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A Comparative Mechanical Study of Net-, Tether-, and Robotic-Based Space Debris Capture Systems in Low Earth Orbit

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Abstract: The proliferation of space debris in Low Earth Orbit (LEO) has precipitated a critical inflection point in orbital sustainability, necessitating the transition from passive mitigation guidelines to active remediation strategies. While the astrodynamics of rendezvous and phasing are well-understood, the mechanical feasibility of physically capturing non-cooperative, tumbling targets remains the primary engineering bottleneck preventing scalable Active Debris Removal (ADR). This paper presents an exhaustive comparative mechanical analysis of three predominant capture architectures: flexible net-based systems, tethered projectile (harpoon) systems, and rigid robotic grasping mechanisms. The study rigorously examines the dynamic interactions, structural loading requirements, and failure modes inherent to each architecture when interfacing with high-mass, high-inertia targets such as the European Space Agency's Envisat satellite and the Soviet-era Zenit-2 rocket bodies.

Analytical models utilizing discretized mass-spring-damper formulations for flexible tethers and nets, Johnson-Cook constitutive material models for high-strain-rate harpoon impacts, and Hertzian contact theories for robotic grasping are synthesized to evaluate performance boundaries. The analysis reveals that net-based systems offer superior compliance and reduced guidance precision requirements for tumbling targets but suffer from complex, stochastic deployment dynamics and potential entanglement uncertainties. Conversely, robotic manipulators provide deterministic control and rigid capture capability but demand high-bandwidth impedance control to manage contact instability and are severely limited by the target's tumbling rate due to actuator saturation limits. Tether-harpoon systems occupy a mechanical middle ground, offering rapid capture with high impulse transfer, yet introducing significant risks of structural fragmentation and recoil dynamics that threaten the chaser spacecraft. Through a systematic trade-off analysis focusing on structural complexity, deployment risk, and post-capture stabilization, this report concludes that no single mechanism is universally optimal; rather, the mechanical selection is strictly governed by the target's angular momentum vector, structural integrity, and the acceptable risk profile of the mission. The results underscore that effective debris removal systems will ultimately depend on robust mechanical design capable of tolerating substantial dynamic uncertainties rather than conceptual novelty alone.

Keywords: Active Debris Removal, Space Debris Capture, On-Orbit Servicing, Spacecraft Dynamics, Robotic Space Systems

I. INTRODUCTION

A. Motivation and The Orbital Debris Crisis

The near-Earth orbital environment is currently undergoing a slow-motion environmental catastrophe. The density of debris objects in Low Earth Orbit (LEO), particularly in the highly congested Sun-Synchronous Orbit (SSO) regimes between 600 km and 1000 km, has reached a density sufficient to sustain a self-propagating collisional cascading effect, theoretically described by Donald Kessler in 1978. Current space surveillance networks track over 36,000 objects larger than 10 cm, while statistical models estimate the existence of millions of smaller, lethal fragments capable of terminating missions upon impact.[1] The mechanical challenge of remediation is fundamentally distinct from mitigation; while mitigation focuses on preventing new debris through passivation or post-mission disposal, remediation requires the active removal of existing massive objects—specifically large derelict satellites and spent rocket upper stages—that serve as the primary mass reservoirs for future fragment generation.[1]

The necessity for Active Debris Removal (ADR) is driven by the physics of these large objects. A single collision between two multi-ton objects, such as two Zenit-2 upper stages, could double the cataloged debris population in a single event. Therefore, space agencies like ESA and JAXA have identified specific high-priority targets, such as the 8,200 kg Envisat and the 9,000 kg SL-16 (Zenit-2) rocket bodies, for removal.[2] However, capturing these objects presents a "perfect storm" of mechanical difficulties. They are non-cooperative, possessing no functional attitude control, navigation aids, or grappling fixtures.

They are often tumbling with complex rotational vectors driven by decades of solar radiation pressure, gravity gradient torques, and residual propellant outgassing.[4] Furthermore, their structural properties are uncertain; materials degrade after decades of thermal cycling and atomic oxygen exposure, altering their response to mechanical stress.[5]

