Detection, Analysis, and Capture of Lethal Non-Trackable Space Debris

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California State University, Northridge (CSUN) has started its second year exploring In-Space Servicing, Assembly, and Manufacturing (ISAM) capabilities through its collaboration with the Aerospace Corporation and participating mentors in the Consortium for Space Mobility and ISAM Capabilities (COSMIC) Capstone Challenge (C3). This challenge was a direct response to the president's call for a national increase in studies and work done towards advancing ISAM capabilities. This cohort was led by Project Advisor Dr Christoph Schaal and mentored by LinQuest Corporation, Corporate Engineer II, Elozor Plotke. CSUN ISAM (2024-2025) sought a conceptual design solution to aid space debris remediation by improving tracking, categorization, and collection of lethal non trackable objects in low-earth orbit.

"Design a payload to be hosted upon a Blue Canyon Technologies Venus Class bus that will autonomously detect lethal non-trackables within a densely populated debris area, robotically capture potential specimens, and non-destructively analyze them for categorization and storage for future use."

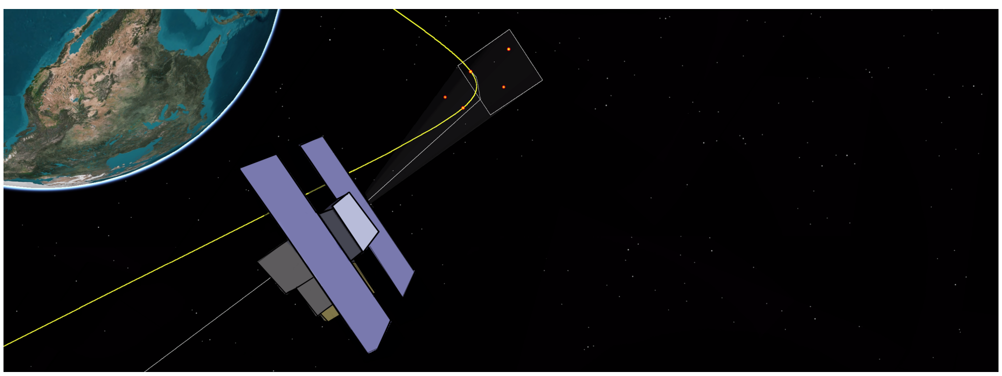


Fig. 1 Lethal non-trackable space debris by size and damage potential.

I. Introduction

The population of the space domain is constantly increasing. From new constellations being launched to the rapid expansion of research and technology looking to take to the stars, Kessler syndrome is looking even more real as the years go by. Once space becomes too crowded, even the slightest disturbance in an orbit may wreak havoc on the entire space domain. The future of space exploration and advancements is dependent on the ability to do such activities safely in one of the most unsafe environments. Many recent developments and emerging projects have begun to take the initiative to tackle the space debris problem. Some target the largest of these debris objects, which are relatively predictable in terms of where they may be located at any given time in their orbit. Removing these larger objects is often seen as the easiest way to reduce the risk of Kessler syndrome. However, a serious risk to space mission safety still exists from the small debris population as well. These fragments fall into the size range where they bypass full protection by standard spacecraft shielding yet still retain enough kinetic energy to potentially cause catastrophic damage upon impact. What makes these debris objects more of a risk is the fact that current ground- and space-based technologies cannot detect such small objects. The next forefront of debris remediation may very well begin with these small debris objects if we wish to continue safe explorations in the future. Because these debris still contain lethal amounts of energy and happen to be too small for current tracking methods, they have become known as lethal non-trackables.

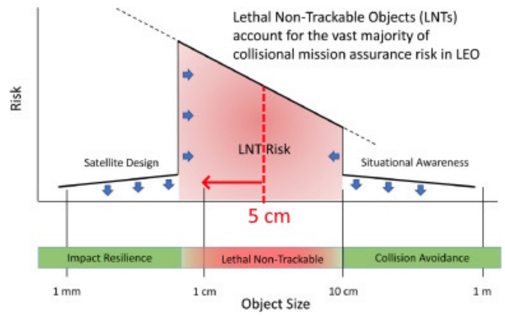


Fig. 2 Lethal non-trackable space debris by size and damage potential.

Lethal non-trackables are a category of space debris designated by their size. NASA describes this size as a characteristic length, which is the average of all three of an object's projected lengths [1] . This is a useful parameter to follow seeing as objects in space tend to be rotating about some axes so their length may be ever changing at one instance in time. The use of this parameter will be for targeting purposes, any object outside the intended size range is ignored while those within range are considered mission-worthy candidates. To determine a precise size range of lethal non-trackables to pursue, current impact resilience and collision avoidance was examined for the orbital population.

