Narrative Review Article

Active Space Debris Removal: Feasibility and Comparative Analysis of Methods for Diverse Targets

Maxwell Mayer[1], Sahangi Dassanayake[2]

[1]Neuqua Valley High School, 2360 95th St, Naperville, IL, 60564, United States;
[2]California Institute of Technology, 1200 E. California Blvd, Pasadena, CA, 91125, United States

ABSTRACT

The rapid growth of orbital debris presents an escalating challenge to spacecraft safety and the long-term sustainability of Low Earth Orbit. While end-of-life and collision-avoidance measures can limit new debris generation, they do little to address the expanding population of inactive satellites, rocket bodies, and fragments already in orbit. To confront this issue, Active Debris Removal (ADR) is required: mission-level interventions designed to capture, stabilize, and deorbit existing objects. This paper provides a comparative review of seven representative ADR methods, categorized into contact-based and non-contact systems. Each approach is evaluated through a set of parameters including capture mechanics, sensing and guidance architecture, control and stability requirements, power and propulsion demands, and mission scalability. The review integrates experimental and simulation data from major demonstrations in each category, notably Astroscale's ELSA-d mission and JAXA's electrodynamic tether program, while also drawing on smaller-scale studies that explore additional ADR techniques. Through this analysis, the paper investigates how operational and technical constraints influence the performance and applicability of current ADR technologies, providing a foundation for ongoing development toward more effective debris-removal solutions.

Keywords: Active space debris removal; orbital debris mitigation; deorbiting technologies; rendezvous and capture; Low Earth Orbit; space sustainability

INTRODUCTION

Orbital debris presents an increasingly urgent threat to routine space operations and to the long-term sustainability of near-Earth space. The existing population of defunct spacecraft, spent rocket stages, and collision fragments has produced an environment in which even millimeter to centimeter-scale particles can inflict catastrophic damage. For instance, in August 2016, a tiny fragment—likely a paint flake or small metal particle just a few thousandths of a millimeter—struck an International Space Station window, leaving a hazardous 7mm chip (1). Although this incident was relatively minor, it highlights a serious risk that even slightly larger fragments could pose: the potential to penetrate the windows, causing rapid depressurization and endangering the lives of astronauts. This issue will continue to grow, as seen in collisions such as the one between Iridium 33 and the defunct Kosmos 2251 satellite, which generated over 2,300 trackable fragments and significantly increased the collision risk

Corresponding author: Maxwell Mayer, E-mail: maxwellpmayer@icloud.com.

Accepted January 20, 2026
https://doi.org/10.70251/HYJR2348.41412421

in Low Earth Orbit (LEO) (2). While measures such as end-of-life disposal and improved spacecraft design are necessary, they cannot address debris generated by accidental collisions or deliberate destruction events, which can rapidly increase the risk of further collisions. The 2019 Indian anti-satellite test produced hundreds of debris pieces and illustrates how quickly collision risk can escalate, including fragments above the ISS orbit (3). With space traffic accelerating, action is required now: Active Debris Removal (ADR) must be rapidly prioritized and operationalized to preserve the long-term stability and usability of LEO.

For the purposes of this study, ADR is defined as any operational technique that reduces the orbital lifetime or collision opportunity of an object, either through direct physical attachment (contact methods) or through remote momentum transfer (non-contact methods). ADR concepts span a broad technical spectrum, ranging from entirely conceptual control schemes and studies to ground-tested hardware and several in-orbit demonstrations. Furthermore, the diversity of debris in size, mass, and operational orbit necessitates an equally diverse portfolio of ADR solutions. Larger debris objects also vary in how they behave in orbit. Debris that maintains a fixed attitude or rotates in a controlled, predictable manner is often referred to as cooperative debris. In contrast, uncooperative debris refers to objects that are tumbling, rotating unpredictably about one or more axes, or otherwise lacking standardized features that would aid in capture.

This paper provides a comparative overview of principal ADR approaches, assessing their relative feasibility, technical complexity, and applicability across various debris types and operational orbits, while also evaluating potential improvements for optimizing these techniques. The analysis focuses on seven representative techniques: Robotic Arm, Magnetic Docking, Tether-Net, Integrated Platform, Ion Beam Shepherd, Laser-Based, and Electrodynamic Tether Systems.

CONTACT METHODS: A GENERAL OVERVIEW

Contact-based ADR approaches remove or manipulate debris through direct physical attachment. These methods vary in maturity, with some having been partially demonstrated in orbit, while others remain conceptual or simulation-based. Regardless, all contact methods share operational requirements: the servicer spacecraft must precisely rendezvous with the debris, stabilize itself relative to the target, and then execute controlled interaction.

