

Evaluating Space Debris Reduction Techniques for Small Satellites in Low Earth Orbit: A Regulatory Perspective

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Abstract:

The increasing proliferation of small satellites in Low Earth Orbit (LEO) has brought significant attention to the issue of space debris. As the number of active satellites rises, so does the risk of collisions, which can generate debris that endangers both existing and future space missions. This paper examines various debris reduction techniques specifically applicable to small satellites, focusing on their regulatory implications. We discuss the current state of space debris, analyze existing and emerging reduction strategies, and highlight the role of regulatory frameworks in enforcing these measures. Our findings indicate that a combination of technical, operational, and regulatory solutions is essential to mitigate the space debris problem effectively. Furthermore, fostering international cooperation and compliance will be crucial for the successful implementation of these strategies.

Keywords: Space debris, small satellites, Low Earth Orbit, debris reduction techniques, regulatory frameworks, international cooperation, collision risk mitigation, sustainable space operations.

I. Introduction:

The advent of small satellites, often referred to as CubeSats or smallsats, has revolutionized space access and applications, ranging from Earth observation to telecommunications. As of 2023, there are thousands of small satellites in orbit, contributing to an ever-increasing congestion in Low Earth Orbit (LEO). While these

satellites provide numerous benefits, their proliferation has also raised concerns about space debris. Space debris consists of defunct satellites, spent rocket stages, and fragments resulting from collisions and explosions. The presence of this debris poses a significant threat to operational satellites and the safety of future missions [1]. The regulatory landscape governing space debris management is evolving, but many challenges remain. Current space laws and treaties, such as the Outer Space Treaty of 1967, provide a foundational framework for space activities but lack specific guidelines for debris mitigation. With the rapid growth of small satellite constellations, such as Starlink and OneWeb, it is crucial to evaluate and implement effective debris reduction techniques [2].

This paper aims to analyze these techniques through a regulatory lens, exploring how they can be integrated into existing frameworks to promote sustainable space operations. Understanding the regulatory perspective is vital for several reasons. First, regulatory measures can enforce compliance with debris mitigation strategies, ensuring that satellite operators adhere to best practices. Second, a clear regulatory framework can foster international cooperation among countries and private entities involved in space activities [3]. Finally, as space debris becomes an increasingly critical issue, regulatory bodies can play a pivotal role in establishing guidelines that promote responsible behavior in space. In this paper, we will review existing literature on space debris, analyze various debris reduction techniques, and assess the regulatory frameworks that govern them [4]. We will also discuss the role of international cooperation in addressing the challenges posed by space debris. The findings from this analysis will provide insights into how the space industry can navigate the complexities of debris reduction while promoting sustainable practices.

II. Current State of Space Debris:

The current state of space debris is alarming. According to the European Space Agency (ESA), there are over 36,000 pieces of debris larger than 10 cm and millions of smaller fragments in LEO. This debris poses a collision risk to operational satellites, which can lead to the creation of even more debris a phenomenon known as the Kessler Syndrome. The Kessler Syndrome suggests that a catastrophic cascade of collisions could render

certain orbits unusable, severely impacting satellite operations and space exploration efforts. The sources of space debris are diverse. They include defunct satellites, spent rocket stages, and fragments from collisions or explosions [5]. For instance, the 2009 collision between Iridium 33 and Cosmos 2251 generated thousands of debris fragments. Furthermore, intentional satellite destructions, such as China's 2007 anti-satellite test, have significantly contributed to the debris population in orbit. As small satellite constellations continue to proliferate, the likelihood of collisions increases, necessitating urgent action to mitigate debris creation. Moreover, the environmental impact of space debris extends beyond operational satellites. Debris can pose risks to crewed missions, as even small fragments can cause catastrophic damage to spacecraft traveling at high velocities. As the international community recognizes the severity of the issue, discussions around space debris mitigation and remediation have gained traction. Regulatory bodies are beginning to address these concerns, but comprehensive and enforceable guidelines are still lacking [6].