Currently, spacecraft are designed for impact resilience with debris less than 1 mm and up to 1 cm in characteristic length. At the same time, collision avoidance systems are operational for detected debris of 10 cm and greater in characteristic length. This provides a middle ground between the safety of impact resilience and collision avoidance for the 1 cm to 10 cm category. This category accounts for the majority of mission risks in low earth orbit. Recent advancements have brought this range down towards the 5 cm mark, thus reducing the project's scope to debris objects of 1 - 5 cm characteristic length [2].

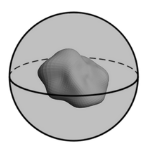


Fig. 3 Potential debris targets must fit within a 5 cm diameter sphere.

This restriction placed on potential debris specimens ensures that only lethal non-trackable in the range of less than 5 cm characteristic length are sought after. Any objects smaller than this threshold are deemed potentially capturable and removal is considered beneficial to the entire space domain. Any object who has a single dimension expanding outside of this sphere would be considered as having a characteristic length larger than 5 cm, thus remain not in the scope of this project.

II. Project Scope

The project has its scope of work laid out in several attainable goals. Firstly, the primary goal of the project is to develop a payload that can autonomously detect, analyze, and capture space debris between one and five centimeters. This primary mission goal is supported by the secondary goals which are to be completed through completion of the primary goal. These secondary goals include gathering detailed data on debris orbits, composition, and geometry, enabling storage of debris for potential recycle or reuse, and the demonstration of scalable, autonomous operations, that may be expanded for future space missions. The three core operations involved in this project; detection, analysis, and capture of the intended space debris, make up the subsystems of the design solution. The detection subsystem will make use of advanced radar and optical sensors to identify and track small space debris. The analysis subsystem will perform in-situ measurements and material analysis using laser induced breakdown spectroscopy and photogrammetry to build a database for material composition and geometric characteristics. Finally, the capture subsystem will engage robotic capturing mechanisms with precise maneuverability to grab the debris and place it into storage. This system is envisioned to operate autonomously for a period of approximately six months in a polar low earth orbit. A polar orbit was chosen to aid in sun exposure time. In addition, the system must conform to the following limitations: a mass of 70 kg or less, a payload volume of 431.80mm x 416.56mm x 685.80mm, and a power usage of 444W. These top-level requirements have been inherited from the C3 information packet with the specific choice of a dual solar array spacecraft.

III. General Requirements

In addition to these top-level requirements, system requirements have also been implemented. These requirements were set based on subsystem operations and what is necessary for each one to be successful. Firstly, collision avoidance has been de-scoped from the design solution. As most spacecraft rely heavily on modularity for their compartments and design, the ability to add this functionality later allows simplification for the focus on purely lethal non-trackables. This decision was ultimately deemed acceptable due to the fact that the greater than 10 cm range is much more widely understood and documented with current tracking capabilities, thus the technology already exists for this functionality to be implemented later down the line. Another supporting factor that gives confidence in being able to ignore collision avoidance for this specific mission is the relative size of the spacecraft and intended maneuvers to be made. Utilizing a parametric analysis derived from Kesslers orbital debris flux model, a comparison can be made between the analysis done for a $2000m_2$ cross-sectional area spacecraft operating a 30 year life span in low earth orbit. This analysis showed that for the debris 10 cm or larger an impact in those 30 years has only a 17 percent chance of happening [3] . Since this analysis was done on a significantly larger spacecraft for a much longer duration, a drastically lower percentage can be expected for the much smaller spacecraft with a cross-sectional area of only approximately $0.3m_2$ and operational lifetime of only 6 months or fewer. This relationship can be summarized in an equation as follows:

$$P_{\text{new}} = P_{\text{old}} \frac{AT}{A_0 T_0} \tag{1}$$

where P_{new} is the new probability of collision, P_{old} of 0.17 is the value for the 17 percent chance of collision for the comparison model, A is the cross-sectional area of the new spacecraft, T is the orbital time in years for the desired mission, while A_0 of $2000m^2$ is the cross-sectional area of the comparison model, and T_0 of 30 years is the orbital lifetime of the comparison model. Applying this equation to the new spacecraft of $0.3m^2$ with a 6 month operational lifetime gives an approximate new probability of collision of $4.25x10^{-7}$. Comparing this collision probability to historically accepted levels, it is assumed that an avoidance maneuver is performed any time the probability exceeds 10^{-4} to 10^{-5}. Considering the new probability of collision for this spacecraft is within the 10^{-7} range, this safety threshold is acceptable to forgo collision avoidance.