Robotic Arm Systems

These systems operate by deploying one or more manipulator arms from the servicer spacecraft. This concept draws on heritage from crewed space servicing missions (e.g., Canadarm2 on the ISS (4)), but its adaptation to autonomous debris removal remains largely at the conceptual or simulation stage. The process begins with the servicer performing rendezvous, using optical sensors, light detection and ranging (LiDAR), or radar to determine the debris' relative position, velocity, and attitude. Once in proximity, the robotic arm extends toward the debris, which may be tumbling or irregularly shaped. The arm's end-effectors, tools such as clamps, hooks, or attachment interfaces, are designed to physically secure the object. Real-time kinematic and dynamic models govern arm movement, while feedback control compensates for the unexpected motion of debris. Once attachment is achieved, the servicer can either directly deorbit the object, deploy a drag-enhancing device such as a sail, or reorient the debris for tether attachment (5).

Magnetic Docking Systems

These systems leverage electromagnetic or permanent magnetic attraction to engage debris; they require cooperative targets equipped with magnetic plates or docking interfaces. Demonstrations have validated this approach in orbit at a small scale, proving that repeated magnetic capture and release cycles are feasible. Operationally, the servicer approaches the debris along a controlled trajectory, aligning its magnetic capture mechanism with the docking plate. Upon engagement, attitude control systems, such as thrusters, reaction wheels, or control moment gyros, stabilize the coupled system to prevent uncontrolled spinning (6).

Tether-Net Systems

These systems remain primarily conceptual and simulation-based, with no full-scale orbital validation. In this method, the servicer deploys a net designed to envelop the target debris. The net is connected to either weighted masses or maneuverable units (MUs), which are small thruster-equipped nodes that actively guide closure. Deployment involves launching the net along a calculated trajectory, where onboard sensors and control algorithms adjust its velocity, angle, and spread to match the debris' motion. Figure 1 illustrates the control for these maneuverable units, showing how feedback algorithms adjust thrust commands during deployment and capture. Once the net wraps around the object, closure occurs either by winches pulling the net mouth tight or by MUs docking together. The servicer can then reel in the tether, using the tension to slow rotation or control orientation before initiating disposal. In simulations, the net is represented as a mesh of nodes linked by spring-damper elements. When the net contacts the debris, these models capture how the mesh conforms to irregular surfaces, redistributes tension, and interacts with tumbling motion (7).

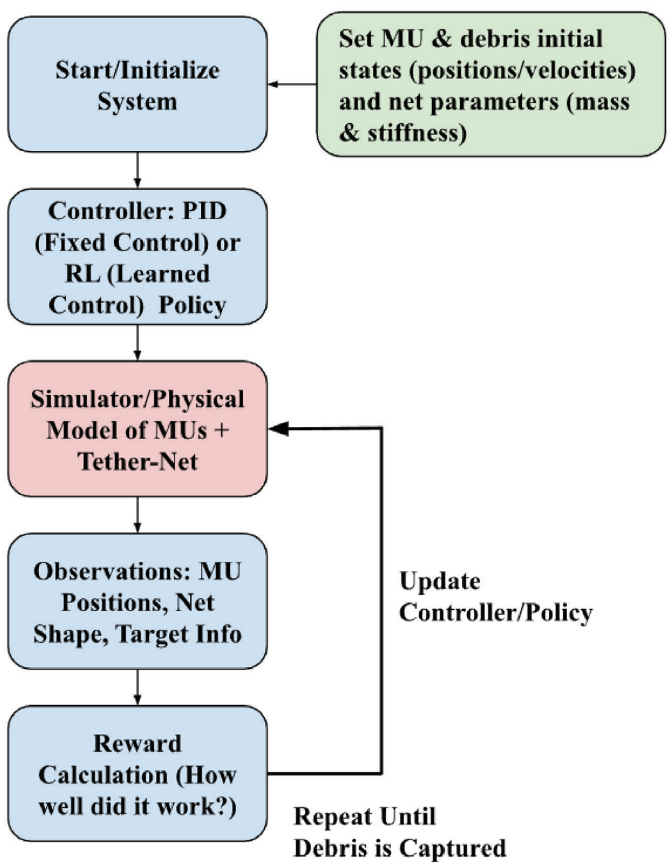

Figure 1. *Simplified control and learning framework for the maneuverable nodes on a simulated tether-net. Proportional, Integral, Derivative (PID) controller or a Reinforcement Learning (RL) controller can be used. The controller sends thrust commands to the MUs. The simulator updates MU positions and tether-net dynamics, which are then observed and evaluated. A reward function scores capture performance, and the controller is updated iteratively until the debris is captured.*

Integrated or Hybrid Platform Systems

These systems combine multiple contact mechanisms, such as nets, harpoons, and robotic arms, into a single servicer spacecraft. They remain largely conceptual, validated only through computer-aided design (CAD) modeling and dynamic simulations. In such a platform, capture begins with selecting the most appropriate tool based on debris mass, geometry, and spin state. A harpoon, for instance, could anchor into a rigid structural element, followed by a net to envelop irregular protrusions, with robotic arms making final adjustments. Coordinating these mechanisms requires real-time sensor integration, predictive dynamic modeling, and tightly synchronized actuation (8).

