International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

ANANTA: A Novel Autonomous Debris Removal System

Sujal Shah[a], Sahil Bag[b]

[a]First affiliation, Jamungachi, Biratnagar 56613, Nepal
[b]Second affiliation, 64/1 Thather wara, mear kotwali, Meerut, Uttar Pradesh 250002, India

A B S T R A C T :

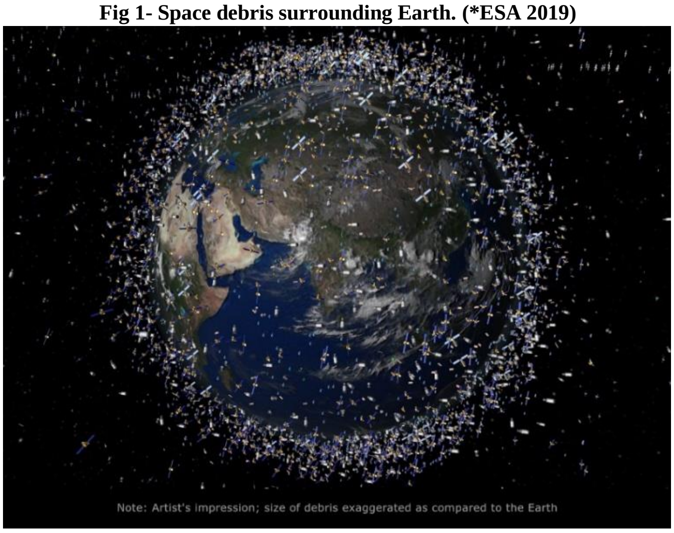
The escalating risks posed by orbital debris to spacecraft and satellites demand urgent advancements in mission safety and operational efficiency. This study critically evaluates current debris removal strategies, dissecting their mechanisms, efficacy, and inherent limitations. Building on these insights, we introduce an innovative solution—an autonomous debris mitigation system that merges state-of-the-art automation with a versatile structural framework. Central to this design is the optimization of key operational parameters, enabling seamless coordination between debris capture and disposal phases. By integrating the strengths of existing methods while addressing their shortcomings—such as fuel dependency and scalability challenges—the proposed system establishes a dynamic, adaptive approach to debris clearance. Preliminary analyses suggest this solution not only enhances precision in debris removal but also significantly boosts the likelihood of long-term mission sustainability, offering a scalable pathway to safeguard critical orbital infrastructure.

Keywords: space debris removal; autonomous; novel device

1. Introduction

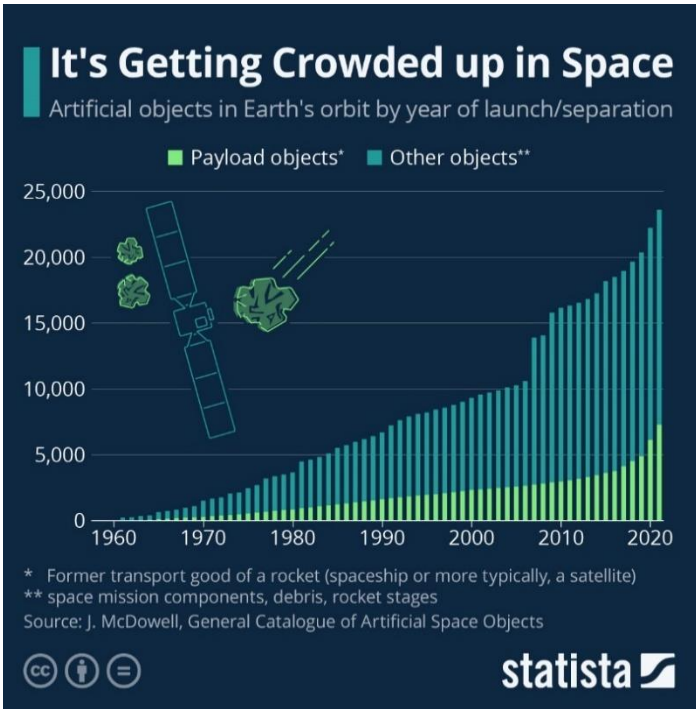
Earth's orbital zones are increasingly cluttered with discarded human-made objects, collectively termed *space debris* or *orbital junk*. These remnants range from defunct satellites and spent rocket stages to minuscule fragments like paint chips—each posing risks to active spacecraft. Most debris accumulates in low Earth orbit (LEO), a region extending up to 2,000 km (1,200 miles) above the planet's surface, though geostationary orbits at 35,786 km (22,236 miles) also host scattered remnants. According to 2021 data from the U.S. Space Surveillance Network, over 15,000 debris fragments larger than 10 cm (4 inches) are actively tracked. Smaller objects—200,000 between 1–10 cm and millions under 1 cm3—lurk undetected, amplifying collision hazards.

