Interdisciplinary Requirements and Recommendations to Remediate Space Debris

University of Michigan Problem Solving Initiative

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1. Summary

The growing volume of orbital space debris, ranging from millimeter-sized fragments to defunct satellites, poses a mounting threat to global space operations. This paper outlines a set of engineering, legal, policy, and economic strategies to address debris larger than 1 centimeter, focusing on solutions that are scalable, feasible in the near term, and minimize environmental and diplomatic risks.

Through a literature review and interviews with legal and engineering experts in the space industry, it is apparent that international collaboration will be necessary to find a long-term solution for the space debris problem. While this may be a common conclusion, this paper seeks to go further by providing recommendations for an actionable plan that creates both engineering and international solutions to the increasing issue of orbital space debris.

We propose a three-tiered remediation framework: (1) a space-based laser system for removing small debris (1–10 cm), (2) the “Pac-Man Method” for capturing and returning larger debris to Earth for reuse, and (3) the creation of a long-term in-space salvage zone or “junkyard” to store recoverable materials. To incentivize these efforts, we introduce three financial options: (1) a fee or tax-based mode (a "Debris Tax") inspired by global aviation standards, which would impose a fee-per-kilogram of payload launched into orbit, (2) transferable permits to incentivize competition, and (3) federal appropriated funding support recommendations for the Office of Space Commerce. This revenue would support debris removal technologies and create financial accountability for all space actors. Our approach avoids creating new debris, adheres to existing international policy, and provides a foundation for a sustainable space-based economy in the future.

We also propose reforms to four legal barriers limiting ADR servicing: (1) international legal reform to establish standardized debris ownership consent and clearance protocols (e.g., a UN-backed authorization mechanism and abandonment criteria based on debris size/inactivity); (2) liability clarity through a “Safe Harbor” regime and multilateral registry to reduce risks for cleanup efforts; (3) regulatory streamlining by centralizing U.S. oversight under the Office of Space Commerce to eliminate bureaucratic hurdles; and (4) dual-use governance via international definitions and standards for acceptable ADR servicest to prevent the militarization of ADR technologies and escalatory actions in space. Together, our strategies aim to create clear, collaborative frameworks that enable safe, lawful debris removal while balancing sovereignty, innovation, and global security.

2. Engineering Considerations

The engineering team's goal is to develop an innovative yet achievable system to reduce space debris, supported by this paper's technical foundation in law, policy, and economics. For consistency in this paper, our team defines space debris as any human-made object orbiting Earth that no longer serves any useful purpose (Colvin et al, 2023).

We've chosen to address the space debris problem by narrowing the scope, not by targeting the most urgent or dangerous debris, but by focusing on remediating debris to enable steady, incremental progress. Rather than attempting to solve the entire problem at once, we start where current physical, technical, and legal constraints allow us to lay the groundwork for a scalable, systematic solution. By doing so, we aim to create a foundation for the debris removal landscape, opening the door to tackling the broader problem over time.

2.1 Problem Constraints

This section focuses on the engineering constraints that impact our preferred design choices. We considered technology development, mitigation, fragmentation risk, macroethical/sociotechnical ideas, debris dynamics, and debris type.

2.1.1 Technology Readiness Level

A major consideration for our solutions is technology development. Most Active Debris Removal (ADR) technology is still in the early stages of development, with most testing done in controlled environments, such as Astrobee's robotic free-flier concept (Luabeya, 2024). As such, the goal is to find a solution that is not years away from being available, but rather to find a solution that can be implemented in a shorter timespan. This includes the consideration of factors such as Technology Readiness Level (TRL) and risk to ensure the technology is reliable and avoid creating further issues. TRL is a measurement system developed by NASA to assess the maturity of technology (Manning, 2023). The system uses a numbering system of 1-9, with 1 being early research on a specific technology and 9 being fully developed and flight tested on missions. Our team prefers solutions with higher TRLs to require less effort to be developed for use in space.

2.1.2 Mitigation

Our approach to the space debris problem focuses on ADR, not mitigation. While we acknowledge that mitigation is essential, especially as the number of space objects continues to increase exponentially, we have excluded it from the scope of our recommendations in this paper. We made this choice due to the time constraints' effect on our solution scope, especially with the knowledge that ADR is heavily underdeveloped in comparison to mitigation efforts. Our solutions are focused on creating groundbreaking solutions to remediate current debris, with the plan to work in conjunction with current United States and global mitigation strategies.

2.1.3 Further Debris Creation

To create viable solutions that are risk-averse and do not contribute to Kessler Syndrome, we have established the goal to not recommend solution architectures that generate any further debris. This includes breaking up already existing debris or inserting objects into the space environment that can become debris. Adhering to this constraint meets many of the lofty goals for long-term space sustainability discussed in the legal and policy sections, and allows us to narrow our recommendations considerably.

2.1.4 Self-Imposed Constraints

We have developed self-imposed constraints based on macroethical and sociotechnical concerns regarding the current practices of debris removal – specifically the practice of burning up objects during atmospheric reentry. There are already concerns about ozone-depleting metal deposits entering the atmosphere from this approach. The clouds of magnetic ash deposited in the mesosphere and stratosphere could alter Earth's climate or even its magnetic field (Pultarova, 2024). The long-term impact of this behavior is still unknown. If it is confirmed that burning satellites up impacts the climate or human health, stricter national or global regulations may be imposed. The US-ratified UN Convention on Long-Range Transboundary Air Pollution (CLRTAP) aims to control atmospheric pollution from heavy metals like lead that can be found in deorbiting satellites by restricting "anthropogenic activities that are subject to long-range atmospheric transport," and could be invoked as the rate of deorbiting satellites burning up in the atmosphere increases (CLRTAP, 2025). To avoid these potential regulations, our team chose to focus on solutions that ensure debris above a certain size will not be placed on an orbital reentry that forces burn up, but rather made available for reuse or study either on Earth or at a convenient location in space.

2.1.5 Debris Dynamics

When creating or suggesting a solution to space debris, analysis of the current state in which the debris resides must be conducted. Most debris is in a dynamic state or rotating around a certain axis. This rotation can range from slow and stable spins to rapid and complex tumbling, and can change over time. Even objects that appear inert may exhibit rotations or transitions in their spin behavior, making debris unpredictable and challenging to interact with for removal missions (Hamara et al, 2018).

Another key challenge is successfully counteracting a debris object's rotation externally. This process, called detumbling, is important to ensure that debris is safe and secure during capturing procedures. Any failure in the process could cause debris to break into pieces, creating more debris or moving to a new undesired location. Detumbling methods vary depending on the size of the object being captured and its location, and are only necessary when physical contact is necessary for remediation. While research was conducted on detumbling methods for a variety of debris sizes, we will only be presenting methods suitable for the targeted debris sizes.

2.1.6 Debris Type

The type of debris being targeted determines the technology used for its removal. Factors such as debris size, location, and ownership are among the most critical considerations, and constraints, when designing a space debris remediation technology. Size and location influence the physical structure of the system, while ownership presents legal and diplomatic challenges discussed in the legal section on ownership. After exploring current solutions and speaking with subject matter experts, we decided to only target debris larger than 1 cm as anything smaller is incredibly difficult to track and monitor. Some of the largest debris pieces pose the greatest danger, yet their ownership complicates removal efforts. These were key considerations in our design. The following sections explain how we addressed these constraints.

2.2 Selection Methodology and Suggested Solutions

Our initial plan to remove the 50 most dangerous debris objects (McKnight et al., 2021) was abandoned due to ownership and liability issues (see Sections 4.1 and 4.2) and uncertainty about the state of these largely Russian or Soviet-origin objects, which would require complex diplomatic and technical efforts to remediate. We shifted to this approach because we can still combat Kessler Syndrome by removing 12 objects from orbit (McKnight et al., 2021), and these do not have to be very risky or dangerous objects. Targeting objects originating from the United States and signatories of the Artemis Accords is easier both legally and technically. While removing high-risk debris would reduce overall environmental risk, assessing such risk is complex and can delay action. Therefore, we prioritize objects that align with higher-TRL mission architectures and fall under US jurisdiction. Given the sheer amount of space debris in the environment, specific debris objects that meet the requirements were not identified for this report/memo/paper. Instead, debris specifications (i.e. size, mass, etc., limits) are shared for each mission architecture/technological solution. An analysis of risk quantification/assessment is discussed in Appendix B, and next steps to address this assessment process are proposed. Focusing on these easier objects also improves our understanding of debris characteristics and facilitates international collaboration during solution development.

Even with our group’s thoughts on reusability and sustainability, we came to the conclusion that the cost to move small debris (CubeSat size or smaller) for reuse was unreasonable compared to completing an atmosphere re-insertion to burn these objects up. The cost of developing a remediation solution for these objects outweighs the minimal benefits from reusing them. Thus, we are saving the reuse-based ideas for medium and large debris objects (e.g. defunct satellites and spent upper stages of rockets).

After careful consideration of our constraints and perspectives, we ideated three engineering architectures that can serve as solutions to the space debris problem. These solutions are designed to avoid the creation of further space debris, burn-up of medium and large debris objects in the Earth’s atmosphere, and complex legal and political issues while providing a scalable, remediation-focused solution. These suggested solutions address debris of various sizes and will span different deployment timelines, providing a gradual approach to ADR. We also attempted to propose solutions that target various debris sizes and orbital shells, so that if all of these architectures were implemented, the most comprehensive solution could be achieved.

2.3 Launch & Rendezvous Strategy

All of the solution architectures proposed here plan to use existing and developing commercial launch methods, as these methods have shown to be on a robust trend of improving reliability, cost-effectiveness, and capability. The technical concerns involved with the orbital maneuvers required to reach specific objects, while certainly non-trivial, do not present a significant obstacle to feasibility for any orbit likely to be impacted by orbital debris. The main manner in which the solution architectures proposed here seek to make rendezvous more technically achievable across mission sets is to reduce the form factor of the ADR solution payloads and make them as adaptable to differing launch and orbital maneuver system architectures as possible.

It’s also important to develop and standardize methods by which debris can be assessed upon initial contact. The physical state of the object relative to its “initial” or functioning state, any tumbling the object may be exhibiting, and other relevant concerns regarding the targeted object should be observed and documented in a rigorous, thorough, and standardized fashion. As this information is nearly impossible to obtain in any real detail prior to first contact for debris removal, a system for accurate measurement of these and any other relevant parameters for capture and disposal- as early as possible in mission timelines- will be critical to maintaining efficiency in the ADR system architecture and operations.

Lastly, a number of regulatory barriers exist to obtain the FAA licenses for launch and potential reentry, FCC spectrum licenses for communications with earth stations, and NOAA approval for utilizing remote sensing during ADR missions. All of our proposed engineering solutions would require compliance with these regulations, as discussed in Section 4.3 of this paper. Section 4.3 also provides our group’s reform proposals to reduce these regulatory barriers.

2.4 Atmospheric Reentry Solutions

In addressing the cleanup of small debris (<10 cm), we deemed it necessary to relax some of our sustainability focus that frowned upon atmospheric burn-up of debris. For the small debris problem, atmospheric burnup is necessary due to the cost, complexities, and size characteristics that come with the small debris issue. Our proposed methodology, which follows from this, is our use of space-based lasers to help solve the issue of debris that is small in size at lower orbits.

2.4.1 Space-Based Lasers

This solution architecture utilizes laser technology to remove small debris objects from orbit, assisting in the process of deorbiting these objects into the Earth’s atmosphere. This provides a relatively scalable and implementable solution that can remove a significant amount of debris objects over time. We believe this to be the most technically feasible, and recommend that it should be developed and explored further immediately.

Underlying Technology

The specific technology behind lasers for space debris solutions generally falls into two methods: (a) laser ablation and (b) photon pressure. Both of these methods utilize a laser to transfer momentum to an object at a distance. Both pulsed lasers and continuous wave (CW) lasers can be used for this purpose. These are considered beyond state-of-the-art technology and have been considered for space capacity in many forms.

Photon pressure applies a radiation pressure force via photons to an object, causing a small perturbation to its orbit. (Walker and Vasile, 2023; “Radiation Pressure”, 2025). Laser ablation actively removes material from a solid by evaporating or sublimating it (low laser flux) or turning it into a plasma (high laser flux), which does not add more debris to the space environment (“Laser Ablation”, 2024). The ablated material is “ejected approximately perpendicular to the surface and generates thrust in the opposite direction” (Colvin and Locke, 2024). This method requires “more powerful laser beams and greater optical precision” than photon pressure, but it can generate much more thrust (Colvin and Locke, 2024).

Our team has chosen to pursue pulsed lasers that perform laser ablation. We are avoiding CW lasers to reduce concerns of weaponization and to allow for this architecture to apply an opportunistic model to removing debris. As for photon pressure lasers, they do not provide enough force to substantially alter a debris object’s trajectory. Photon pressure could still be used as a defense system against active debris on future high-value spacecraft, but that is out of scope for this suggestion.

Ground-based lasers are another option for contactless space debris removal via laser. However, we are not recommending it as a solution. A ground-based laser system targets debris of sizes 1-10 cm, utilizes ablation, and has a limit of debris at an altitude of around 425 km for a maximum (Colvin and Locke, 2024). Since 1-10 cm debris is generally considered untrackable, a ground-based laser system has a smaller window for finding and observing a piece of debris before removing it. This is due to the need to both identify an object and remove it before it passes over the observation zone and is lost from view. A ground-based laser also experiences added complexity as the laser beam may distort due to atmospheric attenuation generated through first passing through the atmosphere before making contact with the debris (Walker and Vasile, 2023).

Space-based platforms are advantageous because they bypass the issue of atmospheric attenuation and turbulence (weakening/loss of a signal due to scattering by Earth's atmosphere). They provide better alignment opportunities and shorten distance between the laser's origin and target (Walker and Vasile, 2023). Space-based lasers employ a more opportunistic approach to removing debris and can actively target specific pieces of debris as long as some characteristics of the debris are known, so we are recommending them as a solution.

Solution Architecture

Space-based laser technology has been explored by Walker and Vasile, Pieters and Noomen, Phipps, Schall, and many others (see references), which our recommendation is heavily inspired by. We are suggesting a scalable, space-based satellite constellation where each satellite is equipped with a pulsed laser (e.g. traditional crystal laser, flexible fiber laser, glass laser, etc) and optics to detect and track debris objects. Specific laser energy and power vary based on concept, and our team has chosen not to set these specifications. This constellation would start in orbital shells highly populated with debris objects and then expand outwards to create a cascading debris removal effect. This expansion method avoids pushing debris into objects at other altitudes as much as possible, minimizing the potential to create more debris. The exact optimal starting altitude is currently undetermined, but should be based on the debris objects' natural decay time. We are also interested in the potential to integrate these technologies into already existing satellite constellations or attach them to space stations or other primary, long-lived objects in LEO.

Debris Size

Space-based laser ablation applies specifically to small debris, typically debris ranging from 1-10 cm in size. This debris often has the potential to cause the end of a mission via collision because most objects under 10 cm in size cannot be adequately tracked. Also, with this debris size, lasers can most effectively ablate material to change an object's trajectory and speed up the natural deorbit process.

Technology Readiness Level

In terms of Technology Readiness Level (TRL), both laser technology and tracking technology (e.g. cameras, radar, lasers) exist and are tested and well-understood, but an in-space laser system for debris remediation has not been qualified (TRL 7) or proven in an operational environment. Progress made towards higher TRLs includes the 2014 concept mission "Laser Ablative Debris Removal by Orbital Impulse Transfer (L'ADROIT)" (Phipps, 2014), which introduces the idea of an ultraviolet pulsed laser that would not pose any hazard to other space-based sensors. A 2015 proposal from international contributors details a staged approach to remediation for debris from

5 mm to 10 cm, starting with a proof of concept, in-space demonstration missions with a laser attachment on the International Space Station, and finally a unique space-based laser system (Ebisuzaki et al., 2015). Walker and Vasile developed and simulated a slightly different mission concept than L'ADROIT using pulsed laser ablation in 2023. Their analysis also confirmed that "it is possible to optically acquire small (2 cm) fragments of debris in orbit using a small camera with no *a priori* knowledge of individual orbits" (Walker and Vasile, 2023). NASA included space-based laser systems as a solution for small debris (1-10 cm) in both their 2023 and 2024 Cost Benefit Analysis reports for debris mitigation and remediation, providing a concept of operations as well as a summary of efficacy and cost. These proposals and concepts must be built upon to ensure that space-based lasers for debris remediation can be flight-tested and proven in the orbital environment.

Timeline

This is a solution that NASA currently deems as the preferred approach for sub-10 cm debris objects, both in terms of cost and TRL. We suggest that this solution be developed as soon as possible. All of the necessary technology currently exists, so executing this solution only requires developing and deploying a system in which these technologies can successfully work together in space.

Risk to Space Environment

The primary risk to the space environment is due to the unknown state of debris objects. Since debris objects are often not uniformly shaped, rough, and made out of multiple materials, there is potential for laser ablation to have issues such as edge effects or punch through/fragmentation (Colvin and Locke, 2024). Edge effects occur when some of the laser pulse is wider than the debris object itself, causing the edges of the material to ablate, causing erroneous forces, and causing parts of the beam to travel past the target object and be potentially harmful to other objects nearby (Colvin and Locke, 2024). If a debris object is small enough, the laser might punch through the debris object, potentially causing fragmentation of the target object and damage to other objects nearby (Colvin and Locke, 2024). These risks invoke concerns under the Liability Convention should the laser cause damage to the space capabilities of under the ownership of another country, discussed in legal section 4.2. However, these risks can be researched and potentially mitigated during solution development, especially if considering a UV laser as proposed in the L'ADROIT mission concept. Another way to mitigate this risk is to test these systems by addressing small debris objects in more sparsely populated orbital shells to refine in-space laser technology. Overall, the risk mitigated by remediating 1-10 cm debris provides more than enough motivation to continue pursuing this solution.

Policy Considerations, Key Challenges, and Next Steps

Laser ablation technology for space debris removal offers a promising, direct, high-tech solution that requires significant policy, technical, and environmental considerations. The NASA policy directive 8715.6E highlights the potential risks of using high-powered lasers on space objects that must be addressed (NASA, 2024a). There are also likely concerns to be addressed regarding perceptions of weaponization, regardless of actual use potential in the offensive sense. Laser ablation technology for space debris removal raises concerns around national security and dual-use technology, as these lasers can have military applications. In addition, laser systems would need to be integrated into international space debris removal frameworks, considering treaties and agreements on space traffic management and debris mitigation. Coordination with other space-faring nations would be essential to prevent accidental damage to satellites and ensure safe operations; additionally, the DoD would prioritize integrating laser systems into Space Situational Awareness (SSA) frameworks to track, while also overseeing the technology's development to prevent misuse or malfunctions.

The primary technical challenges include avoiding any damage to the laser, since once it is launched, there is no current way to repair the technology. Potential technical failures include laser contamination, optical damage, or the effects of vibrations on the laser system. Optical damage is especially important because these systems require powerful optics to track small debris objects at a distance. A failure of these systems in space would be expensive and unfortunate, so it is vital to explore these concepts further when developing this solution.

Current legal challenges create hurdles to implementing a space-based laser system. The technical difficulty of tracking small debris, especially within the 10cm and below range, makes it difficult to determine legal ownership of the debris. As discussed in legal Section 4.1, without highly efficient communication between sovereign space operates with the potential to have such a collision, a presumptive principle of abandonment should be adopted for smaller debris so that countries are authorized to use space-based laser systems to remove their small debris or protect their space capabilities from other pieces of debris at 10 cm or less. Questions of liability for such abandoned debris would have to be further considered, and while legal Section 4.2 discusses a list of general liability reforms, the ability for other countries to take actions against such small debris once established should reduce the need for such current strict liability in these circumstances. Lastly, the regular deorbiting and burning up of small debris at a high volume could invoke CLRTAP, discussed in Section 2.1, however our proposal limits this risk by only authorizing debris at 10 cm or less and we still anticipate the development of debris mitigation efforts to improve rapidly over time to reduce the necessity of such small debris deorbiting.

Another important challenge to consider comes from the international concerns about putting lasers in space and the implications of these systems on one nation's space defense capability. A laser system directly invokes concerns about dual-use potential to be an ASAT weapon and not receive regulatory approval, as discussed further in the legal section 4.4. However, by ensuring that rules and regulations from Laser Clearinghouse and the governing international space treaties and conventions are met, these systems would not (and could not) be used as weapons.

