Practical path towards net-zero debris

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Abstract — **Reaching the target of net-zero debris requires the whole space ecosystem to be built around robustness. In this paper, we conduct a thorough analysis of the long-term sustainability of in-orbit operations from different perspectives, including not only the technical but also regulatory, financial, and commercial aspects. We approach the topic from these different perspectives and analyze the state-of-the-art and potential future developments, building an overall picture of how the whole ecosystem could work, from the perspectives of different actors. These actors include space agencies, governments, large corporations, small businesses, research organizations, universities and non-profits, including open-source developers. The aim is to build a baseline view of the net-zero debris future which can then be adapted based on actual advancements in the industry. Since single predictions will likely not be accurate, the model describes a robust ecosystem where an equilibrium state can be established and directed by regulators to reach the target of net-zero debris. Each stakeholder's incentives are analyzed as a crucial step in building the equilibrium state where deviations by single parties or technologies are corrected by the ecosystem. This game-theoretic approach is of paramount importance in reaching the targets in the real world where each actor has different targets and priorities. Different strategies of debris mitigation and remediation are considered, with existing models for financing them analyzed from different perspectives. Commercial viability of different actors are also touched upon in the different scenarios, with the target of maximizing the long-term return-on-investment of the whole space industry, requiring effective but low-overhead regulation as well as standardized (either de jure or de facto) solutions to the core problems, allowing for the economy of scale to kick in. To reach a net-zero debris, the core technical problems to be solved are space debris mitigation (disposal, collision avoidance and prevention of breakup) to minimize the generation of debris, combined with Active Debris Removal (ADR) to remove an equal amount of debris as is being generated. The cost overhead of ADR is high, and so high-reliability mitigation measures are important. Current disposal measures (deorbiting with a thruster or other method requiring the satellite to be functional) can't not only reach high reliabilities but also create a conflict of interest between continuing satellite operation versus disposing of it while it is still functional. Similarly, the collision avoidance infrastructure requires solutions that allow automated management of the maneuvers, requiring major changes in the way many satellites are operated. In-orbit servicing and related technologies are taken into account, but their impact on the necessity of other solutions is small. Core technologies required in the long term are highlighted, along with an attempt to identify their most important features. Similarly, core models of operation are identified for mission operators, building on the view of the whole ecosystem.**

I. Introduction

The rapid expansion of in-orbit activity has brought significant benefits to society but also escalated the risk posed by space debris. To ensure the long-term sustainability of space operations, the concept of net-zero debris is at the forefront. It means that the amount of debris removed equals or exceeds the amount of new debris generated. Unlike purely technical fixes, achieving net-zero debris requires a holistic transformation of the space ecosystem to emphasize robustness, accountability, and long-term planning.

This paper presents a high-level but comprehensive analysis of how the space industry can evolve toward a net-zero debris future. We examine the interplay between technical capabilities (e.g., mitigation and active removal), regulatory enforcement, financial mechanisms, and stakeholder behavior. Our approach recognizes that sustainable outcomes depend not only on technology but also on aligning the incentives of the actors involved, including space agencies, governments, large corporations, SMEs, academia, and non-profits.

Given the uncertainty of future developments, we do not attempt to prescribe a single path. Instead, we propose a robust ecosystem model that allows for a dynamic equilibrium to form where deviations by individual actors or technologies are corrected by systemic responses. The analysis draws on game-theoretic reasoning to explore how regulations, economic tools, and standardization can guide the sector toward stability and sustainability.

II. Technical foundation

Achieving net-zero debris requires both minimizing the generation of new debris and removing existing debris from orbit. This forms the foundation for the technical strategies, which can be divided into two core areas: M**itigation** and **Remediation**.

A. Mitigation

Mitigation focuses on preventing the creation of debris through end-of-life disposal, collision avoidance, and the design of more robust spacecraft. Two prevailing disposal strategies exist: natural decay by atmospheric drag and deorbiting via propulsion. The former limits the operational altitudes severely, especially with the 5-year deorbiting rules that has come into effect in the United States, ESA missions and an increasing number of countries globally [1][2]. The latter strategy is viable for high-profile missions that have high reliability requirements and the budget to support such approach, but as the industry is leaning increasingly towards faster-paced, lower-budget solutions the strategy suffers from the lower reliability of the satellites, especially at the CubeSat scale, as the propulsion-based deorbiting is dependent on the whole satellite remaining operational at end-of-life. A conflict of interest is created: operators may prioritize continued revenue over timely disposal and end up aiming to pass the regulation requirements with minimum possible costs rather than trying to truly minimize the generation of debris. As launching missions at a cheaper price point becomes more and more feasible, using high-reliability platforms is not something commercially feasible. Hence, the only approach that avoids a direct conflict of interest in the design choices of the platform is to utilize mitigation measures that function independent of the Platform. Even if experienced actors in the market could supply reliable enough platforms, any new player entering the market has to be able to develop their platform without endangering the LEO environment. This independence can be achieved partially through passive systems (e.g., drag sails) or more comprehensively with independent subsystems capable of performing disposal and/or collision avoidance. The most difficult is that of satellites that are dead on arrival, AKA that are never successfully communicated with. Currently 7% of all nanosatellites have faced this fate [3]. That corresponds to 186 nanosatellites that were left as debris on their initial deployment orbit. Reaching a > 95% reliability for deorbiting, such as outlined in [2] for the protected LEO region, is obviously impossible if the disposal is reliant on the platform and > 5 % of the satellites never function in the first place. The high-level approach should move towards fail-safe, rather than fail-free design. Collision avoidance faces similar problems but is additionally reliant on receiving the maneuver data from ground as direct detection of potential collisions in time to avoid them is not practically possible.