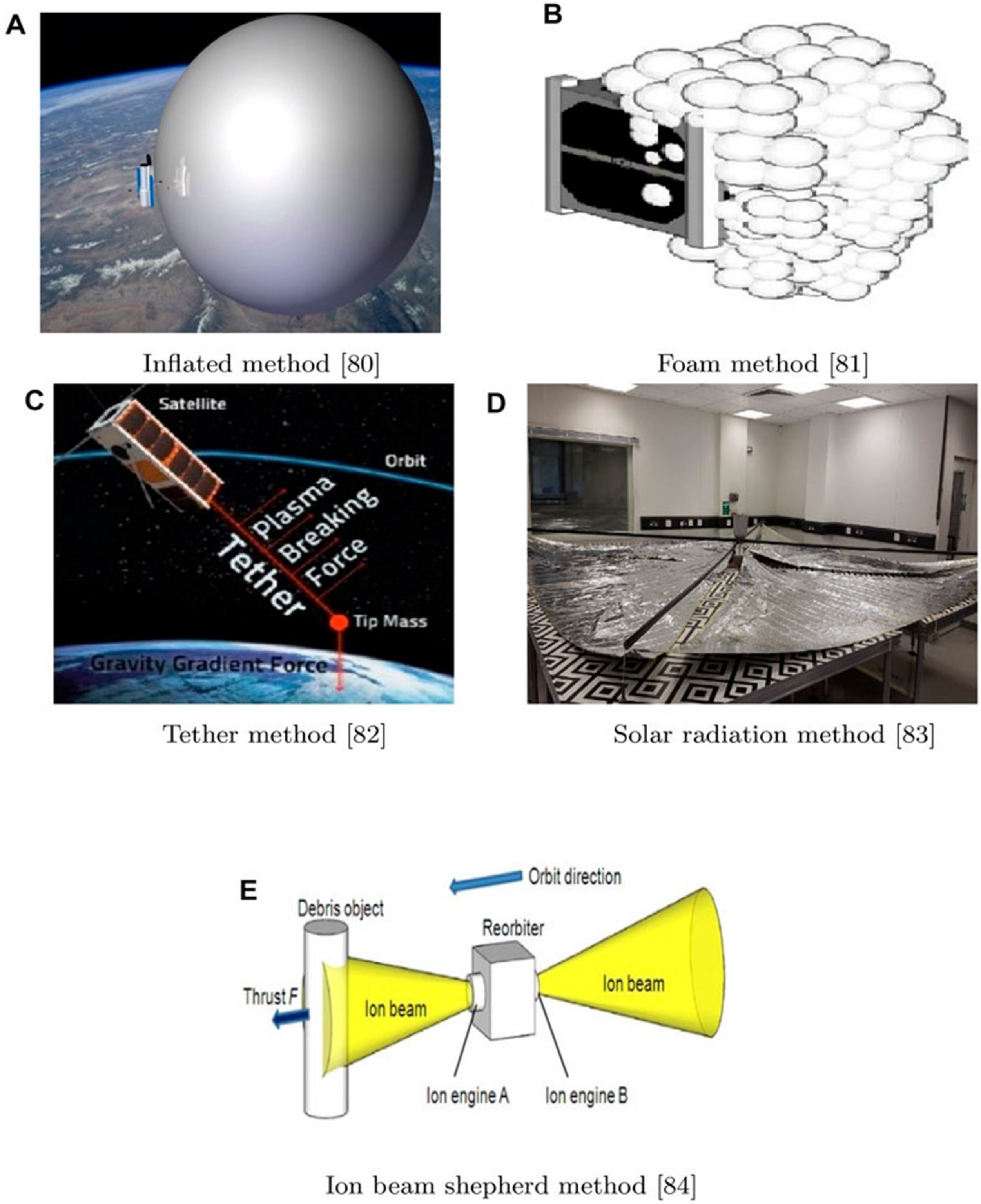

Figure 1: Examples of existing ET1 methods: potential energy dissipation. Energy Transfer Class 1 methods focus on decreasing the potential energy of the debris **(A)** inflated method, **(B)** foam method, **(C)** tether method, **(D)** solar radiation method, and **(E)** ion-beam shepherd method. [5]

B. The Mechanical Gap in ADR Research

The literature on ADR is historically saturated with high-level mission design concepts, orbital trajectory optimization, and legal or policy frameworks.[6] Significant effort has been expended on the astrodynamics of far-range rendezvous and the legalities of liability. However, a critical gap persists in the detailed mechanical feasibility analysis of the capture phase itself—the few seconds of physical interaction that determine mission success or failure. Many architectural studies treat the capture mechanism as a "black box" or assume a successful "grasp" as a binary event, neglecting the transient contact dynamics, the propagation of shock waves through flexible structures, and the mechanical limits of materials under the unique conditions of vacuum and microgravity.[7]

For instance, while individual technologies like nets or harpoons have been simulated in isolation or tested in sub-orbital demonstrators like the RemoveDEBRIS mission, there are fewer comprehensive comparative studies that evaluate them under identical boundary conditions.[9] Specifically, the mechanical failure modes—such as tether snap-back loads, net entanglement failure due to geometric mismatch, or robotic joint saturation during detumbling—are often underrepresented in system-level trade studies. This report addresses this deficit by focusing specifically on the mechanical engineering aspects: the forces, stresses, deformations, and control dynamics that dictate the physical interaction between the chaser and the target.[10]

C. Scope and Contributions

This report provides a nuanced, expert-level mechanical evaluation of the three primary contact-based ADR technologies: Nets, Harpoons, and Robotic Arms. It moves beyond qualitative descriptions to analyze the governing equations of motion, energy dissipation requirements, and structural trade-offs. The contributions of this analysis include:

- Unified Mechanical Framework: Establishment of a comparative analytical framework for evaluating capture forces, energy dissipation, and structural loads across flexible, semi-flexible, and rigid systems.
- Dynamic Modeling Deep Dive: Comparison of high-fidelity models, including Johnson-Cook penetration formulations for harpoons, Absolute Nodal Coordinate Formulation (ANCF) for nets/tethers, and Hertzian contact models for robotics.
- Target-Specific Feasibility: Application of mechanical models to real-world targets (Envisat, Zenit-2), incorporating their specific mass properties and inertia tensors to validate capture feasibility.
- Failure Mode Analysis: A detailed examination of mechanical failure modes, identifying critical design sensitivities such as impact velocity limits, net mesh geometry, and robotic actuator torque saturation.

II. MECHANICAL ENVIRONMENT AND REQUIREMENTS IN LEO

The design of any capture mechanism is fundamentally constrained by the physical properties of the target and the dynamic environment of LEO. Unlike terrestrial robotics, where a stable ground provides a reaction base, orbital capture involves the coupling of two free-floating bodies, often with significantly different masses and inertias.

A. Mechanical Characteristics of Orbital Debris

The targets of highest interest for ADR are not generic point masses but complex, distributed structures with specific inertial characteristics that drive mechanical design.