There are two key differences between the lasers used for small debris remediation and for military weapons: the type of emission and power levels. Weaponized lasers (ones that could melt or destroy a satellite) are generally CW, meaning they emit a high-power beam for seconds to minutes to deliver as much destructive energy as possible. Lasers used in our solution for space debris remediation are pulsed, emitting bursts that last only nanoseconds or picoseconds, ablating small surface layers of material. Since 2021, the United States military has been developing pulsed high-energy lasers for missile defense, but these systems require “minimum peak power of one terawatt and a maximum of five terawatts” (Peck, 2021). This illuminates the other key difference between weaponized lasers and debris remediation lasers. According to NASA’s 2023 Cost Benefit Analysis, weaponized lasers require 100 MJ per pulse with energy densities of up to 100 kJ/cm² for hardened targets, while debris-removal lasers use tens of kJ of power per pulse with energy densities up to 5 J/cm². This means that, on average, a laser system used for debris removal is about 1,000 times weaker than a laser needed to destroy a spacecraft, meaning debris remediation using laser technology has limited weaponization potential. While some types of lasers could dazzle or damage satellite sensors, much lower-powered lasers already exist that can do this, many of which are already commonly used by astronomers and observatories (Colvin et al., 2023). Also, this system would not pose a threat to humans on Earth for similar reasons, but also due to atmospheric attenuation of laser beams, which causes the signal to weaken or vanish.

Business Case

When implementing this system and considering its cost, it is vital to start in orbits that will clean up considerable amounts of debris to best protect future missions that could be impacted by small debris. There are currently LEO orbits that are either filling up or already not in use due to large numbers of active satellites and space debris that leave those places unusable. This is inherently a loss of profit potential and a hindrance to the in-space economy that is rapidly growing. This means there is a pressing need to clean up these orbits from space debris so that they remain usable and don’t hinder future advancements. A primary location for the constellation to start is a region where satellite collisions or anti-satellite weapons testing have occurred, as there will be many small fragments to remove. Another option is to consider orbits that are populated and also have a naturally long decay time. So, while cleaning up the space debris may not provide a return on investment in the short term, it could provide the potential to use orbits in the long run that can benefit Earth for the foreseeable future.

The concept we have suggested thus far provides opportunities where the laser satellite constellation may not always be firing at pieces of space debris. This could be for various reasons, but generally when the lasers are not firing at debris, they have the opportunity to have a multi-use case where they could potentially be doing another line of business that may or may not be profitable (Colvin et al, 2023). The potential of a dual-use laser constellation system has the ability to find profitable areas while performing the space debris removal mission. This inherently doesn't have any form of ROI with burning up the debris. Another, slightly different, dual-use case comes from the potential to put laser systems on already existing constellations. Remediating debris from the orbital shell around a constellation can reduce the number of necessary maneuvers, thus reducing propellant and power use while prolonging spacecraft life.

In 2023, NASA created a low-cost estimate based on the L'ADROIT mission concept created by Phipps and a high-cost estimate by expanding on L'ADROIT with legacy mission assumptions and constraints on efficiency and debris irregularity. With their analysis, it would cost \$300–\$3,000 to remove one piece of cm-sized debris, and a total of \$15 M–\$150 M to remove 50,000 pieces. This would be for one spacecraft flying in a polar orbit with a laser system attachment, so the cost for our proposed solution would likely be lower on a per satellite basis but higher overall, given we are suggesting a constellation of satellites, but this provides order of magnitude estimates for mission cost.

2.5 Reusability-Focused Disposal Methods

The in-space laser solution goes against our philosophy regarding sustainability, but as outlined in the Problem Constraints and Selection Methodology and Suggested Solutions sections, our team deemed these debris objects acceptable to burn up on reentry. The next two recommended solutions cover larger debris sizes and have the potential to support an in-space economy by focusing on the reuse of materials, either via Earth insertion or via a space Junkyard.

2.5.1 Pac-Man Method

Underlying Technology

Our second recommended solution relies on inserting debris back into the Earth without burnup to reuse the debris. This solution would occur on a shorter time scale than reusing the debris in space. The technologies required for this concept exist, but combining them for this context would require significant advancements, with the final goal being similar to how humans and larger vehicles return to Earth. This is a field that has had lots of investment within the last 5 years, and we are seeing companies create a realistic market for orbit-to-earth surface-controlled and safe reentry vehicles. Companies like Varda Space, Inversion Space, Space Forge, and others are starting to have successful missions validating hypersonic reentry technology, leading to a growing industry that is scaling up the abilities that we currently see to larger platforms.

The Earth insertion method we are proposing in this paper has been dubbed the "Pac-Man Method." This method utilizes future upper-stage rockets that release their satellite payloads and renter Earth with debris. Although this technology is challenging to develop, it could be a realistic solution to bring down debris to Earth in a controlled manner, also allowing for potential reuse of the debris materials.

Solution Architecture

Depending on upper stage volume and geometry, the Pac-Man Method could be used to remediate multiple smaller pieces of debris or one/a few large pieces of debris, either option filling the available space. This solution would require sending an ADR spacecraft to rendezvous with, capture, and maneuver the target debris to the upper stage return vehicle.. Since the concept of upper-stage reentry is not fully developed, technology like a reentry heat shield (similar to the one used by Varda Space) may be utilized for the ADR spacecraft and its captured debris.

Capture Technology

There are two types of capture technology that are best utilized for this solution architecture: robotic arm(s) and tentacles. Both of these are considered to be physical capture methods which are attached to a chaser satellite, a spacecraft which approaches the debris target.

Robotic Arm

A robotic arm capture system would include a configuration of either a single or multiple mechanical arms controlled by a computer and used to complete different functions. This configuration requires the ability to grab onto a part of the debris target (Saunders, et al., 2014). A robotic arm may have several types of mechanical effectors, the end part which makes contact with and ultimately grabs onto the target. There are many types of mechanical end effectors that may be simplified into three main categories: grippers, tools, and sensors (B2E Automation, 2022). Each type of mechanical effector may have different uses and may be best suited for different targets. For the purposes of this architecture, a gripper end effector would likely be the most suitable. Even within the gripper category, there are many types of end effectors (Wu, et al., 2016). In this application, it would be important to choose a mechanical effector, in this case a type of gripper, which is suitable for a wider range of target types, is adaptive, and does not require specifically designed capture attachments or the creation of a force closure during capture.

Robotic arms have been readily used in space environments as seen in various applications, including Canadarm2 on the International Space Station (ISS) (Canadian Space Agency, 2024), orbital express of DARPA (Friend, 2008), and many others (Flores-Abad, et al., 2014). However, capturing a space debris object has the added complexity of being a non-cooperative target, meaning an object that does not send signals or characteristics to an approaching satellite (Zhang, et al., 2022). This requires additional steps to be taken to safely secure a debris target with a robotic arm. Since all debris is tumbling to some degree, de-tumbling is often required when using a robotic arm. The only cases where additional de-tumbling measures may not be needed are when tumbling is relatively small. De-tumbling may require an additional attachment or hardware to be included on the chaser satellite to safely detumble the target before capture (Liu, et al., 2019).

There are a few detumbling options that are especially useful for physical contact solutions like the robotic arm and tentacle. One such idea is a guidance algorithm that combines capture and detumbling into a single maneuver, allowing for a smooth capture by aligning with the target's motion (Romano and Virgilili-Llop, 2019). There is also a flexible brush that acts as a passive end effector, generating friction and elastic forces that gradually reduce its angular velocity (Cheng, Li, and He, 2019). One other method is an ion beam shepard concept, which emits an ion beam at an object (Bombardelli and Pelaez, 2012). This beam applies a continuous low-force thrust to the object, allowing for modification to the debris's orbit or altitude.

Tentacles

Another method is capturing using tentacles. The tentacle method also utilizes a chaser satellite, to which the tentacles are attached, to rendezvous and capture the target debris. The tentacle attachment refers to tentacle-like gripper arms containing clamping mechanisms that can grab onto space debris (Shan, et al., 2016). There are multiple types of tentacles that have been proposed, including looped belt configurations (Chiesa, et al., 2015), shape memory alloys (Feng, et al., 2017), and those similar to biology, such as an octopus or an elephant's trunk (Shan, et al., 2016). In general, this method encircles the target debris with the tentacle mechanisms before the tentacles stiffen and bring the debris closer to the chaser satellite to secure it.

There is precedence for combining the tentacle method with a robotic arm including ESA's proposed e.Deorbit mission (Biesbroek, et al., 2013) and research that resulted from the proposal. This seeks to first grab onto the target debris with a robotic arm before maneuvering the debris to fully secure it with the tentacles. In this instance, a robotic arm is useful for additional precision and control with maneuvering the debris target. A robotic arm can also be useful in aiding in detumbling a debris object to the point where tentacles can safely grab on (Singh, et al., 2019). Without a robotic arm, the tentacles must first loosely grab onto the target before completing additional maneuvers and attitude adjustments required to allow the tentacles to stiffen and lock around the target. This is necessary to avoid collisions related to capturing an object which may undergo movements when the tentacles are operated, since there is no connection prior to the stiffening of the clamping mechanisms. An addition of a robotic arm would reduce the precision needed for approach and introduce a stabilization aspect before tentacles are fully engaged (Singh and Mooij, 2020); however, this does result in several disadvantages, including higher mass, cost, and complexity (Shan, et al., 2016).

Additional Considerations on Capture Technology

Both the robotic arm and tentacle configurations may require additional data for rendezvous including accurate relative positioning and velocity of the target (Liu, et al., 2019). It may also be beneficial to know the state of the target, through being able to observe it prior to contact being made (Zhang, et al., 2022). Due to both being physical capture methods, it will be necessary to grab onto the target which may be made difficult or result in additional debris creation if the proper procedures are not taken into consideration. This is mainly to avoid additional collisions or by grabbing onto a point of the target which may have reached a previously unknown state of degradation. Knowing the state of the object and knowing how or where to grab onto may prove more challenging for a target whose state is unknown or which has been defunct for longer.

Both robotic arms and tentacles may be enhanced through gecko gripper attachments. This refers to mechanical attachments which can grip surfaces similar to the pads of a gecko's feet, which have unique adhesion qualities that allow them to adhere to surfaces using van der Waal forces, weak electrical attractions (Hickman and Kubota, 2017). Gecko grippers do not require additional force to be applied since they contain tiny flaps that only need to be placed in the right direction to generate the intermolecular forces needed for adhesion (Gasparini, 2021). This may enhance the ability of the tentacles or robotic arm to grab onto the debris target more easily without accidentally losing it. In the case of the robotic arm, the ability to apply this may depend on the mechanical effector chosen.

The size of the debris able to be captured using these methods will be 10 cm or larger. While there has been research into capturing larger pieces of debris using these capture methods (Chiesa, et al., 2015), for the purposes of the "Pac-Man Method" which fills up an Earth reentry vehicle, it may be more beneficial to focus on smaller-sized debris greater than 10 cm. Capturing and removing smaller debris around 10 cm and exceeding several U in size (1U refers to the size of a standard CubeSat of 10 cm x 10 cm x 10 cm, with each additional U being an extendable version of this) will have higher TRLs. Currently, tentacle methods have been tested on the International Space Station (ISS) by Kall Morris Inc. (KMI), likely rendering this technology at a higher TRL (Morris, 2024). As previously mentioned, there have also been several robotic arms used in space (Canadian Space Agency, 2024; Friend, 2008; Flores-Abad et al., 2014). The base technology for this would render a higher TRL.

There are previously proposed missions and missions in development that include the use of robotic arms or tentacles to capture space debris. One of the previously proposed missions, which has since lost funding, was ESA's e.Deorbit mission. This mission was intended to capture the 8-ton Envisat satellite using either tentacles with the possibility of a robotic arm addition or a tether net mentioned in Appendix A (Biesbroek, et al., 2013). Aviospace's Capture and DE-orbiting Technologies (CADET) research and development project also looked into capturing larger debris objects such as upper stages of older launch vehicles and decommissioned satellites (Chiesa, et al., 2015). There has also been research and prototype design into capturing and deorbiting a CubeSat-sized object using dual robotic arms (Nagavarapu, et al., 2024). Missions in development include Astroscale's Adras-J technology, which is being developed for JAXA's Commercial Removal of Debris Demonstration (CRD2) mission. Up to this point, Astroscale has demonstrated rendezvous capabilities during the first phase of the project (JAXA, 2024a). The second phase will seek to utilize robotic arm technologies aboard Adras-J to capture and deorbit the debris target (a Japanese upper stage rocket body) (JAXA, 2024b). Further development into the rendezvous and actual approach and capture would be needed since this has yet to be fully tested on non-cooperative space debris objects.

Timeline

With regards to the timeline for implementing this sort of technology, it is not an immediate technology that could be implemented today, but we could start working to implement this within the next 5 years. There are two parts of this technology that need to be further developed to make this a realistic option for the present. First, we need to establish and demonstrate rendezvousing, detumbling, and capturing debris to show that this sort of methodology is capable. Secondly, to be able to utilize the "Pac-Man" method, we need the fully reusable reentry vehicles to be established. We see companies like RocketLab, SpaceX, and Blue Origin pushing to make these a reality. Optimistically, we will see the successful completion of the first one of these, the SpaceX Starship, which will be operational by the end of the year. Once the reentry vehicle is completed, there will need to be all new analyses on how they can rendezvous with the debris and hold onto them securely so that they can bring them back down to earth with the vehicle's reentry.

Key Challenges and Policy Considerations

The Pac-Man Method has inherent risks for the rest of the space environment. The transfer of debris from a higher orbit to lower orbits, either for the sake of earth insertion, reentry via an attached drop capsule, or a Pac-Man reentry, presents risks of hitting other pieces of debris or active satellites. Further, this methodology raises unique considerations regarding both technological feasibility and international regulations. Per NASA's policy directive NPR 8715.6E, it must comply with the controlled re-entry protocols and safety measures. It must, too, work within the framework of the UN Outer Space Treaty: (1) implementing strict safeguards to avoid damage to other space assets or interference and (2) states must remain responsible for any space activities conducted by private entities to ensure transparency and effective communication among space-faring nations (NASA, 2024a). Moreover, the Liability Convention and Registration Convention under the UN Framework should be taken into account to establish clear protocols of liability in case of damage; i.e., clearly designing who is responsible if debris removal results in damage to another country's satellites or infrastructure. The legal reforms proposed in section 4.2.5 address ways to support a regulatory environment that could utilize this method Lastly, the method's technological advancements could have dual-use implications, particularly because re-entry technologies have military applications related to capture and disabling the space capabilities of other countries, and legal section 4.4 addresses these concerns and potential reform. The Pac-Man Method also requires compliance with FAA reentry guidelines as discussed in legal section 4.3, which is one of the many regulatory barriers this method will face. As such, there should be regulatory policies implemented to ensure that technologies remain restricted to peaceful uses and are governed by stringent national and international security protocols.

Business Case

This type of architecture is not cheap, it would likely require an individual satellite for each debris that is acquired and although you can likely rendezvous multiple pieces together for reentry to save costs, this would drastically increase the complexities and increase personnel and planning costs. This method is one, however, that could provide a return on investment to the users though. The ability to return the material to Earth provides the ability to reutilize whatever is brought down.

2.5.2 Junkyard

Junkyards on Earth serve as sites for disposal and waste management, but they are also places where discarded materials are reclaimed and repurposed. This same concept can be applied to space. If we consider space debris as junk, why not create a junkyard for it? After all, one person’s space junk could be another’s space treasure. It is important to note that from a logistical and policy standpoint, decision-makers might prefer a term like "Salvage Zone," which aligns with the precedential standards of maritime salvage and abandonment laws which can be used to efficiently push forward the development of international norms for national or international space junkyards (National Space Society, 2019).

Underlying Technology

The Space Junkyard concept involves designating a specific area, outside the graveyard orbit, where space debris can be decommissioned and stored for potential repurposing. To populate this junkyard, debris would need to be retrieved and placed using ADR technologies or, when possible, self-navigation.

The two most promising technologies for capturing debris for transportation to a Space Junkyard are a robotic arm or a tentacle configuration. Similar to the recommended technology for the Pac-Man Method, a robotic arm configuration may include a single robotic arm or multiple. In addition, the tentacle configuration may include solely tentacles or a combination of tentacles and a robotic arm. A gecko gripper enhancement may also be useful to add to this architecture. Both of these methods were chosen for the same reasons as previously described and would be implemented in the same, or similar, ways.

Solution Architecture

The location of the Space Junkyard is a key factor in determining how it can be implemented today. Less frequently used Earth-Moon Lagrange points (L4 and L5) (Kaiser, 2024) were considered as potential sites, as objects in these regions tend to remain stable without requiring containment structures like nets or enclosures. Once a location is established, spacecraft of any size could be captured and maneuvered to the junkyard, though the focus would likely be on larger debris (10 cm or more), as we have decided that redirecting smaller fragments is not worth the effort. Currently, the TRL for this concept is low, making it one of the more complex solutions to implement. It relies heavily on technologies in the ADR field, which is currently at a low TRL since there has not yet been an example of a successful, repeatable ADR solution.

For this solution to be viable, transportation of target debris from LEO to the Junkyard would be necessary. If the target object is decommissioned and without contact or power, it will be necessary to supply the debris target with propulsion, a control system, and power systems to move the debris in a safe manner while avoiding collisions with other space objects. Hall-effect thrusters (HET) can be used for propulsion to maneuver target debris. They operate through converting inert gases to ionized plasma (Li, 2024). They are relatively less complex and require less propellant than other propulsion systems . When equipped with a mechanical suspension system, a HET can generate thrust in three spatial directions. To steer and effectively maneuver debris, thrust vector control could be integrated into a HET (Stark, Gondol, and Tajmar, 2022). An additional option may be to incorporate the HET into a CubeSat which can then be attached to the debris target, based on a HET's usefulness in orbital satellites and deep space missions (Bapat, Salunkhe and Patil, 2022). In this instance, the CubeSat would have a control system onboard which can then be integrated with the HET to make maneuvers to reach the desired 'Junkyard' location.

Timeline

Given the highly futuristic nature of this solution and its dependence on the advancement of ADR technology, the Space Junkyard represents the longest-term approach. Its development cannot be fully outlined until the timeline for ADR technology becomes clearer and more established.

Key Challenges and Legal/Policy Considerations

The Space Junkyard is a highly complex solution that requires careful consideration of both technical and logistical challenges. Key technical questions include which ADR methods will be used to transport debris, how the junkyard itself will be structured, and whether spacecraft will be stored in close proximity to one another. Beyond these technical hurdles, ownership and security present additional concerns. The Outer Space Treaty (OST) Art. I establishes outer space for the benefit and interests of all countries, and Art. II bans the national appropriation of space, creating difficulties on the ownership of national junkyards in space. Issues of Organizations and governments may not be comfortable with their defunct spacecraft being stored in an easily identifiable location without protections against other nations. This issue is particularly sensitive for government spacecraft that may contain classified technology or data. Safety is another critical factor as some debris may include explosive or volatile components that could degrade over time, posing a potential hazard within the junkyard. This invokes the

One significant risk is the potential for clogging up Lagrange points, which could limit their availability for future scientific or operational missions. While these points offer stable regions for storing debris, overcrowding could create new navigation and collision hazards. Another concern is the presence of explosive or volatile components within the junkyard. Over time, these materials could degrade, leading to accidental detonations or fragmentation, further contributing to the space debris problem rather than solving it. Proper mitigation strategies, such as controlled disposal or secure containment, would be essential to managing these risks.

To highlight, this methodology requires careful policy considerations centered around environmental stewardship and the long-term sustainability of orbital space. This concept must address the passivation of debris, as outlined in NASA-STD-8719.14C, to ensure that the debris in storage does not pose explosion risks or create safety hazards for operational satellites (NASA, 2021). The policy framework must be established to include debris passivation protocols that mitigate the potential for hazardous scenarios, ensuring that debris is deactivated or neutralized before being moved to the junkyard. This means that international regulations will need to be established to create clear guidelines for the collection, storage, and transport of debris, ensuring that these activities are carried out in a transparent, coordinated, and responsible manner. Furthermore, the regulatory oversight from agencies such as NASA and the Department of Defense (DoD) will be essential in maintaining compliance with both international and national space laws, unless the reforms we propose in the legal section 4.3.2 are adopted in which case it would be the Office of Space Commerce (OSC). This oversight should include monitoring to ensure that the junkyard remains aligned with the goals of sustainable space operations and international efforts should ensure that it does not become a tool for military purposes or exacerbating space-based conflicts.