Current space traffic management systems also face challenges due to the increasing number of satellites. The capability to track and predict satellite trajectories and potential collisions is limited, making it difficult to manage the congested LEO environment effectively. The need for improved tracking and monitoring systems is paramount, alongside regulatory measures that mandate operators to adhere to debris mitigation practices. The United Nations Office for Outer Space Affairs (UNOOSA) has initiated efforts to address the space debris issue, advocating for the adoption of guidelines for the long-term sustainability of space activities. These guidelines emphasize the importance of debris mitigation measures, including the responsible disposal of defunct satellites and the avoidance of collisions. However, the implementation of these guidelines relies on the cooperation of various stakeholders, including government agencies, private companies, and international organizations.

In summary, the current state of space debris presents significant challenges that threaten the sustainability of space operations. As the number of small satellites increases, the urgency for effective debris reduction techniques and regulatory frameworks becomes more pronounced. Addressing these challenges requires collaboration across the global space community and a commitment to responsible practices [7].

III. Debris Reduction Techniques:

One of the primary debris reduction techniques is end-of-life disposal. This approach involves designing satellites to ensure they can be safely deorbited at the end of their operational lifespan. The best practice is to have satellites re-enter the atmosphere and burn up, minimizing the risk of leaving debris in orbit. Various methods, such as controlled re-entry and utilizing propulsion systems, can be employed to achieve this goal. For small satellites, which often have limited propulsion capabilities, innovative designs are necessary to ensure successful end-of-life disposal. Active debris removal (ADR) is another promising technique aimed at addressing existing debris in orbit. This approach involves deploying specialized spacecraft to capture and deorbit defunct satellites or large debris fragments. Various technologies are under development, including nets, harpoons, and robotic arms. While ADR offers the potential to reduce the overall debris population, it also presents technical and regulatory challenges. The successful implementation of ADR requires international cooperation and the establishment of clear guidelines for operations [8]. The "design for demise" principle focuses on ensuring that satellites are constructed from materials that will disintegrate upon re-entry into the atmosphere. By using materials that burn up completely during re-entry, the risk of creating debris is minimized. This technique is particularly relevant for small satellites, where weight and design constraints may limit options. Incorporating this principle into the design phase can significantly reduce the potential for long-term debris generation. Collision avoidance maneuvers involve altering a satellite's trajectory to prevent potential collisions with other objects in orbit. Operators can utilize tracking data to predict potential collision events and take proactive measures to adjust satellite orbits. This technique is essential for maintaining the safety of operational satellites, especially as the number of objects in LEO increases. Regulatory frameworks must mandate the use of collision avoidance maneuvers as a standard operational practice.

The establishment of shared space traffic management systems can enhance debris reduction efforts by improving coordination among satellite operators. By sharing data on satellite trajectories and potential collision risks, operators can make informed decisions about maneuvering their satellites. This collaborative approach fosters a culture of responsibility and accountability, ensuring that all stakeholders prioritize debris

mitigation. Regulatory bodies can play a vital role in facilitating data sharing agreements and standardizing practices across the industry. Improving tracking and monitoring capabilities is crucial for effective debris management. Current tracking systems may struggle to keep pace with the increasing number of satellites in orbit. Enhanced tracking technologies, such as radar and optical sensors, can provide better situational awareness of space objects. Regulatory frameworks should encourage investment in tracking infrastructure and mandate compliance with tracking protocols to ensure accurate data is available for collision prediction and avoidance.

