Mitigating Orbital Debris

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The exponential growth of orbital debris poses a critical threat to operational satellites, human spaceflight, and future space missions. With increasing congestion in low Earth orbit and beyond, space agencies and private industries are developing active debris removal (ADR) and mitigation strategies. This paper examines the latest efforts to manage space debris, including electrodynamic tethers, laser-based deorbiting, and drag-enhancing materials. Additionally, policy frameworks such as debris tracking improvements and international collaboration initiatives are assessed. By evaluating current and proposed mitigation techniques, this study provides insight into the feasibility and effectiveness of different solutions in ensuring long-term orbital sustainability.

I. Introduction

The rapid growth in space exploration has led to a significant increase in orbital debris, commonly referred to as space junk. As of 2025, it is estimated that millions of debris fragments, ranging from defunct satellites to tiny paint chips, are orbiting Earth at high velocities. This growing accumulation poses substantial risks to operational satellites, human spaceflight, and future missions. The potential for collisions not only threatens valuable assets but also exacerbates the debris problem, leading to a cascading effect known as the Kessler Syndrome. This scenario envisions a self-sustaining chain reaction of collisions, rendering certain orbital regions unusable. The increasing congestion in low Earth orbit underscores the necessity for effective debris management strategies.

In response to these challenges, space agencies and private industries are actively developing strategies for active debris removal (ADR) and mitigation. These efforts aim to ensure the long-term sustainability of space operations by addressing both existing debris and preventing the generation of new fragments. This paper provides an in-depth examination of current ADR techniques, most of which are still in a developmental stage, dividing them into contact-based and non-contact-based methods. Contact methods involve physical interaction with the debris, employing mechanisms such as robotic arms, nets, harpoons, and tethers to capture and deorbit objects. Non-contact methods utilize forces or energy to influence the debris' trajectory without direct contact, including laser ablation, ion beam shepherding, electromagnetic manipulation, and solar sails. Each approach presents unique advantages and challenges, necessitating comprehensive evaluation to determine their applicability in various scenarios. Additionally, it assesses policy frameworks that facilitate debris-tracking improvements and international collaboration initiatives. By evaluating these approaches, the study offers insights into the feasibility and effectiveness of various solutions for maintaining a sustainable orbital environment.

II. Contact-Based Active Debris Removal Methods

One of the most straightforward approaches to ADR involves physically capturing debris using robotic arms. These arms are mounted on a servicing spacecraft, allowing for controlled retrieval of debris through precise mechanical movement. The arm extends toward the debris, securely grasping it before either deorbiting the object or transferring it to another system for controlled disposal, as seen in Fig. 1. Robotic arms offer high accuracy in capturing debris, particularly large and cooperative targets. However, this method requires sophisticated guidance, navigation, and control (GNC) systems to ensure successful docking. The European Space Agency, which hopes to reach a standard of "Zero Debris" by 2030, developed a GNC simulation tool for ADR with a robot arm [1]. This project relied on simulating the control algorithms, satellite dynamics, kinematics, and robot arm control. The simulation of deorbiting a satellite was deemed successful, and they are continuing to model more complex models to ensure simulation accuracy. Another notable example in use currently is Northrop Grumman's Mission Extension Vehicle (MEV), which uses a robotic docking mechanism to attach itself to non-functional satellites [2]. The MEV provides propulsion and

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control, either extending the satellite's operational lifespan or guiding it toward a controlled reentry. This satellite-servicing vehicle helps reduce the number of nonfunctional satellites in orbit, thus reducing space debris overall. Robotic arms are one of the more promising ADR technologies because they are versatile and manageable.