1) Target Morphology and Inertia

The distribution of mass within the target dictates its rotational stability and the torque required for detumbling.

- Envisat: The Envisat satellite is a massive box-type bus measuring approximately 26 m × 10 m × 5 m (with solar array deployed) and a mass of roughly 8,200 kg.[2] Its most prominent mechanical feature is the large Synthetic Aperture Radar (ASAR) antenna and the single large solar array, which create significant asymmetry.
  - *Inertia Tensor:* The inertia tensor is highly anisotropic. Estimates derived from observational data and CAD models suggest principal moments of inertia in the range of $I_{xx} \approx 17000$ kg m², $I_{yy} \approx 125000$ kg m², and $I_{zz} \approx 129000$ kg m² (values vary by fuel load and configuration).[11]
  - *Mechanical Implication:* The large appendages create extensive "keep-out zones" for robotic arms and significant snagging hazards for nets. The offset Center of Mass (CoM) relative to the geometric center complicates the application of thrust during post-capture stabilization, as any force vector not passing through the CoM induces residual torque.[4]

- Zenit-2 Upper Stage (SL-16): This is a large cylindrical object, approximately 11 meters in length and 3.9 meters in diameter, with a dry mass of roughly 9,000 kg.[3]
  - *Inertia Tensor:* Due to its cylindrical symmetry, the Zenit-2 stage behaves more like a classic rigid rotor. However, the presence of residual propellant in the tanks can introduce sloshing dynamics, acting as a fluid damper that affects the nutation angle over time.[12]
  - *Mechanical Implication:* The smooth metallic surface presents challenges for friction-based grasping mechanisms, which may struggle to find purchase. Conversely, the nozzle provides a geometrically distinct feature for grasping, though it requires high-precision insertion.[1]

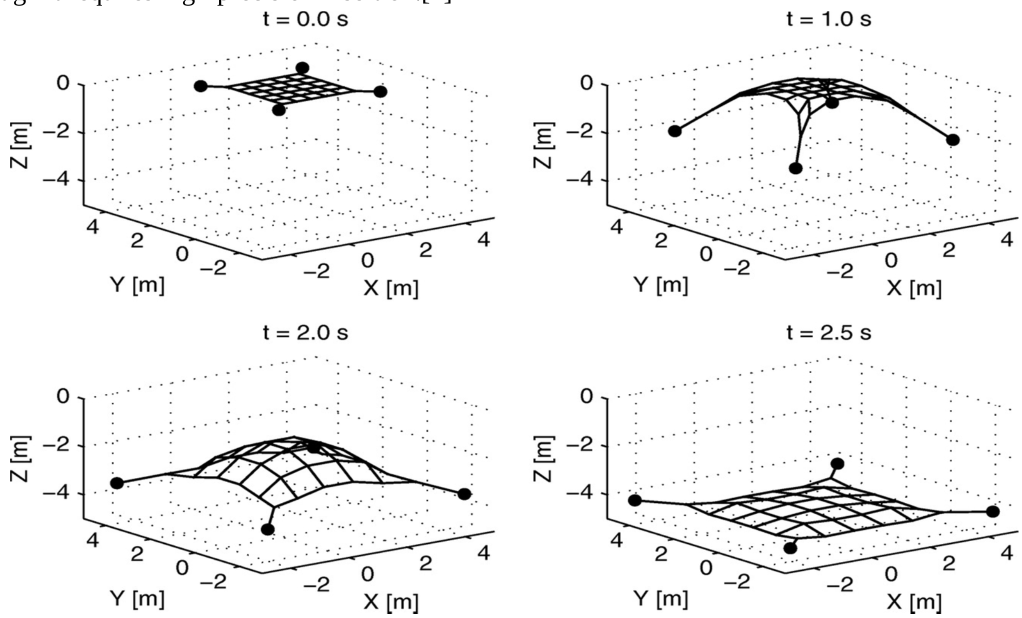

Figure 2: Tether Nets Deployment sequence. [7]

