

SpaceOps-2025, ID # 369

"Design a Spherical-Shaped Space Debris Collector for the Sustainability of Low Earth Orbit

Selvathasan Geerthanana*

^a Former Non-Technical Project Manager, Aeronautical Division, SEDS Sri Lanka. geerthanana96@gmail.com

*Corresponding Author

Abstract

The sustainability of outer space has garnered global attention from technological, legal, and policy perspectives, with a focus on preserving the space environment for future generations. Since the 1970s, space debris has emerged as a growing concern, posing significant risks to both Earth and space operations. The U.S. Department of Defense's Space Surveillance Network tracks more than 27,000 pieces of debris larger than 10 cm, while NASA estimates that 150 million objects exceed 1 cm in size, with 700,000–750,000 pieces measuring between 1 and 10 cm.

This accumulation of manmade debris, particularly in Low Earth Orbit (LEO), consists of fragments from past missions, inactive satellites, and other objects. These fragments, especially those smaller than 1 cm, travel at high velocities and can inflict severe damage on active satellites and spacecraft, endangering future missions and increasing operational vulnerabilities.

To address this growing threat, this paper proposes the design of a SSDC (Spherical-Shaped Space Debris Collector) to mitigate the risks posed by debris in LEO. The innovative device incorporates advanced technical mechanisms tailored specifically to capture debris smaller than 1 cm, which is difficult to track but capable of causing significant harm to operational spacecraft. The spherical shape optimizes maneuverability and collection efficiency, ensuring even the smallest particles are removed from orbit.

This solution represents a vital step toward ensuring the long-term sustainability of outer space, safeguarding future space missions, and minimizing the potential impact of space debris on Earth-based systems and infrastructure.

Keywords: future mission, low earth orbit, space debris, sustainability.

Acronyms/Abbreviations

ESA: European Space Agency
ELSA-d: End-of-Life Services by Astroscale-demonstration
LEO: Low Earth Orbit
NASA: National Aeronautics and Space Administration
SSDC: Spherical-Shaped Space Debris Collector
U.S: United States

1. Introduction

Space debris, which mostly consists of pieces from human-made objects like abandoned satellites, spent rocket stages, and collision fragments, is abundant in the space environment outside of LEO. About half a century ago, space debris was not considered a serious issue because nothing was known about the usefulness of space outside the stratosphere. Since this point, there has been a steady rise in the quantity and mass of spacecraft in orbit for different uses. This expansion caused space debris to become a major problem by the end of the 20th century, which sparked official international discussions. But as space research has progressed, several nations have put in place specific rules and regulations to lessen the production of space debris.

The existence of a sizable number of retired spacecrafts is what defines the space debris issue today which are passively traveling around the planet after their intended function has ended, raising the possibility of both colliding with one another and collapsing with artificial earth satellites that are now in operation. In addition, each spacecraft collision will unavoidably result in more space junk because of the numerous pieces of debris that are created at random during the collision.

José Bezerra Pessoa Filho's [1] research highlights the significant growth in the number of operational satellites in Earth's orbit over the past decade. On January 31, 2011, there were 975 operational satellites, a number that more than tripled by 2021, reaching 3,372 satellites (Table 1). A particularly notable trend is the sharp increase in satellites

operating in Low Earth Orbit (LEO), which surged by 464%. This data underscores the rapid expansion of satellite deployments and the growing challenge of space debris management.

Table 1. Evolution of Satellite Numbers and Space Debris

Date	Total Number of Operational Satellites	Total Number Space Debris in LEO
January 31st, 2011	975	463
December 31st, 2020	3,372	2,612

Several space agencies and companies are focusing on advanced tracking systems to monitor debris and predict collision risks. ClearSpace, a Swiss-based start-up, is leading a robotic mission designed to capture and remove a defunct satellite from orbit. The project was selected by the European Space Agency (ESA) from among 11 competitors to develop a spacecraft equipped with robotic arms for space debris removal. Astroscale's ELSA-d (End-of-Life Services by Astroscale-demonstration) was a pioneering mission that successfully demonstrated magnetic capture technology for space debris removal.