A. System Requirements

While in the conceptual stage, it is crucial that requirements are laid out and include all of the key traits needed for a particular mission. Many of these requirements are unknown at first but arise out of necessity for something to happen to meet a given success criteria. The majority of these requirements derive from actions that must be completed in order to perform a desired operation. For instance, the system relies on on-board chemical and electrical thrusters for maneuverability, therefor a requirement was set that the system should optimize its maneuvers in such a way that it remains on the most fuel conserving flight path. This is because while chemical propulsion systems may be finite, the electrical propulsion may be given time to recharge for additional maneuvers. It becomes utmost importance to prioritize timing to allow sufficient fuel for each path throughout the mission.

In addition, the system must be able to operate within the harsh space environment, so a requirement is set for the specific temperature ranges and radiation levels. While these ranges may not specifically be known at first, placeholders may be used until levels of certainty are reached for these values. In this instance, the project applied placeholders of "To Be Decided" (TBD) for both maximum temperature and minimum temperature ranges. This concept can be carried out through any other currently undefined requirement parameters.

Finally, a concluding system level requirement was set such that the system will only target objects designated as being in-track relative to the satellites velocity vector. Being in-track means the orientation of the two velocity vectors for both debris and satellite is within $0° \geq \theta \leq 45°$ [4]. This will limit the system to only look for debris that happens to be orbiting in the same direction depending how close that angle is to zero. This requirement was brought forth because as the angle exceeds 45 degrees between the debris and satellite, the impact forces begin to be significantly higher than those collisions which are considered less head-on. Depending on the missions level of risk the mission is willing to take, a more refined requirement could be set to reduce this threshold down to a more reasonable range such as not exceeding 15 degrees, which in turn would limit the impact energy to a scale factor of less than 10 percent of the total possible kinetic energy. Comparing this to a conjunction with an object of an angle greater than 45 degrees, there is a difference in over 40 percent or more in the energy reduction for these impacts.

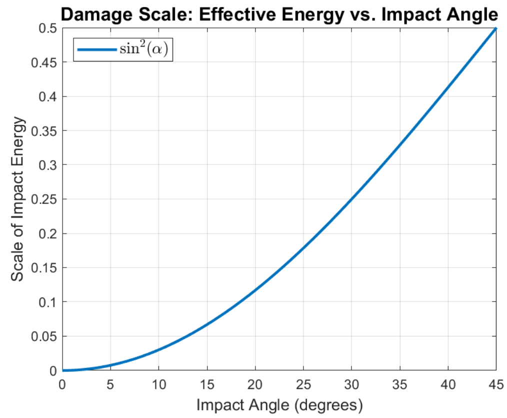


Fig. 4 Increase in impact energy with collision angle.

This figure helps show the nonlinear relationship between the energy that a debris object has with respect to its collision angle between the satellite. The value of sin $^2(\alpha)$ in this instance represents the fractional value of the objects kinetic energy that is directed perpendicularly to the colliding surface. This is the direct amount of energy that will cause damage to the satellite during collision.

B. Mission Requirements

When writing these requirements, some specifics may be wished upon the system but not necessarily required for mission success. These criteria can be included as "should" statements which often back up one or more "shall" statements for a requirement. In this project for example, a requirement for proof of concept was set that a minimum amount of three separate debris must be collected. Since this requirement is not necessarily critical for mission success, it was reworded as a requirement that the system "should" be capable of capturing a hundred debris or more. This larger number was included because a singular capture will demonstrate proof of concept, but the utility comes with the overall increased number of objects removed from orbit.

System level requirements are the defining technical parameters that the system must have in order to meet a missions set of needs, goals, and objectives. These mission level requirements are more goal oriented rather than focusing on technical aspects of the system. Certain mission level requirements are used to help define system level requirements.

For this project, a mission level requirement was set such that the mission should operate in a densely populated debris cloud chosen before launch. Once a debris area as been identified, mission parameters would be set to operate only within a small relative altitude and inclination to the parent objects orbit. The idea behind this was that once the spacecraft has entered its target orbit plane, only minor maneuvers would be made occasionally to prioritize fuel consumption and prolong mission longevity. Such a requirement was supported by currently available data on the most populated debris clouds such as the Fengyun-1C and Iridium debris populations. According to debris flux and density from analysis conducted on these orbital debris populations, a minimum spread of approximately two to five kilometers exists between each consecutive object [5].

