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Study of Current Situation about Space Debris and Mitigation Strategies.

* Project SDMS: Study of Current Situation about Space Debris and Space Debris Mitigation Strategies

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***Abstract* — What goes up doesn't always come down, Like Space Debris. Space junk, or space debris, is any piece of machinery or debris left by humans in space. It can refer to big objects such as dead satellites that have failed or been left in orbit at the end of their mission. It can also refer to smaller things, like bits of debris or paint flecks that have fallen off a rocket. The proliferation of space debris is one of the major threats to the sustainability of space operation, considering the potential collision that may cause a catastrophic loss of satellites and further generation of debris. This paper reviews the status of space debris distribution and density, and the related risks to active space assets. In this paper, orbital simulations will be used to discuss efficiency on space debris mitigation techniques, such as collision avoidance maneuvers and active debris removal methods, including passive ones like satellite disposal at the end of their life. Efficiency of current techniques will be derived from these, and optimized strategies will be proposed to mitigate collision risks. This research makes another step in the ongoing effort to protect the space environment and ensure the long-term sustainability of space operations and overall safety of both people in space and on earth.**

Keywords— Space Debris , Low Earth Orbit , Optimized Strategies , Active or Passive debris removal (ADR) (PDR).

I. Introduction

As if recently there is a rising trend in many aerospace companies popping up which has led to more space related missions causing Kessler syndrome. Kessler syndrome is when a global phenomenon characterized by the presence of tens of millions of debris pieces of various sizes that disrupt satellite operations. Once there is a critical density of objects in orbit around Earth, one collision can set off a chain reaction, causing our orbit to become so dense with shrapnel that it becomes unusable. Which the Interconnected Disaster Risks report treats as a tipping point. More than half of the rockets leave some kind of unwanted pieces in space which kept of accumulating, Slowly and steadily every year all of this summed up to the problem we are facing right now. And that is how it rose a question about how is the current situation of space debris and what can be the different mitigation strategies that we can apply to reduce the risk for the next space missions. There is not much emphasis laid on this problem but it counts for the most significance when it all comes down to safety and sustainable environment.

II. Low Earth Orbit

Low Earth Orbit (LEO) refers to the region of space closest to Earth, ranging from about 160 kilometers (100 miles) to 2,000 kilometers (1,200 miles) in altitude. It is a highly utilized orbit due to its proximity, which allows for shorter communication delays and lower launch costs compared to higher orbits. Satellites in LEO complete an orbit around Earth in approximately 90 to 120 minutes, making it ideal for Earth observation, scientific research, and communications. The International Space Station (ISS) also operates in LEO. However, the high concentration of satellites in this region has led to a significant accumulation of space debris, raising concerns about potential collisions and the long-term sustainability of space activities in this orbit.

III. Debris In Numbers

Space debris has become a significant concern in the space industry, with numbers that reflect the vastness and complexity of the issue. Since the beginning of the space age in 1957, there have been approximately 6,710 rocket launches, placing about 19,160 satellites into Earth's orbit. Out of these, around 13,030 satellites remain in space, with roughly 10,200 still functioning. The Space Surveillance Networks track and catalog approximately 36,390 space objects regularly. However, the actual number of debris objects in orbit is much higher, as many are not tracked. According to statistical models, there are an estimated 40,500 debris objects larger than 10 cm, 1.1 million objects between 1 cm and 10 cm, and a staggering 130 million objects ranging from 1 mm to 1 cm in size. These numbers highlight the growing accumulation of debris in space, which poses significant risks to both active satellites and future space missions, underlining the importance of effective space debris mitigation strategies.[1]