Numerous space debris collection initiatives have been undertaken by space agencies and governmental bodies. However, capturing debris smaller than 1 cm remains a significant challenge, with ongoing conceptual proposals being explored by space organizations. In response to this challenge, this research presents an advanced design for a Spherical-Shaped Space Debris Collector, specifically aimed at capturing debris smaller than 1 cm.

2. Design of SSDC

1.1 Design a Spherical-Shaped Space Debris Collector

The initially proposed design was for a spherical shaped debris receiver consisting of 15 hexagonal components, each integrated with a fixed control turbine tube connected to 12 pentagonal components. The design also includes 150 cameras with built-in sensors, two fuel supply tanks, and three debris collecting bins.

Seven of the pentagonal components, along with all hexagonal components, form the solar panel surface, which generates power for the SSDC while operating in orbit. The remaining five pentagonal components are detachable and are designated for housing the two fuel supply tanks and three debris collecting bins. Additionally, sensors and cameras are installed along the edges of both hexagonal and pentagonal components to detect debris in low Earth orbit (LEO). The functionality of the all components will be discussed in following Section. A view of the spherical debris collector is presented below by the author.

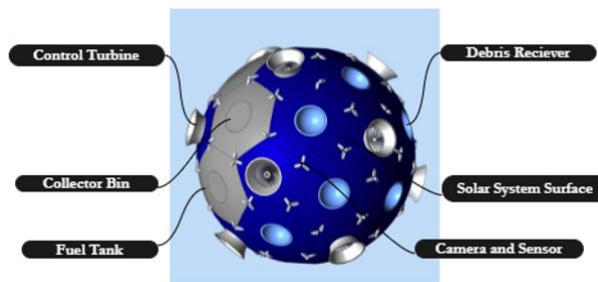


Fig. 1. Spherical-Shaped Space Debris Collector

Detail explanation of y Spherical shape?

1.1.1 Camera with Sensor

The onboard camera and sensor system first detects the debris, analyzing its size, velocity, and material composition. The spherical collector can identify the kind of debris material, its size, and its velocity using this detection method.

The spherical collector's ability to capture trash up to 1 cm × 1 cm × 1 cm is a significant research restriction. Materials that can be successfully captured include bulletproof glass, titanium, Kevlar, and aluminum. Furthermore, 4.5 g/cm³ is the most debris density that the collection can handle.

1.1.2 Control turbine tube

The control turbine tube facilitates the repositioning of the spherical-shaped debris collector, enabling it to capture debris after detection by the camera and sensor components. This mechanism ensures that the spherical-shaped

collector aligns itself with the trajectory of the incoming debris, enhancing its ability to intercept and capture particles effectively. Thrusters control the turbine tube, ensuring that the collector aligns optimally with debris trajectories.

Additionally, the control turbine tube provides an added advantage by minimizing the risk of debris directly impacting and damaging the surface of the spherical-shaped collector. This protective feature helps maintain the structural integrity and functionality of the collector over extended operational periods.

1.1.1 Spherical shaped debris receiver

An aerogel plate is incorporated into the construction of the spherical debris collector. Previous research indicates that aerogels with a bulk density exceeding 0.06 g/cm^3 demonstrate higher capture efficiency for velocities ranging from 5 to 6 km/s. This is consistent with findings from NASA's Stardust mission, which utilized aerogel to capture dust particles traveling at 6.1 km/s. Additionally, an isolation tube will be positioned in front of the aerogel plate to secure the gun chamber. The schematic diagram below illustrates the operational flow of the spherical debris collector during the debris capture process.

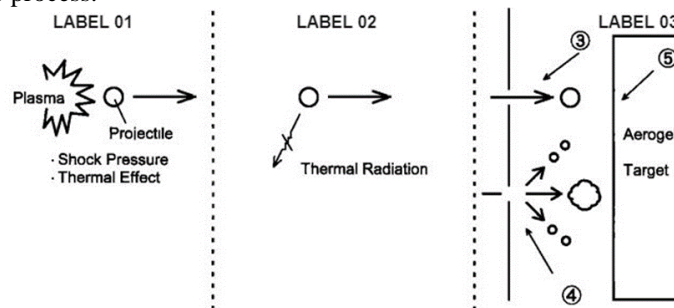


Figure 1: Schematic flow of the spherical-shaped debris collector during the debris capture process

The procedure involving the plasma gun is schematically depicted in Figure 2, which has a substantial impact on the projectiles' physical states (such as melting and fragmentation) prior to their interaction with the aerogel. The projectiles in the gun chamber (LABEL 01) are exposed to plasma, which causes shock pressure and thermal effects.

