



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

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1. 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, we must turn toward Active Debris Removal (ADR): 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.

2. 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 (Pine, 2025). Although this incident was relatively minor, it highlights a serious risk that even slightly larger fragments could pose: potentially penetrating 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 in Low Earth Orbit (LEO) (ESA - About Space Debris, n.d.). 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, an intentional wrecking that produced hundreds of debris pieces demonstrating the danger of large fragments above the ISS orbit (Safi & Devlin, 2019) can illustrate this. With space traffic accelerating, action is required now: Active Debris Removal (ADR)—deliberate, mission-level interventions to remove or neutralize existing



orbital objects—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; no single technology is suitable for all debris classes or mission scenarios. Larger debris objects also vary in how they behave in orbit: some remain relatively stable and predictable, while others rotate uncontrollably. 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.

Despite growing recognition of the debris problem, the current availability of practical ADR solutions remains extremely limited. Most concepts are still in the early research or prototype stages, and only a few have achieved in-orbit demonstration and proof-of-concept. Furthermore, no international consensus exists on which techniques should be prioritized or standardized, resulting in the field being fragmented across multiple competing approaches.

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.

3. 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.

3.1 Robotic Arm Systems

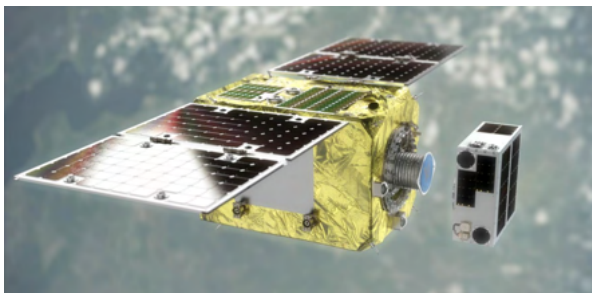
These systems operate by deploying one or more manipulator arms from the servicer spacecraft. This concept draws on heritage from crewed space servicing missions (e.g., Canadarm2 on the ISS (About Canadarm2, 2024)), but its adaptation to autonomous debris removal remains largely at the conceptual or 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. These systems are mechanically versatile, but no large-scale, autonomous robotic arm capture has yet been operationally demonstrated in orbit (Basana, 2024).

3.2 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. Because this capture method relies on specialized hardware, only satellites launched with standardized magnetic plates or docking fixtures can be serviced. This requirement is both a design feature and a drawback: it simplifies capture for cooperative targets but excludes debris objects that were never equipped with such interfaces. Demonstrations such as the ELSA-d mission have validated this approach in orbit at a small scale, proving that repeated magnetic capture and release cycles are feasible. Figure 1 shows the magnetic docking sequence from ELSA-d, where the servicer approaches the client satellite and achieves full magnetic engagement. 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. While magnetic docking offers simplicity (due to its few moving parts) and reliability, it is currently constrained by the need for pre-installed magnetic interfaces, making it unsuitable for the vast majority of existing debris objects that were not originally designed with such features (Forshaw et al., 2019).

(a)



(b)

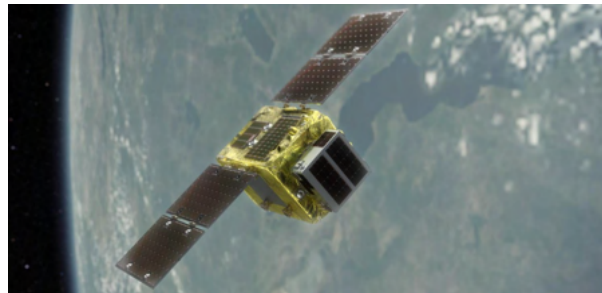


Figure 1. Magnetic docking of a servicer spacecraft and client satellite. **(a)** Magnetic docking sequence in progress as the servicer approaches the client satellite. **(b)** The servicer and client satellite fully docked in orbit (Forshaw et al., 2019).

3.3 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 2 illustrates the control framework 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 physics of this process are complex: in simulations, the net is represented as a mesh of nodes linked by spring-damper elements. The springs capture the elastic stretching of the strands, while the dampers simulate energy loss due to material friction, allowing for nonlinear deformations such as twisting, sagging, or snapping under load. When the net contacts the debris, these models capture how the mesh conforms to irregular surfaces, redistributes tension, and interacts with tumbling motion. Figure 3 shows a four-MU simulation sequence, where the net expands toward the debris and closes successfully under adaptive control. The servicer can then reel in the tether, using the tension to slow rotation or control orientation before initiating disposal. Although attractive for their flexibility and safe standoff distance—they can adapt to irregular debris shapes and spin states while maintaining distances of tens to hundreds of meters to reduce collision risk—tether-net systems are currently limited to virtual and ground-based testing (Boonrath et al., 2024).