Applying this, approaches towards potential nearby debris objects may be similar to approaching members of a constellation where each party remains in a relatively parallel motion with minimal differences in orientation and velocity. Approaching conjunctions this way makes the mission more of a passive approach towards debris remediation instead of a fully active approach. This passive stance was taken as it proves beneficial to overall mission safety and longevity by naturally decaying through the target orbit and only maneuvering slightly towards sequential interceptions.

Continuing this approach, a relative velocity requirement was also implemented. As the velocity of an orbiting object has to do with its semi-major axis, as well as the delivered amount of energy during conjunction, this requirement constrains two important parameters for the mission. By requiring that any potential debris have a relative speed of 5 m/s or less ensures that both the distance from the spacecraft to the debris is within a certain acceptable range, as well that the impact energy will not be greater than an acceptable value. From a study done on the Sentinel-1A spacecraft debris impacts, it was noted that closest distance to relative fragments was as low as 2.5 km while the lowest relative speed of any fragment was recorded at approximately 2 m/s [6].

Because these collisions are not fully understood in the moment, a simplification can be applied to consider them as elastic or inelastic. The majority of space conjunctions will be inelastic thus it is crucial to identify a survivable upper limit. These specifics will be determinant off of spacecraft properties as well as the debris properties but this simplification shows the influence of the speed of impact, time of contact during impact, and the potential damage done. The upper limit can be chosen from here by identifying which speed the energy exchanged does not exceed 40 J/g. This limit of 40 J/g has been identified as the amount of energy required to cause a catastrophic collision [7]. According to calculations summarized below, the maximum relative velocity before reaching a catastrophic exchange in energy during a collision would place the upper limit around 50 m/s. This is a change of approximately 2,000,000 J that is deemed catastrophic for this sized spacecraft.

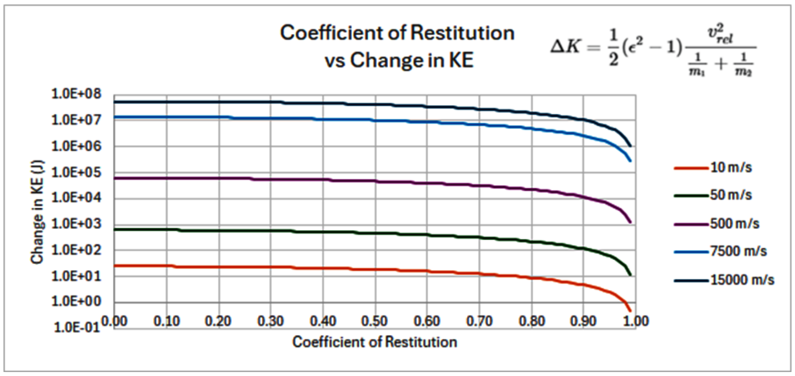


Fig. 5 Exchange in kinetic energy during impact with respect to the coefficient of restitution.

Much like the other requirements, this requirement also will vary with how much risk the operator is willing to accept. Obviously, a collision with an exchange of 2,000,000 J is still very significant and an amount below this may still also be considered mission ending. Therefor, one must define an acceptable level of risk when pursing such a mission. In order to consider these risk levels, they were simplified into low, medium, and high risk categories. By utilizing the *Number of Encounters Assessment Tool* provided by COMSPOC, allows a user to examine conjunction probabilities for a specified orbit. A theoretical orbit is chosen for a target mission in one of the most densely operated debris planes.