The isolation tube (LABEL 02) allows the projectiles and any remaining plasma flow from the gun chamber to escape heat by radiation, so facilitating cooling even if the projectiles are subjected to thermal effects from the plasma. The rate at which this cooling process occurs is proportional to the temperature's fourth power.

The debris then hits the aerogel plate after entering LABEL 03. Debris moving at up to 6 km/s can be efficiently captured by the aerogel plate. The greatest energy that the aerogel plate can absorb in these circumstances is $81 \times 10^3 \text{ KJ}$. The pressure meter detection lock will be released once this energy level is surpassed. After that, the spring plate will make contact with the moving aerogel plate. Following process will conclude with an explanation in end of this Subsection.

According to the research study, the view of the bullet impact on the aerogel plate is shown in the following figure.

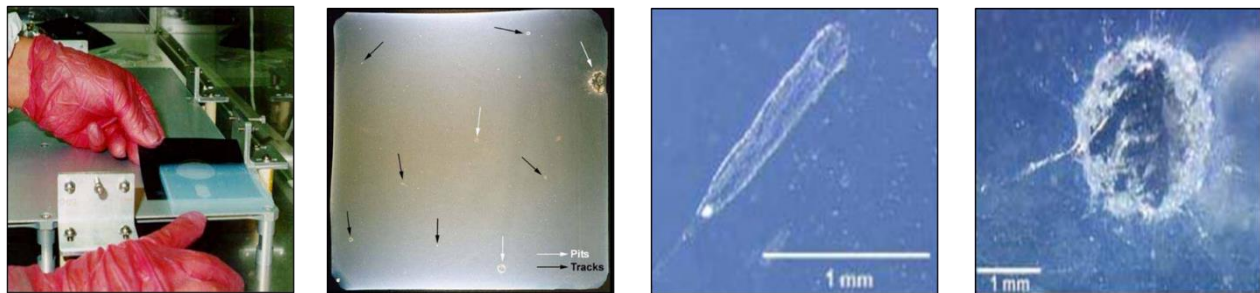


Figure 2: Close-up photography of impact on Aerogel plate.

Photo Credit: Article "Impact Features and Projectile Residues in Aerogel Exposed on Mir" [2]

Step 01: Space Debris Capture and Deceleration System

The Spherical-Shaped Space Debris Collector will orbit the Earth after being launched into Low Earth Orbit (LEO). The onboard camera and sensor system will use this time to detect debris objects and calculate their size and speed. The spherical collector can identify the kind of debris material, measure its size, and determine its speed by using this detecting technique. The Spherical-Shaped Space Debris Collector will make minor positional modifications to collect the debris in the debris receiver after it has been spotted. The rotational alignment will be adjusted with the help of a control turbine tube to make debris capture easier. The debris will enter the system and then be routed into the gun chamber's LABEL 01 projectiles. Due to the plasma exposure of these chambers, shock pressure and thermal impacts are produced.

The debris will enter the system and then be routed into the gun chamber's LABEL 01 projectiles. The shock pressure and heat effects created by the plasma exposure of these chambers lower the velocity of the debris. Furthermore, LABEL 02's thermal radiation processing will further reduce the debris speed. Ultimately, the debris velocity will be lowered to a maximum of 8,000 m/s upon impact with the aerogel plate.

Step 02: Debris Deceleration Mechanism Using Spring and Hydraulic Pressure Systems

After capturing the debris, the spring mechanism and hydraulic pressure mechanism within the hexagonal section of the spherical collector reduce its speed to 0 m/s. The image below presents a sectional view of the spring mechanism and hydraulic pressure system, illustrating the process of decelerating the debris to 0 m/s.