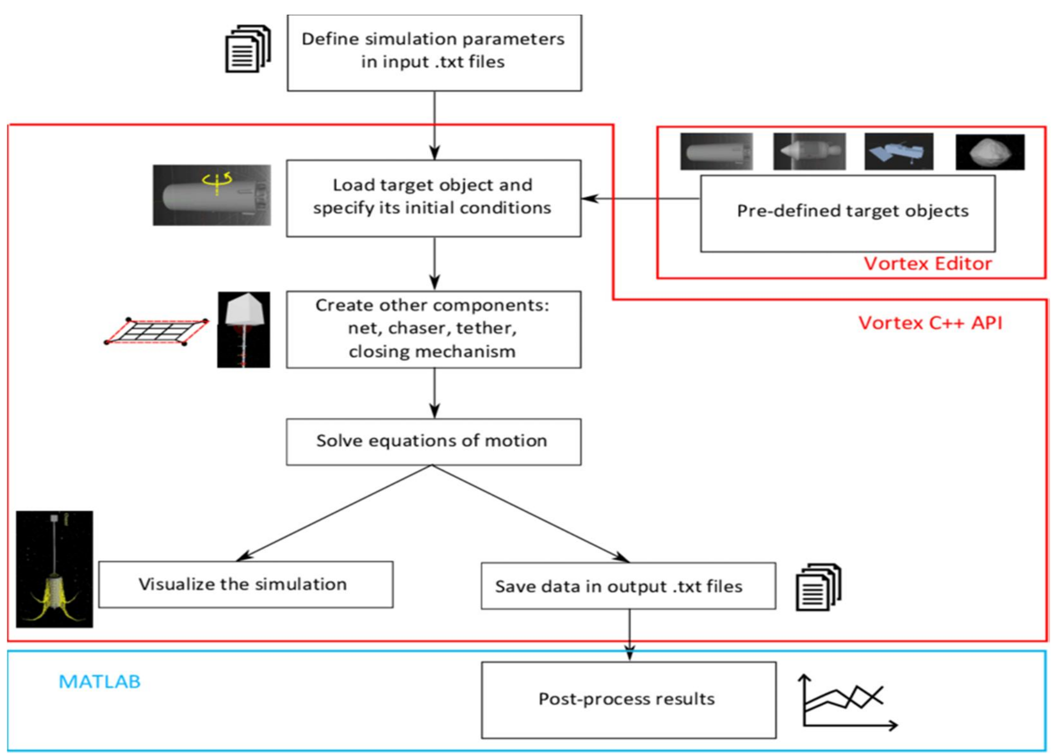

Figure 3: Architecture of Vortex-Dynamics-based simulator. [33]

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2) Tumbling and Angular Momentum

Debris objects are rarely static; they exhibit tumbling motion characterized by an angular velocity vector **ω**. The capture mechanism must accommodate not just the static mass but the rotational kinetic energy:

$$E_{rot} = ½\ \boldsymbol{\omega}^T \mathbf{I}\ \boldsymbol{\omega}$$

For a target like Envisat, observations have shown a tumbling evolution. Initially stable, it transitioned to a tumbling state with rates estimated between 1°/s and 3°/s due to environmental torques like the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect or potential micrometeoroid impacts.[13] While 3°/s appears slow, for an object with a moment of inertia exceeding 10^5 kg m², the angular momentum is enormous (thousands of Nms). A rigid robotic grasp of such a target would transmit massive torque to the chaser, potentially saturating reaction wheels or damaging the joint motors.[14] Flexible systems like nets utilize structural deformation and friction to dissipate this energy over time, reducing the peak loads on the chaser.[5]

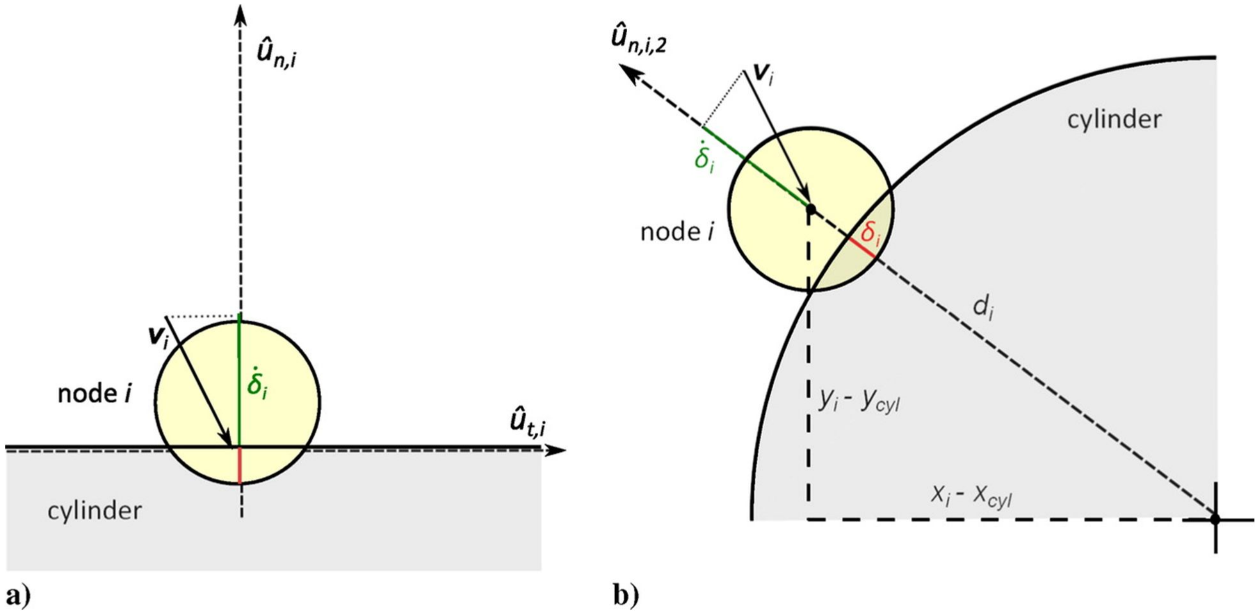

Figure 4: Collision detection and definition of penetration and rate of penetration for impact between node i and the cylinder: a) faces 1 and 3, and b) face 2. [7]

3) Relative Motion Dynamics

The relative motion between the chaser and target is governed by the Hill-Clohessy-Wiltshire (HCW) equations for circular orbits. The mechanical design must account for the drift caused by orbital mechanics during the finite time of capture. For a net shot at the target, the projectile trajectory is not a straight line but a curved path relative to the target, influenced by the Coriolis force and the differential gravity field.[16]

$$\ddot{x} - 2n\dot{y} - 3n^2x = f_x/m$$
$$\ddot{y} + 2n\dot{x} = f_y/m$$
$$\ddot{z} + n^2z = f_z/m$$

where n is the mean orbital motion. Capture mechanisms must operate within a timeframe where these drift effects are negligible or actively compensated.