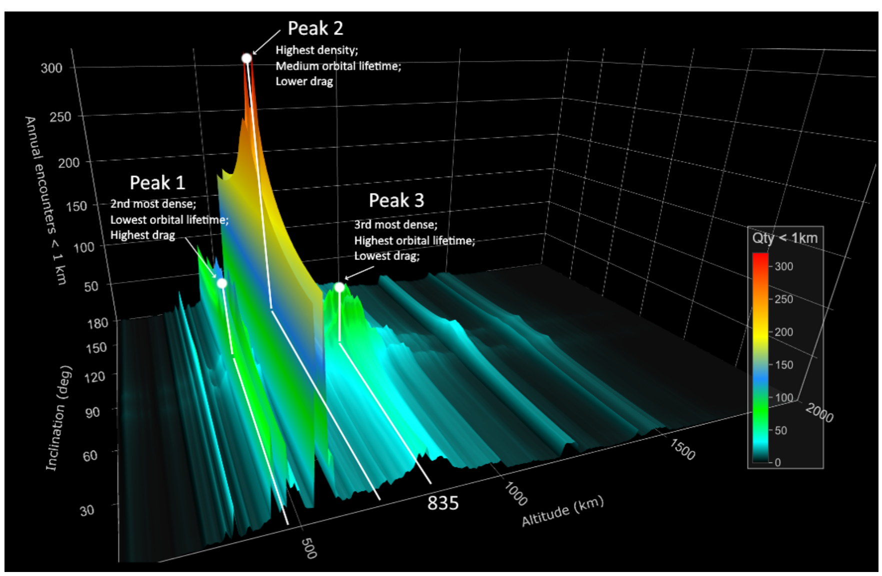


Fig. 6 Top three most dense orbital altitudes with respect to inclination and debris flux.

The first highest peak is avoided simply because mission safety would benefit from avoiding the highest density population before proof of concept. The second highest peak is ignored for the fact that it resides in the lower altitudes that naturally decay sooner and don't remain in orbit as long to cause potential damage. Finally, the third highest peak proves to be most mission worthy for a proof of concept. Also, this orbit in particular resides in the higher altitudes which remain in orbit for much longer periods thus increasing the overall risk.

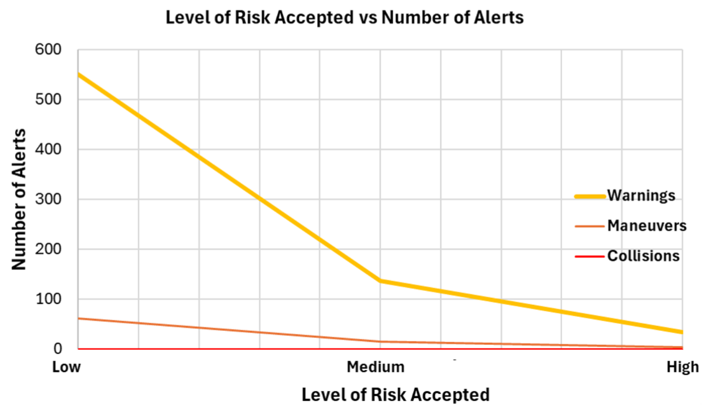


Fig. 7 Number of alerts with respect to level of risk accepted.

For a mission targeting the peak chosen at 835 km and 95 degree inclination, the tool shows results for a user defined level of risk acceptance. Generic levels are summarized below for low, medium, and high level risk acceptance for this mission. Depending on how reactive the system is designed to be, the operator may choose which specific risk level to operate in.

	Low	# of Incidents	Medium	# of Incidents	High	# of Incidents
Warning Threshold (km)	3	**550.505**	1.5	**137.626**	0.75	**34.407**
Maneuver Threshold (km)	1	**61.167**	0.5	**15.292**	0.25	**3.823**
Collision Threshold (km)	0.005	**1.53E-03**	0.005	**1.53E-03**	0.005	**1.53E-03**
	Warnings: 550.505 Maneuvers: 61.167 Collisions: 1.53e-003		Warnings: 137.626 Maneuvers: 15.292 Collisions: 1.53e-003		Warnings: 34.407 Maneuvers: 3.823 Collisions: 1.53e-003	

Fig. 8 Defining parameters for alert thresholds.

Additional requirements for mission and/or system level may be added as necessary for the respective project. Because this design solution is specific to the Venus Class bus which contains all the necessary components required for basic space missions, such as equipment for telemetry, ground communications, data handling, and transportation, requirements around these specific components and what they can accomplish are removed from the scope of this project. This is because these details are not provided as the process is intended for a stepping stone introduction into the world of space systems engineering. For a system with precisely known components and parameters, these additional mission and system level requirements will need to be considered.