Business Case

The Space Junkyard presents one of the most challenging business cases to justify. Its profitability would rely entirely on the ability to repurpose collected debris into valuable resources. Companies like CisLunar have already demonstrated techniques for converting space debris into structural materials or even fuel for electric propulsion. However, the financial viability of such efforts remains uncertain, as the return on investment is not yet substantial enough to drive widespread adoption. The primary competitor to this technology is the simple cost of launching mass to orbit, and with that cost/kg decreasing as launch costs decrease the challenges for making financial viability of this increase. For this concept to succeed, advancements in in-space manufacturing, recycling technologies, and economic incentives, such as government subsidies or private sector investments, would be necessary to offset the high costs of debris retrieval and processing. We believe this will be an industry of the future that revolutionizes space manufacturing, but until it is ramped up to that scale the challenges remain.

2.6 Future Engineering Research

Overall, ADR technologies need to be developed expeditiously in order to achieve any of our proposed solutions. Each of our solutions has clear next steps that have been outlined in the respective *Key Challenges* sections, but there are some overarching considerations that must be addressed. Funding research into the proposed solution architectures and working toward technology demonstrations should be the highest priority. This includes analyzing the feasibility of the solutions at an in-depth technical level and generating cost models and other necessary budgets (power, mass, link, etc). Confirmation of an economic, legal, and policy framework is also required for these solutions to exist. Once implemented, these solutions aim to create a domino effect, spurring other nations to follow suit in debris remediation efforts in order to remain competitive in the space industry.

2.7 Engineering Conclusion

The intention of this project is to suggest scalable, remediation focused solutions to space debris. We came up with three solutions: 1) laser ablation for small debris with the relatively shortest timeline, 2) Pac-Man for medium to large debris with the second longest timeline, and 3) Junkyard for medium to large debris for the longest timeline. These suggestions are agnostic of regulation and ultimately require a combination of financial foundations and policy frameworks to support the technical solutions. Each of our provided solutions can be picked up individually from each other but any combination of these together would help tackle different facets of the space debris problem. The ideal goal would be a commercially funded model that supports all three of these in addition to mitigation methods, to not create new debris, to keep the outer space environment as safe and sustainable for the future as possible.

3. Economic Considerations

A key challenge inhibiting debris removal is the current state of the space economy and incentives. Alongside continued technological development, it is vital to support incentives and a financial system that supports the execution of active debris removal (ADR) missions. In this discussion, we will focus on two different medium term solutions to address the issue, including developing a funding source for technology for space debris remediation and a cap and trade-like tradable permit scheme. Later in this report, we will discuss how in-space manufacturing and recycling orbital debris could eventually create a self-sustaining economy and generate returns in a much longer term time horizon.

3.1 Debris Tax Funding Model

We have developed a tax-based funding model called the “Debris Tax.” It is inspired by the Carbon Offsetting and Reduction Scheme for International Aviation (ICAO, 2025) system used in aviation, which has 131 member states creating the first global market-based scheme that applies to a sector. This suggested “Debris Tax” could be the second global market-based scheme applicable to the space sector. The CORSIA system helps fund efforts to offset environmental damage from air travel. Currently, rocket launch vehicles, many of which use the same carbon-based fuels, are not subject to a similar tax. Rocket launch vehicles contribute to environmental harm and space debris, yet face no equivalent cost per-kilogram of fuel or payload. The "Debris Tax" would change that. It proposes a mandatory fee based on the mass of each payload sent to orbit. The revenue would fund initiatives aimed at mitigating space debris and supporting sustainable space operations.

Charging a fee for every kilogram launched into orbit creates a financial incentive that holds all space actors accountable for orbital debris. We acknowledge that quantifying these costs is a major challenge, but have outlined a minimal cost example below. To ensure shared responsibility, only 50% of this disposal tax can be passed from launch providers to satellite operators. This split guarantees that everyone involved, from launching to operating in orbit, pays their fair share toward maintaining and cleaning up space. Making it a 50% mandate ensures an equal split in those using orbital environments and those that allow those to get there equally get affected as space faring actors.

If the United States were the first to implement a space launch tax, it could face short-term disadvantages, such as restricting launch capabilities for the rest of the world. However, the U.S. currently leads the world in launch capabilities by a large margin and has room to absorb a modest cost increase while still undercutting global competitors, thereby hindering capital allocation to move outside of the United States. This opens the door to a "first-mover" advantage, driving investment in sustainable space infrastructure and future technologies that could become vital for national security. Crucially, this could be achieved without raising government spending or increasing the burden on taxpayers.

A key element of this proposal is the creation of an independent regulatory body, separate from government to prevent bias in investments, that would manage the funds collected through a disposal tax. This setup ensures that funding decisions remain unbiased, with resources directed toward companies developing technologies for active debris removal. Over time, as international collaboration around this issue grows, the regulatory body could evolve into a global institution. Its role would be to coordinate and distribute funds among participating nations, advancing innovation through international perspectives. Addressing space debris is a global challenge, and it demands a globally unified response.

The example below shows the potential financial impact of the Debris Tax if it were applied in the U.S in 2024, focusing only on SpaceX. It’s important to note that this analysis covers just one company, not the entire launch industry. With launch technology advancing quickly, the financial estimates here are likely conservative. Table 3.1 shows how this cost could be implemented and how that would affect launch providers and satellite producers and Table 3.2 shows potential annual tax revenue that could be gained, if only implemented against SpaceX based on 2024 launches and future projections. (SpaceX, 2025) (Davis, 2024)

Table 3.1: Debris Tax Implementation Cost Outline

Falcon 9 2024 Launch Cost	$70,000,000
Kilograms to LEO	9500
Cost $/kg to orbit	$7,368
Disposal tax ($/kg)	$250
Total Increase Cost	$2,375,000
Increase Cost to Launch Provider per/launch	$1,187,500
Increase Cost to Satellite Producer $/kg	$125
New Total $/kg for satellite manufacturers	$7,493

Table 3.2: Annual Tax Revenue Generation if implemented for just SpaceX over the next 5 years.

Year	2024	2025	2026	2027	2028	2029	2030
# Launches a year	135	162	194	233	279	335	403
Annual Disposal Tax Revenue ($)	320,625,000	384,750,000	461,700,000	554,040,000	664,848,000	797,817,600	957,381,120
Estimated Annual Launch Increase	20%						

This model assumes launch costs remain constant and launch frequency increases steadily. That's a weak assumption. With next-gen vehicles like SpaceX's Starship, launch costs are expected to drop significantly. This reduction in price will likely increase the already rising frequency of launches that we see today.

One concern some might raise about this model is the potential cost burden on satellite providers, possibly limiting access to space. However, the proposed tax is small and unlikely to impact the overall budgets of large satellite programs. Smaller companies launching fewer or smaller satellites would face minimal costs, while larger companies with more or bigger satellites would pay more. This creates a fair system where those who use space the most, which contributes to more debris, bear a larger share of the cleanup costs.

3.2 Lack of Short-Term Economic Viability of In-Space Manufacturing

Regarding reusability of materials within space, we have decided to stay away from the topic of In-Space or On-Orbit Assembly and Manufacturing (ISAM/OSAM). This is the alternative option from a tax-based government incentivized model that creates finances for creating technology for space debris remediation. This method would create an economy out of the debris and allow for commercial and natural return on investments. Long-term there is significant potential within this as an economy that supports itself in debris cleanup that would incentivize cleaning up previous debris for its resources.

However, for the short-term the reason behind why this is not a viable option to produce natural commercial funding for the issue is that the technology isn't infeasible, but rather that we believe this technology is too far out in terms of development timeline. The first five to ten years of building up solution architectures should be focused on collecting and disposing of previous debris. This technology should not necessarily wait for future development but rather refrain from deployment until the technology is mature enough to capture previous debris, ensure its reusability, and then apply ISAM/OSAM methods.

This in conjunction with our "junkyard" disposal method fits the mold for creating a long-term in-space sustaining economy around debris cleanup that would support in-space developments.

3.3 A Space Economy Powered by Tradable Permits

As space activity accelerates, so does the threat posed by orbital debris. Tens of thousands of defunct satellites, spent rocket stages, and fragmentation debris now clutter Earth's orbits, particularly low Earth orbit, increasing the risk of collisions that could damage active satellites, trigger cascade effects, and jeopardize the long-term sustainability of the space environment. Despite growing awareness, current international regulations are voluntary, enforcement is weak, and the market does not yet internalize the cost of debris creation. To address this, a US-led cap-and-trade permit system offers a promising, market-based solution that could reduce debris risk while enabling continued commercial growth (United States).

A permit system would be similar to those adopted for other natural-resource management uses, including most notably, cap-and-trade systems for greenhouse gas emissions, but the similar concepts are also used for taxi medallions and telecommunications spectrums (Buchs, 2021).

Under such a system, the US government would set an annual cap on allowable debris-generating activity, measured in units such as mass, satellite-years in orbit, or a risk-based index, and issue tradable permits to satellite operators. These permits would be required for new launches and ongoing satellite operations, effectively placing a price on orbital capacity. Operators who launch fewer satellites, shorten orbital lifetimes, or adopt more sustainable designs could sell excess permits, while those with larger constellations or riskier orbital profiles would need to purchase additional permits. Over time, permit prices would reflect the scarcity and value of orbital space, guiding industry behavior toward more responsible practices.

Creating a system of tradable permits also creates a powerful incentive for active debris removal and international collaboration. Groups that remove legacy debris, such as dead satellites or uncontrolled rocket bodies, would be issued permits, rewarding the removal of debris that increases orbital capacity. These credits would be fungible within the system, meaning they could be sold to satellite operators needing additional launch or orbital permits. This directly monetizes orbital cleanup and turns ADR into a viable, revenue-generating service. In this framework, private firms or public actors investing in ADR are rewarded through market participation, while satellite operators can offset their impact by funding or performing debris removal.

This model also invites international participation without requiring formal treaties. Foreign firms or space agencies that remove US-tracked debris (with owner consent) would be eligible to receive permits, which could be sold within the American permit market. This provides new incentives for international actors to participate in orbital cleanup efforts. The US could further require that any satellite accessing its launch services, spectrum licensing, or ground infrastructure must hold the appropriate permits, ensuring compliance even from foreign entities. As a gesture of goodwill, the US could provide a list of objects that it maintains control over. This system leverages American market dominance to promote global standards, while creating a pathway for international debris removal firms to profit from participation.

Over a 10-year horizon, the cap-and-trade system is expected to have manageable compliance costs, perhaps adding 2-5% to satellite operating budgets, while generating substantial revenue for the US government. Although permit prices will be set by the market, one current conception of the optimal fee to internalize collision risk would start around $15,000 per satellite-year in orbit in 2020 and escalate about 14% annually, reaching roughly $235,000 per satellite-year by 2040 (Adilov, Alexander, and Cunningham, 2020). This corresponds to steadily rising permit prices as orbits become more crowded (the increase encourages faster removal and fewer launches). If we apply that growth rate, a debris permit in the early 2030s might cost on the order of $50,000–$100,000 per satellite per year of orbital lifetime. As an example: a company launching a satellite that it plans to operate for 5 years would need permits for 5 satellite-years, which by 2030 could cost ~$250k (if permits are ~$50k each on average).

Depending on permit prices and the size of the cap, annual auction revenue could exceed $500 million by 2035, with total revenues potentially reaching $3 to 5 billion. These funds could support ADR bounties, research and development, and improvements in space situational awareness. For the industry, the presence of a functioning permit market provides planning certainty, while pricing orbital use creates incentives to innovate in low-debris technologies and post-mission disposal.

Enforcement would be integrated into the existing US licensing system. Permits would be required as a condition of launch and spectrum licensing through agencies like the FAA and FCC. Violations, such as operating without a permit or generating unpermitted debris, would trigger fines, license revocation, or denial of future launches. Space tracking systems, both governmental and commercial, would verify compliance and confirm successful debris removals that qualify for ADR credit issuance.

A cap-and-trade system with integrated ADR permits offers a practical and scalable solution to the orbital debris crisis. It shifts the burden of mitigation onto those who profit from orbital access while rewarding those who clean up the environment. By starting with domestic authority and expanding access to international actors through ADR incentives, the US can lead a global effort without waiting for fragile international consensus. This work is important, and implementing an optimal incentive system (like fees or permits) could more than quadruple the long-run value of the space industry by 2040, from around $600 billion under business-as-usual to about $3 trillion. A tradeable permit scheme not only protects the long-term viability of orbits but also ensures the space economy can continue to grow, cleaner, safer, and more sustainably.

3.4 Office of Space Commerce Recommendations for Federal Appropriation Request Support

This section is providing economic recommendations given the federal appropriation approval of $75.6 million for the Office of Space Commerce, significantly enhancing its operational and research capabilities. This funding level boost is by a coalition of expert organizations, including the National Space Society (NSS), the American Institute of Aeronautics & Astronautics (AIAA), and the Secure World Foundation (SWF) (National Space Society, American Institute of Aeronautics & Astronautics, & Secure World Foundation, 2024). The requested appropriation would enable three critical initiatives: expanded orbital debris material research, development of robust space situational awareness (SSA) and space traffic management (STM) capabilities, and acquisition and retention of specialized professional staff for operational excellence. These initiatives align with U.S. commercial and national security interests while adhering to international frameworks established by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) (United Nations Office for Outer Space Affairs, 2023a).

3.4.1 Orbital Debris Research Imperative

The proliferation of orbital debris represents an existential threat to continued space operations and future missions. Current tracking systems catalog approximately 23,000 debris objects 10 centimeters or larger. In comparison, estimates suggest approximately 500,000 objects of 1 centimeter or larger and upwards of 100 million debris objects of at least 1 millimeter exist in Earth's orbit (NASA Orbital Debris Program Office, 2024).

The FY 2026 OSC plan necessitates comprehensive research into orbital debris materials, longevity characteristics, and disposal methodologies. This research would benefit from centralized laboratory facilities and designated "neutral landing zones"—more vacant or undeveloped geographical areas can safely receive deorbited materials for analysis and disposal (Office of Space Commerce, 2025).

Scientific analysis conducted by AIAA-affiliated researchers indicates that debris approximately one centimeter in size poses a significant risk to operational satellites. Current models project the loss of one active satellite roughly every 20 years due to debris impacts. According to White House analytical projections, this risk profile worsens as debris populations increase (Office of Science and Technology Policy, 2024).

3.4.2 SSA and STM Capability Development

The commercial space sector currently represents an annual economic value of approximately $22.4 billion (Space Foundation, 2024a). To sustain this growth trajectory, Congress must accelerate Space Traffic Management initiatives that provide operational stability and regulatory certainty, enabling continued private sector innovation and investment. With projections indicating support for nearly 20,000 additional satellites from commercial and defense entities, enhanced SSA and STM capabilities are essential for managing this unprecedented orbital congestion (Federal Aviation Administration, 2024). Recent collaborative investments, such as the $550,000 grant from NASA and OSC for the "RAD Framework for the Moon" project at the University of Maryland, exemplify research initiatives requiring expansion under increased funding (NASA, 2024b). Robust STM capabilities serve three critical national interests:

1. **National Defense:** Countering adversarial threats from increased satellite deployments and non-kinetic interference with critical space-based assets
2. **Meteorological Forecasting:** Enabling proactive responses to transient space weather phenomena, including X-ray flares, GPS disruptions, and communication interference
3. **Technological Competitiveness:** Furnishing advanced tracking equipment, data correlation systems, and predictive modeling for spacecraft positioning and orbital allocation (Department of Defense, 2024)

3.4.3 Professional Expertise Requirements

Although rural America represents only 13% of the U.S. workforce and merely 5% of computer and mathematical occupations, this demographic disparity presents a strategic opportunity for space sector development (U.S. Bureau of Labor Statistics, 2024). The current workforce limitations in rural regions—particularly across Appalachia (West Virginia, eastern Kentucky), the Mountain West (Colorado, New Mexico), and the Deep South (Alabama, Mississippi)—have created infrastructure gaps that expanded Office of Space Commerce (OSC) funding could address through specialized training and retention programs (National Science Foundation, 2022). Rural communities in these regions often possess geographical advantages for space operations, including lower population density, reduced light pollution, and proximity to existing aerospace corridors. Yet, they lack the professional workforce capable of managing the growing complexity of space operations.

This expertise gap is especially pronounced in states like Alabama, which hosts NASA's Marshall Space Flight Center but struggles with brain drain in surrounding rural counties; West Virginia, where topographical challenges have historically limited economic diversification; and New Mexico, home to Spaceport America but facing persistent rural employment challenges (Aerospace Industries Association, 2024). The workforce deficiencies extend beyond technical positions, including regulatory specialists, orbital dynamics experts, and communications professionals needed to support the space industry ecosystem.

The recommended funding increase would enable additional research and data collection sites focused on orbital Space Situational Awareness (SSA) and Space Traffic Management (STM) capabilities, creating specialized employment opportunities in STEM fields previously unavailable to rural populations (Space Foundation, 2024b). Expanded OSC funding would simultaneously address rural economic development needs while enhancing national security through distributed space operations infrastructure by establishing targeted education pathways and incentives for professionals to remain in or relocate to these regions (U.S. Department of Commerce, 2023).

4. Legal & Regulatory Challenges for Active Debris Removal Missions

In the rapidly evolving field of space development, the pressing issue of space debris management raises complex legal questions spanning ownership, liability, regulatory approval, and national security. We begin with exploring the nuances of international law concerning ownership and sovereignty, examining whether entities can legally claim, remove, or alter space debris without violating legal statutes. The legal framework surrounding these actions presents challenges in navigating sovereignty claims and property rights in outer space. Turning to liability and risk allocation, we delve into the intricacies of accountability in instances where debris removal operations might damage operational satellites or exacerbate the debris problem, necessitating a thorough understanding of who bears responsibility in such scenarios. Next, we review regulatory approvals necessary for ADR missions, which currently require coordination among various agencies, including the FCC, FAA, NOAA, NASA, and DoD. The need for a streamlined process that facilitates efficient operations without regulatory bottlenecks is clear. Finally, we grapple with geopolitical and security risks, raising concerns that active debris removal (ADR) missions might be perceived as military threats or dual-use technology, potentially leading to international tension. Collectively, these discussions underscore the core legal complexities in managing space debris through various ADR missions.

4.1 Cross Border Communication and Coordination on Sovereignty and Ownership

The proliferation of space debris poses an existential threat to the sustainability of near-Earth orbits. Active Debris Removal (ADR) technologies offer a promising solution, yet their deployment is hindered by unresolved legal ambiguities surrounding ownership and sovereignty.

Existing international space law. This part examines these challenges and proposes reforms to reconcile state sovereignty with the urgent need for global debris mitigation.

4.1.1 Legal Framework in Ownership and Sovereign Rights of the Space Debris

Table 4.1: Current International Treaties and Guidelines on the Space Debris

Outer Space Treaty 1967	Ownership and Jurisdiction (Article VIII): The OST establishes that launching states retain perpetual jurisdiction and control over their space objects, even if they become non-functional. This creates a legal barrier to removing debris without explicit consent from the original state.
	Liability and Responsibility (Article VI): States bear international responsibility for national activities in space, including those conducted by private entities. This places liability risks on governments if ADR operations by commercial actors cause harm, discouraging states from endorsing third-party debris removal.
	Prohibition on Harmful Interference (Article IX): ADR technologies such as robotic capture or laser nudging could be interpreted as “harmful interference” if they disrupt other states’ assets, particularly in contested orbits like GEO.
Liability Convention 1972	Absolute Liability (Article II): Launching states are absolutely liable for damage caused by their space objects on Earth or to aircraft. However, the treaty does not clarify liability for damage caused during ADR operations, such as accidental collisions during debris capture.
	Fault-Based Liability (Article III): For damage occurring in space, liability is based on fault. Proving fault in the chaotic orbital environment—where debris trajectories are unpredictable—is nearly impossible, creating legal uncertainty for ADR operators.
Registration Convention 1975	Incomplete Ownership Records: While the treaty mandates registration of space objects, it does not require states to update the operational status of objects (e.g., marking them as "abandoned" or "non-functional"). As a result, decades-old debris remains legally tied to launching states, complicating removal efforts.
Non-Binding Guidelines	The UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS) has issued debris mitigation guidelines, but these lack enforceability. Similarly, the International Telecommunication Union (ITU) regulates orbital slot allocations but has no authority over debris removal.

4.1.2 Sovereignty Concerns and Jurisdictional Conflicts

The OST grants launching states perpetual jurisdiction over their space objects, but it does not address scenarios where debris crosses multiple orbital regions or interacts with assets from other states. A U.S.-based ADR operator seeking to remove a defunct Chinese satellite in a shared LEO corridor, for instance, would need to navigate conflicting interpretations of jurisdiction, liability, and consent. The Liability Convention's fault-based liability regime for damage in space (Article III) adds another layer of complexity, as ADR operators risk legal action if their activities inadvertently harm third-party assets.