B. Remediation

As long as the humankind operates devices in space, there exists a risk of generating new debris since no mitigation measure can be 100% reliable. The term net-zero debris means preventing the total increase of the amount of debris in orbit, meaning that the total amount of debris removed from the orbit is at least as great as the amount of debris generated. Existing debris luckily does naturally decay from lower orbits, thus providing a small amount of naturall remediation. However especially when looking at the orbits above 600 km, this flux is negligible compared to the risk missions generating new debris. The direct approach to remediation is referred to as Active Debris Removal (ADR). It aims to reduce existing debris, especially large, non-maneuverable objects that pose high collision risk and have long natural decay periods. Technically feasible ADR missions have been demonstrated at a small scale, but they remain costly and complex. The critical performance metric in ADR is the upmass-to-downmass (UTD) ratio: the ratio of mass deorbited by a mission for a given launched payload mass. The ClearSpace-1, the first ESA project to perform an Active Debris Removal mission has a spacecraft mass of 580 kg and is able to remove a piece of debris with a mass of 95 kg [4], making the UTD ratio 6.1. This means that removing a kilogram of mass from orbit is by rough approximation also 6.1 times more expensive than launching it (assuming the removal mission has a similar cost structure than the original mission; in reality the current disposal missions' cost structures are many times more expensive than those of an average satellite). Hence, a satellite with 80% probability of successful disposal would cause an expected value of disposal expenses greater than its project budget. Hence, the role of reaching low UTD ratios cannot be understated when discussing the economics of net-zero debris.

Additionally, there are currently no clear funding mechanisms or regulations to support actual large-scale implementation of ADR.

Finally, while technologies such as in-orbit servicing and life extension may reduce the frequency of launches and hardware obsolescence, they only partially alleviate debris concerns. The central challenge remains: balancing cost, operational complexity, and reliability across both mitigation and remediation efforts in a way that is economically viable.

III. REGULATION AND MARKET DYNAMICS

While current regulation is starting to address the issues of debris mitigation, it currently lacks effective mechanisms to fund remediation or reward high-reliability mitigation. While disposal timelines are mandated by some national regulations (such as [1]), they are largely focused on pre-launch compliance and do not necessarily tie economic consequences to real-world outcomes in orbit. Issuing fines seems to be the leading strategy, such as was done in the case of DISH [5]. However, the risk of such fine is low enough for a single operator that there is little financial incentive for operators to go beyond minimum compliance required to receive the permits required to launch. Additionally, no structured system to fund remediation activities such as Active Debris Removal (ADR) exists.

A sustainable regulatory framework should shift from prescribing technical approaches to creating economic signals that influence operator behavior. This also leaves the field open for innovation, compared to regulation that mandates certain technical approaches and may prevent the incorporation of related future innovations. The key principle should be that those generating debris risk should also fund the cleanup. There are two straight-forward regulatory approaches: either to force the parties that caused the debris to be generated to pay for the removal of an equivalent amount of mass; or to bill every mission for removing the mass equivalent to the statistical expected value of debris generated by the mission, taking into account the reliability of the mitigation measures. In practice, these approaches would be nearly equivalent from the perspective of operators, as in the first case an insurance provider would be used as the middleman to provide the risk analysis (the use of an insurance could be mandated to ensure the actual capability to pay for the removal). This would naturally guide operators towards the most effective solutions while facilitating innovation both on the part of mitigation as well as remediation by providing a clear market and price points to develop new solutions for.

Other possible approaches for the funding of remediation exist as well, but the most important aspects for such approaches to be effective are that they must incentivize actors towards sustainable practices and provide a predictable operational environment for all actors in the industry. Relying solely on pre-launch documentation or intent does not provide the correct incentives.

At present, ADR missions remain government-funded pilot projects, with no viable path to commercial sustainability. Without integrating remediation costs into the economic model of satellite operations, net-zero debris cannot be achieved, regardless of technical capabilities. A predictable debris removal market has to be generated to allow the entry of commercial operators and private venture capital to the market.

IV. Conclusion

Achieving net-zero debris is not only a technical challenge but a systemic one. While mitigation and remediation technologies are advancing, their effectiveness is limited without corresponding evolution in regulatory and economic structures. The core issue is that of misaligned incentives: as long as debris remains an externality, the space industry will continue to underinvest in long-term sustainability.

A realistic path forward requires an ecosystem where regulatory frameworks support market-based mechanisms to internalize the cost of debris. Operators must be financially accountable for the risks they generate, and the economic model of satellite missions must include both high-reliability mitigation and contributions to remediation. This creates a foundation for commercial ADR viability and supports the development of robust, low-overhead solutions.

No single actor can enforce or implement this transition alone. Governments, agencies and commercial entities each have distinct roles to play. A level of interoperability is required from standards, incentives, and responsibilities.

A net-zero debris future is achievable, but only if robustness and accountability are built into the entire space ecosystem. We are all guided by a shared goal: maintaining access to orbit.

References

[1] FCC, "FCC Adopts New '5-Year Rule' for Deorbiting Satellites" https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites (accessed 2025-04)

[2] ESA, "ESSB-ST-U-007 ESA Space Debris Mitigation Requirements", 30/10/2023

[3] Kulu E., "Present status of launched nanosatellites", https://www.nanosats.eu/ (accessed 2025-04)

[4] Steimle C. et al. "ClearSpace-1 In-Orbit Demonstration Mission", https://indico.esa.int/event/516/contributions/9983/attachments/6342/10932/ClearSpace-1%20IOD%20Mission_Clean%20Space%20Days.pdf (accessed 2025-04)

[5] FCC. "FCC Takes First Space Debris Enforcement Action" https://www.fcc.gov/document/fcc-takes-first-space-debris-enforcement-action