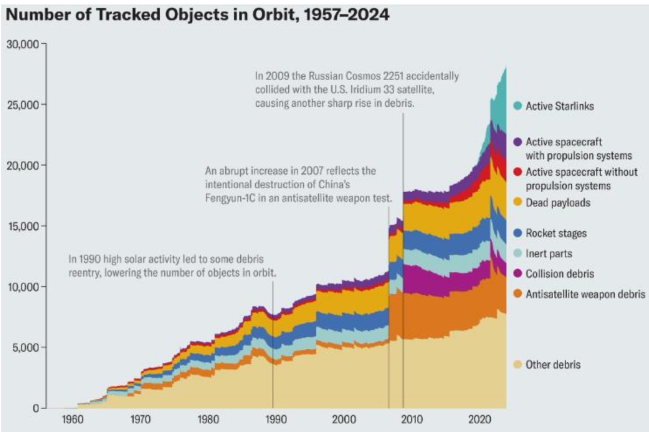
IV. Kessler Syndrome

Kessler Syndrome, named after NASA scientist Donald J. Kessler who proposed the concept in 1978, refers to a theoretical scenario in which the density of objects in Low Earth Orbit (LEO) becomes so high that collisions between objects generate more debris, leading to a chain reaction of further collisions. This cascading effect could result in a situation where space in certain orbits becomes so cluttered with debris that it is unusable for satellites, spacecraft, or any other space missions. The accumulation of debris increases the likelihood of collisions, which then produce even more debris, exacerbating the problem. If left unchecked, Kessler Syndrome could severely hinder future space operations, making it difficult to safely launch satellites or conduct manned space missions. This potential for a runaway situation underscores the urgent need for effective space debris mitigation strategies to prevent the onset of Kessler Syndrome and ensure the long-term sustainability of space activities.

V. Accumulation Over The Years

It all started off with a ball with 4 legs attached to it. Sputnik 1 was the first artificial Earth satellite. It was launched into an elliptical low Earth orbit by the Soviet Union on 4 October 1957 as part of the Soviet space program. It has only lasted a few weeks before it stopped working. The launch of Sputnik I in 1957 not only resulted in the creation of humanmade orbital debris-the first piece being the rocket stage that launched the artificial satellite and the second being the satellite itself—but also revealed the need to keep surveillance of these objects in space. A combination of academic curiosity and the need for intelligence gathering continued to drive the Whole world in its desire to understand this new and unfamiliar frontier. A network of early warning radars was established to watch the skies for potential incoming nuclear missiles. This surveillance system helped the military distinguish between objects in orbit that posed no threat and sub-orbital ballistic weapons that did. A catalog was created from the information collected and provided insight on satellites' predicted route over radar sites. [5]

Historically, breakups have been the largest contributors to the fragmentary space debris population, with tests among the largest single events. Millions of lethal but nontrackable particles can be a consequence of explosive breakups or tests. For example, the Ariane 1 breakup in 1986 created nearly 500 trackable pieces and the 1996 Pegasus/HAPS breakup generated over 750 trackable fragments. For every trackable fragment, models suggest tens to hundreds of non-trackable fragments exist and the number of this debris type increases in quantity as the fragment size diminishes.
A pattern can be noticed here about how it keeps increasing.



[3]

A relatively rapid sequence of debris events in the late 2000s resulted in questions from U.S. government leaders about debris and the risk it could present to spacecraft. Events like the Chinese FY-1C ASAT test in 2007, which added more than 3,500 trackable pieces, and the 2009 Iridium 33 satellite collision with the Russian Cosmos 2251 satellite that brought about more than 2,300 pieces of debris gave a tremendous push to efforts surrounding collision prevention and debris cleanup.

VI. International/Global efforts

A. *European Space agency*

At the Ministerial Conference of 2022, ESA was encouraged by its Member States to implement "a Zero Debris approach for its missions; and to encourage partners and other actors to pursue similar paths, thereby collectively putting Europe at the forefront of sustainability on Earth and in space, while preserving the competitiveness of its industry". The Zero Debris approach is ESA's ambitious revision of its internal space debris mitigation requirements that builds on more than a decade of ESA-wide collaborative work and will drive the development of technologies required to become debris-neutral by 2030. The Zero Debris Charter, in addition, is a community-driven and community-building document and initiative for the global space community. [2]

B. *United Nations General Assembly*

The United Nations Office for Outer Space Affairs (UNOOSA) developed the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (COPUOS) as part of its efforts to address the growing problem of space debris. These guidelines are not legally binding but serve as an important international framework aimed at reducing the generation of space debris, thereby ensuring the long-term sustainability of space activities.

C. *International Treaties and Frameworks[4]*

- Outer Space Treaty (1967): This treaty establishes a framework for international space law, including principles related to the use of outer space and the responsibilities of nations regarding space activities.

- Liability Convention (1973): This convention outlines the liability of countries for damage caused by their space objects, which is crucial for addressing issues related to space debris.