B. Mechanical Design Requirements

To successfully remove large debris, the capture system must satisfy four primary mechanical requirements, distinguishing it from standard docking mechanisms:

1) Structural Robustness: The mechanism must withstand the impulse of capture ($\Delta p = \int F\, dt$) without plastic deformation or fracture. For nets, this means threads must not snap under tensile shock. For harpoons, the penetrator must not buckle upon impact.[18]

2) Energy Dissipation: The relative kinetic energy between the chaser and target, plus the rotational energy of the target, must be dissipated. This requires mechanical compliance (springs, dampers, material hysteresis) or active control (thruster compensation) to convert kinetic energy into heat or potential energy.[5]
3) Deployment Reliability: The deployment phase (shooting a net or harpoon, extending an arm) occurs in a vacuum with extreme thermal gradients. Mechanisms must be immune to cold welding, vacuum stiction, and thermal distortion. Reliability is paramount because pyrotechnic deployments are typically non-reversible one-shot events.[20]
4) Post-Capture Stabilization: Once connected, the chaser and target form a composite rigid or flexible body. The mechanism must act as a rigid or damped link to prevent collision between the two bodies during de-orbit burns. A flexible tether, for instance, introduces the risk of the target bouncing back or winding around the chaser, requiring complex tension control.[8]

III. OVERVIEW OF DEBRIS CAPTURE MECHANISMS

This section details the mechanical architecture of the three primary capture modalities, examining their operational principles and component-level mechanics.

A. *Net-Based Capture Systems*

Net capture systems utilize a flexible mesh deployed from a canister to entangle and envelope a target. This method is classified as a flexible-link capture, relying on tension rather than rigid compression or friction to secure the object.[9] [22]

1) *Deployment Mechanics*

The deployment is typically actuated by corner masses (often called "bullets") ejected by spring or cold-gas systems. The dynamics of deployment are governed by the conservation of momentum and the strain energy of the expanding net.

- System Components:
  - Canister: Stores the folded net, often utilizing specific folding patterns (e.g., petal or concentric) to minimize snagging.
  - Corner Masses: Provide the inertia to pull the net taut and envelope the target. Their trajectory defines the "cone" of capture.
  - Net Mesh: Usually made of high-strength fibers like Dyneema or Kevlar to resist tearing and thermal degradation.[20]
  - Closing Mechanism: A winch or drawstring system to secure the net around the debris. Without active closure, the net may simply drift off the target after impact.[20]

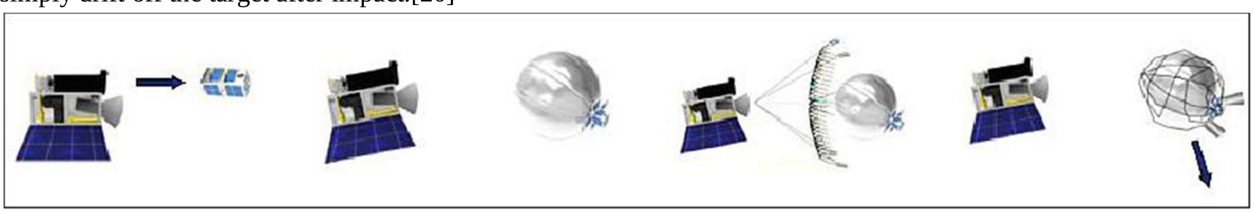

Figure 5: This figure shows the sequence in the net experiment: (a) CubeSat ejection, (b) balloon inflation, (c) net capture, (d) deorbiting (image credit: RemoveDebris consortium) [9]

The deployment sequence involves the corner masses diverging at an angle θ. The tension T in the net threads acts as a restoring force, eventually halting the expansion. If the initial velocity is too low, the net fails to fully open; if too high, it may bounce off the target or tear due to excessive strain energy.[17]

2) *Force Distribution on Impact*

Upon impact, the net behaves as a discretized continuum of point masses. The contact forces are distributed across multiple nodes, reducing the local stress concentration on the target debris. This is a critical advantage when capturing fragile targets with appendages (e.g., solar panels) that might shatter under point loads.[16] The equation of motion for a net node i can be approximated as:

$$m_i \, \ddot{\mathbf{r}}_i = \Sigma_{j \in \text{neighbors}} \mathbf{F}_{\text{elastic, ij}} + \mathbf{F}_{\text{ext}} + \mathbf{F}_{\text{contact}}$$

where $\mathbf{F}_{\text{elastic}}$ represents the spring-damper forces from connecting threads. The mechanical model must account for self-collision (the net tangling with itself) and friction between the net fibers and the target surface.[24]

3) Advantages and Limitations

- Pros: Large capture tolerance (can capture objects with uncertain tumbling or shape); minimal precision required compared to robotics; scalable to very large targets; effectively distributes impact loads.[24]
- Cons: High risk of snagging on chaser during deployment; complex dynamics making simulation and validation difficult; generation of secondary debris if net tears or impacts fragile components (e.g., solar arrays); single-shot nature (usually non-reusable).[19]

B. Tether-Based Capture Systems (Harpoons)

Tethered harpoon systems rely on a high-velocity projectile penetrating the structural skin of the target to establish a hard point for towing. This method is structurally invasive but mechanically simple, borrowing heavily from terrestrial whaling and military ballistics.[18]

1) Harpoon Penetration Mechanics

The core mechanical event is the high-strain-rate deformation of the target material (typically aluminum honeycomb or plate).