Addressing the space debris challenge requires international collaboration among governments, space agencies, and private entities. Sharing knowledge, resources, and best practices can lead to more effective debris reduction strategies. International treaties and agreements can establish a framework for cooperation, enabling stakeholders to work together to address common challenges [9]. Regulatory bodies should facilitate discussions and negotiations aimed at promoting collective action in debris mitigation. Raising public awareness about the space debris issue is vital for fostering a culture of responsibility in space activities. Engaging the public through educational initiatives, outreach programs, and advocacy can help highlight the importance of debris reduction. Regulatory bodies can play a role in promoting awareness campaigns and encouraging industry stakeholders to take responsibility for their contributions to the debris problem. Increased public awareness can lead to greater accountability and pressure on operators to adopt sustainable practices.

IV. Regulatory Frameworks for Space Debris Management:

The current regulatory landscape for space debris management is largely fragmented. While various international treaties, such as the Outer Space Treaty and the Convention on Registration of Objects Launched into Outer Space, provide a foundational framework, they lack specific provisions for debris mitigation. As space activities have evolved, the need for comprehensive regulatory measures addressing debris has become increasingly apparent [10]. Organizations such as the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) have initiated discussions on developing guidelines for the long-term sustainability of space activities, emphasizing the importance of debris

mitigation. In response to the growing concern over space debris, several countries have developed national regulations aimed at mitigating debris risks. For example, the United States has implemented guidelines through the National Oceanic and Atmospheric Administration (NOAA) and the Federal Aviation Administration (FAA) that require satellite operators to adhere to debris mitigation practices. Similarly, the European Space Agency (ESA) has established guidelines for member states to follow, promoting responsible satellite design and operations. National regulations serve as important tools for enforcing compliance and ensuring that operators prioritize debris reduction. International guidelines, such as those developed by COPUOS, offer a framework for best practices in debris mitigation. These guidelines emphasize the importance of end-of-life disposal, collision avoidance, and design for demise principles. However, their non-binding nature poses challenges for enforcement. Regulatory bodies can enhance the effectiveness of these guidelines by advocating for their adoption at the national level and fostering international cooperation to establish a unified approach to debris mitigation.

The question of liability and responsibility for debris generation is a critical aspect of regulatory frameworks. Current treaties establish liability for damages caused by space objects, but the complexities of debris management complicate accountability. Clear definitions of responsibility for debris mitigation and remediation efforts are necessary to ensure that operators are held accountable for their actions. Regulatory frameworks should address liability issues, establishing mechanisms for compensation and remediation in the event of collisions or debris-related incidents. Effective compliance and enforcement mechanisms are essential for ensuring adherence to debris mitigation practices. Regulatory bodies can implement monitoring systems to track operator compliance with established guidelines. Penalties for non-compliance, such as fines or restrictions on future launches, can serve as deterrents against negligent practices. Collaboration among regulatory agencies, industry stakeholders, and international organizations can enhance the effectiveness of compliance efforts and promote a culture of accountability. The rapid advancement of technology presents both opportunities and challenges for regulatory frameworks. Innovative debris reduction techniques, such as active debris removal, require regulatory considerations to ensure safe and responsible

operations. Regulatory bodies must keep pace with technological developments and adapt existing frameworks to accommodate new solutions. This includes establishing guidelines for the deployment of ADR missions and ensuring that operators adhere to safety protocols during operations [11].

As the space industry continues to evolve, future regulatory trends are likely to focus on sustainability and responsible practices. Regulatory bodies may prioritize the integration of debris mitigation measures into licensing processes for satellite operators. Additionally, the establishment of international agreements addressing debris management may become increasingly important. Regulatory frameworks will need to balance innovation with accountability, ensuring that operators are incentivized to adopt sustainable practices while fostering an environment conducive to technological advancement. Engaging stakeholders in the regulatory process is crucial for developing effective debris management frameworks. Collaboration among government agencies, private companies, and international organizations can lead to the establishment of comprehensive regulations that reflect the interests of all parties involved. Regulatory bodies should facilitate discussions and encourage stakeholder participation in developing guidelines and best practices. By fostering a collaborative environment, the regulatory process can be more responsive to the needs of the space community and promote responsible behavior in space.