Fig 1- Space debris surrounding Earth. (*ESA 2019)



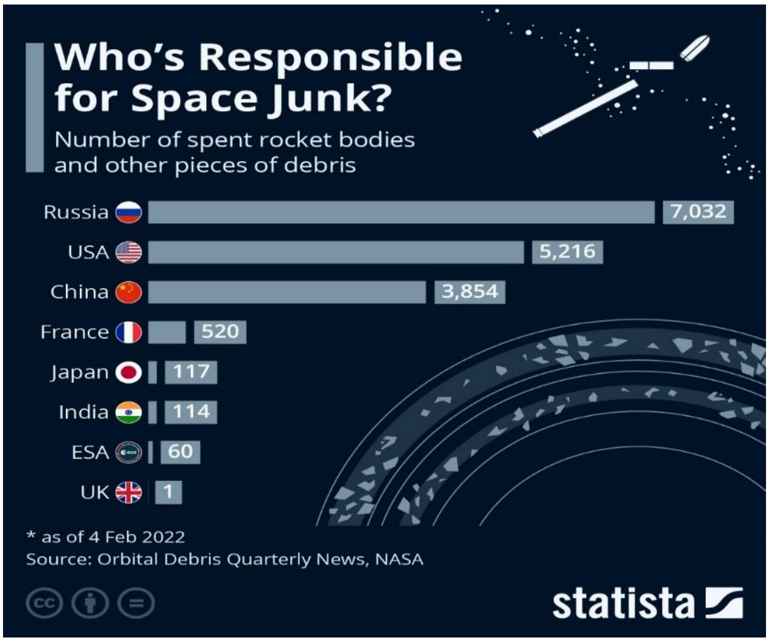
The congestion in near-Earth space is escalating rapidly. With entities like NASA, ISRO, SpaceX, and Blue Origin planning over 100 lunar missions in the next decade, orbital traffic now surpasses the sparse expanse between Earth and the Moon. While the Moon lies 384,400 km (240,000 miles) away, LEO—a mere 160–800 km (100–500 miles) above Earth—already hosts approximately 7,700 operational satellites. Projections suggest this number could skyrocket to hundreds of thousands by 2027, further straining an environment already saturated with hazardous debris.

Fig 2- Graph showcasing growing numbers of non-payload objects in space. (*Statista 2021)