The dual-use nature of ADR technologies also amplifies sovereignty risks. Technologies such as robotic arms and rendezvous and proximity operations, while designed for debris removal, could theoretically be repurposed for anti-satellite (ASAT) activities. Please see more at 4.4

4.1.3 Proposed Solutions for Ownership and Sovereignty Challenges

International Debris Clearance Authorization Mechanism

Institutional innovations are equally critical. An International Debris Clearance Authorization Mechanism (IDCAM), housed within UNCOPUOS, could serve as a centralized platform for verifying ownership status, mediating disputes, and issuing multilateral removal licenses. The IDCAM's mandate could mirror the International Seabed Authority's role in regulating deep-sea mining, balancing state sovereignty with collective resource management. Complementing this, a Space Dispute Arbitration Tribunal under the Permanent Court of Arbitration (PCA) could adjudicate conflicts over sovereignty or liability, leveraging precedents from maritime and aviation law to ensure impartiality.

"Presumptive Abandonment" Principle

To address ownership ambiguities, the international community should adopt a "presumptive abandonment" principle. Drawing from ISO 24113 orbital debris mitigation standards, objects that remain uncontrolled for over 25 years—a timeframe aligned with current guidelines for post-mission disposal—could be deemed legally abandoned. This would allow multilateral ADR missions to proceed without requiring explicit consent from the original launching state, provided efforts are made to notify and consult relevant parties. For example, the European Space Agency's ClearSpace-1 mission, scheduled for 2028, has established a precedent by securing removal authorization from 12 states whose debris is targeted, demonstrating the feasibility of multilateral coordination.

Table 4.2: “Presumptive Abandonment” Principle Breakdown

Size Category	**Examples & Risk Level**	**Specific Abandonment Criteria**
Small Debris (< 10 cm)	Small fragments, paint flecks, bolts, screws; Untrackable, extremely numerous (millions); Very high risk due to collision threat.	**Automatically** considered abandoned at the moment of creation (or 6 months), unless the launching state explicitly declares sovereignty or ownership upon creation in an international registry. Any actor may freely remove without specific permission.
Medium Debris (10 cm – 1 m)	Small defunct satellites, mission-related debris; Trackable, numerous (tens of thousands); Significant collision risk.	Presumed abandoned after **20 consecutive years** of inactivity (no signals, no maneuvers, no telemetry data), **unless the launching state explicitly claims** continued ownership or sovereignty in the international registry. Once presumed abandoned, any capable entity may remove it.
Large Debris (1 m – 100 m)	Large satellites, rocket bodies, boosters; Potential strategic, technological value; Trackable, significant collision hazard.	Presumed abandoned after **20 consecutive years** of inactivity. A **notification** is provided to the original launching state by an international oversight entity at least **6 months** in advance. If the launching state does not respond or object within these 6 months, **abandonment is implied,** and the debris may be removed.
Very Large Debris (> 100 m)	Space stations, large spacecraft, upper rocket stages; High strategic sensitivity and collision risk; Rare but critical risk objects.	Presumed abandoned only after **20 consecutive years** of inactivity, with explicit notification provided by the international oversight entity to the original launching state 1 year in advance. **Explicit written consent** from the launching state is required before debris can be declared abandoned and removed (notification + explicit consent rule).
Additional Conditions and Measures	- A comprehensive international registry and notification system maintained by a multilateral entity; - Regular status reviews by an international oversight authority; - States requesting exemptions must regularly reaffirm object safety and orbit management; - If debris enters a critical high-collision-risk orbit, the oversight entity can request immediate remedial action from the launching state (launching state retains responsibility for consequences if failing to act); - Incentives (salvage awards, insurance benefits, international reputation bonuses) to encourage active debris abandonment declarations and removals. - All declarations, exemptions, notifications, and consents must be publicly documented to ensure transparency; - Sensitive technological debris removal must include coordination with or oversight by the original launching state to ensure safe disposal or secure destruction, preventing sensitive technology proliferation.	

Transparency and Confidence-Building Measures

Sovereignty concerns could be mitigated through Transparency and Confidence-Building Measures (TCBMs). A mandatory disclosure regime, managed by the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS), could require states and private operators to publish ADR mission plans, orbital trajectories, and risk assessments. This would reduce suspicions of covert military activities and align with the OST's mandate for "due regard" to other states' interests (Article IX). Additionally, the ITU could prioritize debris removal in congested orbits, such as GEO, by integrating ADR objectives into its satellite coordination processes. Compensation mechanisms, funded through an International Debris Removal Fund (IDRF), could offset losses for states whose orbital assets are affected by removal operations.

Revision on the Treaties and Interpretations

Legal reforms are essential to modernize the outdated space law framework. Amending the Registration Convention to mandate periodic updates on space object status—such as marking objects as "abandoned" or "scheduled for removal"—would clarify ownership and streamline ADR approvals. A new Binding ADR Protocol, negotiated under the OST, could define standardized procedures for obtaining consent, exempting compliant ADR operators from fault-based liability, and establishing dispute resolution mechanisms. For instance, the protocol could require ADR operators to demonstrate adherence to technical guidelines, such as using non-destructive capture methods approved by the Inter-Agency Space Debris Coordination Committee (IADC).

4.1.4 Conclusion and Recommendations

The escalating space debris crisis demands urgent legal and institutional reforms to reconcile state sovereignty with collective responsibility. Key recommendations include: Adopt a “Presumptive Abandonment” Principle: Legally define debris abandonment under different standards to enable multilateral removal; Establish an International Debris Clearance Authorization Mechanism (IDCAM) under UNCOPUOS: Centralize cross-border ADR approvals and dispute resolution.; Enhance ITU-UNCOPUOS Collaboration: Integrate debris removal priorities into orbital slot allocation processes.

4.2 Rights, Responsibilities and Reform

There are significant legal obstacles that arise when one country removes another country's debris during an ADR mission. This section explores four key concepts: (1) the rights that authorize countries to conduct debris removal; (2) the obligations countries must observe during removal operations; (3) the international responsibility and liability framework that applies to removal activities; and (4) potential reforms to encourage more effective debris removal while ensuring proper accountability. Understanding these concepts is essential for policymakers, space agencies, and other stakeholders involved in addressing the growing challenge of space debris management.

4.2.1 Current Framework

Legal Classification of Space Debris

Under international space law, "space debris" refers to all human-made objects, including fragments and elements, in Earth orbit or re-entering the atmosphere that are non-functional. Despite their non-functionality, these objects maintain their legal status under the Outer Space Treaty regime. The legal classification of an object as "debris" does not exempt it from the jurisdiction and control provisions established in space law, which has significant implications for removal operations by third parties.

Legal Basis for Active Debris Removal

International agreements form the foundation for space debris management:

1. The Outer Space Treaty (OST) establishes fundamental principles:
   - Article I: Space exploration should benefit all countries and be "the province of all mankind"
   - Article III: Activities must comply with international law and promote cooperation
   - Article IX: States must conduct space activities with "due regard" for others and avoid harmful contamination
2. The Space Debris Mitigation Guidelines developed by the Inter-Agency Space Debris Coordination Committee (IADC) and adopted by the UN Committee on the Peaceful Uses of Outer Space (COPUOS) provide voluntary measures for debris reduction.

4.2.2 Rights and Obligations in Active Debris Removal

Rights to Remove Debris

Countries have legitimate rights to conduct active debris removal based on several principles:

1. **Environmental Protection**: Article IX of the OST and the 1963 Treaty Banning Nuclear Weapon Tests create an obligation to protect the space environment. When facing space debris pollution, a country may take action to fulfill this duty.
2. **Common Interest**: Article I of the OST establishes that space activities should benefit all humanity. Removing debris that threatens future space access serves this common interest.
3. **Cooperation Principle**: The Declaration on International Cooperation in Space (1996) emphasizes that countries should cooperate in addressing challenges like space debris.

Obligations When Removing Debris

Despite the rights mentioned above, countries must observe important legal constraints:

1. **Respect for Jurisdiction**: Article VIII of the OST establishes that countries maintain "jurisdiction and control" over their space objects indefinitely. This means the country

that registered the satellite (the "registry state") retains legal authority even when the object becomes debris.

2. **Procedural Obligations**:
    - Consultation with the registry state
    - Notification of removal plans
    - Information exchange about technical approaches
    - Due diligence to prevent damage during removal
3. **Emergency Exceptions**: In urgent situations threatening the space environment or human safety, removal might proceed with expedited procedures, but still requires reasonable efforts to notify relevant parties.

4.2.3 Responsibility and Liability Framework

The international legal framework distinguishes between two types of accountability:

1. **Responsibility for wrongful acts**: Based on fault and applies when a country violates international obligations.
2. **Liability for damages**: Applies even for lawful activities that cause harm.

Responsibility for Wrongful Acts

A country removing debris could commit wrongful acts in several ways:

1. **Violating International Obligations**: This includes:
    - Using techniques that violate safety standards (causing biochemical spills, radiation release, or creating more debris)
    - Using force contrary to the UN Charter
    - Conducting military activities under the guise of debris removal
2. **Acts at Fault**: Fault exists when a country:
    - Fails to fulfill consultation obligations with the registry state
    - Conducts removal without consent or UN authorization
    - Neglects due diligence toward the registry state or third parties
    - Intentionally uses incorrect techniques
    - Operates beyond agreed parameters

Liability for Damages

Even when removal activities are lawful, liability for damages may arise based on:

1. **Negligence and Causation**: The removing country is liable if:
    - It fails to meet reasonable standards of care and diligence
    - There is a direct causal link between the removal action and resulting damage
    - The damage was reasonably foreseeable

2. **Types of Compensable Damage**:
    - Loss of life or personal injury

    - Property damage to space objects
    - Environmental contamination
    - Potentially certain consequential damages
3. **Reversibility Considerations**: Liability may be reduced if the damage:
    - Aims to restore a lawful situation
    - Protects fundamental international interests
    - Is naturally recoverable (like temporary laser dazzle effects)

4.2.5 Potential Areas for Reform

The current liability regime creates significant disincentives for countries to undertake active debris removal. Several reforms could address these challenges:

Liability-Sharing Mechanism

Countries could establish a more equitable approach to liability through:

1. **Clear Agreements**: Before removal operations, the removing country and registry country should negotiate agreements that:
    - Clarify the legal status of removal actions
    - Establish proportionate liability sharing
    - Outline specific procedures and approaches
2. **Dispute Resolution**: When damages occur, both parties should:
    - Engage in prompt consultation
    - Determine proportionate compensation
    - Refer unresolved disputes to the UN or specialized organizations

Liability Waiver Agreements

Drawing inspiration from the International Space Station (ISS) Intergovernmental Agreement, countries could:

1. Establish mutual waivers between participating states for damages resulting from legitimate removal activities
2. Include all relevant parties: registry states, removing states, and potentially affected third parties
3. Position active removal as a "public" activity serving common interests

International Fund for Debris Removal

To overcome economic barriers to active removal suggested reforms include:

1. Create a dedicated international fund for debris removal under UNCOPUOS oversight
2. Require contributions from spacefaring nations based on their debris inventory
3. Use the fund for both removal operations and potential compensation claims
4. Impose additional contributions when new debris is generated

Public-Private Partnerships
Engaging private entities could expand resources and capabilities for debris removal:

1. **Cleanup Cost Guarantees:** Private companies could provide financial guarantees for removal operations through national licensing systems
2. **Commercial Recycling:** Create legal frameworks allowing private entities to:
    - Acquire removed debris for recycling purposes
    - Develop innovative technologies for debris processing
    - Generate economic value from waste materials

4.2.6 Conclusion

Space debris presents a growing threat to the sustainable use of outer space. While the legal framework governing active debris removal involves complex questions of jurisdiction, responsibility, and liability, there are clear pathways to enhance international cooperation in this area.

By respecting the rights of registry states while establishing more reasonable liability sharing, creating financial mechanisms to support removal operations, and engaging both public and private actors, the international community can make significant progress in addressing the space debris challenge.

Active debris removal represents an exemplary domain for applying cooperative principles in space. As countries continue to develop removal capabilities, evolving legal frameworks should aim to balance accountability with practicality to ensure that technical solutions can be deployed effectively for the benefit of all humanity.

4.3 Navigating Legal, Security, and Licensing Complexities

The exponential growth of satellites and space missions has led to a dramatic increase in orbital debris, posing serious risks to both current and future space operations. Commonly referred to as "space junk," these defunct satellites, spent rocket stages, and fragmentation debris orbit Earth at high velocities and can cause catastrophic damage upon collision with active spacecraft. According to NASA, more than 27,000 pieces of orbital debris are currently tracked, but many smaller, untrackable fragments continue to threaten operational satellites and crewed missions (NASA, 2022b).

In response to this growing hazard, Active Debris Removal (ADR) has emerged as a promising technological solution. ADR systems are designed to identify, capture, and deorbit debris, preventing further collisions and mitigating the risk of a cascading chain reaction known as the Kessler Syndrome. However, despite technical advancements in ADR technologies, regulatory challenges remain a significant barrier to deployment. In the United States, multiple federal agencies share jurisdiction over different aspects of space activity, leading to a fragmented and often inconsistent regulatory landscape (Weeden and Chow). This complexity causes delays and uncertainty for commercial operators seeking authorization for ADR missions.

A unified, transparent regulatory process is essential to support the safe and timely implementation of ADR initiatives. Designating the Office of Space Commerce as the lead federal regulator for ADR could streamline approvals, reduce interagency conflicts, and provide the clarity necessary for private-sector investment and international cooperation. Without such reform, the promise of commercial debris removal may remain grounded in legal red tape rather than launched into action.

4.3.1 Fragmented U.S. Regulatory Landscape

The regulatory framework governing Active Debris Removal (ADR) in the United States is characterized by a patchwork of overlapping and incomplete authorities. As commercial entities develop innovative ADR technologies, they face a complex and often unclear licensing process involving multiple federal agencies, each of which regulates a narrow slice of the broader mission.

The Federal Aviation Administration (FAA), operating under Title 51 of the U.S. Code, oversees the licensing of commercial space launches and reentries. However, ADR missions—particularly those involving in-orbit activities like debris capture and repositioning—fall outside the FAA's current jurisdiction. Since ADR operations typically do not include launch or reentry components in the traditional sense, there is no explicit requirement for FAA approval of in-orbit servicing missions (Federal Aviation Administration).

The Federal Communications Commission (FCC) plays another critical role by licensing the radio frequencies used for telemetry, tracking, and command functions. While the FCC is responsible for preventing radio interference and ensuring spectrum coordination with international partners, it does not regulate the debris removal activities themselves. The 2020 *Orbital Debris Mitigation Rule* introduced stricter standards for satellite deorbit planning but did not provide a regulatory framework for ADR operators (Federal Communications Commission).

The National Oceanic and Atmospheric Administration (NOAA), through its Commercial Remote Sensing Regulatory Affairs (CRSRA) office, oversees the licensing of private satellite imaging systems under the Land Remote Sensing Policy Act. ADR missions often involve imaging debris to assess and engage targets, which may bring them under NOAA's remote sensing rules. However, NOAA's authority in this context is ambiguous, and companies must often seek clarification on whether licensing is required (National Oceanic and Atmospheric Administration).

Amid this fragmented landscape, the Department of Commerce (DOC)—specifically its Office of Space Commerce (OSC)—has been identified as a potential lead regulator. *Space Policy Directive-3 (SPD-3)*, issued in 2018, tasked the DOC with taking the lead on space traffic management, including the development of systems for tracking and coordinating objects in orbit. While SPD-3 envisioned an expanded role for the OSC, it did not grant the office formal authority to license or regulate ADR missions, leaving the regulatory gap unresolved (White House).

This diffusion of responsibility creates a burdensome and confusing process for ADR providers. Companies must seek approvals from multiple agencies with overlapping jurisdictions and no clear lead, resulting in regulatory delays, increased costs, and reduced investment certainty. Without a unified framework, operators are left navigating a bureaucratic maze that stifles innovation and deters progress in addressing the urgent problem of orbital debris.

4.3.2. Need for a Lead Agency & Proposed Reforms

Given the regulatory fragmentation surrounding Active Debris Removal (ADR), establishing a lead federal agency to oversee ADR licensing and compliance is a necessary step toward unlocking the commercial potential of debris mitigation technologies. A unified regulatory framework would offer clarity for private operators, reduce bureaucratic inefficiencies, and align U.S. policy with broader space sustainability goals. The most viable candidate for this role is the Office of Space Commerce (OSC) within the Department of Commerce, which has already been tasked with leading space traffic management initiatives under *Space Policy Directive-3 (SPD-3)*.

While the Federal Aviation Administration (FAA) and Federal Communications Commission (FCC) retain crucial responsibilities over launch safety and spectrum use, respectively, they are not well-positioned to regulate in-orbit ADR operations. The FAA's statutory authority centers on launch and reentry activities and lacks a clear mandate to govern spacecraft that engage in debris removal while remaining in orbit (Federal Aviation Administration). Similarly, while the FCC ensures safe and coordinated use of frequencies, it does not evaluate mission-specific risks or authorize physical operations in space (Federal Communications Commission). Both agencies serve important roles, but neither provides the holistic oversight necessary to manage the unique legal, technical, and international implications of ADR missions.

The OSC is uniquely suited to fill this regulatory gap. SPD-3 directed the Department of Commerce to develop a civil space traffic management framework and to modernize the delivery of space situational awareness services to commercial operators (White House). Elevating the OSC's role from a coordinating office to a licensing authority would create a one-stop shop for ADR mission approvals. Such centralization would streamline interagency consultations, expedite review timelines, and provide regulatory certainty to commercial ADR providers and investors.

To implement this reform, Congress would need to enact legislation formally granting OSC the authority to license and regulate ADR operations. This legislative mandate should clearly define OSC's jurisdiction, establish mission authorization criteria, and set out coordination mechanisms with the FAA, FCC, and other relevant agencies. The framework could also include international cooperation protocols to ensure compliance with treaty obligations and promote interoperability with foreign regulators.

Additionally, a centralized approach would enhance the United States' ability to engage with international organizations such as the United Nations Committee on the Peaceful Uses of Outer

Space (UNCOPUOS) and the International Telecommunication Union (ITU), both of which play roles in shaping global norms around space activities. By consolidating domestic oversight, the U.S. would be better positioned to lead efforts toward standardized global practices for debris removal.

In short, designating the OSC as the lead ADR regulator would reduce duplication, clarify legal responsibilities, and provide a coherent policy framework for managing debris in Earth's orbit. As ADR technologies move from demonstration to deployment, regulatory modernization is no longer optional—it is essential.

4.3.3 Conclusion

As the threat of space debris intensifies, Active Debris Removal (ADR) has become an indispensable tool for preserving the safety and sustainability of Earth's orbital environment. However, despite technological progress, the regulatory landscape in the United States remains ill-suited to support the commercial deployment of ADR missions. With authority currently divided among the FAA, FCC, NOAA, and other entities, private operators face a fragmented and opaque approval process that stifles innovation and delays urgently needed solutions.

To address this challenge, the federal government must take decisive steps to modernize its regulatory approach. The Office of Space Commerce (OSC)—already tasked with coordinating space traffic management under *Space Policy Directive-3*—should be formally designated as the lead agency for ADR licensing and oversight. Empowering the OSC to manage end-to-end approvals for ADR missions would reduce interagency friction, provide legal clarity, and encourage private-sector investment in debris mitigation technologies.

This centralized framework would also strengthen the United States' position in shaping international norms around debris removal, fostering global cooperation through forums like the United Nations Committee on the Peaceful Uses of Outer Space and the International Telecommunication Union. By consolidating oversight and embracing regulatory clarity, the U.S. can pave the way for a commercially viable and internationally coordinated approach to space debris mitigation.

A regulatory system designed for the realities of ADR is not just a policy upgrade—it is a prerequisite for safeguarding the shared domain of outer space for future generations

4.4 The Legal Implications of Active Debris Removal Missions as "Dual-Use" ASAT Weapons

ADR missions designed to mitigate the growing risks of space debris have significant geopolitical and national security implications. The growing proliferation of satellites in LEO and geostationary orbit (GEO), has exacerbated concerns over the increasing risk of collisions and cascading debris events. This creates the risk of harming space assets that provide essential services like communications, surveillance, weather monitoring, and navigation systems including GPS (Imburgia, 2011). From this perspective, ADR missions are crucial for ensuring orbits leave room for countries to have the access they need to operate effectively in space. In contrast, ADR missions also create national security risks because of their potential to be misused as anti-satellite (ASAT) weapons, further complicating the development and use of ADR capabilities due to potential international backlash (NSS, 2019). International treaties and guidelines, as well as US regulatory initiatives, inform how national space programs and commercial space ventures might navigate the geopolitical tensions and national security concerns that arise from ADR operations.