VII. Literature Reveiw

This is a grim scenario, with tens of millions of pieces of debris in all sizes orbiting Earth. Their growing density has increased the possibility of collisions capable of producing the Kessler Syndrome: a chain reaction of collisions making Earth's orbit unusable. Various studies have documented the current distribution of space debris, with a greater focus on LEO, where the debris density is the highest. This ever-growing debris field has been identified as one of the critical threats to satellite operations and future space missions by the Interconnected Disaster Risks report and other sources. As there is a growing research community around this people have started working on two types of mitigation strategies that is active and passive. While there is a consensus on passive strategies, such as disposing of satellites at the end of their operational lives, compliance and technical considerations set limits to the effectiveness of this measure. Active debris removal methods are promising but face big technical and economic hurdles, with continuous research aimed at devising feasible solutions. Notwithstanding the research done so far on space debris, there remain a number of gaps. More comprehensive studies are needed regarding the long-term efficacy of current mitigation strategies and developing newer, more effective ones. A standardized global debris tracking and reporting system is one major factor missing in mitigating the problem in a unified manner. The future research will go a long way in advancing the technologies of ADR, improving international cooperation, and developing different policy frameworks toward the sustainability of space activities.

Some major challenges to active space debris management in the year 2024 include developing effective and affordable ADR technologies, as current approaches using robotic arms and lasers are still under evaluation. The improvement of the tracking systems should be enhanced in respect of the detection of small fragments of debris. Inconsistent international adherence to guidelines on space debris hinders regulatory efforts. Expanded satellite constellations heighten collision risk and point up the need for better space traffic management. Further research is needed regarding effective techniques of end-of-life disposal and understanding the impacts of fragmentation. The challenges can be overcome only with global collaboration and various innovative solutions to render space operations truly sustainable.

VIII. Methodologies

A. Mitigation Strategies

Space debris mitigation can be categorized into short-term and long-term risk reduction strategies. Short-term mitigation involves spacecraft executing Just-in-time collision avoidance maneuvers to minimize the likelihood of impact and subsequent debris generation. However, this approach does not address the underlying long-term risk of collisions. Long-term space debris risk reduction encompasses active debris removal, space debris remediation measures, the deliberate de- orbiting of decommissioned satellites into the Earth's atmosphere, or the relocation of debris or satellites to designated graveyard orbits.

1) Drag Augmented Sails (DAS)[[4]

One effective method for managing space debris, especially for small satellites in Low Earth Orbit (LEO), is the use of a compact drag augmentation sail. This sail, which is deployed at the end of the satellite's mission, increases the satellite's area-to-mass ratio without significantly adding to its mass. This increase in drag reduces the satellite's orbital speed, leading to a faster re-entry into Earth's atmosphere where it will burn up. A key benefit of this drag augmentation sail (DAS) is that it does not require any power or fuel. However, further research is needed to develop a sail material resilient enough to withstand impacts with other space debris.

Studies indicate that a satellite at altitudes of 650-700 km above Earth's surface will naturally de-orbit within 25 years if it maintains a typical area-to-mass ratio of 0.005 to 0.015 m^2/kg. With a moderately sized drag sail, which has an area-to-mass ratio of 0.1 m^2/kg, this altitude can be extended to over 800 km. The drag sail is most effective at altitudes up to 950 km. Above this, the size of the sail required becomes impractically large for heavier satellites. For example, to de-orbit a 1-ton satellite from 1000 km within 25 years, a drag sail of at least 20 meters by 20 meters would be necessary. Cranfield University has designed and manufactured three such drag sails, which are currently installed on orbiting satellites.

2) Laser-Based Systems[4]

One of the possible methods for real-time collision avoidance is targeting the space debris using lasers. In this technique, either ground-based or space-based lasers are used to heat up the debris until its surface layer vaporizes. The vaporization results in plasma and a high-velocity exhaust plume that travels backward from the debris, thus pushing it off its trajectory. This technique is very suitable for LEO against the debris less than 10 cm. But it would tend to produce more debris and requires precision targeting and tracking technology in order to be performed safely. International concerns about the use of such technology as a "space weapon" also limit the freedom to research and develop those systems.

In the L'ARDOIT project, the basis is a principle called Laser Ablative Debris Removal by Orbital Impulse Transfer. Considering this principle, a spacecraft in LEO should be equipped with a 100-picosecond ultraviolet pulse laser which is able to target an object from as far as 25 km and with an optical system designed for debris detection at a distance of 600 km.