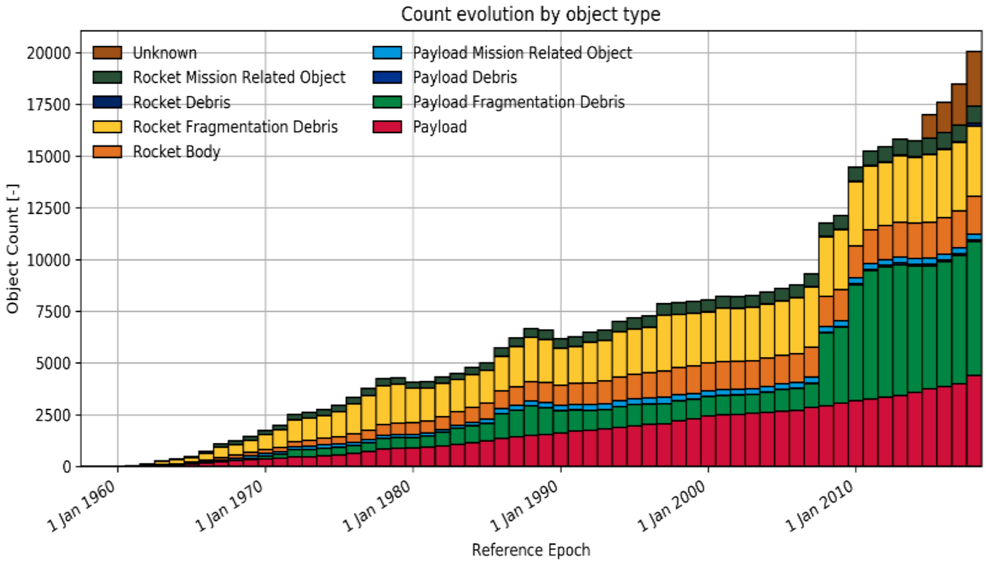
The biggest contributors of space debris as of Feb 2022 are Russia (7032), USA (5216), China (3854), France (520), Japan (117), India (114), ESA (60), UK (1). (Refer to Fig3).

Fig 3- Countries' contribution to space junk. (*Statista 2021)



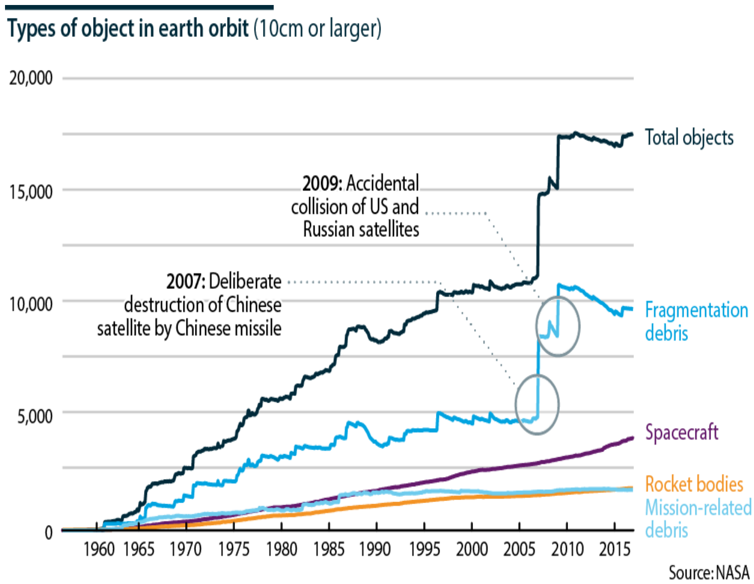
The amount of space debris created by Rocket fragmentation and payload fragmentation has been increasing year by year (refer to fig -4) according to ESA. After 2010, Main Polluters of space are the Payload fragmentation debris, so a new type of passive system has to be developed that reduces to the debris we put into the space in the future but for debris already scattered in space we need to develop a active debris removal system that takes the debris and bring it back for recycling or disposal.

Fig 4- Debris Count evolution by object type (* ESA)



The deliberate destruction or any accidental collision causes a great spike in the number of trackable space debris. In 2007 when China deliberately destroyed its satellite it caused the number of space debris to jump from around 4900 to more than 7000 (Graph at Fig5) Similarly In 2009, when US and Russian Satellites accidentally collided it also caused a spike in number of debris and caused the number to cross over 10000. (Graph at Fig5). These numbers are just the debris we could track but there are a lot more of untraceable and smaller debris.

