**ME 597 Small Spacecraft Design I**

**Report 2: Orbit Debris Mitigation**

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# Acronyms/Abbreviations

* LEO (Low Earth Orbit)
* ADR (Active Debris Removal)
* EDTs (Electrodynamic Tethers)
* ODMSP (Orbital Debris Mitigation Space Program)

# Introduction

The accumulation of artificial debris in Earth's orbit presents an increasing challenge to space operations. While interplanetary dust and meteoroids continuously interact with Earth's atmosphere, the more pressing issue comes from millions of kilograms of human-made orbital debris. Defunct satellites spent rocket stages, and mission-related fragments have led to a growing congestion in Low Earth Orbit (LEO), posing risks to operational spacecraft, human spaceflight, and the long-term viability of space activities.

This paper explores a strategy for protecting spacecraft using a simplified Space Mission Engineering process. Following the U.S. Government's Orbital Debris Mitigation Standard Practices (ODMSP), the study will define the problem, establish key objectives and constraints, assess current and emerging solutions, and propose an optimal shielding approach. The evaluation will prioritize feasibility, effectiveness, and long-term sustainability, offering a structured framework for future implementation.



Figure : Artist Rendition of Orbital Debris (European Space Agency)

# Background

Orbital debris is one of the most significant challenges facing modern space operations. While natural hazards such as meteoroids and asteroid fragments have always been present, human made debris now far exceeds them in both quantity and risk. Millions of objects, ranging from defunct satellites to centimeter scale fragments, travel at speeds exceeding 7 km/s—fast enough to cause severe damage upon impact. Notable incidents, including satellite collisions and fragmentation events, have worsened the issue, increasing the likelihood of cascading debris generation, commonly known as the Kessler Syndrome.

Addressing this threat requires proactive measures such as debris avoidance, advanced shielding technologies, and adherence to established mitigation guidelines. The OSMSP provide a framework for limiting debris generation, but the rapid growth of space activities, driven by constellations, commercial spaceflight, and deep space exploration necessitates more advanced protection strategies. This paper examines potential solutions to enhance spacecraft resilience, ensuring the continued sustainability of space operations in an increasingly crowded orbital environment.

# Problem Definition

The primary objective in addressing this issue is to minimize the risk of spacecraft collisions with debris while also ensuring the long-term sustainability of space operations. Spacecraft designers must navigate the complex challenge of avoiding debris while also balancing the need to limit the creation of additional debris. Furthermore, as the space environment becomes more congested, there is a pressing need to develop innovative methods to protect spacecraft from debris impact.

An effective solution must address the following key needs:

* **Collision Avoidance:** The solution should reduce the likelihood of spacecraft colliding with orbital debris, particularly high velocity fragments that can cause significant damage.
* **Sustainability:** The approach should support the long-term viability of space operations by limiting the creation of additional debris and mitigating the risk of debris proliferation.
* **Scalability and Adaptability:** The solution should be applicable across various mission types and spacecraft designs while remaining flexible to evolving conditions in LEO.

Several constraints must also be considered:

* **Technological Feasibility:** The system should utilize existing or emerging technologies, focusing on practical, deployable solutions that can be integrated into spacecraft design and operations.
* **Cost Effectiveness:** The approach must balance the need for advanced protection with the financial limitations of space missions.
* **Reliability and Efficiency:** Any proposed system should operate with high reliability and minimal operational burden, ensuring spacecraft can continue their missions without added complexity or risk.

Building on existing research in debris removal and mitigation, this study will explore and evaluate strategies for reducing collision risks. Solutions will be assessed from both a design and operational standpoint, with the goal of identifying feasible and effective approaches to protect spacecraft from the growing threat of orbital debris.

# Literature Review

The growing accumulation of orbital debris in Low Earth Orbit presents significant risks to operational satellites and human space exploration. As space missions increase, managing space debris has become a critical priority. Researchers have explored various technologies and strategies to address this issue, including mechanical capture systems, laser-based removal methods, and inflatable drag devices. This review examines key studies and advancements in orbital debris removal, highlighting the effectiveness and feasibility of different approaches. This is by no means an extensive literature of current approaches but a few have been selected that are deemed relevant.

## Active Debris Removal (ADR) Approaches

Active Debris Removal (ADR) is a widely studied approach to mitigating space debris. [1] explore several ADR methods, including robotic arms, nets, and harpoons, which physically capture defunct satellites or large debris for controlled deorbiting. While effective, these mechanical solutions require high precision, advanced robotics, and the ability to manage non-cooperative debris. Laser-based debris removal has also gained attention. Ground-based or space-based lasers can target small debris, using high-powered beams to induce localized heating and ablation, causing objects to lose altitude and re-enter the atmosphere. [1] highlight advancements in laser technology that improve its feasibility for debris removal. [2] propose spacecraft missions designed to capture multiple debris objects in a single operation. Using nets or robotic arms, this approach aims to enhance efficiency and reduce the number of launches needed for debris clearance, offering a scalable solution to the growing space debris problem.