DETAILED CASE STUDY: ASTROSCALE'S ELSA-D MISSION

Among contact-based ADR concepts, the End-of-Life Services by Astroscale demonstration mission (ELSA-d) is one of the most complete in-orbit demonstrations to date.

Mission Architecture and Spacecraft Design

ELSA-d launched in March 2021 from Baikonur Cosmodrome into a roughly 550 km orbit. The mission flew two spacecraft: a servicer (~175 kg) and a smaller client (~17 kg) designed to represent cooperative debris (10). The client acted as a controlled surrogate target and carried a docking plate so capture attempts could be repeatable and safely tested. The servicer measured about 0.7 × 0.7 × 1.1 m (stowed), and the client measured about 0.5 × 0.5 × 0.2 m (10). They launched stacked together, with the client attached to the servicer by a separation mechanism, allowing the CONOPS to ramp from low-risk demonstrations (non-tumbling capture) to higher-risk ones (tumbling capture and disposal maneuvers) (6, 10).

For guidance and control, the servicer used GPS for absolute navigation and short-range relative sensors (optical/LiDAR-type) for rendezvous and proximity operations. Propulsion was provided by green monopropellant (LMP-103S), which offers lower toxicity than hydrazine while still enabling 6 degrees-of-freedom (DOF) thrusting, which matters when managing attitude and alignment during burns with a coupled servicer-client configuration (10). This redundancy also mattered when the mission later lost four thrusters but continued controlled operations. Power came from deployable solar arrays with batteries, and operations were supported by ground oversight through the UK National In-Orbit Servicing Control Centre (9).

Magnetic Capture Mechanism and Docking Plate

The capture system centered on Astroscale's magnetic docking approach. The client's Docking Plate (DP) was a ferromagnetic, optically marked disc on a stand-off structure, serving as both the physical capture interface and a navigation aid by providing an identifiable pattern for relative sensing and attitude estimation (6).

The servicer carried an extendable capture head containing concentric permanent magnets. When aligned and extended to the DP, magnetic attraction formed a secure but reversible connection. Astroscale also incorporated a mechanical push-off feature so the servicer could deliberately break the bond and separate the client, enabling repeated dock/undock cycles needed for staged demonstrations (6). Compared to robotic-arm capture, this reduced mechanical complexity while still requiring precise alignment, particularly during capture of a rotating client (6).

Proximity Operations and Capture Scenarios

ELSA-d's CONOPS proceeded through phases of increasing complexity. After commissioning, the servicer began with non-tumbling capture: the client held a fixed attitude while the servicer approached from defined holding points (e.g., 5 m behind the client). These standoff points also supported in-space calibration of rendezvous sensors before final approach (6). During capture runs, the servicer synchronized relative position, velocity, and roll with the client before extending the capture head to dock to the DP (6).

The mission then progressed to tumbling capture, commanding the client into a natural tumbling profile to simulate a harder capture case. The servicer executed a continuous tracking approach and alignment to keep the capture mechanism aligned with the DP despite rotation, then performed capture (6). Client motion data was downlinked and used with ground flight-dynamics processing to generate updated guidance for subsequent attempts, validating a combined on-board sensing and ground-supported closed-loop approach for dynamic targets (6).

Other demonstrations included fly-around inspection (servicer circumnavigation of the client to simulate pre-capture assessment) and search-and-approach scenarios in which the servicer had to reacquire the client using sensors after separation (6).

Deorbit and End-of-Mission Operations

After the capture demonstrations, ELSA-d conducted disposal-relevant orbit changes. Using chemical propulsion, the servicer lowered its orbit with disposal operations intended to simulate end-of-life removal services (9). The servicer's final orbit was reduced to about 500 km, with expected natural re-entry in roughly 3.5 years; the released client is predicted to naturally deorbit within about five years (9).

Future Implications and Potential Optimization

From a general engineering perspective, there are some potential areas for improvement with the design of ELSA-d. One lies in the capture mechanism itself. Future systems could investigate adjustable or hybrid magnetic systems: for instance, combining permanent magnets with controllable electromagnets to modulate capture strength during approach and release. This could allow the servicer to dock softly with a rapidly rotating target and then increase magnetic force once alignment is stable, reducing impact loads and minimizing rebound or misalignment. Another limitation of relying solely on permanent magnets is magnetic decay: over time, exposure to the harsh orbital environment (including thermal cycling and radiation) can gradually weaken the field strength. This long-term degradation raises concerns for multi-year missions, as capture reliability may diminish unless reinforced by active or hybrid systems (11).

Propulsion also presents opportunities. A future hybrid propulsion system could be used with low-thrust electric propulsion for precision station-keeping during delicate capture or for fine-tuning deorbit burns after capture. Studies of multimodal propulsion systems show that combining chemical and electric thrusters can provide both the high thrust needed for rapid maneuvers and the efficiency required for fine control, making them well-suited for debris removal scenarios (12). Electric thrusters could also enable a slower, more controlled orbit-lowering process for massive debris objects without exceeding force or torque limits on the docking interface.