Fig-5 Types of objects in earth orbit (*NASA)



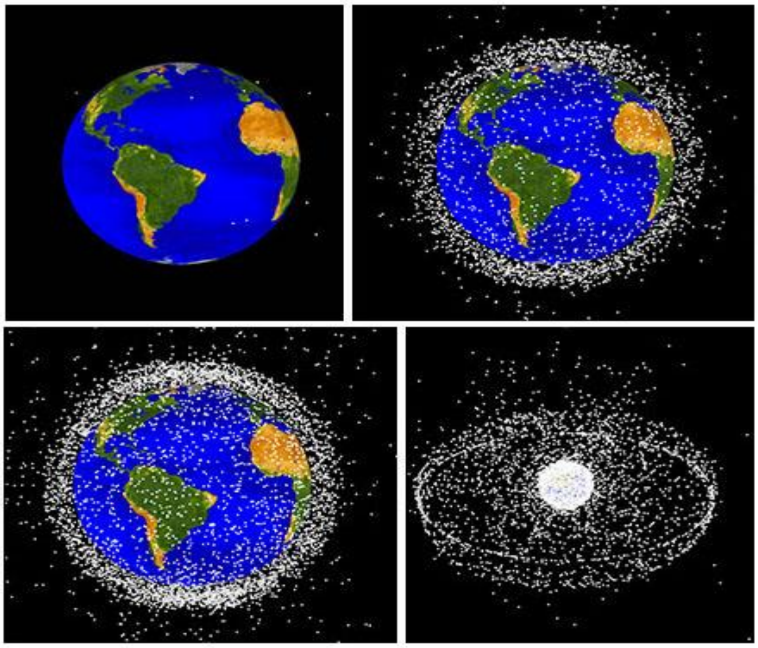
on January 4th the Russian satellite Kosmos 2499 met with a breakup in orbit which nearly caused 85 pieces of trackable debris. These debris fragments are currently orbiting at an altitude of 726 miles (1,169 kilometers) and are expected to remain in space for over a century before atmospheric drag gradually causes them to descend back to Earth. The de-orbitation of this debris could take up to a century by natural processes. That's why Man-made or artificial solutions are required to fasten this process or find a different solution altogether.

Russia also shot its satellite on Nov 15, 2021, to test its new direct-ascent hit-to-kill (ASAT) which led to the creation of more than 1500 new debris found.

2.Hazards and effects of space debris

The hazards of space debris include collisions with operational satellites, spacecraft, and the International Space Station (ISS), potentially resulting in catastrophic damage. The Kessler syndrome, proposed by Donald J. Kessler in 1978, describes a scenario where the density of debris becomes so high that collisions between fragments generate more debris in a chain reaction, making certain orbital regions unusable for future missions. When the smallest of the objects move at incredibly high speeds of approximately 7km/s the impact is known to be as much as a hand grenade. So, any impact from a small object like screws or paint chips can cause enormous damage and also form many new debris. Kessler Syndrome states that there is a possibility of humans being trapped on Earth as escaping the atmosphere without any collisions wouldn't be possible due to debris surrounding the low orbit. This is also known as "Earth Prison". Kessler syndrome is a theoretical scenario till now but as natural deorbitation could take up to several decades or centuries it could be a reality in the upcoming future.

Fig-6 The Kessler Syndrome



Walter Flury (Researcher at ESA) has invested several years in advocating profoundly for the establishment of an international code of conduct, along with globally accepted standards and regulations to develop a comprehensive framework aimed at enforcing mitigation compliance, reducing the creation of new debris and enhancing spaceflight safety. Following Flury's seminal work on the "probability of collision and spacecraft disposition in the geostationary orbit," significant efforts have been made to address the issue of space debris. Comprehensive reviews of these efforts can be found in references [1]-[10]. A key objective of this research is to determine the most effective methods for calculating long-term space debris trajectories with specified accuracy requirements and strategies to prevent space debris from colliding with spacecraft.

3.Existing Solutions or designs

Many designs and ideas have already been proposed in an attempt to solve the problem of space debris but all of them have some restrictions or fatal flaws. The removal of space debris is classified into two categories Active removal and Passive removal.