## Electrodynamic Tethers

Electrodynamic tethers (EDTs) provide an innovative alternative to traditional mechanical and laser-based debris removal techniques. As explained by [1], EDTs are long conductive cables that generate thrust by interacting with Earth's magnetic field. When deployed from a spacecraft, these tethers can gradually reduce the orbit of debris, ultimately leading to its re-entry into the atmosphere. The primary advantage of EDTs is their ability to function without relying on conventional propulsion systems, instead using the natural magnetic forces present in space. This makes EDTs a low-cost, fuel-efficient solution for debris removal. However, the feasibility of this method depends on factors such as the size and type of debris, as well as the length and strength of the tether, which must be carefully considered to ensure effective operation.

## Inflatable Drag Devices

Inflatable drag devices as a promising solution for orbital debris removal [3]. These devices are designed to increase the drag area of defunct satellites or larger debris, aiding in their controlled deorbiting. Inflatable structures are particularly effective for large, non-cooperative debris, as they enhance drag forces, causing the debris to gradually lose altitude and re-enter the atmosphere. A notable advantage of inflatable drag devices is their ability to maintain structural integrity with minimal gas use, as natural leakage from smaller particle impacts replenishes the device over time. This self-sustaining feature ensures long-term operational effectiveness, especially during solar maximum when atmospheric drag is elevated. Strategically deploying these devices can significantly improve debris removal efficiency.

## Spacecraft Shielding and Maneuvering

As spacecraft missions evolve to remove multiple debris objects, advanced shielding technologies and maneuvering systems have become crucial complements to active debris removal (ADR) methods. In addition to ADR, spacecraft may be equipped with shielding systems, such as Whipple shields, which consist of multiple layers designed to absorb and deflect smaller debris impacts, reducing the risk of damage to critical spacecraft components. Maneuvering systems, often used in collision avoidance technologies, provide another layer of protection by enabling spacecraft to perform evasive maneuvers when debris is detected along their trajectory. While these systems are effective, they can be fuel-intensive, particularly when dealing with fast-moving or large debris. [4] notes the combination of maneuvering systems and debris tracking technologies is often regarded as the most effective strategy for mitigating collision risks with orbital debris.

## Global Collaboration and International Standards

The growing threat of orbital debris is a global challenge that requires international cooperation for effective solutions. The fragmentation of space debris poses risks to satellites and space stations worldwide, making it essential for space-faring nations to establish shared standards, protocols, and funding mechanisms for debris removal efforts. [5] highlight the need for collaborative efforts, as no single nation can tackle the space debris issue alone. Developing international standards for debris mitigation and removal is crucial for ensuring the sustainability of space activities and protecting valuable assets in orbit.

Addressing orbital debris requires innovative and multifaceted solutions to ensure the safety and sustainability of space operations. A combination of active debris removal methods, including robotic capture systems, laser-based removal, inflatable drag devices, and electrodynamic tethers, shows potential in reducing the debris volume. In addition, technologies such as advanced shielding, maneuvering systems, and real-time debris tracking are vital for safeguarding spacecraft and minimizing collision risks. As the field progresses, international collaboration will be key in creating standardized and scalable solutions to manage the growing debris problem. A concerted global effort is essential to ensure space remains a safe and sustainable domain for future exploration and development.

# Proposed Solutions

To protect spacecraft from the escalating threat of orbital debris, innovative solutions are needed that both prevent debris impacts and mitigate potential damage. Here are three proposed high-level approaches that could improve spacecraft protection

## Active Debris Shielding

One potential solution is the development of active debris shielding, which would incorporate a system capable of detecting and tracking orbital debris in real-time and engaging to either deflect or destroy it before it collides with the spacecraft. The concept behind active shielding involves equipping spacecraft with sensors to identify debris of various sizes and speeds, alongside systems that can adjust the spacecraft's trajectory to avoid impact.

These shields could consist of repulsion systems like lasers or high-energy particle beams, which neutralize debris by altering its velocity and trajectory, or physical shielding such as deployable meshes or barriers that absorb or redirect impact energy. The key advantage of this approach is its ability to mitigate impacts from a broad range of debris sizes. However, challenges include the need for fast, accurate debris tracking and power-intensive mechanisms.

## Passive Shielding with Advanced Materials

Another solution involves passive shielding techniques, particularly through the integration of advanced materials into spacecraft design. These materials, such as multi-layered shields or self-healing materials, are engineered to absorb or deflect debris impacts without the need for active intervention. Examples include lightweight materials like Kevlar, aluminum, or specialized polymers that effectively disperse impact energy.

In addition to conventional materials, innovative options like "Whipple shields" (which use a thin outer layer to dissipate energy through impact with a secondary layer) or composites could be incorporated. These materials would function continuously without relying on sensors or energy input, providing a low-maintenance approach. However, their effectiveness, especially for smaller debris particles, is still being researched.