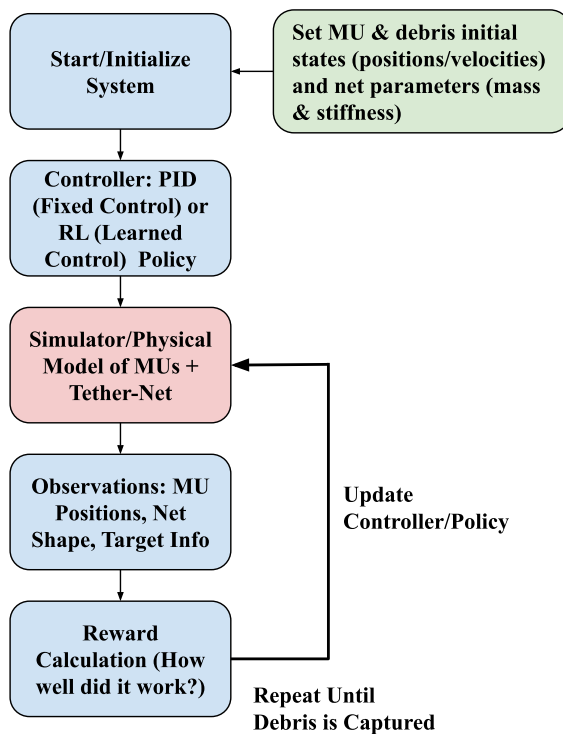


Figure 2. Simplified control and learning framework for the maneuverable nodes on a simulated tether-net. Two types of controllers can be used: a PID controller, which applies fixed rule-based corrections by combining proportional, integral, and derivative terms of the error, or a Reinforcement Learning (RL) controller, which learns policies from repeated simulations and adapts thrust commands to maximize capture success. In both cases, 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.

(a) 15 seconds

(b) 35 Seconds

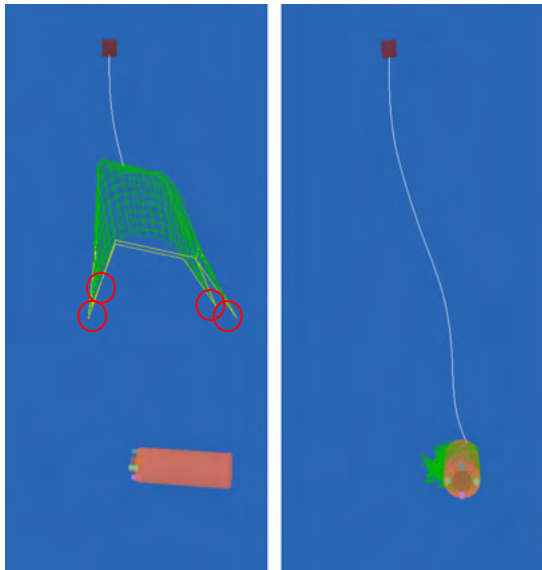


Figure 3. Simulation of a learning-aided controlled 4-MU tether-net system. **(a)** The net expanding toward the target debris. The four MUs marked with red circles control the net's shape and trajectory. **(b)** The net closing and successfully capturing the debris under RL guidance (Boonrath et al., 2024).

3.4 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 multiple mechanisms requires real-time sensor integration, predictive dynamic modeling, and tightly synchronized actuation. While promising in principle for versatility, hybrid platforms significantly increase system complexity and have yet to be tested in orbit (Lv et al., 2022).

4. Detailed Case Study: Astroscale's ELSA-d Mission (Astroscale, 2024; Forshaw et al., 2019; Wokes et al., 2021)

Among all contact-based ADR concepts, the End-of-Life Services by Astroscale demonstration mission (ELSA-d) stands out as the most advanced and comprehensive in-orbit demonstration to date. While robotic arms, tether-nets, and hybrid concepts remain largely at the simulation or ground-test stage, ELSA-d executed a full suite of proximity operations, autonomous rendezvous, and repeated capture maneuvers using real spacecraft in LEO. Figure 4 illustrates the ELSA-d concept of operations, outlining the servicer's approach, magnetic capture, release, and controlled deorbit phases. This mission, therefore, provides a unique, high-fidelity data point for assessing the technical feasibility and operational challenges of contact-based debris removal.

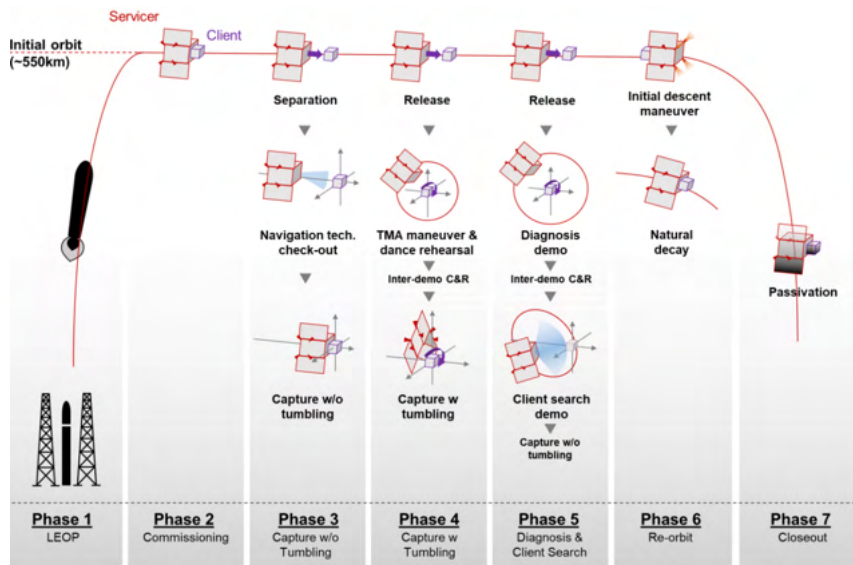


Figure 4. ELSA-d Concept of Operations (CONOPS) (Forshaw et al., 2019).