3) Net Capture Method[4]

The net capture method for active space debris removal involves using a chaser satellite equipped with a net. This net features weighted corners, or "bullets," that secure around the debris upon contact. The chaser satellite tracks and follows the designated debris object, deploying the net to capture it. The process includes three main stages: deploying the net, capturing the target, and then de-orbiting the debris. This method offers several benefits, such as the ability to capture debris of various shapes and sizes, and maintaining a safe distance between the chaser satellite and the debris, which reduces the risk of collision. It is effective only in Low Earth Orbit (LEO), where both the net and debris can burn up upon re-entry into the atmosphere.

The feasibility of this technology was demonstrated in 2018 with the Remove DEBRIS mission. During this mission, a target CubeSat with inflatable booms was released to simulate space debris. The target was successfully captured using a 5-meter net made from high-strength fibers. The net, equipped with concentric weights and a central cover, was closed around the target using motors and winches. Further research is needed to develop effective methods for disposing of the captured debris.

4) Electromagnetic method (Possibility)

The electromagnetic space debris removal method involves deploying a specialized spacecraft or debris removal satellite equipped with powerful electromagnets to manage and mitigate space debris. The system generates a strong magnetic field that can attract and influence metallic debris, including ferromagnetic and conductive objects. This method works by directing the magnetic field towards targeted debris, which is then pulled into a collection area or containment system on the spacecraft. One of the key advantages of this approach is its ability to selectively target and capture metallic debris, reducing the need for physical contact and thus minimizing the risk of generating additional fragments. The method also allows for scalable solutions to address different sizes and quantities of debris. However, challenges include its limited effectiveness on non-metallic debris, significant power requirements for generating strong magnetic fields, and complex engineering demands for ensuring stable field generation and effective debris capture. Further research is needed to optimize electromagnetic systems, including enhancing power efficiency, improving targeting precision, and integrating this method with other debris management technologies. Successful development and deployment of electromagnetic debris removal could offer a novel and effective solution to reducing the risks associated with space debris, contributing to safer and more sustainable space operations.

B. Difference between Active and Passive

Active debris removal (ADR) involves the use of technology and missions specifically designed to capture and remove space debris from orbit, employing methods such as net capture, harpooning, laser ablation, and drag augmented sails to directly engage with debris objects. This approach faces challenges including high costs, legal complexities, and the risk of generating additional debris during removal attempts. In contrast, passive debris removal focuses on preventing the creation of new debris and mitigating risks associated with existing debris through design and engineering solutions, such as end-of-life plans for satellites and adherence to international debris mitigation guidelines. While ADR targets the active removal of debris, passive measures emphasize long-term sustainability and responsible practices in space operations, making both approaches essential for addressing the growing problem of space debris and ensuring the future viability of space activities..

IX. Results

1) Effectiveness of Mitigation Strategies

a) Drag Augmented Sails (DAS)

Drag augmented sails have indeed presented a very promising use in the improvement of the de-orbiting process concerning small satellites operating within Low Earth Orbit. As an example, this is going to be an area-to-mass ratio for DAS at 0.1 m^2/kg, extending the effective altitude range for de-orbiting beyond 800 km up to 950 km. This technique would allow a satellite, for that matter, to enter Earth's atmosphere faster, spend less time in orbit, and reduce its chances of collision with other objects. Still, efficacy is bound to the materials required for the sail, which also needs to be durable enough to survive any impact from other debris. Above an altitude of 1000 km, the theoretically required drag sail size becomes impracticably large and may pose certain logistical problems when deployed.

b) Laser-Based Systems

The systems based on lasers-vacuum proposed in the L'ARDOIT project are capable of changing debris trajectory by vaporizing the surface, and this technique seems to be particularly effective for small-sized debris with diameters less than 10 cm in low Earth orbit. The vaporization creates a high-velocity exhaust plume that pushes debris off its orbit. This otherwise apparently promising method is not without its own problems, such as generating even more debris, and it does require very sophisticated targeting and tracking technology. Research and development are further constrained by international regulations out of fear of the weaponization of space.