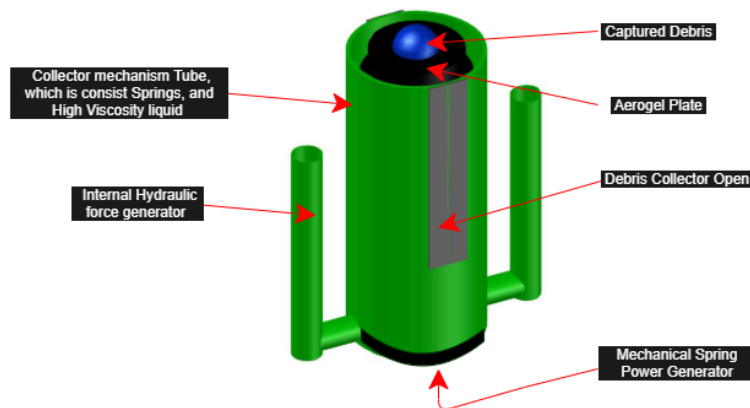
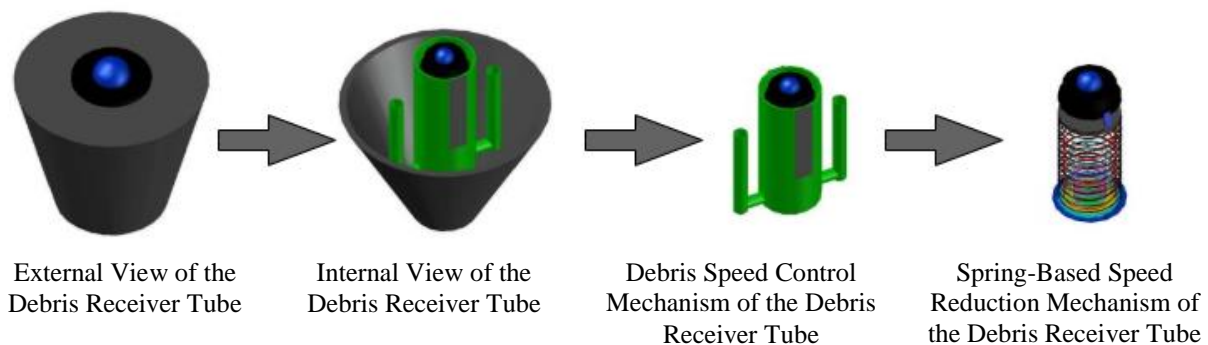


Figure 3 Design of Debris Receiver Tube

Inside the receiver tube, multiple springs are incorporated as part of the Spring-Based Speed Reduction Mechanism. This mechanism is designed to decelerate space debris captured by the aerogel plate, which initially impacts at a velocity of 8 km/s. Upon capturing the debris, the aerogel plate retracts into the receiver tube, where the multiple springs aid in reducing its speed.

The image below illustrates the structure of the Spring Mechanism inside the receiver tube. However, the Spring-Based Speed Reduction Mechanism alone is insufficient to decelerate the debris to 0 km/s within a compact receiver tube. Achieving complete deceleration would require an extended receiver tube, which, in turn, would significantly increase the overall size of the spherical-shaped debris collector.

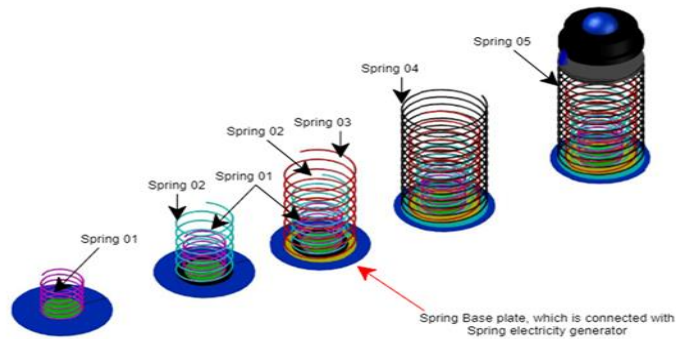


Figure 4 Spring Mechanism inside the Debris Receiver Tube

In addition, a Mechanical Spring Power Generator is installed at the base of the spring plate to generate electricity when the spring plate is compressed. This electrical energy is then converted to power the spring plate breaker. Furthermore, a high-viscosity liquid such as Petroleum Jelly is present inside the receiver tube, which helps to reduce the travel length of the spring, thereby enhancing the deceleration process. The Internal Hydraulic Force Generator is designed to amplify a small applied force into a significantly larger force acting in the opposite direction on the spring plate. This mechanism utilizes hydraulic force transmission to enhance the deceleration process within the receiver tube, further optimizing the efficiency of the Spring-Based Speed Reduction Mechanism. The image below presents a sectional view of the debris receiver tube.