3.1. Active Debris Removal –

In active removal, a spacecraft approaches orbital debris, and then the removal spacecraft captures it to descend together or attach a device that descends orbital debris alone.

3.2. Passive Debris Removal –

PDR works by penetrating debris and reducing its kinetic energy and forcing them into the atmosphere by reducing the orbital radius of the radius.

3.3. Some of the existing technologies working in the DRS are –

3.3.1. Space Claw Spacecraft –

The space claw spacecraft is a concept that has been developed to remove space debris from Earth's orbit. The European Space Agency (ESA) has finalized a contract to begin removing space debris in 2026. ClearSpace was awarded a $105 million contract to use its space claw to extract space junk. The ClearSpace-1 mission will remove a washing machine-sized (250-pound) piece of junk—a payload adapter—with a four-armed claw spacecraft. After plucking it from space, the claw will force it downward until it is incinerated.

Advantages -

- Always will come down with a piece of debris that can be recycled.

- It is a more precise method for removing specific pieces of debris, as it can target and grasp individual objects.
- It is a more scalable solution, as multiple space claw spacecraft can be deployed to remove debris in different orbits.

Disadvantages -

- It requires a lot of fuel as it requires matching the speed of the debris and maintaining it.
- There are several size constraints.
- The maintenance cost of the claws after every trip would be very high.
- The space claw spacecraft may not be able to remove debris that is in a rapidly decaying orbit or that is tumbling uncontrollably.

Fig 7 - Illustration of Space Claw Spacecraft capturing debris. (*ClearSpace)

3.3.2. Net and harpoon - The net and harpoon methods are two of the several technologies that have been proposed for the capture and removal of space debris. The RemoveDEBRIS mission, led by the Surrey Space Centre, successfully tested both the net and harpoon methods for capturing large space debris. For the future of space debris removal some potential candidates are flexible connection capturing methods, such as the harpoon system, tether–gripper system, and the net system.

Advantages -

- They are relatively simple and cost-effective technologies.
- No fuel is required for the nets and harpoons.
- They can be used to capture debris that is spinning or tumbling.
- No need for matching the speed of the debris.

Disadvantages -

- Debris should be within the range of the net.
- Not effective against small pieces of debris.
- Additional pieces of debris can be created if the target misses or if debris breaks during the capture.
- Not effective against debris in rapidly decaying orbits.

Fig 8 - Net and Harpoon contraption

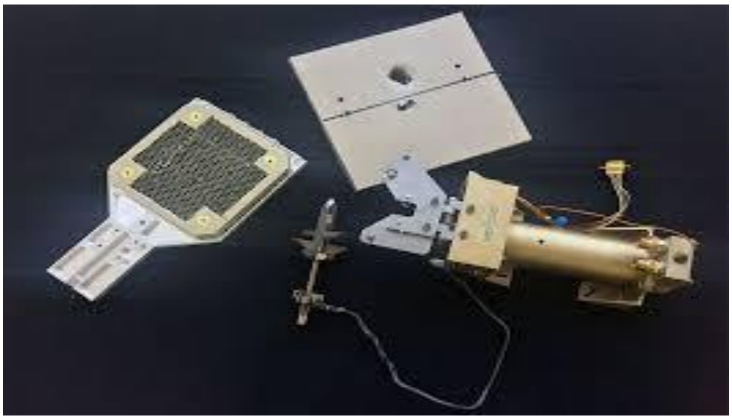
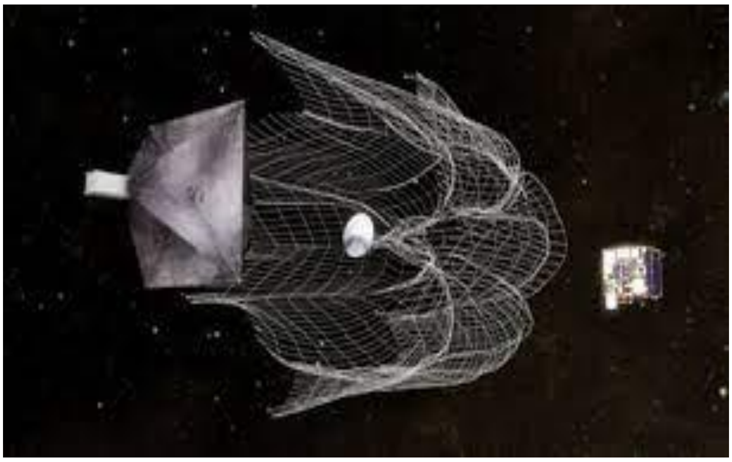