This section examines a key legal and policy challenge facing ADR operations by exploring the overlapping jurisdictions and legal barriers—including national security concerns and international treaty obligations— ADR missions must consider before launch. Given increasing geopolitical tensions rising in conjunction with the need for addressing the growing risks of space debris, future ADR missions hinge on compliance with existing domestic and international obligations as well as an international effort to establish guidelines to define “rules of play” for such ADR missions that overcome “dual-use” concerns.

4.4.1 Legal Barriers ADR Technology Confronts When Defined as “Dual-Use”

ADR technology presents a regulatory challenge due to its "dual-use" nature—it can be deployed for civilian purposes, such as cleaning up space debris, or for military applications, like disabling adversary satellites. This dual-use characteristic creates tension with international space regulators. The Outer Space Treaty lays the groundwork for the peaceful use of outer space for the benefit of all nations and prohibits national appropriation and militarization, the UN's Prevention of an Arms Race in Outer Space (PAROS) initiative seeks to prevent space weaponization (PAROS, 2024), opposing technologies with dual-use potential, and the Liability Convention imposes absolute liability on launching states, extending to private ADR actors, presenting national security concerns.

Ths US plays an active role in regulating ADR norms because of the nation’s competing interests in space commercial and national security. Statements from the Department of Defense’s Space Command (Foust, 2023), the White House (White House, 2018), and Congress (McCall, 2014) have demonstrated US recognition of ADR technologies as “dual-use.” The operation of ADR technologies creates national security implications that invoke the UN Charter. The UN Charter prohibits the use of force but allows for defensive actions if necessary and proportionate under the principle of *jus ad bellum*, although disputes on use of force are subject to the veto of major space-active states including China, the US, and Russia (O’Meara, 2025). Additionally, in an effort to curtail space weaponization, the UN General Assembly passed a resolution against Direct-Ascent Anti-Satellite (ASAT) testing—a step recognized by the US via a self-imposed moratorium in December of 2022. Furthermore, domestic regulators like the DoD, FCC, and the Department of State are forced to regulate all forms of ADR technologies which can create barriers to innovation and business feasibility.

Below, we have provided brief summaries extrapolating on the relevant treaty and legal obligations hindering ADR technologies due to their "dual-use" capabilities mentioned above.

Summaries of Relevant Legal Barriers for "Dual-Use" ADR Technology

- **Outer Space Treaty:** Art. I of the OST establishes outer space for the benefit and interests of all countries, with free exploration by all states furthered by Art. II highlighting that there is no national appropriation of space for personal or military use. Additionally, Art. VI places responsibility for national activities in outer space on state parties carrying out such activities, including the non-governmental entities of a given country. Lastly, Art. IX of the OST requires obligating states to conduct their space activities "with due regard to the corresponding interests of all other States Parties to the Treaty, where failures to prevent collisions can invoke the UN Charter as discussed below. However, it is worth noting that the OST is not a legally binding instrument.
- **UN Prevention of an Arms Race in Outer Space:** PAROS additionally aims to prevent the weaponization and militarization of space, ensuring its peaceful and sustainable use. This is triggered by the "dual-use" definition of ADR technology because of the ability such technology has to serve as an ASAT weapon. However, not all countries are signatories, and a few nations have a veto power, including the US. The US has vetoed the PAROS Treaty effectively at the UN, opting instead to invest into efforts like the Space Force.
- **UN Charter, Use of Force & *Jus Ad Bellum*:** The failure to provide due regard for satellites and space objects owned by another country under the OST can invoke the UN Charter when it comes to the ability of a country to use force and the principle of *jus ad bellum*. UN Charter Ch. I, Art. 2(4) (UN Article 2) "prohibits the threat or use of force" and calls on Members to respect the sovereignty, territorial integrity and political independence of other States, which includes their operations in space. However, UN Charter, Ch. VII Art. 51 (UN Article 51) reflects the principle of *jus ad bellum*, or right to use of force by a country, is invoked when performed as a form of self defense. Thus, if a country deems that another country's debris places essential space operations at risk, they may invoke these principles to use force and remove such debris or attack ADR missions approaching their own space capabilities. States taking defensive actions in space are restricted by the international law principle of *jus ad bellum* which requires necessity and proportionality when choosing to use force against a target, meant to protect civilians and the interests of other states (O'Meara, 2025). These principles have nearly been invoked, with Russian satellite operations alleged to be monitoring US spy satellites sparking similar debates (Wolff, 2020). A hurdle to UN Charter enforcement is that attempts to review the legitimacy or wrongdoing of an ADR mission with the UN Security Council will face a potential veto from the states most likely to engage in ADR missions like the US, Russia, and China (Voting System).
- **ASAT Testing Regulations:** ASAT testing and capabilities create greater risk in the orbital environment, invoking concerns on the weaponization of space. After a series of

recent ASAT tests created significant space debris, China's 2007 ballistic missile ASAT test (Zissis, 2007), India's 2019 ASAT Test "Mission Shakti" (Tellis, 2019), and Russia's 2021 direct-ascent (DA) ASAT test in LEO (U.S. Space Command Public Affairs Office, 2021), international debates spurred the UN General Assembly to overwhelmingly adopted resolution A/RES/77/41 (Resolution 77/41, 2022). DA-ASAT testing involves launching missiles from Earth to destroy or damage satellites in-orbit. While DA-ASAT testing is banned in the US unilaterally through the country's own moratorium in December of 2022, limits apply since Russia, China, and India have not agreed to moratoriums and ASAT testing using less destructive means is still authorized in the US (Panda and Silverstein, 2022). On a positive note, this regulation highlights a case where a significant portion of countries were able to agree to set a restriction on certain ASAT weapons for the sake of the orbital environment.

- **Liability Convention Implications of "Dual-Use" ADR Missions:** Art. VII of the Liability Convention has national security implications when it comes to who is responsible for a given action. It places absolute liability on the launching state to pay compensation for damage caused by its space objects to the surface of Earth or to aircraft, and for damage due to the launching state's faults in space. Since nations are liable for the activities of their launching private actors in space under OST Art. VI, their actions are a risk to national security and international conflict mitigation.
- **FCC Review & US Executive Branch Agencies:** Members of the Department of Defense's Space Command (Foust, 2023) and Congress (McCall 2018) have recognized the "dual-use" nature of ADR technologies. The US has competing interests between preserving the domain of space for commerce and having the ability to protect national assets and capabilities. Satellite operators must obtain a license from the FCC to operate a satellite Applicants for satellite licenses from the FCC, especially those involving foreign ownership, undergo a national security review process, with the FCC referring such applications to the Committee for the Assessment of Foreign Participation in the United States Telecommunications Services Sector (CAFPUSTSS) (US Department of Justice, 2025) for feedback from Executive Branch Agencies like the Department of Defense. This review process and the current stance of the DoD on ADR technologies make it difficult to obtain the essential regulatory approvals necessary to operate ADR technologies that require functions that only the FCC can provide through their operating licenses.
- **International Traffic in Arms Regulations (ITAR) & Export Regulations (EAR):** The Department of State plays a role in the production of ADR technologies, because of ITAR, which regulates the export of technologies with potential military applications. Commercial ADR service providers must meet all disclosure and reporting requirements as they operate across international supply chains and work with foreign national workers in the US due to "deemed export" rules. "Deemed export" under the Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR)

refers to the release of controlled technology or technical data to a foreign person, even if the release occurs within the United States, which is considered an export to the foreign person's home country (Deemed Export BIS, 2025). Similarly, the Wassenaar Arrangement requires disclosure of international transfers of conventional arms and dual-use goods and technologies which requires additional disclosure (Wassenaar BIS, 2025). As the US relies on commercial space ventures and international cooperation across signatories of the Artemis Accords, ITAR and EAR compliance will be essential, creating a barrier to market entry due to increased compliance costs and complexity.

4.4.2 Legal Case for ADR Capabilities Despite "Dual-Use" Potential

ADR capabilities may have "dual-use" ASAT weapons, but many treaties and US regulation contradict the view that ADR technologies should be limited. The core principles of the majority or treaties and regulations around a sustainable and clear orbital environment require ADR services, some opting to not only encourage but essentially require ADR services. The seminal Outer Space Treaty of 1967, although not specifically tailored to ADR technologies, provides a foundational legal framework that promotes the sustainable use of outer space for the benefit of all humankind. By establishing space as a domain for collective benefit and exploration, the treaty indirectly advocates for activities like ADR that enhance the safety and usability of space. Despite the treaty not explicitly addressing ADR, its overarching principles are critical in framing efforts to remove space debris and require the consideration of ADR technologies to accomplish.

The IADC has outlined its own set of guidelines that offer technical recommendations on the management and movement of space debris. Member space agencies utilize these guidelines to develop standardized practices and principles aimed at promoting the safety and sustainability of outer space operations. The IADC's emphasis on collaborative international efforts provides critical support for efforts to consider developing an internationally agreed upon standard for acceptable ADR technologies or "rules of play," for their operation and tracking by potential adversaries.

The regulations promulgated by the International Telecommunications Union (ITU) concerning satellite operations indirectly endorse the need for ADR technologies. The ITU's guidelines on orbit management and the prevention of collisions serve to encourage the removal of non-operational satellites, thereby supporting preparations for future collision avoidance (ITU, 2010). By stressing the importance of maintaining clear communication pathways and preventing harmful interference, the ITU fosters an environment in which ADR can be viewed as an essential part of sustainable space operations.

In addition to international treaties and guidelines, various national and regional regulations further support the deployment of ADR technologies. For instance, the United States has integrated debris removal policies like the Federal Communications Commission's 5-year deorbiting requirement which could invoke forms of ADR technologies to push forward deorbiting timelines (FCC, 2020). The agency could promote ADR as a component of responsible space stewardship. Additionally, the FCC's national security review by "Team Telecom" could serve as the regulatory center for US governmental approval and guidelines for what ADR technologies are defined as "dual-use" or not. Congress (McCall, 2014), the Trump Administration (White House, 2018), and NASA's Orbital Debris Program Office (NASA ODPO, 2025) have all recognized the need to adopt ADR technologies. These national policies demonstrate significant support and potential for the normalization of ADR technologies as part of broader strategies to safeguard the orbital environment and ensure the continuous viability of space-based activities.

Collectively, these international and national frameworks, while grappling with dual-use concerns, contradict themselves when trying to establish a comprehensive legal structure supporting ADR initiatives crucial for maintaining the long-term sustainability of space activities. The core principles for the sustainable use of space and the orbital environment require ADR services to further maintain the peaceful use of orbits. With an ever increasing amount of space debris, ADR services may be necessary to prevent international conflict in space, even if they are intimidating at first themselves. That is why international definitions on acceptable ADR technologies and "rules of play," are essential policy reforms moving forward.

4.4.3 Dual-Use Conclusion

In order to act on international obligations and national security concerns related to the removal of space debris and the maintenance of the orbital environment, definitions of acceptable ADR capabilities or "rules of play" for ADR services are essential. Regulators should begin by defining which ADR technologies are acceptable, and which ones have "dual-use" capabilities considered too high risk. Improving the definition of what qualifies as dual-use ADR capabilities will enable investors, startups, regulators, and military personnel to identify acceptable areas to develop ADR capabilities and empower actors to use them in space.

4.5 Legal Conclusion

The escalating crisis of space debris necessitates urgent legal and institutional reforms to harmonize state sovereignty with collective global responsibility. One key recommendation is adopting a "Presumptive Abandonment" principle to clearly define debris abandonment rules based on size, which will facilitate smoother debris removal operations. Also, a fragmented regulatory landscape currently hampers progress, with complex questions of jurisdiction, responsibility, and liability creating barriers for Active Debris Removal (ADR) missions. Addressing these challenges requires adopting liability-sharing mechanisms to distribute accountability fairly, waiver agreements inspired by frameworks like the ISS Intergovernmental Agreement, an international fund for debris removal overseen by the UN, and public-private partnerships to enhance resources and capabilities to manage issues of liability and coverage. Additionally, establishing a unified regulatory approach by designating a lead ADR regulatory agency and streamlining licensing processes can position the U.S. as a leader in space sustainability and create an efficient regulatory environment for ADR servicers. Furthermore, crafting specific definitions for what qualifies as “dual-use” ADR capabilities and “rules of play” for their use will reduce regulatory redundancies and provide clearer guidance for commercial actors. These legal reforms and considerations can help the spacefaring community make significant strides in mitigating the space debris threat and ensuring the long-term sustainability of outer space for the benefit of all humanity.

5. Conclusion

In this paper, we proposed a three-tiered remediation framework for space debris: (1) a short-term space-based laser system to target small debris (1–10 cm), (2) a medium-term "Pac-Man Method" to capture and return larger debris for reuse, and (3) a long-term in-space salvage zone, or "junkyard," to store recoverable materials. To support these engineering approaches, we outlined two funding mechanisms: a domestic tax or fee scheme and an international tradable permit scheme, along with a proposed increase in the Office of Space Commerce budget. On the regulatory side, we recommend creating an international debris clearance system grounded in a size-based "Presumptive Abandonment" principle to enable clearer removal operations. Additional reforms include establishing shared international liability frameworks, creating removal funds, encouraging public-private partnerships, and designating the Office of Space Commerce as the lead U.S. regulatory body for Active Debris Removal. Streamlining licensing processes and defining “dual-use” ADR technologies alongside standardized operational rules would also provide clarity for commercial actors. Together, these engineering, financial, and legal recommendations provide a cohesive path toward sustainable orbital stewardship.

Let’s clean up space together. Supporting long-term growth and utilization of the final frontier that has the potential to revolutionize human life back on Earth. GO BLUE!

Appendix A: Engineering Information

A.1 Problematic/Not-Recommended Strategies

There are several ADR technologies that we considered but are not recommending at this time. This section provides background as to why we moved away from these technologies.

A.1.1 Foam

One of these methods includes a foam based method. This method increases the area to mass ratio of debris by forming a ball-like structure to cause atmospheric drag to speed up the re-entry process into Earth's atmosphere. This does mean that debris remains in orbit for some time in some cases, however it increases the deorbiting and/or decay time of the debris allowing for the debris to deorbit passively. The success and other removal factors are dependent upon foam selection and the foam's corresponding properties (Gasteiner, et al., 2024). The approximate worst case is around 1 ton of debris deorbited in 25 years from 900 km (Andrenucci, Pergola, and Ruggiero, 2011) which would violate current FCC regulations of 5 years. This would be most effective for the one to many method where multiple debris are targeted. At this time, technology may be too far out and it relies on burning up debris in the atmosphere which this recommendation seeks to avoid for the noted concerns. Additionally, due to its passive reentry nature, the altitude at which debris can be targeted may be limited due to a 5 year disposal regulation.

A.1.2 Harpoon and Net

Another set of capture methods that is not recommended at this time include a few referred to as flexible connection methods which also lie under the broader physical connection umbrella. These methods have a softer attachment to a main chaser spacecraft such as a tether (Shan, et al., 2016).

The first method is a harpoon which is attached to a tether and launched and deployed at debris to penetrate it. The size of the harpoon must be proportional to the debris target size but may be adaptable for multiple different debris types. The harpoon design/size may also be dependent on other factors of the target debris such as the type of material and thickness of outside material (Dudziak, Tuttle, and Barraclough, 2015). While rendezvous may not be as complex and allows for launch from a distance, there are added complexities and factors that must be known when employing this method. The velocity of harpoon launch, the distance to target, and the incident angle for successful impact of harpoon launch will also depend on target debris characterizations such as size, mass, and velocity (Sizov and Aslanov, 2020). Due to some designs penetrating the target debris, there is a risk of creating more debris. Additionally, there is a risk of increased momentum and damage to tethered chaser spacecraft due to launching harpoon and adding mass once debris is caught (Wayman, et al., 2017).

The second method is a tether net. This is a net with weights in its corners deployed at debris often with deorbiting mechanisms (Shan, et al., 2016). A net has several benefits for rendezvous such as launching from a distance. Additionally, while the net typically needs to be proportional to the debris target size, it may be more adaptable for different debris. While there may be less complex rendezvous strategies needed, the distance from the target and velocity of net launch is also proportional to target debris size and may be dependent on other factors such as target velocity and mass. There are also added challenges with being able to control and successfully capture using this method. For example, if the debris target is not centered on the net during capture, the risk of tanglement of the net increases which may pose additional risks. These additional risks may include the loss or damage to the debris target or increased momentum of net and debris combination which poses risks since it is connected to chaser spacecraft via a tether (Kosuge and Kojima, 2024).

Overall, the flexible connection methods previously detailed may have added complexities such as being more difficult to control and deploy. They also have a possible likelihood of causing damage or additional debris. Utilizing either may also require more varied optimization for each debris target based on target characteristics such as size, mass, composition, velocity, etc.

A.2 In Depth Explanation of Detumbling Solutions

This section will discuss a few of the ideas that are an option when it comes to detumbling, especially useful for physical contact solutions like the robotic arm. One such method is using a guidance algorithm which can integrate capture and detumbling into a single maneuver rather than treating them as two separate steps. The robotic arm is guided using convex optimization to align with the target's motion, allowing a smooth, impact free capture. After attachment, the manipulator continues to move in a coordinated fashion with the debris, passively transferring angular momentum and gradually reducing the target's spin. This detumbling approach eliminates the need for additional thruster-based stabilization, making the process more fuel-efficient and mechanically simple. The method is validated through simulations and hardware-in-the-loop experiments and is demonstrated to be effective for small to medium sized debris that are larger than ten centimeters (Romano and Virgilili-Llop, 2019).

Another such solution proposed is a robotic detumbling strategy for space debris using a flexible brush attached to a spacecraft platform. The flexible brush acts as a passive end-effector that makes brief contact with the rotating debris, generating friction and elastic forces that gradually reduce its angular velocity. The paper in which this concept was developed creates a detailed dynamic model to describe the interaction between the brush and debris, including the effects of contact force, friction, and elastic deformation. The control system uses a classical proportional-derivative (PD) controller to maintain the platform's relative position and attitude during repeated contact phases. Simulations show that the platform can reduce the debris' angular velocity from 10 degree per second to less than 0.06 degree per second after four controlled contact cycles, while keeping the spacecraft stable and minimizing disturbance. This approach provides a non-intrusive and energy-efficient solution to detumble rotating debris before capture, especially when the debris has unpredictable spin or cannot be handled by rigid contact methods (Cheng, Li, and He, 2019).

One other concept that could be used is an Ion Beam Shepherd (IBS) concept, a contactless method for space debris removal using a spacecraft that emits a high-velocity, ion beam directed at a target debris object. The momentum from the ion beam applies a continuous, low-force thrust to the debris, enabling controlled modifications to its orbit and attitude without physical contact. This approach avoids the risks associated with docking or capture, which are particularly challenging with tumbling or non-cooperative objects. Although the primary aim of the IBS system is deorbiting, misalignment between the beam and the debris center of mass can generate torque, which can be exploited to induce or reduce rotation thus making the system capable of contributing to detumbling. The method is especially suitable for large debris and allows operation at safe distances by minimizing beam divergence through high-specific-impulse ion thrusters. Overall, IBS offers a scalable solution for debris removal with the added benefit of potential detumbling via contactless force application (Bombardelli and Pelaez, 2012).

A.3 Comprehensive Disposal Solutions

Table A.1: Disposal Solution Categorization Matrix

	Small Debris (1-10 cm)	**CubeSat (≤16u)**	**Medium Sat (<100 kg)**	**Large Sat (< 500 kg)**	**Extra Large Sat (> 2 Tons)**
LEO (Low)	- Ground-Based Laser - Space-Based Laser	- Electrodynamic Tether - Earth Reinsertion with Heat Shield	- Electrodynamic Tether - Earth Reinsertion with Heat Shield	- Starship or Large reentry vehicle	- Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit
LEO (High)	- Space-Based Laser - Solar Sails	- Earth Reinsertion with Heat Shield - Electric Thruster transfer to another orbit - Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit - Solar Sails	- Earth Reinsertion with Heat Shield - Electric Thruster transfer to another orbit - Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit	- Starship or Large reentry vehicle - Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit	- Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit
MEO	- Electric Thruster transfer to another orbit (Electrospray) - Solar Sails	- Electric Thruster transfer to another orbit - Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit - Solar Sails	- Electric Thruster transfer to another orbit - Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit	- Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit	- Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit
GEO	- Solar Sails	- Solar Sails	- Electric Thruster transfer to another orbit - Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit	- Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit	- Nuclear Propulsion transfer to another orbit - Impulsive maneuver to another orbit

Appendix B: Notes on “Risk” - The Problem of Assessment and Paths Forward

Targeting which debris objects should be removed to most benefit the space environment requires the “risk” a debris object poses to the space environment to be quantified; the higher the risk, the more dangerous the object is and the more pressing its removal. Quantifying risk also allows for quick comparisons to be made between debris objects, cutting through technical jargon to effectively communicate a simplified but straightforward assessment of the danger an object poses to the orbital environment.