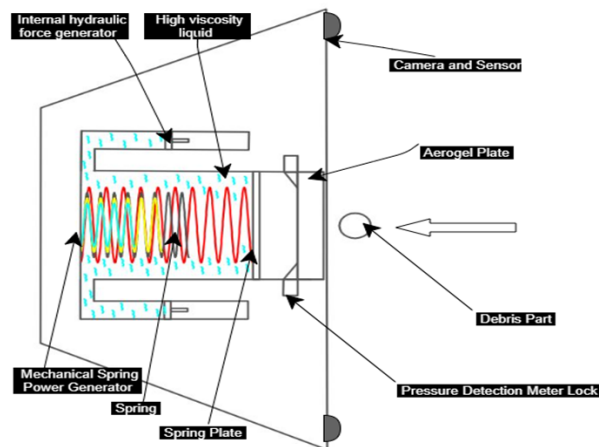


Figure 5 Section View of Spring Mechanism inside the Debris Receiver Tube

In this Spring Plate Mechanism, we have designed a high spring constant spring that is directly connected to both the spring base and the spring plate. The remaining springs are connected only to the spring base and are cut according to the spring diameter, ensuring that the spring length does not exceed three times its diameter. Additionally, the spring tube contains a high-viscosity liquid, which helps to minimize the travel length of the springs.

Furthermore, the spherical collector applies internal pressure through a small tube within this high-viscosity liquid. According to the hydraulic force mechanism, the liquid generates a high counteracting force against the direction of

spring travel, effectively enhancing the deceleration process. This approach allows for a reduction in the overall size of the spherical collector while enabling early debris deceleration.

Simultaneously, to maintain the velocity of the spherical collector, a turbine operates in the opposite direction while debris is captured by the aerogel plate. This ensures stability and control during the debris collection process. Consequently, once the debris reaches zero velocity within the spherical collector, a robotic arm retrieves the aerogel plate and transfers it to the collector bin. The system utilizes three collector bins, ensuring a continuous collection process. When a bin is fully loaded, it is detached from the spherical collector and transported to the main collector. After disposing of the collected aerogel plates, the empty bin is reattached to the spherical collector, allowing the process to resume efficiently.

Once all debris is collected and transferred from the collector bins to the main collector, the main collector returns to the Earth's surface. Upon arrival, the Earth station retrieves the collected debris particles for processing and potential reuse. After completing the recovery and preparation process, the main collector is relaunched into Low Earth Orbit to continue debris collection operations.

3. Theory and calculation

In space orbit, various types of debris are in motion, including titanium, Kevlar, aluminum, and bulletproof glass. Among these materials, titanium has the highest density, measuring 4.5 g/cm³. Due to its relatively high mass, titanium debris possesses greater momentum compared to other materials of similar size.

According to the NASA Standard Breakup Model, most orbital debris in Low Earth Orbit (LEO) travels at velocities ranging between 7 to 8 km/s. Given this high velocity, debris in LEO carries significant kinetic energy, which increases the potential impact force upon collision. The kinetic energy (KE) of an object is given by the equation:

$$KE = \frac{mv^2}{2} \quad (1)$$

Where:

- m is the mass of the debris, and
- v is its velocity.

Since velocity is squared in this equation, even small fragments of debris moving at these speeds can exert substantial energy, making them a critical concern for spacecraft and space infrastructure.