ELSA-d has already demonstrated the viability of magnetic docking, autonomous rendezvous, and controlled orbit changes. By experimenting with variable-strength capture mechanisms and hybrid propulsion options, future ADR systems could move beyond single-client demonstrations to become reliable, repeatable services capable of maintaining a safe orbital environment.

NON-CONTACT METHODS: A GENERAL OVERVIEW

Non-contact ADR approaches achieve debris removal without physical interaction, instead applying remote forces that gradually modify an object's orbit. These methods reduce the risk of collision or entanglement but place heavy demands on control accuracy, relative positioning, and sustained power. Most remain conceptual or simulation-based, although they build on well-established physics.

Ion Beam Shepherd (IBS) Systems

These systems use a spacecraft equipped with ion thrusters to direct a continuous plasma beam toward the debris. The beam transmits momentum to the object, slowly changing its orbit. At the same time, the IBS spacecraft must counteract the equal and opposite reaction force by firing a second ion thruster in the opposite direction, maintaining a fixed formation distance, typically tens of meters. This requires precise tracking of the debris' position, velocity, and orientation. Beam-target interactions are modeled to predict how momentum transfer will affect not only translation but also torque; if the beam strikes off-center, it can induce unwanted rotation. Thus, closed-loop control continuously adjusts beam pointing and thrust levels. Simulations have assumed ion thrusters operating at a specific impulse of ~3000 seconds using xenon propellant, with the shepherd spacecraft stationed a few target diameters away to account for beam divergence (13). IBS concepts remain unflown, but extensive simulations demonstrate that the system could, in principle, engage multiple large debris objects sequentially (14).

Laser-Based Systems

These systems apply energy at a distance by firing high-powered lasers at debris surfaces. The laser ablates a thin layer of material, generating a reactive plasma jet that gradually shifts the object's orbit (15). Ground-based systems would rely on adaptive optics to correct for atmospheric distortion, while space-based lasers would eliminate atmospheric effects but require significant onboard power sources. For example, vaporizing and ionizing a 10 cm cube (approximately 2,700 g) of aluminum requires 87,160 kJ of energy (16). Furthermore, removing this quantity of aluminum requires a continuous laser beam power of at least 5.38 MW, and pumping such a laser would require approximately 108 MW (16). Precise targeting is critical; the laser must remain locked onto the debris despite rapid orbital motion. Models of debris geometry, surface composition, and spin state are used to predict ablation behavior, ensuring thrust is applied consistently. Misalignment or uneven ablation risks generating unwanted torque, potentially destabilizing the debris. In concept studies, space-based lasers in Sun-synchronous orbit (~800 km) have been modeled with an average power of 20 kW, firing 600J pulses at 33 Hz through a 1.5m mirror (17). From approximately 500 km away, the laser triggers sufficient ablation, decelerating debris objects 1-10 cm in size and significantly reducing their orbital lifetimes (17). However, laser ADR remains at the experimental stage, especially considering debris of larger magnitude, with only limited ground tests performed (15).

Electrodynamic Tether (EDT) Systems

These systems offer a propellantless alternative for deorbiting debris, relying on conductive wires interacting with Earth's geomagnetic field. In this method, a servicer first attaches a long conductive tether to the debris. Attachment can be achieved through several proposed methods, including robotic capture arms, harpoon-like penetrators, adhesive or magnetic contactors, and pre-installed interfaces on cooperative targets. Current concepts simply assume a physical docking or grappling mechanism, since establishing an electrical connection with the debris surface is essential for current flow through the tether, so this discussion focuses primarily on the non-contact phase of the process. As the combined system orbits Earth, the tether cuts across geomagnetic field lines, inducing a current. This current, when driven through the tether, interacts with the magnetic field to generate a Lorentz force, which acts opposite to orbital motion, creating drag that slowly reduces altitude. See Figure 2, which illustrates the EDT concept, where the conductive tether interacts with Earth's magnetic field to generate a Lorentz drag force that gradually lowers orbital altitude. Conceptual studies indicate that EDTs could repeatedly deorbit large debris; however, in-orbit demonstrations remain extremely limited (18).

DETAILED CASE STUDY: JAXA'S ELECTRODYNAMIC TETHER DEBRIS REMOVAL SYSTEM AND TETHER LIBRATION DYNAMICS

Among non-contact ADR concepts, JAXA's electrodynamic tether (EDT) concept is one of the most hardware-grounded systems.