- Design: The harpoon tip usually features barbs or toggle mechanisms that deploy after penetration to prevent retraction.
- Ballistic Limit: The harpoon must possess sufficient kinetic energy to perforate the skin but not so much that it passes completely through the spacecraft (over-penetration), potentially severing internal fuel lines or creating debris from the exit wound. The required impact velocity is typically in the range of 20 to 90 m/s depending on the target material thickness.[18]

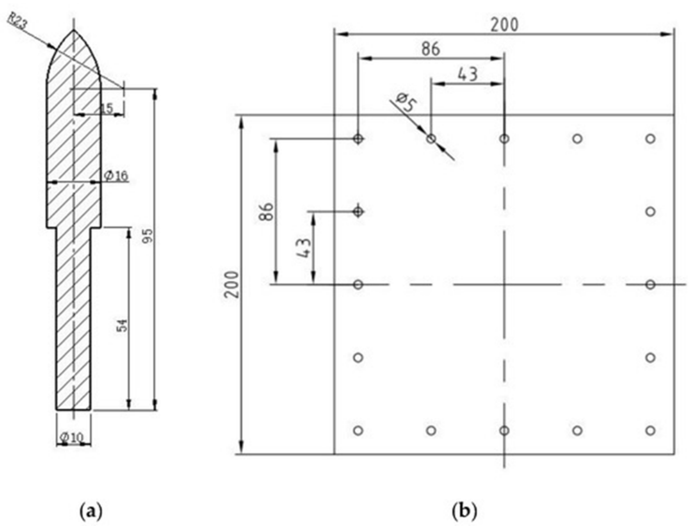

Figure 6: Structural model (the unit of measurement is mm). (a) Harpoon and (b) target board. [18]

2) Tether Dynamics and Oscillations

Once attached, the system acts as a Tethered Satellite System (TSS). The tether provides a unilateral constraint (it can pull but not push).

- Vibration: Longitudinal oscillations (stretch) and transverse vibrations (string modes) are excited by the impact and subsequent towing maneuvers.
- Snap Loading: If the tether goes slack and then snaps taut, the impulse force can exceed the tensile strength of the tether or the pull-out strength of the harpoon anchor. This phenomenon, known as "snatch loading," is a primary failure mode for tethered towing operations.[21]

3) Advantages and Limitations

- Pros: Simple mechanism; potential for reusable tether (if harpoon tip is replaceable); enables capture of tumbling targets without complex matching maneuvers (shoot-and-pull); demonstrated in orbit (RemoveDEBRIS).[25]
- Cons: Requires precise knowledge of target material to ensure penetration without fragmentation; risk of creating additional debris (ejecta) during impact; recoil force on chaser spacecraft requires robust attitude control.[19]

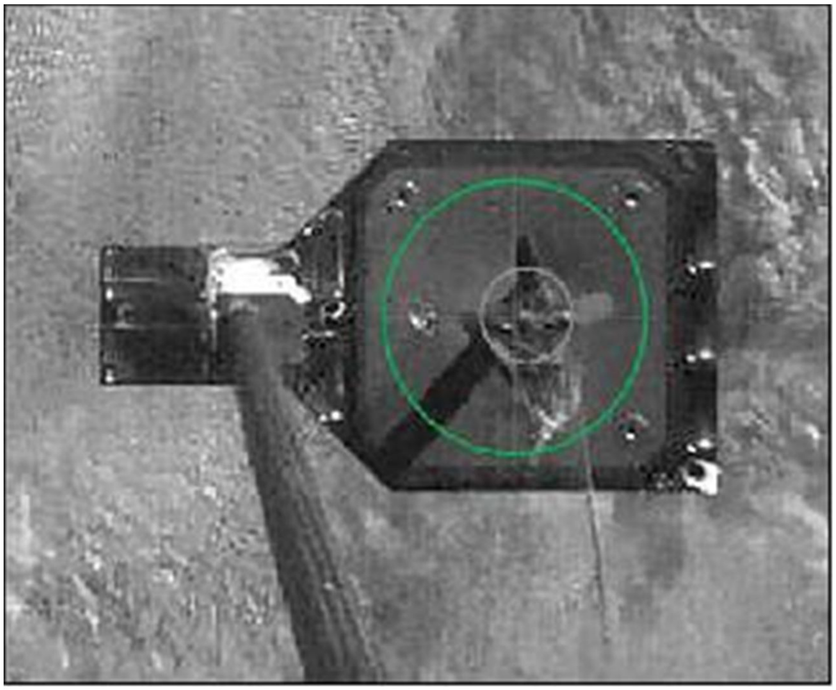

Figure 7: Harpoon imbedded in the target (image credit: RemoveDebris Team) [9]

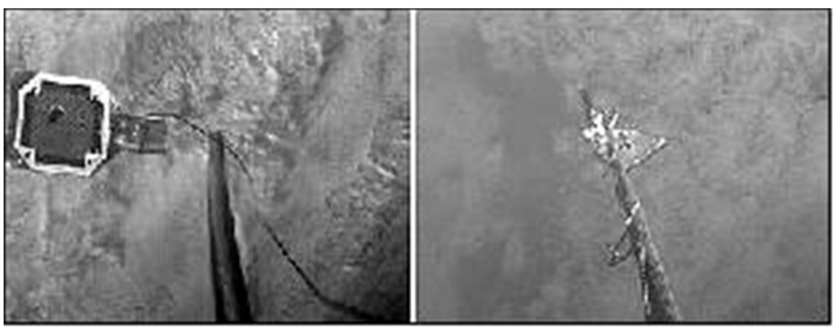

Figure 8: Left: Target captured by the harpoon, floating in space tethered to the mothercraft. Right: Target and tether line wrapper around the boom (image credit: RemoveDebris Team) [9]

C. Robotic Arm / Grasping Systems

Robotic capture involves a rigid manipulator arm equipped with a gripper (claw, hand, or docking interface) that physically grasps a structural feature of the target (e.g., a launch adapter ring). This approach mimics the human arm and hand, providing dexterity and reversibility.[14]

1) Kinematic Constraints and Actuation

The manipulator typically possesses 6 or 7 degrees of freedom (DoF) to allow arbitrary orientation of the end-effector.

