of decomposition, damage, or change in mass. Murata and his team choose to create a prototype wood satellite out of magnolia bovate wood due to its cells being small and uniform in size, making the wood easier to work with and less likely to split or break. Murata and his team are now working with NASA and the Japan Aerospace Exploration Agency (JAXA) to launch the prototype satellite named LignoSat into orbit in the summer of 2024.

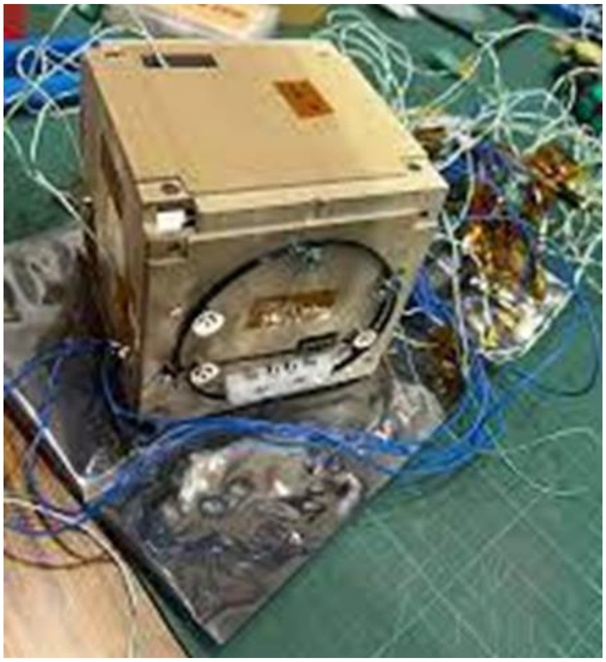


Figure 14: LignoSat Prototype measuring only 10 square centimeters [8].

Though wood's advantages have allowed the LignoSat's design to be simplified, such as the ability to put the antennas on the inside of the body due to its vulnerability to electromagnetic waves, and positive results from the LignoStella Space Wood Project, there is still much unknown about wood's ability to survive in space. As said by Tatsuhito Fujita, an engineer at the Japanese space agency JAXA: "The use of natural resources for space hardware makes sense from a sustainable development goals perspective, but since wood has never been used in satellites, we cannot tell what kind of benefit we can obtain at this moment. [12]"

In conclusion, the task of addressing existing space debris in Low Earth Orbit and preventing future accumulation remains formidable. Ethical and regulatory hurdles must be overcome, necessitating international collaboration. The LignoSat satellite exemplifies such cooperation, marking a crucial step towards mitigating space debris.

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