Fig 9 - Illustration of net and harpoon method. (*ISISPACE)



3.3.1. Lasers - Emerging laser-based technologies are being explored to address the growing threat of orbital clutter. One approach involves deploying spaceborne lasers that emit steady, targeted beams to either neutralize small debris or alter its trajectory. By focusing energy on these fragments, their structural integrity can be compromised, causing them to disintegrate harmlessly or redirect away from critical pathways. A related method uses short, intense laser pulses to generate localized bursts of ionized gas (plasma) on debris surfaces, inducing momentum shifts that push objects into safer orbits or hasten atmospheric reentry.

Meanwhile, ground-based systems dubbed laser brooms offer a complementary strategy. These devices aim high-powered beams at debris, asymmetrically heating its surface. The resulting thermal expansion nudges the object into a lower orbit, accelerating its descent into Earth's atmosphere where it burns up. This method could protect vital infrastructure like the International Space Station by clearing collision-prone zones. While promising, challenges such as energy demands, international regulations on space-based weapons, and precision targeting remain hurdles to large-scale implementation.

Advantages -

- Lasers can be used to accurately measure the distance to debris, even in full daylight. This precision allows for better tracking and prediction of debris orbits, which is crucial for avoiding collisions.
- Lasers provide a non-contact method of debris removal, reducing the risk of collision during the removal process.
- The use of adaptive optics in laser technology removes the haziness caused by turbulence in the atmosphere, allowing for clearer images of space debris. This makes it easier to identify and track small objects like space junk.
- This method is very cost-effective compared to sending spacecraft into orbit.
- The idea of lasers is very scalable and can be implemented quickly in many places.

Disadvantages -

- The power consumption would be very high hence very challenging for ground-based systems.
- Weaponizing space - Lasers of this power can be considered as weaponizing space which is not allowed by international law.
- May not be effective against larger debris.

Fig 10 - Space laser(*www.esa.int)

4) Design Proposal and solution Methodology

To remove and eradicate the problem of space debris/junk we need to build and propose ideas which satisfy these 3 points:

1. Prevent - This basically refers to how to prevent the problem before it becomes bigger. For example, we can attach some attaching plates to spacecrafts which we are going to launch in the future, or we can develop technologies which take the spacecraft back to earth for recycling purposes before its dead or in its last bit of fuel.

2. Capture - The spacecraft which were previously launched without any type of prevention must be captured and safely brought back to earth before Kessler's Syndrome. The spacecraft can drop back into the atmosphere of the earth by the natural gravitational pull, but it takes a very long time, and the landing is very uncertain. So, we can fast forward the natural method by some manmade or artificial methods.

3. Remove - After capturing the debris we can eject it back into the earth's atmosphere after treating it and researching it. We can use several methods to eject the debris as most of it is going to burn down during it descends.