- Capture Strategy: The chaser must match the tumbling rate and axis of the target to effectively "freeze" the relative motion before grasping. This requires high-authority Attitude Control Systems (ACS) on the chaser and precise GNC (Guidance, Navigation, and Control).[14]
- Contact Dynamics: The moment of contact introduces a closed-loop kinematic chain. Any mismatch in velocity results in a collision force that back-drives the motors and transfers momentum to the chaser base. The conservation of angular momentum means that moving the arm causes the base satellite to rotate in the opposite direction, a disturbance that must be actively compensated.[26]

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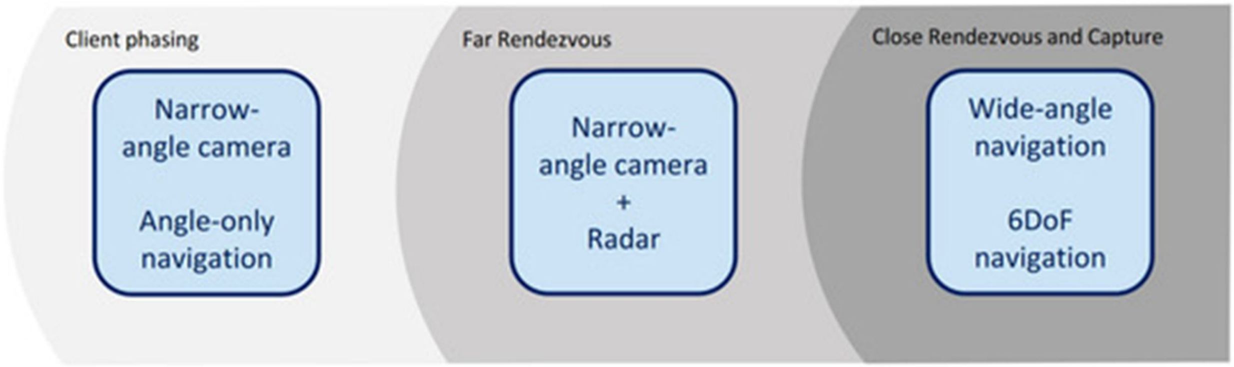

Figure 9: Navigation system architecture. [32]

2) Structural Stiffness and Compliance

Robotic arms for space are designed to be lightweight, often resulting in flexible links (low structural stiffness). However, capture requires stiffness to apply grappling forces. This contradiction is managed through impedance control, where the arm acts as a virtual spring-damper system to absorb impact energy mechanically or logically.[27]

3) Advantages and Limitations

- Pros: Highly controlled and reversible capture (can let go if needed); capability for repeated attempts; potential for post-capture servicing/repair; rigid connection simplifies de-orbit maneuvering; mature technology (Canadarm heritage).
- Cons: Requires precise knowledge of target motion and geometry; high complexity and cost; difficult to capture fast-tumbling objects due to actuator torque limits; risk of collision during close proximity operations.[15]

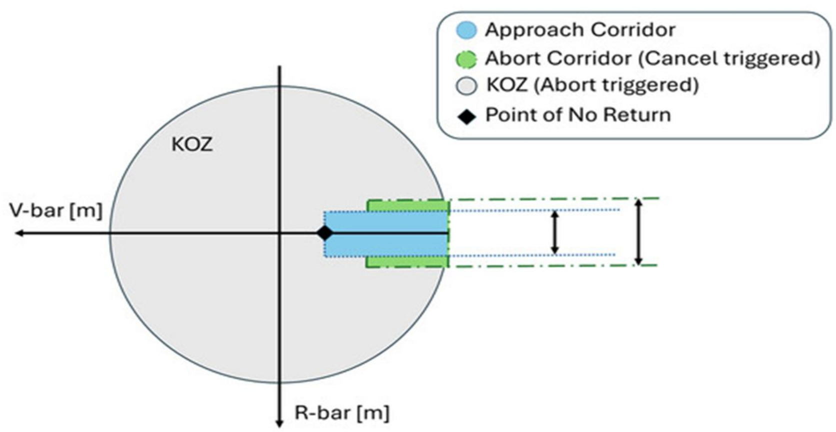

Figure 10: Abort and Approach corridors, defined within the KOZ. The gray area denotes where an Abort is triggered, the green area denotes where a Cancel is triggered, and the blue area is where no recovery action is needed. [32]

IV. DYNAMIC AND FORCE ANALYSIS (MECHANICAL CORE)

This section provides the rigorous mechanical analysis underpinning the feasibility of each system, utilizing analytical models to quantify the forces and energies involved.

A. Capture Impact and Energy Considerations

The fundamental mechanical problem of capture is the management of relative kinetic energy. Let subscript *c* denote the chaser and *t* the target. The relative velocity is $\mathbf{v}_{rel} = \mathbf{v}_t - \mathbf{v}_c$. The kinetic energy to be dissipated or converted during capture is:

$$T_{rel} = \tfrac{1}{2}\, \mu\, |\mathbf{v}_{rel}|^2$$

where $\mu = m_c m_t/(m_c + m_t)$ is the reduced mass of the system. In addition to translational energy, the target's rotational energy E_{rot} must be managed. For a target like Envisat ($I_{zz} \approx 129{,}000$ kg m², $\omega \approx 3°/s$ or 0.05 rad/s)[11], the rotational energy is substantial. A rigid capture mechanism must absorb or counteract this angular momentum transfer.