c) Net Capture Method

The in-orbit net capture method has already shown good results in trials, as in the case of the RemoveDEBRIS mission, with a 5-meter net catching a target CubeSat. This approach will enable the chaser to catch debris of irregular shape and size and keeps the chaser satellite at a safe distance from the target object to avoid collision. The net and the captured debris will burn upon atmospheric re-entry, hence addressing debris disposal. But nowadays, the efficiency of the method is restricted to LEO, and further research is needed to perfect debris removal techniques and ensure that the net will not create debris itself.

d) Electromagnetic Method

The electromagnetic debris removal has a potential of selectivity in targets, especially metallic debris, with the use of powerful electromagnets. It is scalable and can handle different sizes and quantities of debris. The minimal physical contact would help reduce further fragmentation. Its disadvantages: this method will work only on metallic and conductive debris, and for its operation, quite an amount of power is needed to be able to make the magnetic fields. Among the engineering challenges involved are optimizing power efficiency and improving targeting precision. These challenges require further research for the full development of this method into a technology that can be combined with other methods of managing debris.

X. Discussions

Discussed strategies of mitigating space debris show achievements but also challenges that are still large in this important field. Indeed, the effectiveness of Drag Augmented Sails for satellite de-orbiting is a promising method to mitigate space debris, especially for small satellites that travel in LEO. Deployment of the sail provides an increase in area-to-mass ratio for faster re-entry into the atmosphere without extra power and fuel. Practical DAS is, however, limited by durability questions about sail material against collisions and large sails become impracticable at altitudes. Laser-based systems are real-time solutions to avoid collision by vaporizing the debris to change its trajectory. While theoretically effective for small debris under 10 cm in LEO, this method faces significant obstacles, such as the possibility of secondary debris generation and technical hurdles regarding precision targeting and tracking. Further, the international regulations about the weaponization of space forbid the development and deployment of such technology. The net capture method presents a workable way of active debris removal, as was successfully done in the mission known as RemoveDEBRIS. The advantage of this method is the capture of debris in various shapes and size and while maintaining a safe distance from the target in order to avoid collision. But for the captured debris, efficient disposal techniques are yet to be developed. The proposed electromagnetic technique is an innovative one, which uses powerful electromagnets to attract and manipulate metallic debris. It enables the selective catching of metallic debris along with scale solutions, which depend on the size and amount of debris. However, it faces power requirements and effectiveness on non-metallic debris; thus, further research is necessary to enhance its efficiency and integration with other technologies. Relatively, these strategies represent varying magnitudes of effectiveness and feasibility. While most of the LEO missions currently see more feasibility in DAS and net capture methods, the laser and electromagnetic methods hold greater potential for wider applicability, but need further development. This is indicative that a multi-faceted approach, where a range of mitigation strategies are combined, could be the most viable means by which to solve the growing problem of space debris. Each solution has its own advantages, but its limitations also make the ground for further innovation and research. In addition, more significant research effort shall be directed to the technological and operational challenges of those methods and also to identify synergistic approaches that optimize their performance and combinations in order to reinforce the entire management of space debris. It would become increasingly important that active and passive mitigation measures are integrated with each other and supported by technology advancement in order to realize sustainability and safety of space operation.

XI. Conclusion

The Space debris turned out to be one of the crucial problems for further sustainability in space operation. Starting from Sputnik 1 in 1957, it grew incrementally up to alarming levels in Earth's orbit. The Kessler Syndrome, where a single collision can trigger a chain reaction of subsequent ones, is a reality today and not just a theoretical one; the threat keeps growing. Events such as the Chinese ASAT test in 2007 and the Iridium-Cosmos collision in 2009 have been significant contributors to the current population of space debris and have contributed to making the space environment increasingly hazardous. While the implementation of satellite end-of-life disposal and collision avoidance maneuvers is extremely important within passive strategies, they cannot solve the worsening debris problem alone. ADR technologies are promising, but there are many technical, financial, and legal barriers yet to be overcome. In mitigating the growth of the debris population, success in technology development and deployment would mean much, but international cooperation would be required in that respect. International collaboration is, therefore, quite crucial in an effective mitigation of space debris. Due to the voluntary nature of current guidelines, such as those coming from the United Nations, their implementation has been quite inconsistent across different nations. In this regard, there is a real requirement for binding international agreements and a global system of space traffic management for uniform adherence to best practices. In other words, the ever-increasing hazard of space debris needs immediate and serious action. The development of more advanced ADR technologies, increasing the world's capability to track more debris, and an increase in international policy-making will help preserve the space environment for continued exploration and use.

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