However, how this debris object risk is calculated varies throughout existing literature. The list of the 50 most high risk objects in the space environment produced by McKnight et. al 2021 was created by aggregating the individual lists of multiple research teams around the world, each with their own unique criterion. This often led to the same object receiving different risk values across teams (McKnight et al, 2021). Within the work, the calculation of risk itself was framed as “consequence” times “probability”, with weights applied to these various consequence or probability factors to tune their influence on the final risk value of an object. The following sections will discuss the consequences and probability factors noted within the literature, with a full table of risk factors located in Table B1 and related reading in Appendix B2.

Consequence or severity factors encompass all factors which describe the consequences of collision with the debris object, and consider the impact that collision would have on the orbital environment. Key examples of consequence/severity factors include debris mass, orbital location activity, and potential for fragmentation (McKnight et al, 2021; Bradley and Wein, 2009). The weighting of consequence factors is subjective; the risk value assigned to the same debris object thus may change depending on the object’s location, and what a stakeholder deems as important.

Probability factors encompass all factors which describe the likelihood of a collision event occurring with the debris object. Calculation of these factors rely on accurate tracking of in-space objects. Key probability factors include orbital location density, average debris lifetime within the orbital location, and prior recorded miss distances to the debris object (McKnight et al, 2021; Pardini and Anselmo, 2021). Similarly to consequence factors, weighting of probability factors may also depend on subjective considerations of priority and importance.

By combining and weighting these consequence and probability factors, the risk of any tracked debris piece can be determined. McKnight et al note the benefits of an aggregate approach to space debris risk assessment, given the variety of risk factors. However, real-world constraints often limit action on removing objects identified as high-risk. Setting aside legal considerations (which often outright prohibit contacting debris objects outside US jurisdiction), the technical design of active-debris removal (ADR) missions are often bounded by available capture technologies. As a result, certain factors may take precedence; for example, large, high-mass objects may be of greater risk but be too difficult to move with current technologies.

Thus, a practical adaptation of the risk assessment processes examined within academic literature may help companies, governments and academics alike in taking immediate steps to actively remove high-risk debris objects with existing technologies. Previous work by the ESA through their DRAMA (Debris Risk Assessment and Mitigation Analysis) tool suite provides an excellent starting point for such a practical adaptation, but DRAMA is primarily aimed at mitigating the potential debris risk of new spacecraft (Oikonomidou et al, 2021; Braun et al, 2020). This leaves a gap for a tool to be developed to assess risk of objects already in space.

For a risk assessment tool to be most effective, risk calculations must be customizable based on user interests, as risk factor inclusion and weighting are subjective. Giving users the power to make these subjective decisions in accordance with their preferences would create risk calculations reflective of stakeholder interests, allowing for the tool to be more practically useful. Additionally, an open-source approach could leverage global expertise, increasing the tool's overall assessment accuracy and effectiveness. To reflect the international nature of space debris, the tool could be hosted and managed by a team of subject experts through the United Nations Office for Outer Space Affairs (UNOOSA), providing equal access to researchers, companies, citizens and governments across the globe.

From a more economic standpoint, having a centralized method/tool for debris object risk quantification would also allow for value to be more easily assigned to each risk object. This opens a link into a proposed cap-and-trade permit market, with higher risk value debris objects corresponding to higher reward. This may help incentivize the growth of an ADR private sector; by placing a "risk price tag" on all tracked debris objects, companies would be able to benefit themselves while also benefiting the orbital environment at large.

Several challenges exist in creating this risk assessment tool, foremost of which is the data processing required to analyze and assign these risk calculations to all tracked objects in the space environment. Artificial intelligence (AI) and machine-learning (ML) may be applied to both reduce the burden of applying custom risk calculations, and more accurately calculate risk factors themselves (Furfaro et al, 2019; Massimi et al, 2024; Larsen and Bevilacqua, 2023). Additionally, many risk factors remain active research areas, requiring calculations to be continually updated. Integrating them into a single tool will necessitate constraints, potentially reducing overall accuracy. Application of these risk calculations is also limited by debris trackability, removing the ability to characterize the risk of small debris objects (Hoffpaulr, 2016; Adushkin, 2020). However, new technologies, such as detecting non-thermal electromagnetic radiation pulses from sub-10 cm debris collisions, may open up new risk assessment avenues in the future (Renno et al, 2024).

Finally, the practical aspects of coding and creating the tool itself will require an unknown amount of development time and effort. However, much of the relevant technical data already exists in various publicly accessible formats. Multiple debris object tracking databases are publically available, such as celestetrak.org, space-track.org and wayfinder.privateer.com, and often include two-line or three-line element (TLE) sets describing the orbit pathways of space objects. Research on risk factors is continually being published and shared to the wider academic world. Taking this first step to move from theory to practice will require time and effort, but the benefits it could provide to the spacefaring world make it a necessary advancement in the effort to solve the problem of space debris.

A full list of citations are included within the references. Related literature on various risk factors is included within Appendix B.1.

Table B1: Commonly Noted Consequence and Probability Risk Factors

Factor	Description	Rationale
Consequence/Severity Factors		
Debris Mass	The mass (in kg) of the debris object. Calculation of debris mass often requires data on the spacecraft design, which may not always be available.	The higher the object's mass, the more mass will be released into the surrounding orbital area through fragments upon collision.
Orbital Location Activity	The density of active spacecraft within the orbital location of the debris object. Calculation of orbital location activity may be weighted differently depending on the types of active spacecraft within the area (e.g. commercial, GPS, government, etc.).*	The more active spacecraft there are in the vicinity of the debris object, the more harm a collision with the debris object may cause to that local orbital environment.
Fragmentation Potential	The potential of the debris object to fragment into smaller pieces. Calculation of fragmentation potential may also consider subfactors such as fragmentation decay (the decay rate of resulting fragments), spacecraft fragility and spacecraft degradation. Additionally, fragmentation dynamics vary heavily depending on the	The higher the fragmentation potential of the debris object, the more likely the surrounding space environment will be negatively impacted, given the release of new, smaller debris pieces into other orbital locations.* These fragments, if small, may be untrackable with current technologies.

Factor	Description	Rationale
	location of the original debris object in space.	
Explosion Potential	The potential of the debris object to explode. Calculation of explosion potential may vary depending on if a collision event is considered as the catalyst. Additionally, spacecraft design information may need to be known to make accurate assessments, which may not always be available.	Spacecraft often contain batteries and/or pressurized tanks for various purposes, which can become explosion hazards at end-of-life. Natural degradation within the space environment may also lead such components to explode.
Re-entry Survival Potential	The potential of the debris object or pieces of the debris object to survive burn-up re-entry and impact the ground.	Large debris objects may not fully burn-up during the atmospheric re-entry problem, introducing a potential human casualty risk upon their impact with the ground. This consequence factor is extremely important as if surviving pieces are large enough, they may lead to loss of human life.
Probability Factors		
Debris Size (Area)	The estimated cross-sectional area of the debris object, which may be impacted by other objects in the orbital environment. Accurate calculation of this factor may also consider tumbling for certain objects, such as stray solar panels, which have varying impact areas depending on profile.	The larger the estimated physical size of the debris object, the more space it takes up within the orbital environment and the more likely it is to come into contact with other space debris objects. Tumbling of space objects may be unknown, making exact calculations difficult.
Orbital Location Density	The density of space objects within the debris object's orbital location. This value considers both active and	The denser the orbital location, or the more space objects are around the debris object in question, the higher

Factor	Description	Rationale
	inactive space objects and seeks to quantify the probability of collision between the debris object in question and another object in the local environment.*	the likelihood of a collisional event. Note that this density includes both active and inactive space objects.
Orbital Location Collision Rates	The known rates of collision between debris objects within an orbital location. This factor heavily relies on accurate data of prior collision rates, and tracked objects.	Orbital locations with higher average collision rates may be more dangerous for space debris objects to remain in. Additionally, introduction of new debris into that area of orbit may increase the risk level of all local debris objects.
Previous Near Miss Collisions	The rate of previous "near-miss" collisions the debris object has experienced. Accurate data on "near-miss" collisions is required for this factor. The distance which defines a "near-miss" collision varies.	A "near-miss" collision is defined as another space object passing a certain distance away from the debris object; closer distances may be weighted higher than further distances. Debris objects which have a history of these "near-miss" collisions may be of higher risk to the local space environment.
Average Debris Lifetime in Orbital Location	The average lifetime of an orbital debris object within an orbital location, when no collisions with other space objects occur and no debris removal technologies are applied.* Lifetime refers to the average length of time a debris object will remain in orbit without interference.	Debris objects in orbital locations farther away from the Earth (e.g. geosynchronous orbit) have longer lifetimes than those closer, as lower orbits are more subject to atmospheric drag effects and stronger gravity. Thus, they can be expected to impact the surrounding space environment longer.

**The bounds on what defines the "orbital location" of a debris object remains rather subjective. Often, this can be defined as the debris cluster in which the object resides (McKnight et al, 2021)*

Debris objects which do not exist within a clear debris cluster have a less defined orbital location, requiring more subjective decisions to be made for calculation purposes.

B.1 Notes on "Risk": Related Reading by Risk Factor

- General:
    - McKnight, D., Witner, R., Letizia, F., Lemmens, S., Anselmo, L., Pardini, C., ... & Grishko, D. (2021). Identifying the 50 statistically-most-concerning derelict objects in LEO. Acta Astronautica, 181, 282-291. https://doi.org/10.1016/j.actaastro.2021.01.021
    - Bradley, A. M., & Wein, L. M. (2009). Space debris: Assessing risk and responsibility. Advances in Space Research, 43(9), 1372-1390. https://doi.org/10.1016/j.asr.2009.02.006
    - Hammerstein, H.C., Daire, S.A. (2021). Hazards of Space Debris. In: Seedhouse, E., Shayler, D.J. (eds) Handbook of Life Support Systems for Spacecraft and Extraterrestrial Habitats. Springer, Cham. pp. 1-23. https://doi.org/10.1007/978-3-319-09575-2_12-1
- Collision/Near-Miss Rates:
    - Dominguez-Gonzalez, R., Sanchez-Ortiz, N., Gelhaus, J., & Krag, H. (2013, August). Update of ESA DRAMA ARES: comparison of envisaged collision alerts with operational statistics and impact of catalogue accuracy. In 6th European Conference on Space Debris (Vol. 723, p. 168). https://conference.sdo.esoc.esa.int/proceedings/sdc6/paper/33
    - Isoletta, G., Opromolla, R., & Fasano, G. (2023). Uncertainty-aware Cube algorithm for medium-term collision risk assessment. Advances in Space Research, 71(1), 539-555. https://doi.org/10.1016/j.asr.2022.09.017
    - Elkantassi, S., Chavez-Demoulin, V., Davison, A. C., Hejduk, M. D., & Morris, H. A. (2025). Statistical Inference on the Miss Distance Compared to Collision Probability for Conjunction Analysis. arXiv preprint arXiv:2503.20085. https://doi.org/10.48550/arXiv.2503.20085
    - McKnight, D. S., & Di Pentino, F. R. (2013). New insights on the orbital debris collision hazard at GEO. Acta Astronautica, 85, 73-82. https://doi.org/10.1016/j.actaastro.2012.12.006
- Debris Object Fragmentation/Explosion/Breakup:
    - Andersson, K. (2023). Risk Assessment for Space Debris Collisions. https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-338835
    - Cimmino, N., Isoletta, G., Opromolla, R., Fasano, G., Basile, A., Romano, A., ... & Cecchini, A. (2021). Tuning of NASA standard breakup model for fragmentation events modelling. Aerospace, 8(7), 185. https://doi.org/10.3390/aerospace8070185
    - Schuhmacher, J. (2021). Efficient Implementation and Evaluation of the NASA Breakup Model in modern C++. https://mediatum.ub.tum.de/1624604
    - Letizia, F., Colombo, C., Lewis, H., & Krag, H. (2017). Extending the ECOB space debris index with fragmentation risk estimation. https://eprints.soton.ac.uk/411725/
    - Manis, A. P., Matney, M. J., Anz-Meador, P. D., & Vavrin, A. B. (2025). Time-Dependent Satellite Explosion Probabilities for Long-Term Orbital Debris Environment Modeling. Journal of Spacecraft and Rockets, 1-10. https://doi.org/10.2514/1.A36118

- Debris Object Re-entry Survival:
  - Park, S. H., Laboulais, J. N., Leyland, P., & Mischler, S. (2021). Re-entry survival analysis and ground risk assessment of space debris considering by-products generation. Acta Astronautica, 179, 604-618. https://doi.org/10.1016/j.actaastro.2020.09.034
  - Pardini, C., & Anselmo, L. (2024). The risk of casualties from the uncontrolled re-entry of spacecraft and orbital stages. Journal of Space Safety Engineering, 11(2), 181-191. https://doi.org/10.1016/j.jsse.2024.02.002
- Object Tracking:
  - Najder, J., & Sośnica, K. (2021). Quality of orbit predictions for satellites tracked by SLR stations. Remote Sensing, 13(7), 1377. https://doi.org/10.3390/rs13071377
  - Renno, Nilton O., et al. “Using Non-Thermal Electromagnetic Radiation to Track and Characterize Space Debris.” 2024 International Conference on Electromagnetics in Advanced Applications (ICEAA), 2024, pp. 036–036. IEEE Xplore, https://doi.org/10.1109/ICEAA61917.2024.10701692.
- Orbital Environment/Location Modeling:
  - Reynolds, R. C. (1990). Review of current activities to model and measure the orbital debris environment in low-Earth orbit. Advances in Space Research, 10(3-4), 359-371. https://doi.org/10.1016/0273-1177(90)90370-F
  - Williamsen, J., Pechkis, D., Balakrishnan, A., & Ouellette, S. (2021). Improving orbital debris environment predictions through examining satellite movement data. Journal of Spacecraft and Rockets, 58(3), 779-785. https://doi.org/10.2514/1.A34765
  - Liu, J., Long, W., Wu, Y., Xu, J., Sang, J., & Lei, X. (2023). TLE orbit determination using simplex method. Geodesy and Geodynamics, 14(5), 438-455. https://doi.org/10.1016/j.geog.2023.03.004
  - Celletti, A., Pucacco, G., & Vartolomei, T. (2022). Proper elements for space debris. Celestial Mechanics and Dynamical Astronomy, 134(2), 11. https://doi.org/10.1007/s10569-022-10064-w

Appendix C: Economic & Policy Inequities in Orbital Debris Management

The growing involvement of emerging space nations, such as Nigeria, Brazil, and the UAE, marks a significant shift in the global space economy. However, as they expand their space programs, these nations face the challenge of orbital debris, which threatens the safety and longevity of space operations (NASA, 2022a). Wealthier nations have the resources to mitigate debris, but developing nations struggle with infrastructure, regulatory protections, and funding (Liou & Johnson, 2020). This creates economic disparities that hinder their ability to compete in the global space industry.

Current space governance, including the Outer Space Treaty (1967) and the Liability Convention (1972), fails to address the complexities of modern commercial space operations and debris generation. Without enforceable global mitigation policies, developing nations face a disproportionate share of the risks and costs related to debris (UNOOSA, 2023b).

C.1 Economic Disparities in Orbital Debris Management

Wealthier nations and private corporations can afford to mitigate debris risks, while emerging nations face significant financial barriers. For example, satellite insurance premiums for developing countries can be 10-12% of the mission value, compared to 3-4% for wealthier nations (Liou & Johnson, 2020). International treaties focus on state actors, leaving gaps in accountability for private companies that contribute to debris. No universal policies mandate cleanup or compensation for damages, placing a financial burden on emerging nations (Boley & Byers, 2021).

The 2009 Iridium-Cosmos collision, which substantially increased debris, illustrates the lack of accountability, as no financial penalties or compensation were provided to affected nations, including developing countries (Boley & Byers, 2021).

C.2 Space Situational Awareness and GEO Slot Competition

Space Situational Awareness (SSA) is crucial for safe space operations, but SSA data is controlled by a few state-backed agencies and private corporations, creating access disparities. Developing nations must rely on data from wealthier countries, which increases risks and limits their ability to manage debris (Lewis, 2020a).

Geostationary orbit (GEO) slots, crucial for telecommunications, are limited and often preemptively claimed by wealthier nations and corporations. This “pay-to-play” system excludes emerging actors and restricts access to orbital resources (Boley & Byers, 2021).

C.3 Policy Recommendations for an Equitable Orbital Economy

- *Decentralized SSA Platforms*: Establish a UN-led SSA database to provide global access to debris tracking and orbital data.

- *Reforming Orbital Slot Allocation*: Implement a “Use It or Lose It” policy and progressive taxation for unused GEO slots (Lewis, 2020a).
- *Market-Based Incentives for Debris Reduction*: Create a "Debris & Slot Credit" system to incentivize debris reduction and provide financial aid to emerging nations for satellite constellations (Boley & Byers, 2021; Jakhu & Pelton., 2017).

C.4 Conclusion

As space activity grows, urgent policy reforms are needed to address the inequities of orbital debris. By decentralizing SSA, strengthening legal accountability, and restructuring financial responsibilities, the global space industry can become more equitable and sustainable for emerging nations.

Appendix D: Rapid Response Capability & The Small-Debris Problem

Small debris in orbit are as-yet impractically difficult to track below 10cm (Mehrholz et al., 2002; Mutoni et al., 2021), yet objects as small as 0.5cm still carry significant kinetic energy at orbital velocities (Klinkrad, 2006). This is a credible risk to mission equipment and people in orbit, one that is well-understood theoretically and exists beyond any reasonable doubt, but is effectively impossible to meaningfully track and predict. Until more credible small-debris tracking can be demonstrated (some progress is being made here, see Gruntman et al. and Miyamoto et al.), this presents a more critical vulnerability than the risks posed by trackable objects, as these can usually be avoided. It's widely understood that there are tens of thousands (if not much more) of objects too small to track but large enough to present catastrophic kinetic risk in orbit.

The orbital lifespan of these objects becomes unacceptably long at altitudes above 800 km (~25 yr lifespan @ ballistic coefficients/BC~3), and even more so at altitudes over 1,000km (~100's of year life spans @ BC~3) (Lewis, 2020b). The density of small debris is thought to thin out appreciably as altitudes approach MEO & GEO, making orbital altitudes between 1,200km and 600km the most persistently populated with small debris (ESA, 2024). These debris are likely not homogeneously distributed – there are examples of identifiable and projected debris fields in roughly constrained orbital parameters. Some of these are valuable or high-demand orbits made inaccessible due to debris presence, like some sun-synchronous orbits affected by anti-satellite (ASAT) testing (Jiang, 2020; Palmer, 2022). Most debris fields are the result of known fragmentation events. The most high-density debris fields are often trackable or projectable to a reasonable degree of confidence.

There is also a large potential for small debris to become a bigger problem. The ultimate nightmare scenario regarding space debris is not a large, trackable object on a collision course. It's the *consequences* of a collision – a field of fragments at extreme velocities that may render the orbit(s) unusable and/or cause runaway impacts, that is the ultimate concern. The actual plausibility of full-blown Kessler Syndrome is debated (Hudson, 2022; Liang et al., 2024), but the threat of an uncontrolled one-ton satellite at orbital velocities is not at the same level as the threat of one combined ton of fragments at orbital velocities. The debris will be wildly difficult to track, and entropic dynamics will almost inevitably make the debris fields expand over time, making them much more difficult to manage. Such a debris field in a high-demand or densely populated orbital inclination could render many satellites inoperable, causing serious problems on the ground. Affected orbits could plausibly remain essentially off-limits for decades or centuries, with small debris leaking out into adjacent orbits and decaying through lower altitude orbits continuously. This is a plausible scenario for which there is, at present, no credible response capability.