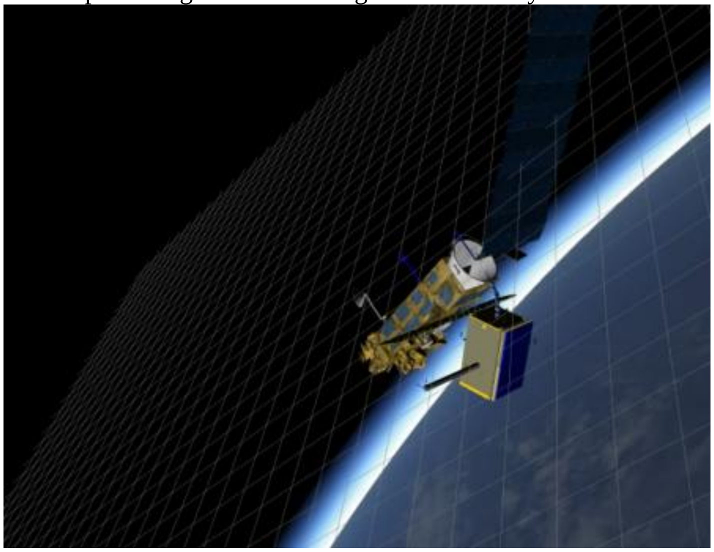

Fig. 1 ESA Capturing Satellite Simulation

Another widely researched contact-based ADR technique is the use of nets. Nets are deployed by a chaser spacecraft to envelop debris, after which they can be tightened to secure the object. Once captured, the debris can either be deorbited directly or attached to a separate propulsion system. This technique is particularly useful for capturing irregularly shaped debris, as the flexible nature of nets allows them to conform to different structures, and the structure can be seen in Fig. 2. The European Space Agency (ESA) has tested this method through its RemoveDEBRIS mission, where a net successfully captured a mock debris target in orbit [3]. The RemoveDEBRIS full mockup can be seen in Fig. 3. The net was ejected at a distance of 6 m and it expanded out to 5 m to wrap around the target. Despite its effectiveness, net-based ADR poses challenges related to deployment precision, as well as potential difficulties in ensuring the captured object remains securely enclosed.

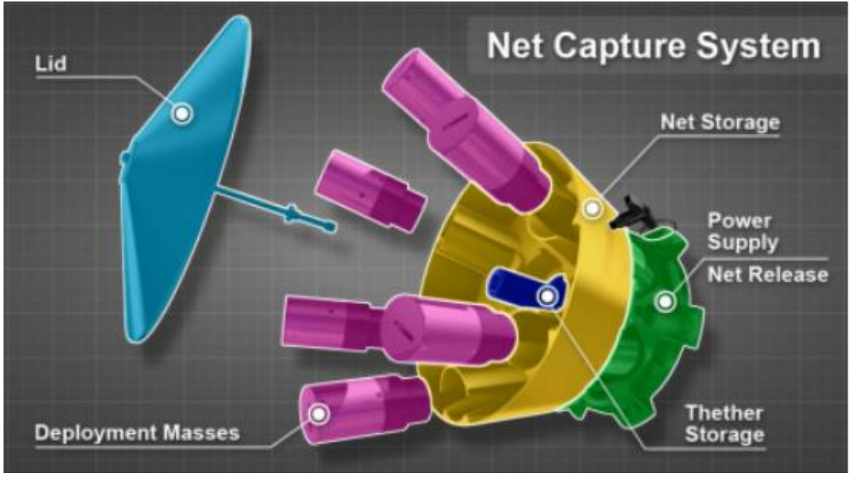

Fig. 2 RemoveDebris Net Capture System

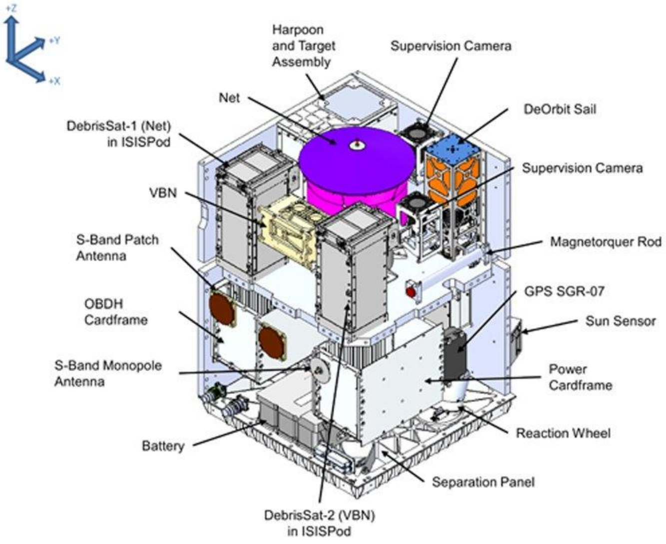

Fig. 3 RemoveDebris Diagram

Harpoon-based ADR methods involve firing a high-speed projectile into a debris object, which then secures itself via barbs or an attached tether. The harpoon mechanism is designed to penetrate debris without causing excessive fragmentation, allowing for controlled retrieval. After attachment, the harpoon system can either tow the debris to a lower orbit or connect it to a retrieval module. The RemoveDEBRIS mission also tested this method, demonstrating its potential for capturing large, non-fragile objects [3]. However, concerns regarding unintended fragmentation and the structural integrity of debris targets remain key considerations.