Table 1. Calculation of Titanium's Energy

Description	Value	Unit
Mass of Titanium		
Titanium Density	4.5	g/cm ³
Titanium Volume	1	cm ³
Titanium Mass (m)	4.5	g
	m = 0.0045	kg
Velocity of Titanium		
Velocity (v)	8,000	ms ⁻¹
	v = 28,800	kmh ⁻¹
Calculation of Titanium's Energy		
Kinetic Energy (1/2mv ²)	1/2 × 4.5 × 10 ⁻³ × (28,800) ²	J
	1,866,240	J
KE =	1.86624	MJ

According to that aerogel plates have been studied for capturing space debris, particularly small, low-mass particles, due to their porous structure that gradually slows down high-speed objects. However, capturing high-density titanium debris traveling at 8 km/s presents significant challenges. While aerogel has successfully captured comet dust at lower speeds, the kinetic energy of a 1 cm³ titanium fragment (1.866 MJ) is extremely high, making full absorption difficult. Most aerogels are effective for velocities below 7 km/s, and beyond this threshold, titanium debris may penetrate,

shatter, or even melt upon impact. A reinforced aerogel plate with additional impact-absorbing layers might partially capture smaller fragments, but for such high-speed, high-mass debris, a multi-layer Whipple shield—combining aerogel with metallic layers—would be a more effective approach, as used by NASA and ESA for satellite protection.

5. Discussion

The Spherical-Shaped Space Debris Collector (SSDC) presents an innovative approach to mitigating space debris in Low Earth Orbit (LEO). By integrating aerogel impact absorption, a control turbine tube for orientation, and a spring-based debris deceleration system, SSDC enhances the feasibility of passive debris capture while reducing secondary fragmentation. However, certain technical and operational challenges must be addressed before large-scale implementation.

One key challenge is the effectiveness of aerogel in capturing high-velocity debris. While aerogels have been successfully utilized in NASA's Stardust mission, further research is needed to optimize their thickness, density, and structural integrity under repeated impacts. Additionally, the spring and hydraulic deceleration system requires advanced simulations to validate its ability to mitigate kinetic energy dissipation effectively.

Another critical aspect is the SSDC's maneuverability and reusability. The control turbine tube allows orientation adjustments, but precise attitude control mechanisms such as reaction wheels or cold gas thrusters may be required for better stabilization. Furthermore, debris collection and disposal strategies must be refined—whether through controlled re-entry, repurposing debris for in-orbit manufacturing, or integration with existing active debris removal (ADR) initiatives like ESA's ClearSpace-1.

To enhance the feasibility of the SSDC, several key improvements are recommended. Material testing should be conducted to evaluate the durability and impact resistance of aerogels under simulated LEO conditions, ensuring their long-term effectiveness in capturing high-velocity debris. Additionally, the kinetic energy absorption system must be optimized for debris traveling at speeds of 7-8 km/s, refining the spring-based mechanism to mitigate excessive force upon impact. The integration of autonomous navigation systems is also crucial, utilizing AI-driven debris tracking to improve interception accuracy and minimize maneuvering errors. Furthermore, collaboration with existing space debris removal programs—including ESA, NASA, and private entities—will facilitate knowledge-sharing and the practical implementation of SSDC within broader orbital debris mitigation strategies. By addressing these challenges, the SSDC can play a pivotal role in ensuring the long-term sustainability of space operations.

Acknowledgements

The author extends sincere gratitude to the organizers of SPACE OPS 2025 for the invaluable opportunity to present this research. Special appreciation is given to the entire Team SPACE CADET—Senthan Thiruselvanathan, Glen Dharshan, Cowsikan Thanabalasingam, Amirthavarshan Kiritharan, and Sujanthan Yogalingam—for their dedication to the concept study, which ultimately led to the selection of this mission for implementation.

Heartfelt thanks are also due to SEDS Sri Lanka and the NASA Space Apps Challenge Colombo Committee for their continuous support and encouragement throughout this endeavor. The author further acknowledges the contributions of industry experts and peers, whose valuable insights and feedback significantly enhanced the refinement of this work.

Finally, deep gratitude is extended to family, friends, and colleagues for their unwavering support and motivation, which played a crucial role in the pursuit of this research.

References

- [1] Pessoa Filho, J. B. (2021). Space Age: Past, Present and Possible Futures. *Journal of Aerospace Technology and Management*, 13.
- [2] HORZ, F. (2000). Impact Features and Projectile Residues in Aerogel Exposed on Mir. *Icarus*, 147(2), 559–579. doi:10.1006/icar.2000.6450