4.1 Mission Architecture and Spacecraft Design

ELSA-d was launched in March 2021 from Baikonur Cosmodrome into a roughly 550 km circular orbit. It consisted of two spacecraft: a 175 kg servicer satellite and a 17 kg client satellite representing a piece of cooperative debris: a controlled, surrogate target equipped with a docking plate to simulate orbital debris in a manner that allows repeatable, safe capture testing. The servicer measured about $0.7 \times 0.7 \times 1.1$ m (without deployed solar panels), while the client measured approximately $0.5 \times 0.5 \times 0.2$ m. Both spacecraft were launched stacked together, with the client attached to the servicer by a separation mechanism. This configuration allowed Astroscale to test a complete end-of-life capture scenario under controlled conditions, gradually increasing complexity from non-tumbling to tumbling capture and eventually deorbit.

The servicer is equipped with an integrated suite of guidance, navigation, and control (GNC) sensors, including GPS for absolute navigation and optical/LiDAR-type relative sensors for short-range rendezvous. Propulsion was provided by eight Ecological Advanced Propulsion Systems (ECAPS) green monopropellant thrusters, mounted symmetrically near the servicer's center of gravity to permit full 6-degrees of freedom (DOF) maneuvering even in the event of a thruster failure. This redundancy became crucial when four thrusters failed later in the mission, but the spacecraft continued operations. Power was supplied by deployable solar arrays with battery storage, and a ground segment at the UK National In-Orbit Servicing Control Centre oversaw operations.

4.2 Magnetic Capture Mechanism and Docking Plate

Central to ELSA-d's capture system was Astroscale's magnetic docking mechanism. The client satellite was fitted with a Docking Plate (DP): a ferromagnetic, optically marked disc mounted on a stand-off bracket—which served as a cooperative interface. This plate not only provided a robust, flat, and magnetically reactive surface but also contained reflective optical markers to assist the servicer's navigation sensors in estimating distance and attitude.

The servicer's capture mechanism consisted of a set of small concentric permanent magnets embedded in an extendable capture head. A permanent magnet is a material whose internal electron spins and orbital motions are aligned, producing a persistent magnetic field without the need for external power. This intrinsic field interacts strongly with ferromagnetic materials on the docking plate, enabling a secure and passive magnetic connection. When the capture head was extended toward the docking plate, the magnetic attraction created a firm but reversible bond between servicer and client. Astroscale engineered a mechanical push-off system behind the magnets so that, when commanded, the servicer could break the magnetic bond and push the client away gently for repeated release–recapture cycles.

This approach simplified capture relative to robotic arms (fewer moving joints and no grapple claws) while still enabling high-precision docking. It also enabled demonstration of semi-autonomous tumbling capture. By knowing the docking plate's optical pattern, the servicer's sensors could track the client's rotation and time the approach so that the capture head aligned correctly with the plate even as the client rotated.

4.3 Proximity Operations and Capture Scenarios

ELSA-d's Concept of Operations (CONOPS) unfolded in progressively more challenging phases over roughly two years of on-orbit activity. After launch and commissioning, the servicer first practiced non-tumbling capture, commanding the client to hold a fixed attitude and approaching it from "Point A" (10 m behind) and "Point B" (5 m behind). These holding points allowed the servicer to calibrate its relative sensors in space for the first time. During capture attempts, the servicer synchronized its relative velocity, position, and roll with the client, extended the magnetic capture head, and latched onto the docking plate.

Once non-tumbling capture was demonstrated, the mission advanced to tumbling capture, commanding the client to rotate with a natural motion profile to simulate an uncooperative debris state. The servicer performed a "dance"—a continuous trajectory that kept its capture head aligned with the docking plate despite the client's spin—and then executed the capture. Data from the client's tumbling motion was downlinked and processed on the ground to update the servicer's flight dynamics system, which in turn generated guidance commands for the next approach. This loop validated the combined use of on-board sensing, ground processing, and closed-loop control for capturing moving objects.

Additional demonstrations included fly-around inspections, where the servicer performed a complete circumnavigation of the client to simulate damage inspection or pre-capture assessment, and search-and-approach sequences, where the client was released at a distance and the servicer had to reacquire it using its sensors. Throughout, collision avoidance procedures and safety ellipses were implemented to ensure that, if a navigation fault occurred, the servicer would drift away rather than collide.