The situation can be summarized as such:

- Small debris is already a serious risk: objects large enough to present a kinetic risk but too small to track are essentially impossible to avoid proactively.
- The life expectancy of this risk varies by altitude, but cannot be mitigated due to the lack of information regarding the disposition of the objects.
- There are orbits which are particularly risky, some of which are high-demand orbits.

- There is significant potential for this risk to drastically increase at any time due to ASAT tests, collisions, spontaneous fragmentation events, or other unforeseen phenomenon.
- At present, there is no credible response capability oriented toward fragmentation events.

D.1 Proposed Rapid Response Capability for Fragmentation Events

A small debris removal & fragmentation event response capability to clear existing or emergent areas of high small-debris density could involve methods described in US Patent #8,579,235: *Technique for de-orbiting small debris from the near-earth space environment* (Ganguli, 2013). The patent describes using "dust" to cause a drag-force shock onto objects in a predetermined debris field, deployed along the leading edge of the debris field in its orbit from a vehicle moving on a trajectory either in the opposite direction of the debris field or on a glancing angle to the debris field. This drag shock is intended to induce an accelerated decay of the orbits of the debris affected. This presupposes that the debris field's orbital parameters can be reliably estimated – an assumption that is viable within a reasonable amount of time after a fragmentation event (such as satellite collision, unexpected decomposition, or ASAT test). The patent describes two methods, a satellite method and a ballistic method. The ballistic method will be focused on here.

The ballistic method involves targeting a debris field of roughly known orbital parameters. After the spread of the debris field across those parameters is determined, a vehicle with the appropriate amount of drag-inducing material (referred to in the patent as "dust") will be launched on a suborbital ballistic trajectory intersecting the debris field's orbital trajectory. This vehicle will release the "dust" such that its trajectory leads it into the actual debris field over as much area as possible, thereby inducing the discussed drag shock onto the debris, accelerating the decay of their orbit. This method is easily scalable with multiple launches and/or with heavier-lift launch methods.

After the interaction between the "dust," or drag medium with the debris field, this drag medium will remain on a suborbital trajectory – that is, it can be expected *not* to remain in orbit, descending back to earth (Ganguli, 2013). Some research will be necessary to understand and predict the behavior of the drag medium at all altitudes, especially its interactions with the upper atmosphere, solar radiation pressure at solar min/max, and the magnetosphere. At present, there is insufficient research on the dynamics of such materials in this context. Steps should be taken to minimize the drag medium's lifetime at altitude, and to minimize other knock-on effects at any level of the earth's atmosphere, above it, or on the ground. Such an eventuality seems avoidable given proper consideration, but certainty in this area is a critical factor.

In considering the dynamics of the behavior of the dust medium, some flexibility in the composition of the medium may be helpful toward ensuring safety & predictability in its behavior post-deployment. Indeed, “dust” may not be the most appropriate term to describe the drag medium. It could indeed be made up of dust (tungsten, metallic, silicate, and other materials have been variably considered, but none thoroughly studied in their behavior at altitude), but could also be composed of water (which would presumably immediately form diffuse ice crystals) or a gas sufficiently dense to induce a meaningful drag shock. Ultimately, the drag medium should be able to induce meaningful drag for a predictable amount of time, behave predictably after this period of time, and should not persist in the orbital, aerial, or terrestrial environment to cause any negative effects. This likely presents the most significant engineering & theoretical challenge to this method, and necessitates a thorough understanding of the behavior of diffuse materials, fluids, or gases in a vacuum environment on a suborbital trajectory. This is an achievable goal, the details of which will determine the suitability of this method.

Areas of risk or challenge involve possible effects on other satellites, possible damage to the launch vehicle, and the possibility that the capability of small-debris deorbiting may be interpreted (or indeed, used) as an offensive capability. Unintentional drag effects on other satellites can be forewarned against, and trajectories may be adjusted (especially if the method is paired with a partner in the growing sector of on-orbit refueling services). Associated damage to satellites related to interactions with the drag medium is a risk that must be minimized and accounted for. Possible damage to the launch vehicle and the subsequent creation of more debris is a difficult problem to address directly due to the inherent uncertainty involved with small debris fields, but subsequent debris would almost certainly be tiny in number relative to the debris field deorbited. Drag medium material is very unlikely to be accelerated to orbital velocity by interaction with debris fields in any significant quality, as it will be at well below orbital velocity upon release. The lower costs of suborbital launches imply lower financial risks related to research into drag medium dynamics, damage or failure of the launch & deployment vehicle, and unexpected mission development obstacles. Further reducing both costs and risk is the fact that missions would almost certainly be unmanned. As for offensive interpretations of the method, this problem is nearly ubiquitous in the field of active debris removal. These capabilities are all inherently kinetic and therefore easily interpreted as aggressive. Adequate communication of the inherently shared value of this capability will likely do much to generate consensus and consent on the viability of its use, while a strict and enforceable policy against offensive deployment of the capability should create a credible track record of non-offensive deployment.

Fragmentation events (collisions, spontaneous breakups, or intentional, offensive acts) can happen anywhere, at any time, and in any set of orbital parameters. A suborbital launch platform is much more mobile than orbital platforms, and therefore easier to orient to a trajectory of maximum effect on a newly-polluted orbit(s). If the drag medium can be studied and understood well enough to have its effects & behavior reasonably predicted, such launches can be quickly and cleanly executed. The suborbital nature of the method likely makes the R&D costs involved much lower. The suborbital nature of the deployment also likely makes the method simpler in the regulatory arena; sounding rockets are much easier to obtain approval for. These regulatory requirements may be relaxed for any credible rapid-response cleanup capability in an emergency. If developed into an operational system, this method would likely represent the *only* option to actively and effectively respond to the small-debris problem created by a fragmentation event.

References

Adilov, N., Alexander, P. J., & Cunningham, B. (2020). An economic 'Kessler Syndrome': A dynamic model of Earth orbit debris. *Proceedings of the National Academy of Sciences, 117*(16), 9154–9162. https://doi.org/10.1073/pnas.1921260117

Admin. Decision No. II (U.S. v. Ger.), 7 R.I.A.A. 23 (1930).

Adushkin, V. V., Aksenov, O. Y., Veniaminov, S. S., Kozlov, S. I., & Tyurenkova, V. V. (2020). The small orbital debris population and its impact on space activities and ecological safety. *Acta Astronautica*, *176*, 591-597. https://doi.org/10.1016/j.actaastro.2020.01.015

Aerospace Industries Association. (2024). *Regional Aerospace Development Report*.

Agreement Concerning Cooperation on the Civil International Space Station, Jan. 29, 1998, T.I.A.S. No. 12,927.

Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space,(1968), 19 U.S.T. 7570, 672 U.N.T.S. 119.

Andrenucci, M., Pergola, P., & Ruggiero, A. *Active Removal of Space Debris. Expanding foam application for active debris removal. Final Report. ESA, 2011, 132 p*. https://www.esa.int/gsp/ACT/doc/ARI/ARI%20Study%20Report/ACT-RPT-MAD-ARI-10-6411-Pisa-Active_Removal_of_Space_Debris-Foam.pdf

B2E Automation. (2022). *Robot End Effector Types and Selection Criteria*. https://www.b2eautomation.com/insights/15-robot-end-effector-types-and-selection-criteria

Bapat, A., Salunkhe, P. B., & Patil, A. V. (2022). Hall-effect thrusters for deep-space missions: A review. *IEEE Transactions on Plasma Science*, *50*(2), 189-202. https://doi.org/10.1109/TPS.2022.3143032

Barbee, B. W., Alfano, S., Pinon, E., Gold, K., & Gaylor, D. (2011, March). Design of spacecraft missions to remove multiple orbital debris objects. In *2011 Aerospace conference* (pp. 1-14). IEEE. https://doi.org/10.1109/AERO.2011.5747303

Biesbroek, R., Soares, T., Hüsing, J., Wormnes, K., & Innocenti, L. (2013, April). The e. deorbit CDF study: a design study for the safe removal of a large space debris. In *64th International Astronautical Congress (IAC), Beijing*. https://conference.sdo.esoc.esa.int/proceedings/sdc6/paper/122

Boley, A. C., & Byers, M. (2021). Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth. *Scientific Reports*, *11*(1), 1-8. https://doi.org/10.1038/s41598-021-89909-7

Bombardelli, C., & Pelaez, J. (2012a). Ion Beam Shepherd for Contactless Space Debris Removal | Journal of Guidance, Control, and Dynamics. *Journal of Guidance, Control, and Dynamics*, *34*. Aerospace Research Central. https://doi.org/10.2514

Bradley, A. M., & Wein, L. M. (2009). Space debris: Assessing risk and responsibility. *Advances in Space Research*, *43*(9), 1372-1390. https://doi.org/10.1016/j.asr.2009.02.006

Braun, V., Funke, Q., Lemmens, S., & Sanvido, S. (2020). DRAMA 3.0-Upgrade of ESA's debris risk assessment and mitigation analysis tool suite. *Journal of Space Safety Engineering*, *7*(3), 206-212. https://doi.org/10.1016/j.jsse.2020.07.020

Buchs, R. (2021). *Pricing space junk: Exploring market-based instruments to mitigate orbital debris* (Master's thesis, ETH Zurich). ETH Zurich Research Collection. https://www.research-collection.ethz.ch/handle/20.500.11850/481152

Cai, G., & Wang, S. (2023). On the construction of cross-immunity liability system for Chinese space station. *Journal of Beijing University of Aeronautics & Astronautics Social Science Edition*, 36, 134–142. https://doi.org/10.13766/j.bhsk.1008-2204.2021.0534

Canadian Space Agency. (2024, July 16). About Canadarm2 | Canadian Space Agency. Retrieved April 7, 2025, from https://www.asc-csa.gc.ca/eng/iss/canadarm2/about.asp

Canham, J. S. (2004). *Investigation of Contamination Effects on Laser Induced Optical Damage in Space Flight Lasers.* NASA's Earth Science Technology Office. https://esto.nasa.gov/conferences/estc2004/papers/b2p2.pdf

Chatterjee, J. (2014). Legal issues relating to unauthorized space debris remediation. 65th *International Astronautical Congress* (p. 8).

Cheng, W., Li, Z., & He, Y. (2019). Strategy and Control for Robotic Detumbling of Space Debris by Using Flexible Brush. *IEEE*. https://doi.org/10.1109/icras.2019.8809050

Chiesa, A., Fossati, F., Gambacciani, G., & Pensavalle, E. (2015). Enabling technologies for active space debris removal: the CADET project. In *Space Safety is No Accident: The 7th IAASS Conference* (pp. 29-38). Springer International Publishing. https://doi.org/10.1007/978-3-319-15982-9_4

Christol, C. Q. (1980). International liability for damage caused by space objects. *American Journal of International Law*, 74, 346–359. https://doi.org/10.2307/2201505

CLRTAP (n.d.) Convention on Long Range Transboundary Air Pollution. *Office of Environmental Quality, U.S. Department of State*. https://www.state.gov/key-topics-office-of-environmental-quality-and-transboundary-issues/convention-on-long-range-transboundary-air-pollution/#:~:text=The%20Heavy%20Metals%20Protocol%20aims%20to%20control,dioxide%2C%20nitrogen%20oxides%2C%20and%20volatile%20organic%20compounds.

Colvin, T. J., & Locke, J. (2024, May). Exploring the Use of a Ground-Based Laser System to Deorbit Small Orbital Debris. In *Annual Directed Energy Science and Technology Symposium*. https://ntrs.nasa.gov/citations/20240005687

Colvin, T. J., Karcz, J., & Wusk, G. (2023). Cost and benefit analysis of orbital debris remediation. https://www.nasa.gov/wpcontent/uploads/2023/03/otps_-_cost_and_benefit_analysis_of_orbital_debris_remediat ion_-_final.pdf.

Convention on International Liability for Damage Caused by Space Objects, Mar. 29, 1972, 24 U.S.T. 2389, 961 U.N.T.S. 187.

Convention on Registration of Objects Launched into Outer Space, Sept. 15, 1976, 28 U.S.T. 695, 1023 U.N.T.S. 15.

Davis, M. (2024, October 17). *The Starship revolution in space*. The Strategist. Retrieved April 16, 2025, from http://www.aspistrategist.org.au/the-starship-revolution-in-space/

Deemed Export BIS. (2025). What is a deemed export. *Bureau of Industry and Security*. https://www.bis.gov/learn-support/deemed-exports/what-deemed-export

Dembling, P. G. (1970). Establishing liability for outer space activities. In Proceedings of the *13th International Institute of Space Law* (pp. 87–88).

Department of Defense. (2024). Space Domain Awareness Strategy. *Office of the Assistant Secretary of Defense for Space Policy*.

Dispute Regarding Navigational and Related Rights (Costa Rica v. Nicar.), Judgment, July 13, 2009 I.C.J. 214, 237.

Dunstan, J. E. (2013). Space trash: Lessons learned (and ignored) from space law and government. *Journal of Space Law*, 39, 23–46.

Dudziak, R., Tuttle, S., & Barraclough, S. (2015). Harpoon technology development for the active removal of space debris. *Advances in Space Research*, *56*(3), 509-527. https://doi.org/10.1016/j.asr.2015.04.012

Ebisuzaki, T., Quinn, M. N., Wada, S., Piotrowski, L. W., Takizawa, Y., Casolino, M., ... & Mourou, G. (2015). Demonstration designs for the remediation of space debris from the International Space Station. *Acta Astronautica*, *112*, 102-113. https://doi.org/10.1016/j.actaastro.2015.03.004

ESA. (2023, September 12). ESA's annual space environment report. https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

ESA. (2024, July 19). Space Environment Statistics. *Space Environment Statistics · Space Debris User Portal*. sdup.esoc.esa.int/discosweb/statistics/.

Federal Aviation Administration. (2023). Commercial space transportation: Licensing and safety. *U.S. Department of Transportation*. https://www.faa.gov/space

Federal Aviation Administration. (2024). *Commercial Space Transportation Forecasts.* Office of Commercial Space Transportation. https://www.faa.gov/dataresearch/aviation/aerospaceforecasts/commercial-space.pdf

Federal Communications Commission. (2020, August 25). *Mitigation of orbital debris in the new space age*. Federal Register. 85(165), 52422–52446. https://www.federalregister.gov/documents/2020/08/25/2020-13185/mitigation-of-orbital-debris-in-the-new-space-age

Feng, L., Martinez, P., Dropmann, M., Ehresmann, M., Ginsberg, S., Herdrich, G., & Laufer, R. (2019, January). MEDUSA–Mechanism for Entrapment of Debris Using Shape memory Alloy. In *1st ESA NEO And Debris Detection Conference*.

Flores-Abad, A., Ma, O., Pham, K., & Ulrich, S. (2014). A review of space robotics technologies for on-orbit servicing. *Progress in aerospace sciences*, *68*, 1-26. https://doi.org/10.1016/j.paerosci.2014.03.002

Friend, R. B. (2008, April). Orbital express program summary and mission overview. In *Sensors and Systems for space applications II* (Vol. 6958, pp. 11-21). SPIE. https://doi.org/10.1117/12.783792

Foust, J. (2023). Space Force backs development of commercial orbital debris removal systems. *SpaceNews*.

https://spacenews.com/space-force-backs-development-of-commercial-orbital-debris-removal-systems/

Furfaro, R., Campbell, T., Linares, R., & Reddy, V. (2019, December). Space debris identification and characterization via deep meta-learning. In *First International Orbital Debris Conference* (Vol. 2109, p. 6123). https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6123.pdf

G.A. Res. 51/122, Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States (1996, Dec 13).

Ganguli, G., Chappie, S. S., Roudakov, L. I., & Crabtree, C. E. (2013). *U.S. Patent No. 8,469,314*. Washington, DC: U.S. Patent and Trademark Office.

Gasparini, A. (2021). *Stanford 'gecko gripper' tested on the International Space Station*. Stanford Engineering. https://engineering.stanford.edu/news/stanford-gecko-gripper-tested-international-space-station

Gasteiner, L. E., Hudáček, L., Marcolongo, G., Blöchlinger, M., Meuwly, N., Moreira, N., ... & Orlandi, V. (2024). Polyurethane-Foam Based Space Debris Remediation: A cost-effective and efficient approach. In *Proceedings of the International Astronautical Congress, IAC* (pp. 1760-1768). International Astronautical Federation, IAF. http://doi.org/10.52202/078360-0169

Giudici, L., Colombo, C., & Letizia, F. (2024). Optimal active debris removal sequence identification through combined debris index analysis and long-term projection of the orbital environment. In *75th International Astronautical Congress (IAC 2024)* (pp. 1-9). https://doi.org/10.52202/078360-0166

Gruntman, M. (2014). Passive optical detection of submillimeter and millimeter size space debris in low Earth orbit. *Acta Astronautica*, *105*(1), 156-170. https://doi.org/10.1016/j.actaastro.2014.08.022

Gupta, A. (2023). Micro satellites and mega constellations: Space debris remediation and perpetual ownership. https://www.researchgate.net/profile/Arpit-Gupta-28/publication/388927891_Micro_Satellites_and_Mega_Constellations_Space_Debris_Remediation_and_Perpetual_Ownership/links/67ad169e461fb56424d7cc92/Micro-Satellites-and-Mega-Constellations-Space-Debris-Remediation-and-Perpetual-Ownership.pdf

Hamara, M., Pittet, J.-N., Schildknecht, T., & Šilha, J. (2018). Apparent rotation properties of space debris extracted from photometric measurements. *Advances in Space Research*, *61*(3), 844–861. https://doi.org/10.1016/j.asr.2017.10.048

Hickman, K., & Kubota, T. (2017, June 28). *Stanford engineers design a robotic gripper for cleaning up space debris*. Stanford Report. Retrieved from https://news.stanford.edu/stories/2017/06/engineers-design-robotic-gripper-cleaning-space-debris

Hoffpauir, D. (2016, July 11). *Space Debris: Understanding the Risks to NASA Spacecraft*. NASA. Retrieved April 16, 2025, from https://www.nasa.gov/centers-and-facilities/nesc/space-debris-understanding-the-risks-to-nasa-spacecraft/

Hudson, J. (2022). KESSYM: A stochastic orbital debris model for evaluation of Kessler Syndrome risks and mitigations. *Authorea Preprints*. https://doi.org/10.22541/au.166990186.63397226/v1

ICAO. (2025). *Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)*. ICAO. Retrieved from http://www.icao.int/environmental-protection/CORSIA/pages/default.aspx

Imburgia, J. S. (2011). Space debris and its threat to national security: A proposal for a binding international agreement to clean up the junk. *Vanderbilt Journal of Transnational Law*, 44, 589–644.

Int'l Law Comm'n. (2001). Draft articles on responsibility of states for internationally wrongful acts. U.N. Doc. A/56/10.

Jakhu, R. S., & Pelton, J. N. (Eds.). (2017). *Global Space Governance: An International Study*. Springer International Publishing. https://doi.org/10.1007/978-3-319-54364-2

JAXA. (2024a). *Outline of CRD2*. PROJECT | CRD2 | JAXA | Research and Development Directorate. Retrieved from https://www.kenkai.jaxa.jp/eng/crd2/project/

JAXA. (2024b). *JAXA concludes partnership-type contract for Phase II of its Commercial Removal of Debris Demonstration (CRD2)*. Japan Aerospace Exploration Agency. Retrieved from https://global.jaxa.jp/press/2024/08/20240820-1_e.html

Jiang, S. (2018). Analysis of international law on outer space military confrontation. *Journal of Beijing University of Aeronautics & Astronautics Social Science Edition*, 31, 80. https://doi.org/10.13766/j.bhsk.1008-2204.2017.0308

Jiang, Y. (2020). Debris cloud of India anti-satellite test to Microsat-R satellite. *Heliyon*, *6*(8). https://www.cell.com/heliyon/fulltext/S2405-8440(20)31535-8

Kaineg, S. (2020). The growing problem of space debris. *Hastings Environmental Law Journal*, 26, 277–314.

Kaiser, C. (2024, November 2). *What Is a Lagrange Point? - NASA Science*. NASA Science. https://science.nasa.gov/resource/what-is-a-lagrange-point/

Kerrest, A., & Smith, L. J. (2013). Article II. In S. Hobe et al. (Eds.), *II Cologne Commentary on Space Law* (p. 139).