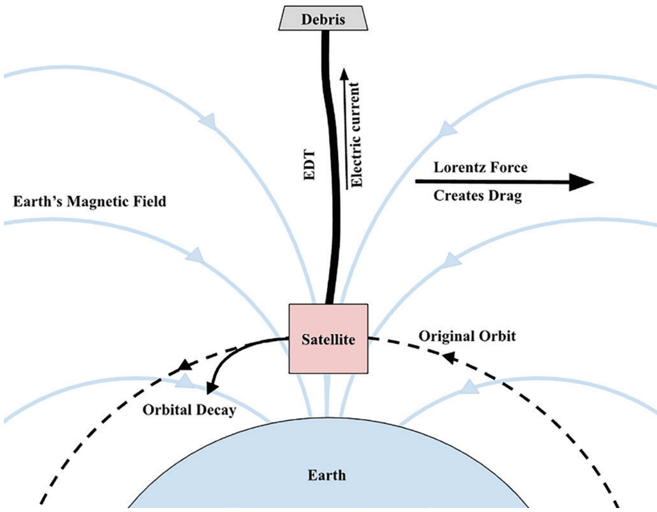

Figure 2. *Electrodynamic tether concept for debris deorbiting: current in a conductive tether interacts with Earth's magnetic field to generate Lorentz drag that lowers orbital energy and reduces perigee over time.*

Mission Architecture and Hardware

JAXA's concept uses a micro-satellite servicer that rendezvous with and attaches to a large non-cooperative target using a lightweight, flexible robotic arm. After attachment, the servicer deploys a bare conductive tether (km-scale) (18). The tether collects electrons from the ionospheric plasma, and Field Emitter Array Cathodes (FEAC), based on carbon nanotube technology, emit electrons to close the circuit. With the current established, the system generates a Lorentz force that gradually reduces orbital altitude without chemical propulsion (18).

Overall, the package consists of four main elements: a bare tether, FEAC emitters, reel/deployment hardware with braking, and a compliant robotic capture arm, with electrical power primarily supporting emission and control electronics (18).

Electrodynamic Mechanism

As the tether moves through Earth's magnetic field in LEO, an electric field is induced along its length ($E = v \times B$), driving current through the tether-plasma circuit. Here, E is the induced electric field (voltage per unit length), v is the tether's orbital velocity relative to the geomagnetic field, and B is Earth's magnetic field vector (18). The resulting current then produces a Lorentz force ($F = I\ell \times B$), where F is the total electromagnetic force on the tether, I is the current, and ℓ is the tether length vector (direction along the tether). This force acts opposite to orbital motion, lowering orbital energy and reducing perigee until atmospheric drag completes reentry (18).

Tether Dynamics and Libration

A long flexible tether attached to a tumbling object introduces major dynamic concerns. Gravity-gradient effects, drag, and Lorentz forces can excite oscillations and twisting, including libration (pendulum-like swinging about an equilibrium orientation). If libration grows, it can increase structural loads, reduce effective current collection, and raise the risk of instability during long-duration deorbit operations (19).

Using a 3D flexible-tether model (Absolute Nodal Coordinate Formulation) with distributed Lorentz forces, Jang *et al.* built on JAXA's concept and showed that increasing tether length/diameter increases current and Lorentz force but also increases oscillation amplitude (19). They model a two-body EDT setup (not the debris itself) with a 10,000 kg main satellite and a 50 kg sub-satellite, and their simulations span ~5-20 km tether length and ~0.5-1.5 mm diameter, with peak Lorentz forces of ~0.06-0.08 N in more aggressive cases, assuming libration is controlled (19).

Control Approach and Operational Sequence

Jang *et al.* demonstrate a practical stabilization strategy: modulating tether current in phase with the tether's motion (an on-off style control) to remove energy from libration and damp oscillations without propellant (19). The reel/braking mechanism can further suppress motion during and after deployment. Operationally, the combined concept is as follows: rendezvous and attach, deploy tether with reel/brake, establish current via plasma collection and FEAC emission, and apply continuous Lorentz-force drag while actively damping libration until reentry (18, 19).

Future Implications and Potential Optimization

Several areas stand out where refinements or new approaches could significantly enhance performance, stability, and operational safety of EDTs. One important aspect that could be implemented is adaptive tether deployment. As Jang *et al.* (2025) demonstrated, tether length and diameter strongly influence both current collection and the severity of libration. Instead of deploying the full tether length at once, future systems could use a phased or staged deployment: initially releasing a shorter, stiffer tether segment to establish a stable current and alignment, then extending to maximum length once the Lorentz force has stabilized. This approach would reduce the initial oscillations that tend to form immediately after deployment while still capturing the performance benefits of a long tether once steady-state conditions are achieved.

Another promising avenue is the integration of tether geometry and mission planning. Because the Lorentz force scales with both current and effective tether length, future servicers could match tether parameters to the debris mass and altitude rather than applying a single "one size fits all" design. For very large or high-altitude debris, a thicker or longer tether could be combined with slower, carefully modulated current ramps to prevent overshoot; for smaller debris, a shorter, lighter tether could still deliver enough drag to shorten orbital lifetime without over-engineering the system. By aligning tether properties, current modulation, and the servicer's attachment geometry, operators could maximize the "drag per unit mass" ratio for each removal scenario.

These improvements, staged deployment and tailored tether sizing, represent plausible next steps beyond the current EDT framework. If implemented, they would allow an EDT servicer to generate steady Lorentz-force drag over months while maintaining geometric stability and structural integrity. With continued refinement of tether stability controls and deployment technology, the electrodynamic tether concept could mature from a promising demonstration into a scalable, reliable non-contact debris-removal method. In doing so, it would provide a propellantless mechanism for reducing orbital debris, representing a crucial step towards long-term orbital environment sustainability.