4.4 Deorbit and End-of-Mission Operations

After proving repeated captures, ELSA-d simulated a real end-of-life scenario by conducting re-orbit and deorbit operations. Using its chemical thrusters, the servicer lowered its orbital altitude with the client attached, demonstrating the ability to initiate a disposal trajectory. Although the mission ended before a full combined deorbit to re-entry, the servicer's final orbit

was reduced to about 500 km, from which natural decay will cause atmospheric re-entry in approximately 3.5 years, well within the 25-year post-mission international disposal guideline. The non-maneuverable client, released at a slightly higher orbit, is predicted to naturally deorbit within five years.

The propellant choice (LMP-1035) provided both high performance and low toxicity compared to traditional hydrazine, and the symmetric thruster layout allowed thrusting in multiple directions, which is critical for aligning the combined servicer–client stack during deorbit burns. By simulating re-orbiting to a lower altitude rather than direct re-entry, Astroscale mirrored real-life end-of-life services, where debris would first be moved out of congested orbits to reduce collision risk and then allowed to decay naturally.

4.5 Future Implications and Potential Optimization

The experience gained from ELSA-d directly informed Astroscale’s current development of ELSA-M: a commercial servicer intended to remove multiple clients in a single mission, with plans to launch in 2026. Whereas ELSA-d proved the core technologies—magnetic capture, autonomous rendezvous, tumbling acquisition, and controlled deorbit—ELSA-M scales up the approach to handle multiple semi-cooperative satellites sequentially. However, like ELSA-d, ELSA-M still requires each client to be equipped with a docking plate, limiting capture to cooperative targets. Nonetheless, this transition from a single-client demo to a multi-client commercial system represents the maturation pathway for ADR services, involving the development of standard docking interfaces (such as Astroscale’s docking plate) and refining autonomous GNC until removal missions become routine.

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. ELSA-d relied on permanent magnets, which provide a fixed magnetic field. 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 (Bowman & NASA Glenn Research Center, 2013).

Another possible enhancement involves the servicer’s motion prediction algorithms. Although ELSA-d already demonstrated optical tracking of the docking plate, future missions could integrate machine-learning-based attitude prediction mapping to build real-time models of debris geometry and rotational state. Such models could improve capture timing, reduce maneuver propellant usage, and shorten the number of rehearsal cycles needed for tumbling capture. For instance, machine learning models have been developed to infer spin rates and axes from light curves, improving estimation of rotation states for debris (Badura et al. 2023).

Propulsion also presents opportunities. ELSA-d used LMP-103S monopropellant thrusters arranged symmetrically for redundancy. A future hybrid propulsion system could supplement these with low-thrust electric propulsion for precision station-keeping during delicate capture or for fine-tuning deorbit burns after capture. Studies of multimode 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 (Rovey et al., 2019). 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, more advanced motion prediction, 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.

5. 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.

5.1 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. Figure 5 illustrates this dual-thruster configuration, where a forward ion beam imparts momentum to the target while a counter-thrust stabilizes the shepherd's position. This requires precise tracking of the debris' position, velocity, and orientation in three dimensions. 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 (Bombardelli et al., 2013). IBS concepts remain unflown, but extensive simulations demonstrate that the system could, in principle, engage multiple large debris objects sequentially (Bombardelli & Peláez, 2011).

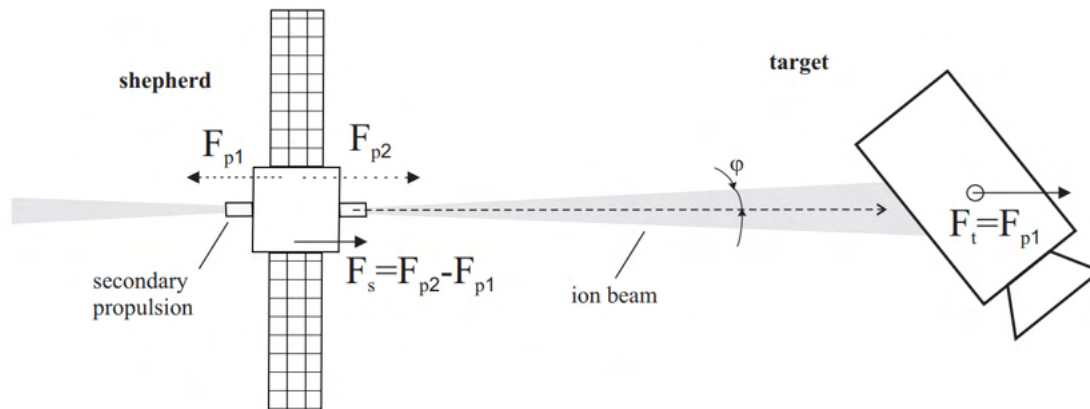


Figure 5. Ion beam shepherd concept. The shepherd spacecraft directs an ion beam at the target, imparting a force (F_t) to move it, while using secondary propulsion to counteract its own recoil. Here, F_{p1} is the primary thrust from the ion beam, F_{p2} is the counter-thrust from the secondary propulsion system, and $F_s = F_{p2} - F_{p1}$ represents the net force acting on the shepherd to keep it in position (Bombardelli & Peláez, 2011).