Our proposal for the removal consists of using the latest technology to provide a feasible and cost-effective solution to the problem of space debris. We can use a spacecraft which has the capability of landing back on earth, Ion Thrusters, Dome shape capturer and a compressor inside the ship. This Spacecraft will be inspired by Starship which is the largest rocket till date to take off and it weighs over 150 tons. It uses superheavy to take off and escape the earth's orbit. Starship was originally designed to deliver building materials and colonize mars but can be repurposed to tackle space debris. Starship has the capacity of over 100 crewmates and 100- 150t fully reusable space and up to 250-300t expandable payload capacity. This capacity can be repurposed to fit in the compressor and the dome systems. Our concept model will weigh around 200 tons. As we are planning to use an ion thruster the fuel consumption of the spacecraft will also be reduced as the fuel will only be used to liftoff and touchdown due to the use of ion thrusters. The ion thrusters use xenon as it is easily ionized and has a high atomic mass, thus generating a desirable level of thrust when ions are accelerated. It also is inert and has a high storage density; therefore, it is well suited for storing on spacecraft. This only creates acceleration of about 4.3km/s which is lesser than the escape velocity but can used to stay in the orbit as it provides slower but longer acceleration compared to chemical engines. The increased area inside the spacecraft can be used to put a dome which would be made of aluminium and titanium alloys as Aluminium is light but also very sturdy. Titanium alloys are a choice to provide the required strength to the structure of the spacecraft. The dome is equipped with special thermal protection tiles, which helps it survive the heat of re-entry. The dome would be designed in such a way that it contracts inside the ship and opens outside the ship. It will also have special magnetic nets attached to its end to capture smaller metallic debris. During the launch, the dome will stay inside the spacecraft and its mouth will be closed (Refer to Fig 11) but when it reaches the orbit, we can signal from earth for the dome to be opened. The mouth of the spacecraft will let out an umbrella like structure (Refer to Fig 12) which will retract and take the shape of a dome, and the magnetic nets will also be attached to the dome's edges capturing the smaller debris like screws and metallic paints.

The remaining area inside the spacecraft can be used to install a compressor which crushes the already decaying satellite and turn its size significantly smaller and attach multiple satellites together and eject them safely towards the atmosphere with a gps installed on it.

The **new modified spacecraft will be called ANANTA- A Novel Autonomous Debris Removal System 1.**