V. Challenges in Implementing Debris Reduction Techniques:

The implementation of debris reduction techniques faces several technical challenges. For instance, end-of-life disposal methods may be constrained by limited propulsion capabilities in small satellites. Designing satellites that can effectively deorbit themselves requires innovation and investment in new technologies. Active debris removal, while promising, also involves technical complexities in capturing and safely deorbiting debris. Overcoming these technical limitations is essential for the successful implementation of debris reduction strategies. Economic factors also play a significant role in the adoption of debris reduction techniques. The costs associated with implementing debris mitigation measures, such as developing propulsion systems for end-of-life disposal or investing in ADR technologies, can be a barrier for many operators, especially smaller companies.

Regulatory frameworks should consider the economic implications of debris mitigation strategies and provide incentives, such as grants or subsidies, to encourage compliance. Balancing cost-effectiveness with environmental responsibility will be crucial for promoting sustainable practices. The fragmented nature of regulatory frameworks poses challenges for implementing debris reduction techniques. Different countries have varying regulations, which can create confusion and complicate compliance for international operators. A lack of harmonization in regulations can hinder efforts to address the global nature of the space debris problem. Establishing unified international guidelines and encouraging cooperation among regulatory bodies can help mitigate these challenges and promote consistency in debris management practices. Limited awareness and understanding of space debris issues among satellite operators and the general public can hinder the adoption of debris reduction techniques. Education and outreach initiatives are essential for raising awareness about the importance of responsible space operations. Regulatory bodies should promote educational programs and resources that inform stakeholders about debris mitigation practices. By fostering a culture of responsibility, operators may be more inclined to prioritize debris reduction efforts.

The global nature of space activities necessitates international cooperation in addressing the space debris challenge. However, geopolitical tensions and differing priorities among countries can complicate collaboration efforts. Establishing effective communication channels and fostering trust among nations will be essential for promoting joint efforts in debris mitigation. Regulatory frameworks should encourage dialogue and cooperation among international stakeholders to facilitate collective action in addressing space debris [12]. The rapidly evolving technological landscape poses both opportunities and challenges for debris reduction efforts. While advancements in technology can lead to innovative solutions for debris management, they also require regulatory adaptation. Regulatory bodies must stay abreast of technological developments and be prepared to adjust guidelines accordingly. This necessitates ongoing collaboration between regulatory agencies and the space industry to ensure that regulations remain relevant and effective.

The successful implementation of debris reduction techniques relies on political will and commitment from governments and regulatory bodies. Strong leadership and advocacy for sustainable space practices are essential for driving change in the industry.

Policymakers must prioritize space debris management as a critical issue and allocate resources to support regulatory efforts. Building a consensus among stakeholders will be crucial for promoting a shared commitment to responsible space operations. Finding the right balance between fostering innovation and implementing effective regulation is a key challenge in debris reduction efforts. Overly stringent regulations may stifle technological advancements, while lenient regulations could lead to irresponsible practices. Regulatory bodies must adopt a flexible approach that encourages innovation while ensuring accountability.

VI. Conclusion:

The increasing presence of small satellites in Low Earth Orbit presents significant challenges related to space debris management. As the number of active satellites continues to rise, the risk of collisions and debris generation escalates, necessitating urgent action. This paper has explored various debris reduction techniques, including end-of-life disposal, active debris removal, and collision avoidance maneuvers. We have also examined the regulatory frameworks that govern these techniques and the challenges associated with their implementation. To effectively address the space debris problem, a multi-faceted approach is essential. Combining technical, operational, and regulatory solutions will be crucial for mitigating debris risks. Regulatory frameworks must evolve to incorporate best practices in debris mitigation, promoting compliance among satellite operators and fostering international cooperation. Moreover, raising public awareness about the importance of responsible space operations can enhance accountability and encourage operators to prioritize debris reduction efforts. The successful implementation of debris reduction techniques will require collaboration among governments, space agencies, private companies, and international organizations.

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