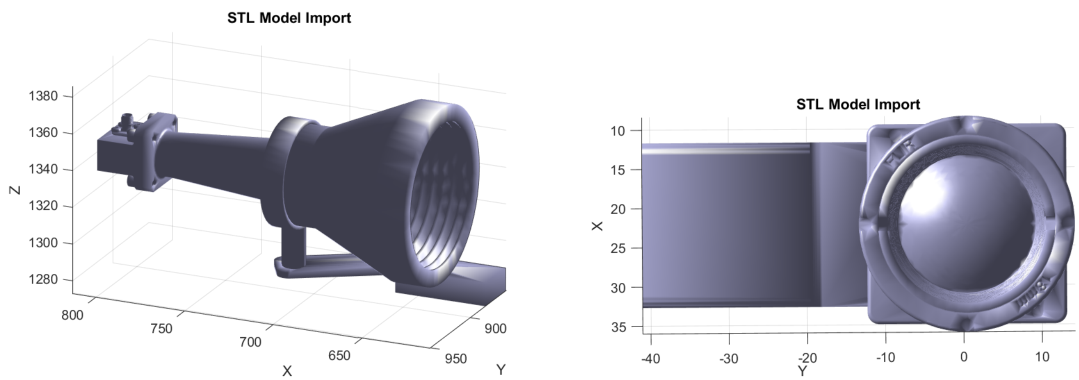
C. Subsystem Requirements

Depending on what tasks are necessary for each operation corresponding to each subsystem, specific requirements are to be set based of those needs, goals, and objectives. These requirements are much more subsystem-specific and have to do with the individual hardware, software, and intended sequence of operations.

The initial subsystem to power on is envisioned to be the detection subsystem as this is the primary influence for the remaining sequence of operations. Afterwards, the analysis subsystem will become operational when a potential target has come within adequate testing range. Finally, the last subsystem to perform its operations would be the capturing subsystem. After relay of information from detection and analysis, the capture subsystem will calculate the inverse kinematics required to successfully capture the designated object. With the final data obtained from all three subsystems, the captured debris is then placed into categorical storage for future use.

These processes are anticipated to repeat as many times as possible within the mission time-frame, until expendable resources become limited, or until satisfied with the amount of debris collected. The benefit of each removed piece of debris both betters the space domain for future exploration and provides utility to reuse and re-purpose in-situ resource utilization from space.

IV. Detection



(a) Ka-band radar horn **(b) Infrared camera**

A. Detection Subsystem & Requirements

The detection subsystem is comprised of a space-based radar and an infrared camera for precise object detection and tracking capabilities. This conceptual design solution combines the long-range effectiveness of millimeter-wavelength radar utilizing Doppler shift to produce relay-able distance and speed information. For the medium to close range detection, a maneuverable infrared camera will be utilized for object identification against the cold space background.

Mission operations depend on the maximum distance of the long range system, followed by subsequent visuals made by the medium and short range solution. An original requirement was set for the detection system such that a minimum detection range of 500 meters relative to the spacecraft is possible. To further define these parameters, definitive resolutions and field of view should be found for each respective method. This way, once parameters are known for the desired mission, an adequate piece of hardware can be chosen for the operation.

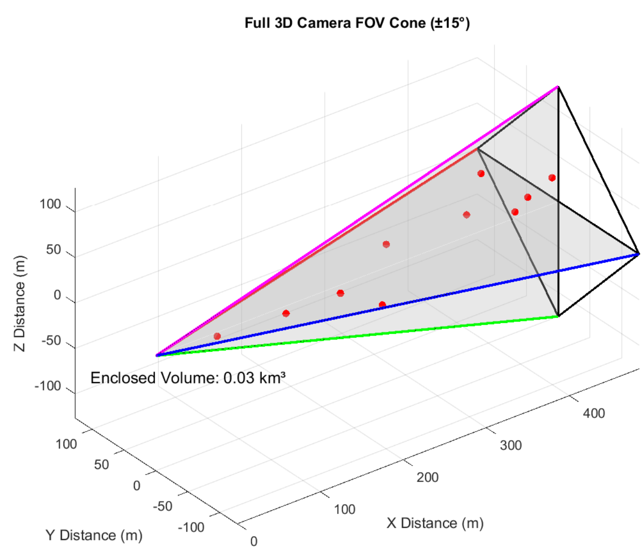
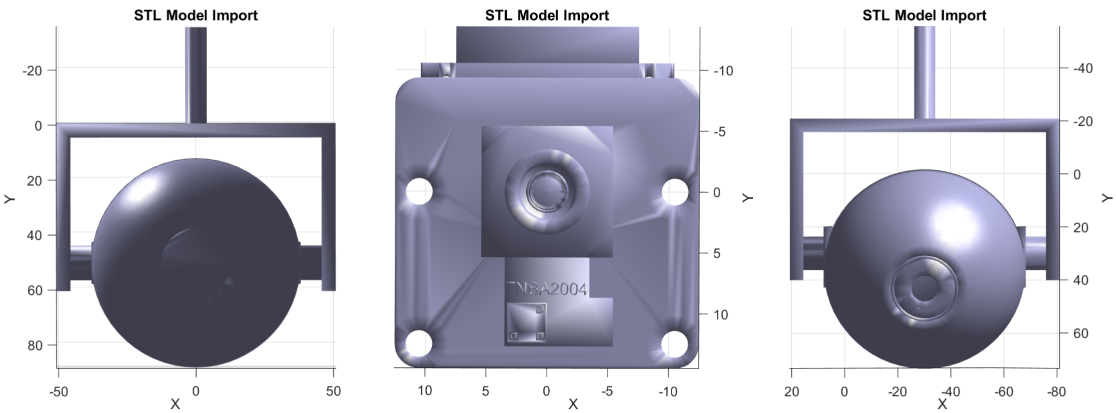