5.2 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 (Scharring et al., 2016). 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 (Choi & Papa, 2011). 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 (Choi & Papa, 2011). 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 (Pieters & Noomen, 2021). From approximately 500 km away, the laser triggers sufficient ablation, decelerating debris objects 1-10 cm in size and significantly reducing their orbital lifetimes (Pieters & Noomen, 2021). However, laser ADR remains at the experimental stage, especially considering debris of larger size, with only limited ground tests performed (Scharring et al., 2016).

5.3 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 grapple mechanism, since establishing an electrical connection with the debris surface is essential for current flow through the tether. Therefore, 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. Figure 6 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. Unlike thruster-based systems, EDTs require only electrical power to maintain current flow. However, they are highly dynamic: the tether can oscillate (librate) under gravity gradient forces, deployment transients, or coupling with debris motion. Conceptual studies indicate that EDTs could repeatedly deorbit large debris; however, in-orbit demonstrations remain extremely limited (Nishida et al., 2009; Jang et al., 2025).

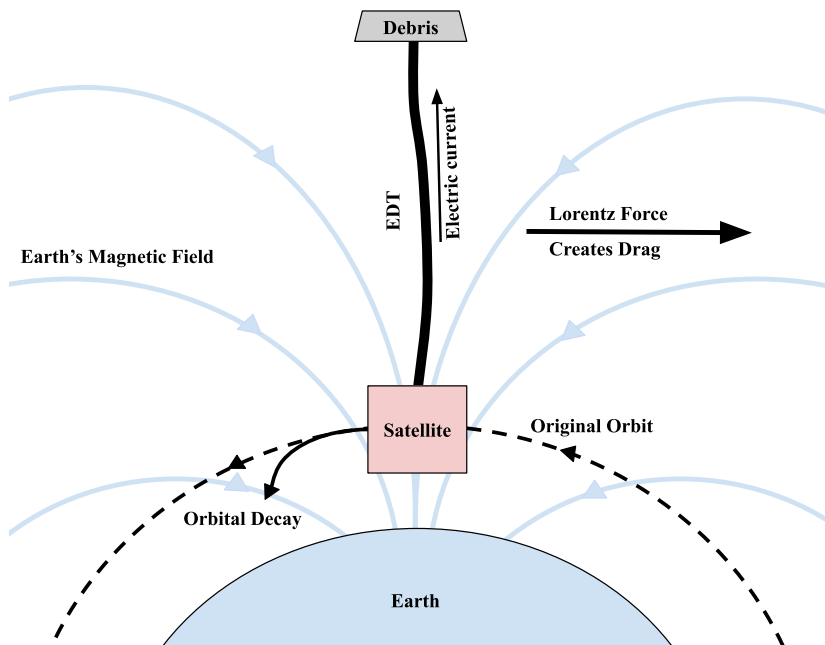


Figure 6. ElectroDynamic Tether (EDT) debris removal concept. A satellite deploys a conductive tether attached to orbital debris. Electric current flowing through the tether interacts with Earth's magnetic field to produce a Lorentz force, gradually lowering the orbit through drag and enabling deorbiting.

6. Detailed Case Study: JAXA's Electrodynamic Tether (EDT) Debris-Removal System and Tether Libration Dynamics (Jang et al., 2025; Nishida et al., 2009)

Among all non-contact ADR concepts, the electrodynamic tether (EDT) project led by the Japan Aerospace Exploration Agency's (JAXA) Institute of Aerospace Technology stands out as the most technically mature and hardware-focused demonstration to date. Whereas laser ablation or ion-beam shepherd concepts remain largely at the simulation stage, JAXA's program integrates real components—a bare conductive tether, carbon nanotube field emitters, reel mechanisms, and compliant capture arms—into a complete end-to-end debris removal concept. This system is designed to lower the orbits of large debris objects without expending propellant,

relying instead on electromagnetic interaction with Earth's magnetic field. As such, it represents the leading candidate among non-contact ADR techniques.

6.1 Mission Architecture and Hardware

JAXA's concept envisions a micro-satellite servicer capable of piggyback launch, rendezvous, and attachment to a large non-cooperative debris object using a lightweight, flexible robotic arm. Once attached, the servicer deploys a bare conductive tether several kilometers long. This tether collects electrons directly from the surrounding ionospheric plasma and completes the circuit using Field Emitter Array Cathodes (FEAC). These cathodes are based on carbon nanotube technology, and emit electrons back into space. With the current established, the combined debris-servicer-tether system interacts with Earth's geomagnetic field to produce a continuous drag force, gradually reducing orbital altitude without the use of chemical propellant.

Overall, the EDT package described in the JAXA study consists of four integrated elements: a bare conductive tether for electron collection, FEAC electron emitters for closing the circuit, a lightweight ejecting and reel mechanism to manage tether deployment and braking, and a compliant robotic arm for initial attachment to non-cooperative debris. By design, the system is essentially propellantless, requiring only electrical power to sustain the FEAC emission and control electronics.