Klinkrad, H. (2006). *Space debris: models and risk analysis*. Springer Science & Business Media

Kosuge, K., & Kojima, H. (2024). Prediction and experimental verification of tether net entanglement for space debris capture. *Astrodynamics*, *8*(2), 223-236. https://doi.org/10.1007/s42064-023-0170-8

Lambach, D., & Wesel, L. (2021, April). Tackling the space debris problem: A global commons perspective. In Proceedings of the 8th European Conference on Space Debris. https://www.researchgate.net/profile/Daniel-Lambach-2/publication/351064949_Tackling_the_Space_Debris_Problem_A_Global_Commons_Perspective/links/60826947907dcf667bb9b107/Tackling-the-Space-Debris-Problem-A-Global-Commons-Perspective.pdf

Larsen, K., & Bevilacqua, R. (2023). Using Machine Learning to Predict Hypervelocity Fragment Propagation of Space Debris Collisions. *Using Machine Learning to Predict Hypervelocity Fragment Propagation of Space Debris Collisions*. https://commons.erau.edu/student-works/196

Larsen, P. B. (2018). Solving the space debris crisis. *Journal of Air Law & Commerce*, 83, 475–498.

Laser Ablation. (2024, July 14) In *Wikipedia*. https://en.wikipedia.org/wiki/Laser_ablation

Lewis, H. G. (2020a). The Growing Threat of Space Debris. *Nature Astronomy*, vol. 4, 2020, pp. 202-213.

Lewis, H. G. (2020b). Understanding long-term orbital debris population dynamics. *Journal of Space Safety Engineering*, *7*(3), 164-170. https://doi.org/10.1016/j.jsse.2020.06.006

Li, F. (2024, November). Analysis the principles and state-of-the-art applications for hall thruster. In *IET Conference Proceedings CP901* (Vol. 2024, No. 24, pp. 211-215). Stevenage, UK: The Institution of Engineering and Technology. https://doi.org/10.1049/icp.2024.4483

Li, S. (2007). International liability for space environmental pollution caused by space debris. *China Aerospace*, no. 5, 15.

Liang, C., Fanto, P., & Signoracci, A. (2024). On the Risk of Kessler Syndrome: A Statistical Modeling Framework for Orbital Debris Growth. *The Journal of the Astronautical Sciences*, *71*(5), 45. https://doi.org/10.1007/s40295-024-00458-3

Liou, J. C., and Johnson, N.L. (2020). *Risks and Mitigation Strategies for Orbital Debris.* NASA, vol. 169, 2020, pp. 85–92. https://www.nasa.gov/wp-content/uploads/2018/12/692076main_orbital_debris_management_and_risk_mitigation.pdf?emrc=e20460

Liu, Y. Q., Yu, Z. W., Liu, X. F., Chen, J. B., & Cai, G. P. (2019). Active detumbling technology for noncooperative space target with energy dissipation. *Advances in Space Research*, *63*(5), 1813-1823. https://doi.org/10.1016/j.asr.2018.11.017

Liu, J., Long, W., Wu, Y., Xu, J., Sang, J., & Lei, X. (2023). TLE orbit determination using simplex method. *Geodesy and Geodynamics*, *14*(5), 438-455. https://doi.org/10.1016/j.geog.2023.03.004

Locke, J., Colvin, T. J., Ratliff, L., Abdul-Hamid, A., & Samples, C. (2024). Cost and benefit analysis of mitigating, tracking, and remediating orbital debris. *Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris*. www.nasa.gov/wp-content/uploads/2024/05/2024-otps-cba-of-orbital-debris-phase-2-plus-svgs-v3-tjc-tagged.pdf

Long, J., & Chen, W. (2024). Breaking dilemmas: The need for an international liability regime for commercial spaceflight. *Hong Kong Law Journal*, 54, 87–110.

Luabeya, M. (2024, December 3). *Astronaut Suni Williams and Astrobee - NASA*. NASA. https://www.nasa.gov/image-article/astronaut-suni-williams-and-astrobee/.

Manning, C. (2023, September 27). *Technology Readiness Levels - NASA*. NASA. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/.

Mariappan, A., et al. (2020, August 24-28). The application of energetic materials genome approach for development of the solid propellants through the space debris recycling at the space platform. In AIAA Propulsion & Energy Forum. https://doi.org/10.2514/6.2020-3898

Massimi, F., Ferrara, P., Petrucci, R., & Benedetto, F. (2024). Deep learning‐based space debris detection for space situational awareness: A feasibility study applied to the radar processing. *IET Radar, Sonar & Navigation*, *18*(4), 635-648. https://doi.org/10.1049/rsn2.12547

McCall, S. M. (2014). Report R43353 - Threats to U.S. national security interests in space: Orbital debris mitigation and removal. *Congressional Research Service*. https://congress.gov/crs-product/R43353

McKnight, D., Witner, R., Letizia, F., Lemmens, S., Anselmo, L., Pardini, C., ... & Grishko, D. (2021). Identifying the 50 statistically-most-concerning derelict objects in LEO. *Acta Astronautica*, *181*, 282-291. https://doi.org/10.1016/j.actaastro.2021.01.021

Medioni, L., Gary, Y., Monclin, M., Oosterhof, C., Pierre, G., Semblanet, T., ... & Nocentini, K. (2023). Trajectory optimization for multi-target Active Debris Removal missions. *Advances in Space Research*, *72*(7), 2801-2823. https://doi.org/10.1016/j.asr.2022.12.013

Mehrholz, D., Leushacke, L., Flury, W., Jehn, R., Klinkrad, H., & Landgraf, M. (2002). Detecting, tracking and imaging space debris. *ESA Bulletin(0376-4265)*, (109), 128-134. https://www.esa.int/esapub/bulletin/bullet109/chapter16_bul109.pdf

Miyamoto, H., Battisti, M., Belov, A., Bertaina, M. E., Bisconti, F., Bonino, R., ... & Turriziani, S. (2019). Space Debris detection and tracking with the techniques of cosmic ray physics. *arXiv preprint arXiv:1909.05601*. https://doi.org/10.48550/arXiv.1909.05601

Morris, T. M. (2024). *the REACCH Capability Statement*. Kall Morris INC. https://static1.squarespace.com/static/5dcf4be7b6529511f6c6445e/t/66ce26434bd8d427c02f7366/1724786253876/NOCTRL+Capability+Statement+REACCH+2024+08+21.pdf

Mosher, D. (2007, August 6). Shuttle Endeavour's leak caused by debris. *SpaceNews*. https://www.space.com/4167-shuttle-endeavour-leak-caused-debris.html

Munoz-Patchen, C. (2018). Regulating the space commons: Treating space debris as abandoned property in violation of the Outer Space Treaty. *Chicago Journal of International Law*, 19, 233–266.

Muntoni, G., Montisci, G., Pisanu, T., Andronico, P., & Valente, G. (2021). Crowded space: a review on radar measurements for space debris monitoring and tracking. *Applied Sciences*, *11*(4), 1364. https://doi.org/10.3390/app11041364

Nagavarapu, S. C., Mogan, L. B., Chandran, A., & Hastings, D. E. (2024). CubeSats for space debris removal from LEO: Prototype design of a robotic arm-based deorbiter CubeSat. *Advances in Space Research*. https://doi.org/10.1016/j.asr.2024.08.009

NASA (2021) *Process for limiting spacecraft charging effects (NASA-STD-8719.14A).* NASA Technical Standards System. https://standards.nasa.gov/standard/NASA/NASA-STD-871914

NASA. (2022a). *Orbital Debris Program Office: Annual Report on Space Sustainability.* NASA Technical Reports Server.

NASA. (2022b). Orbital debris quarterly news. *NASA Orbital Debris Program Offic*e, 26(1). https://orbitaldebris.jsc.nasa.gov/quarterly-news/

NASA. (2024a). *NPR 8715.6E*. Orbital Debris Mitigation, Office of Mission Assurance. https://web.archive.org/web/20250305215126/https://nodis3.gsfc.nasa.gov/npg_img/N_PR_8715_006E_/N_PR_8715_006E_.pdf

NASA. (2024b). *Space Technology Research Grants Program Awards*. NASA Office of Technology, Policy, and Strategy.

NASA Orbital Debris Program Office. (2024). Orbital Debris Quarterly News. vol. 28, no. 1, pp. 4-8. https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/ODQNv28i1.pdf

NASA ODPO. (2025). *Debris Remediation*. NASA Orbital Debris Program Office. https://orbitaldebris.jsc.nasa.gov/remediation/

National Oceanic and Atmospheric Administration. Commercial Remote Sensing Regulatory Affairs (CRSRA). *U.S. Department of Commerce*. https://www.nesdis.noaa.gov/CRSRA

National Science Foundation. (2022). *Rural STEM Education Research Report.*

National Space Society, et al. (2024). *Joint Recommendation on Office of Space Commerce Funding.* Coalition Policy Statement.

Nevala, E. M. (2017). Waste in space: Remediating space debris through the doctrine of abandonment and the law of capture. *American University Law Review*, 66, 1495–1544.

NSS (2019). NSS position paper: Space debris removal. *National Space Society*. https://nss.org/wp-content/uploads/2023/06/NSS-Position-Paper-Space-Debris-Removal-2019.pdf

Office of Science and Technology Policy. (2024). *National Orbital Debris Research and Development Plan.* The White House.

Office of Space Commerce. (2024). *Research Priorities for Fiscal Year 2026.* Department of Commerce.

Oikonomidou, X., Braun, V., & Lemmens, S. (2021, March). Guidelines for space debris and meteoroid impact risk assessment with DRAMA/MIDAS. In *Proceedings of the 8th European Conference on Space Debris, Darmstadt, Germany* (pp. 20-23). https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/163

O'Meara, C. (2025). Self-defence in outer space: Anti-satellite weapons and the jus ad bellum. *Leiden Journal of International Law*, 1–23. https://doi.org/10.1017/S0922156524000670

Palmer, C. (2022). Russian anti-satellite test spotlights space debris danger. *Engineering*, *12*(1), 3-5. https://doi.org/10.1016/j.eng.2022.03.005

Panda, A., & Silverstein, B. (2022, April 20). The U.S. moratorium on anti-satellite missile tests is a welcome shift in space policy. *The Carnegie Endowment*. https://carnegieendowment.org/posts/2022/04/the-us-moratorium-on-anti-satellite-missile-tests-is-a-welcome-shift-in-space-policy?lang=en

Pardini, C., & Anselmo, L. (2021). Evaluating the impact of space activities in low earth orbit. *Acta Astronautica*, *184*, 11-22. https://doi.org/10.1016/j.actaastro.2021.03.030

PAROS (2024). "PAROS" Prevention of an arms race in outer space. *U.S. Mission to International Organizations in Geneva*. https://geneva.usmission.gov/2024/03/28/prevention-of-an-arms-race-in-outer-space/

Peck, M. (2021, August 10). *he U.S. Military Wants to "Slice" Enemy Missiles in the Air… With Laser Weapons*. The National Interest. https://nationalinterest.org/blog/reboot/us-military-wants-slice-enemy-missiles-air-laser-weapons-191576

Phipps, C. R. (2014). L′ ADROIT–A spaceborne ultraviolet laser system for space debris clearing. *Acta Astronautica*, *104*(1), 243-255. https://doi.org/10.1016/j.actaastro.2014.08.007

Pieters, L., & Noomen, R. (2023). Simulating arbitrary interactions between small-scale space debris and a space-based pulsed laser system. *Advances in Space Research*, *72*(7), 2778-2785. https://doi.org/10.1016/j.asr.2022.04.049

Pultarova, T. (2024, October 15). *Pollution from rocket launches and burning satellites could cause the next environmental emergency*. Space. Retrieved from https://www.space.com/rocket-launches-satellite-reentries-air-pollution-concerns

Punch News Network. (2021, November 1). The world's largest garbage dump is above our heads? The number of space debris exceeds 100 million. https://www.thepaper.cn/newsDetail_forward_15166124

Radiation Pressure. (2025, April 3). In *Wikipedia*. https://en.wikipedia.org/wiki/Radiation_pressure

Recommendation ITU-R S.1003-2 (2010) Environmental protection of the geostationary satellite orbit. *International Telecommunication Union.* https://www.itu.int/dms_pubrec/itu-r/rec/s/R-REC-S.1003-2-201012-I!!PDF-E.pdf

Renno, N. O., Zhang, Y., Akhavan-Tafti, M., Atilaw, T., & Fischer, E. (2024, September). Using Non-Thermal Electromagnetic Radiation to Track and Characterize Space Debris. In *2024 International Conference on Electromagnetics in Advanced Applications (ICEAA)* (pp. 036-036). IEEE. https://doi.org/10.1109/ICEAA61917.2024.10701692

Resolution 77/41 (2022, December). Destructive direct-ascent anti-satellite missile testing. *United Nations General Assembly.* https://digitallibrary.un.org/record/3997622/files/A_RES_77_41-EN.pdf

Salter, A. W. (2016). Space debris: A law and economics analysis of the orbital commons. *Stanford Technology Law Review*, 19, 221–238.

Samson, N., Kazaz, N., Malkowsky, V., & Greenbaum, D. (2022). Space debris: It's time to look up and do something. *Intellectual Property Journal,* 34(3), 267–316. https://proxy.lib.umich.edu/login?url=https://www.proquest.com/scholarly-journals/space-debris-time-look-up-do-something/docview/2711038203/se-2.

Saunders, C., Chiesa, A., Forshaw, J. L., Parreira, B., & Biesbroek, R. (2014, June). Results of a system feasibility study on a heavy active debris removal mission. In *3rd CNES European Workshop on Space Debris Modeling and Remediation*.

Schall, W. O. (1991). Orbital debris removal by laser radiation. *Acta Astronautica*, *24*, 343-351. https://doi.org/10.1016/0094-5765(91)90184-7

Shakilyan, T. A. (2021). International trash pick-up: The need for a neutral orbital debris removal organization. *Southwestern Journal of International Law*, 27, 410–432.

Shan, M., Guo, J., & Gill, E. (2016). Review and comparison of active space debris capturing and removal methods. *Progress in aerospace sciences*, *80*, 18-32. https://doi.org/10.1016/j.paerosci.2015.11.001

Singh, S., & Mooij, E. (2020). Robust control for active debris removal of a large flexible space structure. In *AIAA Scitech 2020 Forum* (p. 2077). https://doi.org/10.2514/6.2020-2077

Singh, S., Mooij, E., & Gransden, D. I. (2019). Multibody approach to the controlled removal of large space debris with flexible appendages. In *AIAA Scitech 2019 Forum* (p. 1916). https://doi.org/10.2514/6.2019-1916

Sizov, D. A., & Aslanov, V. S. (2020). Space debris removal with harpoon assistance: Choice of parameters and optimization. *Journal of Guidance, Control, and Dynamics*, *44*(4), 767-778. http://doi.org/10.2514/1.G005484

Space Foundation. (2024a). *The Space Report: Q1 2025.* Space Foundation Quarterly.

Space Foundation. (2024b) *The Space Report: Rural Workforce Development.*

SpaceX. (2025). *Launches*. http://www.spacex.com/launches/#:~:text=Thuraya%204%20Mission,November%2011%2C%202024

Stark, W., Gondol, N., & Tajmar, M. (2022). Concept and design of a hall-effect thruster with integrated thrust vector control. *Journal of Electric Propulsion*, *1*(1), 21. https://doi.org/10.1007/s44205-022-00023-w

Steele, S. M. (2020). Can international law provide a basis for actively removing space debris? https://amostech.com/TechnicalPapers/2020/Orbital-Debris/Steele.pdf

Steele, S. M. (2021). Space debris: A basis for actively removing objects under an international legal order. *American Journal of Aerospace Engineering*, 45. https://doi.org/10.11648/j.ajae.20210802.11

Tellis, A. (2019, April 15). India's ASAT test: An incomplete success. *Carnegie Endowment for International Peace*. https://carnegieendowment.org/research/2019/04/indias-asat-test-an-incomplete-success?lang=en

The Committee Assessment of Foreign Participation in the United States Telecommunications Services Sector. (2025). *U.S. Department of Justice*.

https://www.justice.gov/nsd/committee-assessment-foreign-participation-united-states-telecommunications-services-sector

Thurston, H. (2023). Space trash: Legal and economic questions about the collection of orbital debris. *Journal of Law, Economics & Policy*, 18, 229–264.

Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water, Aug. 5, 1963, 480 U.N.T.S. 43.

Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, Jan. 27, 1967, 18 U.S.T. 2410, 610 U.N.T.S. 205.

UN Article 2 (n.d.) "Article 2" Repertory of Practice of United Nations Organs, *United Nations.* https://legal.un.org/repertory/art2.shtml

UN Article 51 (n.d.) "Article 51" Repertory of Practice of United Nations Organs, *United Nations*. https://legal.un.org/repertory/art51.shtml

U.N. Comm. on the Peaceful Uses of Outer Space. (2007). Space debris mitigation guidelines; see also Zhao, Y. (2022). Study on the international law basis of space debris mitigation obligations. *Shanghai Law Research Collection*, 7, 180–181.

United Nations Office for Outer Space Affairs. (2023a). *Guidelines for the Long-term Sustainability of Outer Space Activities.* UN Committee on the Peaceful Uses of Outer Space.

United Nations Office for Outer Space Affairs. (2023b). *Space Sustainability: Policy and Regulatory Considerations for Emerging Space Nations.* United Nations.

U.S. Bureau of Labor Statistics. (2024). *Occupational Employment Statistics by Geographic Distribution.* Department of Labor.

U.S. Department of Commerce.(2023). *Rural Space Economy Initiative: Strategic Plan.*

U.S. Space Command Public Affairs Office. (2021, November 15). Russian direct-ascent anti-satellite missile test creates significant, long-lasting space debris.https://www.spacecom.mil/Newsroom/News/Article-Display/Article/2842957/russian-direct-ascent-anti-satellite-missile-test-creates-significant-long-last/

Varda Space Industries. (2025). *Space born, Earth bound • Varda Space Industries*. Retrieved from http://www.varda.com/

Vienna Convention on the Law of Treaties, May 23, 1969, 1155 U.N.T.S. 331.

Virgili-Llop, J., & Romano, M. (2019). Simultaneous Capture and Detumble of a Resident Space Object by a Free-Flying Spacecraft-Manipulator System. *Frontiers in Robotics and AI*, *6*. https://doi.org/10.3389/frobt.2019.00014.

Von Der Dunk, F. (2001). Space debris and the law. *Space & Telecommunications Law Program Faculty Publications*, 4.

Voting System. (n.d.). *United Nations Security Council*. https://www.un.org/securitycouncil/en/content/voting-system

Walker, L., & Vasile, M. (2023). Space debris remediation using space-based lasers. *Advances in Space Research*, *72*(7), 2786-2800. https://doi.org/10.1016/j.asr.2023.06.031

Wassenaar BIS (2025). Multilateral export control regimes, Wassenaar Arrangement. *Bureau of Industry and Security*. https://www.bis.doc.gov/index.php/policy-guidance/multilateral-export-control-regimes#:~:text=The%20Wassenaar%20Arrangement%20on%20Export,requirements%20on%20its%20member%20governments.

Wayman, A., Ratcliffe, A., Barraclough, S., Lurie, J., Fernandez-Nunez, I., Lupsa, M., ... & Campbell, J. (2017, April). Design and testing of a full scale harpoon capture system. In *7th European Conference on Space Debris* (p. 86).

Weeden, B., & Samson, V. (Eds.). (2023). Global counterspace capabilities: An open-source assessment. *Secure World Foundation*. https://swfound.org/counterspace

White House. (2018, June 18). Space policy directive-3: National space traffic management policy. *Trump Administration*. https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/

Wolff, J. J. (2020). Space law, what it is and why it matters. *Army Lawyer*, Issue 5(3). https://tjaglcs.army.mil/Periodicals/The-Army-Lawyer/tal-2020-issue-5/Post/4625/No-3-Space-Law

Wu, J., Fan, S., Jin, M., Sun, K., Zhou, C., & Liu, H. (2016). Design and experiment of a universal space-saving end-effector for multi-task operations. *Industrial Robot: An International Journal*, *43*(2), 193-203. https://doi.org/10.1108/IR-07-2015-0132

Zissis, C. (2007, February 22). China's anti-satellite test. *Council on Foreign Relations*. https://www.cfr.org/backgrounder/chinas-anti-satellite-test

Zhang, T., & Li, B. (2008). On international liability for environmental damage in outer space. *Journal of Beijing University of Aeronautics & Astronautics Social Science Edition*, no. 3, 38.

Zhang, W., Li, F., Li, J., & Cheng, Q. (2022). Review of on-orbit robotic arm active debris capture removal methods. *Aerospace*, *10*(1), 13. 13. https://doi.org/10.3390/aerospace10010013