EVALUATION AND COMPARATIVE ANALYSIS OF ADR METHODS

To complement the narrative comparison, Table 1 provides a summary of the representative ADR methods discussed in this review, highlighting typical target types, technology maturity, demonstration status, key strengths, and primary limitations.

ADR is not a single "best technology" problem: performance depends on target mass, altitude, geometry, and whether the object is cooperative or uncooperative. Each method is defined by its capture/interaction mechanism, navigation burden, and the time scale over which it can meaningfully change an orbit.

Contact-based systems generally provide the most control once attachment occurs, but their feasibility is limited by proximity risk and the cost of maneuvering a combined servicer-debris stack. Robotic arms are most plausible for small-to-medium targets when rotation is slow or predictable, but they face a high risk during the grapple if the debris is tumbling or irregular. Magnetic docking is mechanically simpler and supports repeated capture cycles, but it is restricted to semi-cooperative targets with compatible interfaces. Tether-nets expand applicability to irregular and spinning debris while allowing safer standoff distances, yet they introduce major deployment and entanglement risks and remain largely unproven at full scale. Integrated/hybrid platforms are conceptually versatile, but added subsystems increase mass, failure points, and coordination complexity.

Non-contact systems reduce collision and entanglement hazards by avoiding physical interaction, but they typically rely on weaker forces applied over long durations and require high precision control. Ion beam shepherding and laser ablation are most attractive for situations where attachment is undesirable or impractical (including higher orbits), but both demand high power and extremely accurate pointing/formation maintenance. Electrodynamic tethers occupy a middle ground: they still require an initial attachment but then provide propellantless orbit lowering through Lorentz drag. Their main limitation is not force generation but stability and dynamics, libration, oscillations, and survivability of long tethers, which increases the importance of modeling and closed-loop control.

Technology readiness also differs sharply across methods. ELSA-d provides direct evidence that autonomous rendezvous and repeated magnetic capture can work in orbit, supporting the plausibility of scalable, multi-client servicing for cooperative targets. JAXA's EDT concept, while not yet flown end-to-end at full scale, has comparatively hardware-developed subsystems (tether, emitters, deployment mechanisms), but still faces a major flight-validation gap in full operational stability and capture-to-deorbit execution. In contrast, most other approaches remain at earlier stages of development, with performance assessments still dominated by simulation and analytical studies.

Across all ADR approaches, the common issues are as follows: autonomous guidance, navigation, and control that remains reliable near uncertain targets, long-duration robustness in the space environment, and cost, mass, and power tradeoffs that determine whether a concept scales beyond a one-off demonstration. Taken together, sustainable debris remediation will likely require a portfolio of complementary methods rather than a single universal solution.

Table 1. *Qualitative comparison of ADR methods by target type, maturity, demonstration status, key strengths, and primary limitations.*

ADR Method	Primary Target Type	Technology Maturity	Demonstration Status	Key Strength	Primary Limitation
Robotic Arm	Large intact debris; cooperative or slowly tumbling objects	Conceptual to early development	Conceptual / simulation-based only	Precise post-capture control and secure attachment	High proximity risk; difficult capture of fast-tumbling debris
Magnetic Docking	Cooperative debris equipped with docking interface	Flight-demonstrated	In-orbit ADR mission demonstration	Reversible, repeatable capture with reduced mechanical complexity	Requires pre-installed docking plate; limited to cooperative targets
Tether-Net	Large, irregular, or tumbling debris	Conceptual to experimental	Subsystem or technology demonstration (limited scope)	Can capture uncooperative and irregular debris	Risk of entanglement; no full-scale operational validation
Integrated / Hybrid Platform	Mixed debris populations	Conceptual	Conceptual / simulation-based only	Flexibility across multiple debris types	Increased system complexity and mass
Ion Beam Shepherd	Large debris where contact is undesirable	Analytical and simulation-based	Conceptual / simulation-based only	Contactless momentum transfer	Requires precise and complex formation control
Laser-Based Removal	Small to medium debris (cm–dm scale)	Experimental	Subsystem or technology demonstration (limited scope)	Remote engagement without rendezvous	High power demands; sensitivity to pointing accuracy
Electrodynamic Tether	Large debris in LEO	Experimental	Subsystem or technology demonstration (limited scope)	Propellantless orbit lowering	Requires initial attachment; tether dynamics and stability

In addition to technical performance, several ADR approaches raise environmental considerations that warrant acknowledgment. Deorbiting debris through atmospheric re-entry can lead to partial material ablation and deposition in the upper atmosphere, and uncontrolled reentries carry a nonzero risk of ground impact from surviving fragments, particularly for larger objects (20). Non-contact methods may introduce additional space-environment effects, including plasma interactions associated with ion beam shepherding and optical or thermal effects linked to high-power laser systems (14). Although these impacts are generally secondary to collision-risk mitigation, environmental effects should be considered alongside technical feasibility when evaluating large-scale deployment of ADR technologies.