Electrodynamic tethers (EDTs) have emerged as a highly promising method for de-orbiting large space debris by utilizing long conductive wires that interact with Earth's ionosphere and geomagnetic field to generate an electrical current. This induces a Lorentz force capable of gradually altering an object's orbit until atmospheric drag takes over and ensures controlled re-entry and burn-up. Unlike chemical propulsion, which requires a significant amount of stored energy and propellant proportional to the satellite's mass, EDTs exploit the natural space environment, harnessing existing kinetic energy to facilitate de-orbiting without additional fuel. This makes them a lightweight and efficient alternative for debris removal. Studies indicate that a system consisting of a 5 km tether and a 10-meter-diameter inflatable balloon could de-orbit a 500 kg satellite from an altitude of 1300 km within 20 to 60 days, depending on the orbital inclination, while generating drag forces up to 0.6 N without compromising stability [4]. The adaptability of EDTs allows them to be used for satellites of varying masses with minimal modifications, ensuring re-entry regardless of size. A major challenge associated with EDTs is ensuring reliability and controllability, as maintaining tether integrity is critical for successful operation. There are multi-strand tether designs being explored to extend operational lifetimes beyond one year. Overall, EDTs will likely evolve into a cost-effective and scalable solution for mitigating space debris and preserving the long-term sustainability of Earth's orbital environment.

III. Non-Contact-Based Active Debris Removal Methods

Laser-based deorbiting is one of the most researched non-contact ADR techniques. High-energy lasers can be directed at debris objects to induce surface ablation, generating a small reactive force that gradually alters their orbit. This method offers the advantage of remote operation, reducing the risk of fragmenting the debris. The fundamental principle behind laser ablation is that the rapid vaporization of material on the debris’ surface creates a recoil effect, pushing the object in a controlled manner. Ground-based and space-based laser systems have been proposed. The space lasers offer improved accuracy and reduced atmospheric distortion. ESA has begun designing an end-of-life deorbit service satellite that will start service in 2026, as seen in Fig. 4 [5]. This method has many advantages including its high safety level; the thrust can be provided at 50-200 m, while most other ADR methods require either direct contact or close proximity. Additionally, this technology can adapt to stop objects from rotating. A torque in the direction of detumbling can be made with the laser. Despite its potential, laser ablation requires significant power resources and precise targeting, making its large-scale implementation challenging.

Fig. 4 Deorbit Operation with Laser Beam Illustration

The ion beam shepherd technique utilizes a spacecraft equipped with ion thrusters to exert a gentle but continuous force on debris, effectively altering its trajectory without physical contact. This method involves positioning a spacecraft ahead of the target debris and directing a low-divergence ion beam at the object, allowing for nearly 100% momentum transfer as the ions embed into the debris surface; this diagram can be seen in Fig. 5 [6]. By continuously applying thrust, the technique can induce controlled deorbiting while avoiding the complexities associated with physical grappling or mechanical stabilization of tumbling objects. However, maintaining the spacecraft's position requires a secondary ion beam of nearly equal magnitude in the opposite direction to counteract the reaction force, meaning that only half of the onboard propellant is available for active debris removal. This fuel constraint significantly limits the number of objects that can be deorbited per mission, as hundreds of kilograms of propellant may be required for a single target. The need for prolonged operation times due to the inherently low thrust of ion propulsion further complicates mission efficiency. One potential solution to mitigate the propellant limitation is the use of ambient neutral atmosphere in low Earth orbit as a fuel source, where the shepherd spacecraft could ionize naturally occurring gas and use it for propulsion. This concept, originally proposed for station-keeping in very low orbits, could potentially extend mission lifetimes and reduce dependency on stored fuel. Despite these challenges, the ion beam shepherd technique remains a highly attractive option for active debris removal, offering a non-invasive and scalable approach to mitigating space debris accumulation in long-lived orbits.