6.2 Physics of the Electrodynamic Tether

When a conductor moves through a magnetic field at high speed, an electromotive force (EMF) is induced across its length according to $E = v \times B$, where E is the induced electric field, v is the velocity of the conductor, and B is the magnetic field. In LEO, the tether sweeps through Earth's geomagnetic field at nearly 7-8 km/s, inducing a voltage that drives electrons from the ambient plasma onto the bare conductive surface. At the opposite end, the FEAC cathode emits electrons back into space, closing the circuit and producing a steady current. This current then interacts with the geomagnetic field to create a Lorentz force according to $F = Il \times B$, where F is the Lorentz force, I is the current, l is the tether length vector, and B is the magnetic field. This force acts opposite to the direction of motion and steadily reduces the orbital energy of the debris-tether system.

In simpler terms, the orbiting tether behaves like a moving wire cutting through a magnetic field, creating a current that pushes back on the wire itself. This force steadily lowers the orbit's perigee, eventually bringing the debris into a denser atmosphere where natural drag completes the reentry process. Unlike thrusters, no propellant is consumed; the only "fuel" is the spacecraft's motion through the magnetic field.

6.3 Tether Dynamics and the Need for Advanced Modeling

Attaching a kilometers-long flexible tether to a tumbling debris object creates significant dynamic challenges. The combined system behaves like a pendulum under multiple influences: gravity gradients, atmospheric drag, and the Lorentz force all tug on the tether, inducing oscillations and twisting that can reduce efficiency or even risk tether failure. One of the most important dynamic effects out of these is libration. In this context, libration refers to the oscillatory swinging or waving of the tether about its equilibrium position, similar to the way a pendulum swings under

gravity. If not controlled, libration can grow in amplitude due to resonances with orbital motion or electromagnetic forces, leading to large structural loads, loss of current collection efficiency, or even tether entanglement with the debris.

JAXA's study provides the hardware and operational framework but leaves the deeper dynamics problems to be addressed by modeling efforts.. Jang et al (2025) builds on JAXA's concept to address EDT stability. In their study, a high-fidelity flexible-body approach known as the Absolute Nodal Coordinate Formulation (ANCF) was utilized to model the tether in three dimensions with elasticity, damping, and distributed Lorentz forces. Their simulations explored tether lengths from 5 to 20 km and diameters from 0.5 to 1.5 mm attached to debris masses up to several tons at altitudes around 450 km. They demonstrated that increasing the tether length and diameter improves current collection and Lorentz force, but also amplifies oscillation amplitudes. For aggressive tether geometries, peak Lorentz forces of 0.06–0.08 N were predicted, which is sufficient to significantly reduce orbital lifetime to months, provided that libration is actively managed.

6.4 Control of Libration and Operational Sequence

This study demonstrated that libration can be controlled by modulating the tether current in synchrony with the tether's swing—reducing current as it swings one way and increasing it as it swings back—effectively removing energy from the oscillation, much like applying a brake at the right moments. This closed-loop control would allow long tethers to maintain stability without thrusters, preserving the propellantless advantage of the system. Additionally, the reel mechanism's braking function can be used to dampen tether motion during or after deployment, further suppressing libration growth. Operationally, this means that after the robotic arm attaches to the debris and the tether is deployed, controllers can dynamically adjust the electrical parameters to keep the tether nearly straight and aligned with the local vertical direction, minimizing lateral loads and maximizing drag efficiency.

6.5 Future Implications and Potential Optimization

Taken together, the Concept of Operations emerging from these two studies would be as follows: launch and rendezvous with the target debris, use the compliant robotic arm to attach the servicer to the debris, deploy the bare tether using the reel and braking mechanism, establish current flow through electron collection and FEAC emission, apply continuous Lorentz-force drag to lower the orbit, and actively modulate the current to damp oscillations until atmospheric drag completes the reentry. This sequence directly addresses each significant risk: capture, tether deployment, force generation, and stability, using either existing hardware or proven simulation-based controls.

However, several areas stand out where refinements or new approaches could significantly enhance performance, stability, and operational safety. 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.

7. Evaluation of Current Debris Removal Technology

A central finding of this study is that active debris removal technologies cannot be evaluated as a single paradigm but must be understood within the specific operational conditions under which they function best. Each technique—contact-based or non-contact—operates within a distinct performance range shaped by debris size, mass, altitude, and degree of cooperativity. This section analyzes the optimal conditions for the systems examined in this paper, evaluates their comparative merits and limitations, and discusses the broader implications of deploying these technologies in real-world space operations.

7.1 Assigning Operational Parameters

Under contact methods, robotic arm systems show the greatest potential for small to medium debris in the tens to hundreds of kilograms range, especially at lower orbital altitudes and with debris in relatively slow or predictable rotation states. In these conditions, rendezvous and capture can be performed with manageable maneuvering and minimal collision risk. Magnetic docking systems are presently limited to semi-cooperative targets—objects equipped with docking plates or ferromagnetic regions—but they excel at repeated capture and release cycles once such interfaces are in place. Tether-net systems push the boundary to larger or irregularly shaped debris, maintaining safe standoff distances of tens to hundreds of meters, a feature that reduces risk but also demands highly reliable deployment mechanisms and precise trajectory modeling.