LIMITATIONS AND UNCERTAINTIES

While the ADR approaches reviewed here span a broad range of capture and interaction mechanisms, their current performance remains constrained by limitations in modeling assumptions and experimental validation. Many analyses implicitly assume that debris properties—such as geometry, mass distribution, and rotational state—are either known in advance or can be estimated with sufficient accuracy during proximity operations. In practice, debris may be structurally degraded, irregularly shaped, or undergoing complex tumbling, introducing uncertainty into guidance and control that is difficult to fully represent in numerical simulations.

A further limitation is the absence of end-to-end, in-orbit validation for most ADR concepts. With the exception of magnetic docking demonstrated in the ELSA-d mission using a cooperative client, the majority of techniques remain supported primarily by analytical studies, numerical modeling, or subsystem-level testing. As a result, several critical behaviors—including tether-net deployment and entanglement dynamics, ion beam plume–surface interactions, debris material response to laser ablation, and long-duration electrodynamic tether libration and stability—have not yet been demonstrated under representative operational conditions. These gaps limit confidence in system robustness, failure characterization, and scalability.

CONCLUSION

The accumulation of orbital debris poses an escalating threat to spacecraft safety and the long-term sustainability of Low Earth Orbit. Mitigation strategies such as post-mission disposal can reduce the growth of future debris but cannot address the large population of existing objects. Active Debris Removal (ADR) has therefore emerged as a critical capability, though the diversity of debris sizes, altitudes, and dynamic states makes a single universal solution unlikely.

This paper presented a comparative analysis of seven representative ADR approaches, spanning contact-based systems (robotic arms, magnetic docking, tether-nets, and hybrid platforms) and non-contact concepts (ion beam shepherding, laser ablation, and electrodynamic tethers). Evaluation drew on case studies of the most developed systems in each category, including Astroscale's ELSA-d magnetic docking mission and JAXA's electrodynamic tether program, alongside supporting simulation studies. The analysis shows that contact methods provide reliable post-capture control but are constrained by target cooperativity and close-proximity risk, while non-contact methods promise scalability yet remain limited by power, stability, and precision requirements.

From a mission-design perspective, these results suggest that future ADR systems should emphasize adaptability over narrow optimization. Architectures capable of handling uncertainty in target properties, through flexible capture mechanisms, scalable propulsion, or robust autonomous guidance, are more likely to remain effective across diverse debris populations. Early in-orbit demonstrations focused on operational robustness, rather than optimized performance for a single target class, will be especially valuable in reducing technical risk, and should be a priority for future research and development.

Broader deployment of ADR also carries coordination and policy relevance. Because debris objects are owned by different entities and occupy shared orbits, large-scale ADR efforts will require coordination across satellite operators and spacefaring nations to ensure safe operations and avoid unintended interference. Legal considerations include ownership and authorization requirements under international space law, as well as liability responsibilities associated with damage caused by space objects (21, 22). Operationally, ADR missions must account for coordination and collision avoidance with active spacecraft as part of safe proximity operations in an increasingly congested LEO environment (23). Economic considerations also affect when ADR is justified, since cost-benefit analyses show that feasibility depends on how removal cost compares to risk reduction and other modeled benefits (24). Overall, common standards for cooperative interfaces, tracking, and servicing practices could significantly expand mission feasibility while supporting long-term orbital sustainability.

PREPRINT DISCLOSURE

This article was previously posted as a preprint titled "Active Space Debris Removal: Feasibility and Comparative Analysis of Methods for Diverse Targets" on the Research Archive of Rising Scholars, DOI: https://doi.org/10.58445/rars.3296. The preprint is openly accessible under a Creative Commons license, and all listed authors approved its posting.

CONFLICT OF INTEREST

The authors declare no conflicts of interest related to this work.

REFERENCES

1. Pine D. Runaway chain reaction of space debris will "threaten our future in space," according to ESA. Live Science. 2025 Apr 12. Available from: https://www.livescience.com/space/its-time-to-clean-up-space-junk-before-orbits-become-unusable-according-to-new-esa-report (accessed on 2025-09-14).
2. European Space Agency. About space debris. Available from: https://www.esa.int/Space_Safety/Space_Debris/About_space_debris (accessed on 2025-09-14).
3. Safi M, Devlin H. "A terrible thing": India's destruction of satellite threatens ISS, says NASA. The