## Debris Removal or Mitigation Systems

A long-term solution to the orbital debris problem is the development of space-based debris removal and mitigation systems, which aim to actively reduce debris in orbit. One method involves robotic spacecraft equipped with capture mechanisms, such as robotic arms, to collect non-functional satellites or debris. These spacecrafts can then push the debris into a controlled re-entry trajectory or relocate it to a disposal orbit.

Another approach is the use of space-based laser systems, which apply continuous low-pressure beams to smaller debris, guiding them into re-entry orbits. This method would help reduce debris density in orbit, making space safer for active spacecraft and future missions. However, these systems face significant challenges, including high costs, the risk of generating additional debris, and the complexity of accurately targeting and removing debris in orbit.

## Recommended Solution

When evaluating solutions for mitigating orbital debris risks, several factors are key: effectiveness, feasibility, cost, and operational complexity. These factors are especially important given the growing concerns and current technological limitations. Active Debris Shielding offers proactive protection by neutralizing debris. Its main advantage is the ability to address various debris sizes and velocities, potentially preventing catastrophic collisions. However, it faces challenges in tracking debris accurately at high speeds, and power requirements for deflection methods like lasers are substantial. The high cost of deployment and the operational burden of continuous monitoring also pose significant hurdles.

Passive Shielding with Advanced Materials, such as Whipple shields or composites, offers a simpler and more cost-effective solution. It requires minimal maintenance and no active power, relying on proven materials for protection. While it can't protect against very small or high-velocity debris, it remains a practical option for many missions, especially where more complex technologies are not feasible. Debris Removal or Mitigation Systems aim to reduce the debris population by actively removing it. However, these systems face technical challenges, including high costs, complexity in capturing debris, and the risk of creating additional debris. Though promising long-term, they are not yet ready for widespread use. Given the constraints, Passive Shielding with Advanced Materials is the most viable short-term solution. It offers effective protection at a lower cost with minimal operational complexity. While it doesn’t address the root issue of debris, it allows spacecraft to continue operating safely, making it the most practical solution for current missions.

# Next Steps

The next steps in the project should follow a phased approach, focusing on further developing and validating the selected solution, Passive Shielding with Advanced Materials. Additionally, complementary technologies for long-term debris mitigation should be explored to enhance the overall effectiveness of debris protection strategies. The project’s next steps will focus on developing and validating the selected passive shielding solution, along with exploring additional technologies for long-term debris mitigation.

The first priority is to research the latest advancements in shielding materials. This will involve identifying promising materials such as multi-layer composites, Whipple shields, and self-healing materials, and testing their durability and effectiveness against various debris sizes in space conditions. Collaborating with material science experts and space agencies will be key to assessing material properties like strength, impact resistance, and longevity.

Once suitable materials are identified, the next step will be designing and integrating them into spacecraft. This will focus on adapting the materials into lightweight forms that won’t negatively impact mass or aerodynamic performance. Prototypes will be developed, and integration tests will ensure compatibility with spacecraft systems. Testing will also include simulations of high-velocity debris impacts.

After successful integration, prototype shields will undergo testing both on Earth and in space. Laboratory tests with high-velocity projectiles will be followed by space-based experiments, potentially using CubeSat missions. These tests will validate the shields' effectiveness in real orbital conditions and help refine designs for improved performance.

Once passive shielding is validated, a cost-benefit analysis will assess the development and deployment costs in relation to the protection provided. The analysis will help identify the most cost-effective strategies for large-scale implementation, from small satellites to larger crewed missions. Efforts will also focus on optimizing material usage to reduce mass without sacrificing effectiveness.

Finally, research into complementary technologies, such as active debris shielding and debris removal systems, will continue. Integrating active shielding with passive materials could provide layered protection for missions at higher risk of encountering debris. Collaboration with space agencies or private companies working on debris removal technologies will offer opportunities to develop synergistic solutions to reduce debris in orbit. These steps will help protect spacecraft in the short term while preparing for more comprehensive, long-term solutions to the debris problem.

# Conclusion

The accumulation of orbital debris presents a growing challenge to the safety and sustainability of space operations. As space becomes more congested, the risks to both current and future missions increase. Mitigating these risks requires a combination of active and passive technologies. Active systems like robotic debris removal and ion propulsion offer solutions for clearing debris but face significant challenges in terms of cost, complexity, and feasibility. Passive shielding solutions, such as advanced materials like Whipple shields and multi-layer composites, provide protective measures but have limitations, particularly for smaller or faster debris.

Success will depend on the ability to integrate these technologies into existing spacecraft systems in a cost-effective and adaptable manner. Additionally, international cooperation and adherence to global debris mitigation standards will be essential. A coordinated global effort will ensure that these technologies have the greatest impact on long-term space safety.

Further research is needed, particularly in testing active debris removal systems and refining passive shielding materials. Prototypes and small-scale missions will be necessary to validate these technologies under real-world conditions. However, challenges remain in the integration of these systems and their technical viability. Ongoing development, alongside global collaboration, will be key to addressing these issues and creating a sustainable space environment.

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