Non-contact methods operate under a different set of constraints. The ion beam shepherd and laser ablation concepts show the most promise for small to medium debris at high altitudes, where direct attachment is not feasible or desirable. These systems apply forces remotely, making them ideal for delicate or hazardous targets but at the cost of requiring high power, precision pointing, and complex beam control. The electrodynamic tether (EDT) system is inherently better suited to massive debris—hundreds of kilograms to several tons—in LEO, where the geomagnetic field is strong enough to induce substantial current and Lorentz force. Together, these distinctions illustrate that ADR must be tailored: optimal results emerge from matching system capabilities to debris characteristics.

7.2 Merits and Limitations of Contact Methods

Contact methods generally provide the highest degree of control once attachment is achieved. Robotic arms offer a versatile mechanical interface, capable of grappling a wide variety of shapes and configurations and even deploying secondary devices such as drag sails or tethers. However, they also introduce risk during close approach, especially with tumbling or irregular debris, where the arm could collide or jam under unexpected motion. Magnetic docking reduces mechanical complexity and enables repeated captures with relatively simple hardware, but it is constrained to cooperative targets and requires precise alignment between magnetic interfaces and servicer sensors. Tether-nets can envelop irregular or spinning debris from a safe distance, offering a unique advantage for targets unsuitable for rigid capture, but their unproven deployment reliability and risk of entanglement remain major engineering hurdles. Integrated or hybrid platforms, which combine several capture techniques into one servicer, promise unprecedented versatility but at the expense of added mass, system complexity, and the need to coordinate multiple subsystems in real time—capabilities yet to be demonstrated in orbit.

Another significant limitation of contact methods is propulsion cost. Once a servicer has captured a piece of debris, the combined mass often exceeds its maneuvering capacity, making large orbit changes expensive in terms of propellant and potentially requiring secondary vehicles or drag-enhancement devices.

7.3 Merits and Limitations of Non-Contact Methods

Non-contact systems avoid the hazards of physical attachment, thereby reducing collision and entanglement risk, but they do so by applying weaker and more distributed forces over long durations. The ion beam shepherd concept is attractive because a single servicer could, in theory, address multiple small debris objects sequentially without ever touching them. Yet it requires extremely precise station-keeping, high power availability, and beam-control accuracy, none of which have yet been validated in orbit. Laser ablation enables engagement from even greater distances, which is valuable for high-risk debris, but the enormous power and adaptive optics required to overcome beam divergence and targeting uncertainties limit its near-term practicality.

The electrodynamic tether occupies a unique position between these extremes. While it still requires an initial physical attachment, it then operates in the absence of propellant and autonomously, applying continuous Lorentz-force drag for months. This offers a major advantage in long-term fuel savings but introduces its own dynamic challenges—notably

libration and tether instability—that must be carefully modeled and actively controlled. These dynamics place heavy demands on control algorithms, deployment mechanisms, and system monitoring but also offer the possibility of a largely self-sustaining removal force once stabilized.

7.4 Technology Readiness and Scalability

The findings of ELSA-d and JAXA's EDT program underscores the importance of real-world demonstration. ELSA-d has already proven magnetic capture, autonomous rendezvous, and repeated docking cycles in orbit, providing confidence that a commercial multi-client servicer can follow. JAXA's EDT, although not yet flown at full scale, has integrated real tether materials, carbon nanotube electron emitters, and reel/braking mechanisms into a coherent design, making it one of the most hardware-ready non-contact concepts. This contrasts sharply with ion beam shepherd and laser systems, which remain mostly in simulation or laboratory testing stages with limited path-to-flight plans.

Scalability for all these systems hinges on modularity and standardization. For contact methods, the widespread adoption of standardized docking plates or magnetic interfaces would transform technologies such as magnetic capture from niche demonstrations into mainstream services. For non-contact systems, advances in high-efficiency power generation, autonomous navigation, and precision pointing would enable longer-duration, multi-object campaigns capable of systematically reducing orbital debris populations.

7.5 Overall Challenges

Despite their differences, all ADR methods share a set of common challenges that define the upper limits of their performance. Autonomous GNC remains essential: whether extending a robotic arm, modulating a tether current, or firing a plasma beam, the servicer must maintain precise relative motion with minimal human oversight. Long-duration reliability is another universal hurdle. Months-long drag operations in an electrodynamic tether or repeated capture cycles with a magnetic docking servicer require robust hardware, fault-tolerant software, and predictive maintenance strategies. Finally, cost and mass constraints are a constant trade-off. Larger, heavier servicers increase launch costs and limit maneuverability, while high power requirements for non-contact methods demand substantial onboard infrastructure that can undermine their theoretical advantages.