Fig 11 – ANANTA -1 Closed Dome

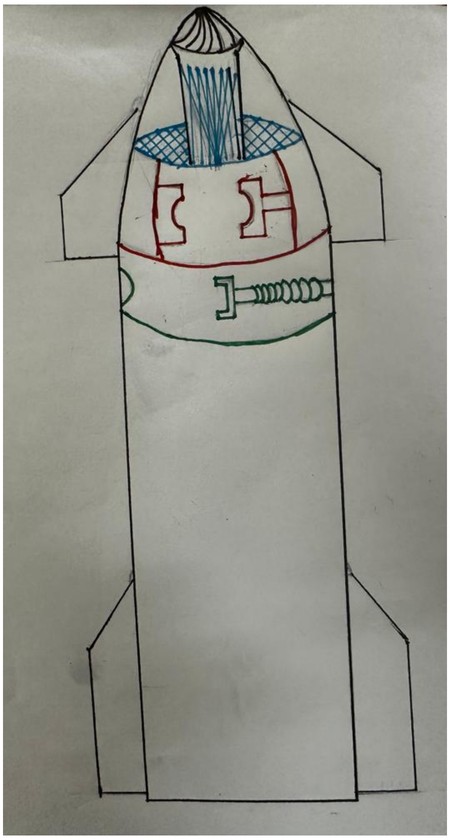


Fig 12- ANANTA-1 Open Dome

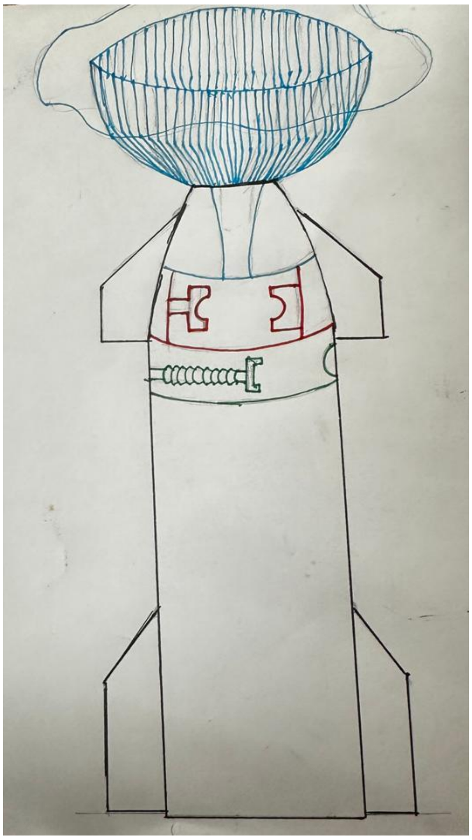
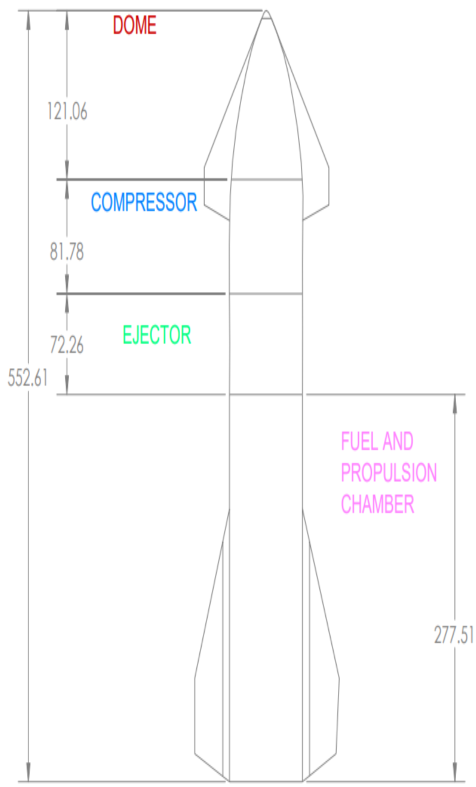


Fig 13 – ANANTA-1 Dimension in meter



REFERENCES

1. Flury, W., “Collision probability and spacecraft disposition in the geostationary orbit”, Advances in Space Research, vol. 11, pp. 67–79, Jan. 1991.
2. Ellis, S. R., “Collision in space”, Ergonomics in design: the magazine of human factors applications, vol. 8, no. 1, pp. 4–9, 2000.
3. Patera, R. P., “General Method for Calculating Satellite Collision Probability”, Journal of Guidance, Control and Dynamics, vol. 24, July 2001.
4. Patera, R. P., “Satellite collision probability for nonlinear relative motion,” Journal of Guidance, Control, and Dynamics, vol. 26, no. 5, pp. 728–733, 2003.
5. Rossi, A., “The earth orbiting space debris” Serbian Astronomical Journal, no. 170, pp. 1–12, 2005.
6. Croomes, S., “Overview of the DART Mishap Investigation Results,” tech. rep., NASA, 2006.
7. Hanada, T., Liou, J. C., “Comparison of fragments created by low- and hyper-velocity impacts”, Advances in Space Research, vol. 41, pp. 1132–1137, Jan. 2008.
8. Kessler, D. J., Johnson, N. L., Liou, J. C., Mathney, M., “The Kessler syndrome: implications to future space operations”, Advances in the Astronautical Sciences, vol.137, pp. 47+, Feb. 2010.
9. Phipps, C., "Removing Orbital Debris with Lasers". Advances in Space Research. 49: 1283–1300. arXiv:1110.3835, 2011.
10. Ghrist, R. W., Plakalovic, D., “Impact of Non-Gaussian Error Volumes on Conjunction Assessment Risk Analysis” in AIAA/AAS Astrodynamics Specialists Conference, (Minneapolis), 2012.
11. http://www.nasa.gov/missionpages/station/news/orbital debris.html (cited on Nov.5,2015)
12. Chawla, S., Malhotra, V., “Autonomous Active Space Debris-Removal System” IEEE Xplore 2019
13. ZHAO P., L. J., W.C, “Survey on research and development of on-orbit active debris removal methods” Vol.63 No.11: 2188–2210, November 2020