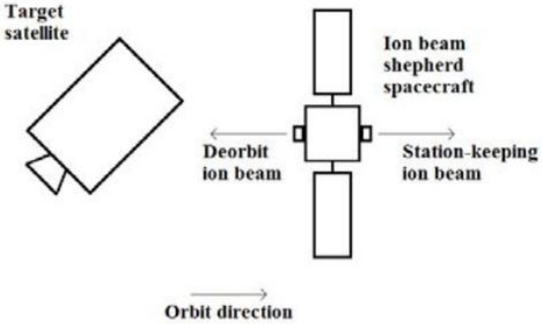

Fig. 5 Ion Beam Sheperd Technique

Electromagnetic manipulation involves using controlled magnetic fields to influence debris movement. By generating dynamic electromagnetic fields, a spacecraft can induce rotational or translational forces on debris, enabling reorientation and trajectory adjustment. One proposed method involves deploying a powerful electromagnet into orbit, capable of adjusting its field strength remotely to attract and maneuver metallic debris of varying sizes [7]. The system would rely on real-time monitoring via sensitive detectors to modulate the electromagnetic force, ensuring the collection of lighter debris with weaker fields and larger debris with stronger fields. This adaptability reduces the risk of destabilizing the electromagnet's orbit while allowing selective targeting of debris. Additionally, the ability to deactivate the magnetic field when approaching operational satellites ensures that critical assets remain unaffected. A major advantage of this technique is its scalability, as a well-designed electromagnet could potentially clear multiple debris objects over its operational lifespan. However, effectiveness is highly dependent on the magnetic properties of space debris, which vary significantly among objects, limiting its applicability. While promising, electromagnetic ADR requires further research to refine field control mechanisms, optimize energy consumption, and develop strategies for handling non-magnetic debris to expand its overall effectiveness.

Solar sails present another potential non-contact ADR solution. By attaching a large, reflective sail to debris, solar radiation pressure can gradually alter its orbit, leading to atmospheric reentry. The continuous force exerted by photons from the Sun provides a slow but steady change in the debris' trajectory. Solar sail technology has been demonstrated in missions such as JAXA's IKAROS, but its application in ADR remains in the experimental stages [8]. The key challenge lies in the deployment and durability of sails, as they must withstand prolonged exposure to harsh space environments.

IV. Policy Frameworks for Space Debris Management

Beyond technological solutions, effective space debris management requires strong policy frameworks to coordinate international efforts. The Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space provide a foundation for national regulations and best practices [9]. These guidelines advocate measures such as post-mission disposal plans and minimizing in-orbit explosions to reduce debris generation. One fundamental principle is to limit the debris released during normal operations. This includes designing to minimize the risk of break-ups and not have sensor covers or separation mechanisms jettisoned into orbit. By doing so, catastrophic failures can be prevented, which have been primary sources of space debris in the past. Other guidelines mandate the controlled removal of defunct spacecraft from the low Earth orbit (LEO) region once their missions conclude. In cases where direct deorbiting is infeasible, objects should be relocated to higher graveyard orbits to prevent interference with active satellites. Similar precautions apply to geosynchronous Earth orbit (GEO), where retired spacecraft must be placed in disposal orbits that ensure they do not return to the operational GEO region. By implementing these policies on a global scale, spacefaring nations and private entities can work collectively to ensure long-term sustainability in Earth's orbital environment.

Another important guideline is limiting accidental collisions. Even small debris fragments can pose a significant threat to satellites and crewed missions. It is important to adjust launch times and perform maneuvers to avoid collisions. To continue avoiding collisions, it is necessary to enhance debris tracking capabilities. Current initiatives aim to expand ground-based sensor networks and deploy space-based tracking platforms to improve real-time monitoring. The European Space Agency (ESA) and the U.S. Space Surveillance Network have been working to develop comprehensive tracking databases to assist in debris management. For example, the ESA has develop a Space Surveillance and Tracking (SST) system [10]. The SST system detects space junk, catalogues the object, determines and predicts their orbit, then monitors the object periodically. It gives other services including conjunction predictions, which is when two objects will have a close approach, fragmentation detection, which is when a fragmentation event has occurred either because of a collision or explosion, and reentry prediction, which helps predicts the orbital lifetime of an object as well as the reentry date and trajectory.

International collaboration plays a pivotal role in ADR efforts. Organizations such as the Inter-Agency Space Debris Coordination Committee (IADC) facilitate dialogue among space agencies to standardize mitigation strategies [11]. Additionally, there is growing support for binding regulations that enforce debris removal responsibilities for satellite operators, ensuring compliance with sustainability goals.

V. Conclusion

The future of space debris management will require a careful and well thought out approach, combining the most promising ADR methods that offer high effectiveness with minimal operational challenges. Robotic arms, nets, and harpoons are among the most viable contact-based techniques, with robotic arms standing out due to their precision and versatility in handling larger debris. Non-contact methods such as laser-based deorbiting and ion beam shepherding also present significant potential, with lasers offering a safe, remote solution for targeting smaller debris, while ion beam shepherding provides a scalable approach for gradual orbit alteration. These methods, when optimized, could play a crucial role in reducing the growing space debris problem. Alongside technological advancements, international collaboration and the implementation of robust policy frameworks will be essential in ensuring long-term sustainability of space. Strict adherence to space debris mitigation guidelines, coordinated efforts to track debris, and binding regulations for satellite operators will be necessary to maintain a cleaner and safer orbital environment.

By integrating these promising ADR methods and fostering global cooperation, we can safeguard the future of space exploration and preserve Earth's orbital regions for the coming generations.

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