8. Analysis Summary

The preceding analysis of ADR concepts can be further emphasized by presenting a structured overview of their technical and operational characteristics through two tables. Table 1 summarizes each method's core design features, target debris types, and propulsion or control requirements, while Table 2 focuses on operational considerations such as capture timeframes, engineering risks, and reusability. Together, these tables provide a concise reference framework for comparing current ADR methods under realistic mission conditions.

Table 1 - Technical Overview

Method	Demonstration Status	Target Debris Size and Type	Power / Fuel Needs	Control / Navigation Characteristics
Robotic Arm Systems	Conceptual and ground-tested; no full-scale in-orbit demonstration	Cooperative and non-cooperative debris; ~0.5-3m and ~50-500 kg	~100 watts from servicer bus; robotic actuators draw additional power; propulsion for rendezvous and deorbit	Active proximity navigation with sensors; precise GNC required for arm motion and trajectory planning
Magnetic Docking Systems	In-orbit demonstration completed (only with pre-fitted magnetic docking plates); not yet proven for unmodified/uncooperative debris	Cooperative satellites ~0.5-1 m, and ~10-50 kg	Uses small satellite power systems (solar + battery); propulsion for rendezvous and deorbit	Onboard sensors for semi-autonomous relative navigation; needs precise alignment with the docking plate
Tether-Net Systems	Conceptual, some simulations and small-scale in-orbit tests	Non-cooperative debris ~0.5-3 m and ~50-500 kg	Net deployment can use springs or pyrotechnic devices; maneuverable nodes may use small thrusters; propulsion for rendezvous and deorbit	Autonomous net deployment guided by onboard sensors; maneuverable nodes may be controlled with algorithms
Integrated / Hybrid Platforms	Conceptual and demonstrated only in simulations	Highly versatile depending on system	Power demands scale with the specific tools used; propulsion for station-keeping and positioning before deployment of each tool	Multi-sensor navigation and guidance systems that coordinate the use of multiple capture tools
Ion Beam Shepherd (IBS)	Conceptual, studied mainly in simulations; no in-orbit demonstration yet	Non-cooperative debris ~0.5-3 m and ~50-500 kg	Multiple kilowatts of power for the ion thruster; additional propellant consumed by counter-thrust	Very precise formation flying; optical or RF sensors needed to maintain relative position; ion beam must be continuously aligned with target
Electrodynamic Tethers (EDT)	Conceptual, tested in simulations and some ground experiments	Large derelict satellites, rocket stages, or upper stages	Propellantless system, requires only tens of watts to power electron emitters that complete circuit	Active control to stabilize tether orientation and damp libration; current switching onboard helps regulate drag force



Laser-Based Systems	Tested in ground and limited space experiments, but no operational in-orbit system	Small debris fragments (centimeter scale) or specific components of satellites	Multi-kilowatt to megawatt power for ground-based lasers; Space-based systems would need very large solar arrays or batteries	Fast and precise beam pointing; ground-based lasers rely on adaptive optics to correct for atmospheric distortion; space systems need beam steering and high-speed tracking
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Table 2 - Operational Considerations

Method	Capture / Operational Timeframe	Known Failure Risks / Engineering Challenges	Potential Reusability / Mission Lifetime Constraints
Robotic Arm Systems	Months to years, depending on debris size and use of additional drag devices or tethers	Arm overload from tracking errors; risk of collision during grapple; debris fragmentation	Reusable until fuel or actuator life is depleted
Magnetic Docking Systems	Months to years, depending on propulsion capability and target altitude	Requires target with compatible docking interface; excessive tumble prevents capture	Reusable for multiple targets; limited by fuel and mechanism wear
Tether-Net Systems	Months to years, depending on altitude and debris mass	Net may not fully close; risk of entanglement or debris slipping out	Net typically single-use; servicer reusable for subsequent missions until fuel is exhausted
Integrated / Hybrid Platforms	Mission duration depends on number and complexity of targets, and type of system being used	Failure of any tool can abort mission; coordination of multiple mechanisms is challenging	Partially reusable: individual capture tools are single-use, but platform could continue operations using remaining tools and fuel
Ion Beam Shepherd (IBS)	Small orbital adjustments take hours to days; full deorbit occurs over weeks to months (continuous beam application required)	Beam misalignment reduces effectiveness; counter-thrust required for station-keeping	Reusable until thruster or propellant is depleted
Electrodynamic Tethers (EDT)	Months to years, depending on tether length, current, and debris mass	Tether libration and oscillations; risk of tether severance or snag	Tether remains attached to debris (single-use); servicer could deploy additional tethers
Laser-Based Systems	Days to months (can be years if used for larger debris), depending on laser power, engagement frequency, and altitude	Pointing errors, atmospheric distortion (ground) or beam jitter (space); partial debris fragmentation	Ground-based lasers reusable for multiple targets; space lasers limited by power supply and optical lifetime

9. 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. These findings suggest that future progress will depend on improving adaptability in capture and propulsion subsystems, standardizing cooperative interfaces to expand mission feasibility, and advancing autonomous guidance to reduce operational risk. Together, these efforts point toward a portfolio of complementary ADR techniques rather than reliance on a single solution, enabling sustainable use of Earth's orbital environment.

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