Fig. 10 Best case scenario: Theoretical detection cone

V. Analysis



(a) Pulsed laser **(b) 2x Visual cameras** **(c) Spectrometer**

A. Analysis Subsystem & Requirements

The analysis subsystem is composed of a hybrid setup for compositional analysis and photogrammetry for geometric analysis. A space-based setup is envisioned to sample debris from a close proximity operation utilizing majority non-contact methods. As the sampled object is being observed, the photogrammetry system will gradually snapshot the imagery from different positions of the debris providing a representable three dimensional point cloud of the object.

The method used in the analysis subsystem for determining the material properties is Laser-Induced Breakdown Spectroscopy (LIBS). LIBS can be broken down into different stages of operation. First, a high energy laser pulse is used to ablate the surface of the tested sample which creates a plasma. This emitted plasma is then analyzed using spectral analysis to determine the material composition of the sample that is tested. The application of LIBS within the Analysis subsystem is to be used outside the payload. The LIBS system is paired with an optical tracking system which will track the surrounding debris and pulse a laser beam onto the debris samples. Once pulsed, the onboard spectrometer would be aimed toward the samples that have been hit with a laser pulse and determine the material composition of the sample.

The data that the Analysis subsystem is concerned with are the volumetric & geometric parameters of the debris samples. These parameters are of interest due to the subsystem having a storage. Additionally, these parameters are also of interest due to the capability of cataloging the type of debris samples that are present within the debris clouds. The method utilized to gather this data is Photogrammetry. This is a technique that utilizes multiple images captured from multiple different angles. Sequentially, these images can be used to render out a 3D mesh/model. From this mesh/model, software is used to be able to determine geometric parameters of the debris. The geometric parameters that are collected from the samples would consist of its length, width, and height. These geometric parameters would enable the system to determine the volume which can assist in determining the density and mass of the captured samples. A final requirement that helps ensure successful operation of the analysis subsystem was set such that all technologies should have sufficient resolution, field of view, and targeting capabilities to maintain line of sight with the debris for sampling.

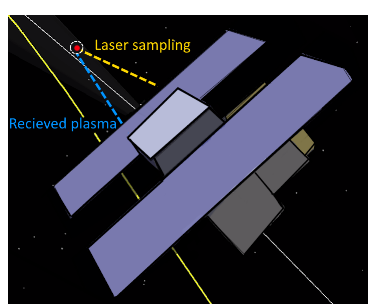
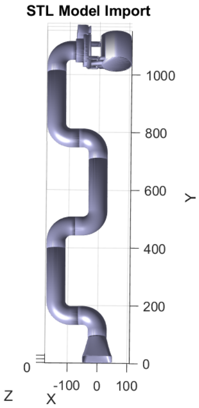
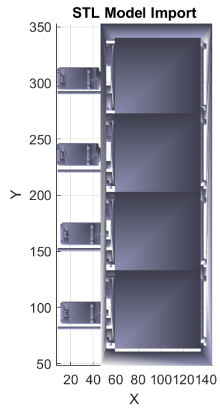