Guardian. 2019 Apr 1. Available from: https://www.theguardian.com/science/2019/apr/02/a-terrible-thing-nasa-condemns-indias-destruction-of-satellite-and-resulting-space-junk (accessed on 2025-09-14).
4. Canadian Space Agency. About Canadarm2. 2024 Jul 16. Available from: https://www.asc-csa.gc.ca/eng/iss/canadarm2/about.asp (accessed on 2025-09-14).
5. Basana F. Active debris removal employing a robotic arm equipped CubeSat. Aerospace Science and Engineering. 2024;IV(Aerospace PhD-Days):108-112. Available from: https://www.mrforum.com/wp-content/uploads/open_access/9781644903193/24.pdf (accessed on 2025-09-18). https://doi.org/10.21741/9781644903193-24
6. Forshaw J, Lopez R, Okamoto A, Blackerby C, Okada N. The ELSA-d end-of-life debris removal mission: mission design, in-flight safety, and preparations for launch. In: Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference. 2019. p. 17-20. Available from: https://amostech.com/TechnicalPapers/2019/Space-Based-Assets/Forshaw.pdf (accessed on 2025-09-18).
7. Boonrath A, Liu F, Botta E, Chowdhury S. Learning-aided control of robotic tether-net with maneuverable nodes to capture large space debris. arXiv. 2024. Available from: https://arxiv.org/abs/2403.07125 (accessed on 2025-09-18).
8. Lv S, Zhang H, Zhang Y, Ning B, Qi R. Design of an integrated platform for active debris removal. Aerospace. 2022; 9 (7): 339. https://doi.org/10.3390/aerospace9070339
9. Astroscale. Astroscale's ELSA-d finalizes de-orbit operations marking successful mission conclusion. 2024 Jan 24. Available from: https://www.astroscale.com/en/news/astroscales-elsa-d-finalizes-de-orbit-operations-marking-successful-mission-conclusion (accessed on 2025-09-18).
10. Wokes S, Forshaw J, Auburn J. ELSA-d: mission design and performance to date. Astroscale. 2021. Available from: https://indico.esa.int/event/321/contributions/6383/attachments/4369/6591/ESA%20CleanSpace%202021%20-%20Astroscale%20ELSA-d.pdf (accessed on 2025-09-18).
11. Bowman CL, NASA Glenn Research Center. Design issues for using magnetic materials in radiation environments at elevated temperature. NASA Technical Reports Server. 2013 Feb 25. Available from: https://ntrs.nasa.gov/citations/20130010718 (accessed on 2025-09-18).
12. Rovey JL, Lyne CT, Mundahl AJ, Rasmont N. Review of chemical-electric multimode space propulsion. American Institute of Aeronautics and Astronautics. 2019. Available from: https://eplab.ae.illinois.edu/Publications/AIAA-2019-4169.pdf (accessed on 2025-09-18). https://doi.org/10.2514/6.2019-4169
13. Bombardelli C, Urrutxua H, Merino M, Peláez J, Ahedo E. The ion beam shepherd: a new concept for asteroid deflection. *Acta Astronautica*. 2013; 90 (1): 98-102. https://doi.org/10.1016/j.actaastro.2012.10.019
14. Bombardelli C, Peláez J. Ion beam shepherd for contactless space debris removal. arXiv. 2011. Available from: https://arxiv.org/abs/1102.1289 (accessed on 2025-09-18).
15. Scharring S, Wilken J, Eckel H-A. Laser-based removal of irregularly shaped space debris. *Optical Engineering*. 2016; 56 (1): 011007. https://doi.org/10.1117/1.OE.56.1.011007
16. Choi S, Papa R. Assessment study of small space debris removal by laser satellites. In: IEEE Aerospace Conference. 2011. Available from: https://ntrs.nasa.gov/citations/20120009369 (accessed on 2025-09-18).
17. Pieters L, Noomen R. Space-based laser ablation for space debris removal. In: 8th European Conference on Space Debris. 2021; 8 (1).
18. Nishida S-I, Kawamoto S, Okawa Y, Terui F, Kitamura S. Space debris removal system using a small satellite. *Acta Astronautica*. 2009; 65 (1-2): 95-102. https://doi.org/10.1016/j.actaastro.2009.01.041
19. Jang W, Yoon Y, Go M, Chung J. Dynamic behavior and libration control of an electrodynamic tether system for space debris capture. *Applied Sciences*. 2025; 15 (4): 1844. https://doi.org/10.3390/app15041844
20. Reentry and Risk Assessment. National Aeronautics and Space Administration, Orbital Debris Program Office. Available from: https://orbitaldebris.jsc.nasa.gov/reentry (accessed on 2026-1-17).
21. Active Debris Removal - An Essential Mechanism for Ensuring the Safety and Sustainability of Outer Space Activities. United Nations Office for Outer Space Affairs. Available from: https://www.unoosa.org/pdf/limited/c1/AC105_C1_2012_CRP16E.pdf (accessed on 2026-1-10).
22. Liability Convention. United Nations Office for Outer Space Affairs. Available from: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html (accessed on 2026-1-10).
23. Automating collision avoidance. European Space Agency. Available from: https://www.esa.int/Space_Safety/Space_Debris/Automating_collision_avoidance (accessed on 2026-1-11).
24. Cost and Benefit Analysis of Orbital Debris Remediation. National Aeronautics and Space Administration. Available from: https://www.nasa.gov/wp-content/uploads/2023/03/otps_-_cost_and_benefit_analysis_of_orbital_debris_remediation_-_final.pdf (accessed on 2026-1-11).