Fig. 12 LIBS sampling process

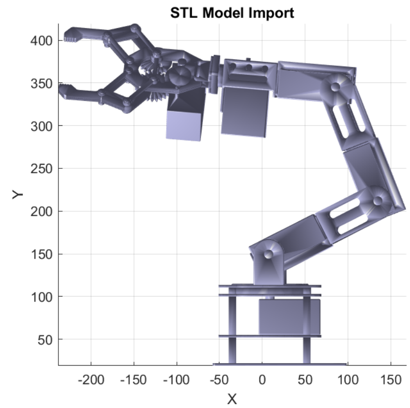
VI. Capture



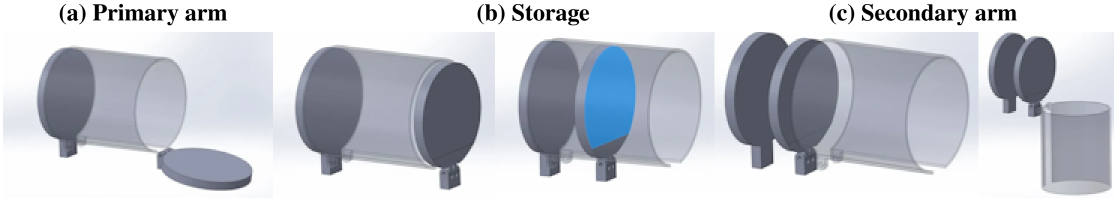
(a) Primary arm



(b) Storage



(c) Secondary arm



(d) Cup capturing mechanism (end effector)

A. Capture subsystem & Requirements

The capture subsystem contains a pair of robotic arms for both primary capture and object storage. The primary arm is a six degree of freedom manipulator with a cup-styled capturing mechanism as the end-effector. This cup-mechanism was designed around the specific size of lethal non-trackables intended on being captured. As long as the requirement that no object with any dimension larger than 5 cm characteristic length is upheld, the capturing mechanism is designed such that two plates will successfully clamp the object together and bring it within the payload for storage. The secondary arm for storage positioning is a much smaller pincher styled grabber which will reach between the two clamped plates to transfer the debris from the mechanism to storage.

For successful mission operation, the capture subsystem requirements are set based off of functional necessity. The capture subsystem must be able to extend to a maximum of one meter from the payload in order to reach potential debris and subsequently store them. In addition, the mechanism is required to accommodate the intended size of lethal non-trackables, which is already implemented into the capture mechanism design. Additional requirements may be set for the components reaction times to ensure the mechanism is quick enough to make such maneuvers.

An extra analysis of the potential specimens to be found and captured in orbit was done to evaluate the material-specific impact properties according to materials density. Objects to be found in orbit that would be worth of recycle or re-purpose are most likely to be metals but glass, fabric, and others are also very possible. A simplified analysis considered low, medium, and high density objects which could represent materials such as fabric, aluminum, and steel, which are some of the most commonly experienced and sought after materials. By re-introducing the idea of the catastrophic collision level of 40 J/g energy transfer, the collisions between these anticipated objects can be better calculated for their respective critical impact velocities. These results are summarized in the table below.

Material density	Low (950 kg/m^3)		Medium (2700 kg/m^3)		High (7850 kg/m^3)	
Diameter (cm)	1	5	1	5	1	5
Mass (g)	0.1134	7.084	2.124	132.742	7.854	490.874
Catastrophic velocity (km/s)	187.9014	23.7337	43.4563	5.4876	22.5489	2.8547

Fig. 14 Catastrophic impact velocity for respective size/density.

B. Additional Benefits Provided

In addition to the benefit of reducing the orbital debris population and improving operational safety for future space missions, there are also a few other benefits from the proposed mission. Currently, ground-based detection systems cannot pick up these small lethal non-trackables, and current space-based systems have yet to target these as well. By staying and observing from its advantage above earths atmosphere, the spacecraft can catalog currently un-tracked objects and provide this data to improve current collections of two-line elements which describe the motion of these objects. One other benefit would be to utilize onboard sensors throughout the mission lifetime to get a better understanding of the effects of drag on a satellite. As the mission progresses, if additional debris are captured, the overall mass of the spacecraft will increase, this increasing mass can be used to study the changing effects of drag on the satellite as its mass is increasing. Overall, both of these contributions would greatly benefit space domain awareness and improve current capabilities.

VII. Conclusion

This conceptual design solution was created by the CSUN ISAM team of 2024-2025 to tackle the problem of space debris remediation. Though this outline represents a conceptual path towards addressing this issue, it is only one of many that may easily be adapted to and changed according to needs. Overall, a passive removal system seems to be the most beneficial, where little to no operator involvement and maneuvering is needed. Requirements laid out in this document only represent some of the main requirements considered during this project, many requirements have values removed for the purpose of this paper and for simplification. The idea is that similar a mission utilizing similar technologies will adapt the hardware and mission needs for their specifications. This concept was created by the culmination of mechanical engineering students as well as computer engineering and computer science. Although a much stronger background is needed before tackling such a daunting tasks, this two semester process helped introduce many new students to the challenging world of ISAM.

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