B. Mechanism-Specific Dynamic Challenges

1) Net Impact Force Spreading

The net capture dynamics can be modeled using the Absolute Nodal Coordinate Formulation (ANCF) or a Lumped-Parameter Model (LPM). The LPM discretizes the net into N nodes connected by viscoelastic springs.

The force in a thread segment k connecting nodes i and j is given by the Kelvin-Voigt model:

$$\mathbf{F}_k = \{ k_s (l_{ij} - l_0)\, \mathbf{e}_{ij} + c_d\, \dot{l}_{ij}\, \mathbf{e}_{ij} \text{ if } l_{ij} > l_0 \text{ ; } 0 \text{ if } l_{ij} \le l_0 \}$$

where k_s is stiffness, c_d is damping, l_{ij} is current length, l_0 is rest length, and $\mathbf{e}_{ij}$ is the unit vector.

- **Impact Analysis:** When the net strikes the target, the momentum transfer is not instantaneous. The net wraps around the object, converting the kinetic energy of the corner masses into strain energy in the mesh and frictional work against the target surface.
- **Simulation Insight:** Finite Element Simulations (FEM) of capturing Zenit-2 stages show that the impact forces are widely distributed, typically remaining below the yield strength of spacecraft aluminum skins, minimizing the risk of localized damage or fragmentation. However, the tension in individual threads can spike if they snag on sharp corners (like solar array hinges), necessitating high safety factors for the fiber strength.[23]

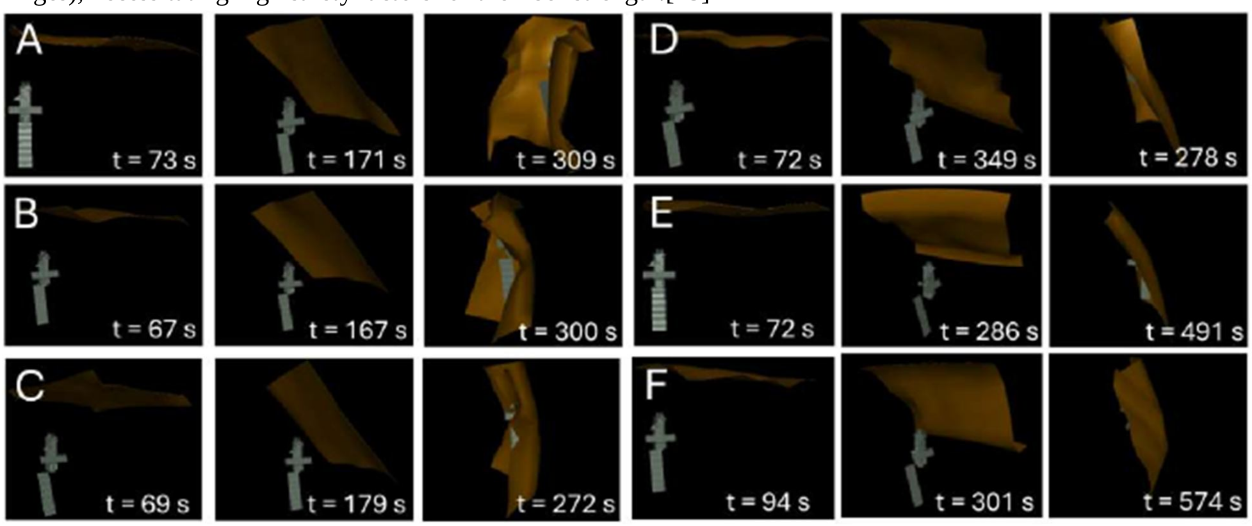

Figure 11: The three phases of the capture of Envisat as a function of the net mechanical model and the controller used: (A) Inextensible edges and PID, (B) Shell and PID, (C) Saint-Venant solid and PID, (D) Inextensible edges and SMC, (E), Shell and SMC (F) Saint-Venant solid and SMC. The starting position of all cases is the same, and the starting relative velocity between the net and Envisat is 0. [16]

2) Tether Tension and Vibration

For tethered systems (harpoon or net towing), the tether is modeled as a continuum with mass density ρ and Young's modulus E. The equation of motion for a tether element at arc length s is:

$$\rho A\, \partial^2\mathbf{r}/\partial t^2 = \partial/\partial s\, (EA\, \varepsilon\, \partial\mathbf{r}/\partial s) + \mathbf{F}_{ext}$$

where ε is the strain.

- Snatch Loading: A critical failure mode is "snatch loading," where a slack tether suddenly becomes taut due to relative drift. The peak tension T_{peak} can be approximated for a sudden velocity change Δv as:

$$T_{peak} \approx A \sqrt{(E\rho)}\, \Delta v$$

For a typical Dyneema tether ($E \approx 100$ GPa, $\rho \approx 970$ kg/m³) and a relative drift of just 1 m/s, the shock load can be enormous, necessitating shock absorbers or elasticity (dampers) in the design to prevent rupture.[11]

3) Harpoon Penetration Dynamics

The harpoon impact is a high-velocity ballistic event (20–90 m/s). The penetration depth P can be estimated using the Johnson-Cook constitutive model for the target material flow stress σ_{eq}:

$$\sigma_{eq} = (A + B\varepsilon^n)[1 + C \ln \varepsilon^*](1 - T^{*m})$$

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where *A*, *B*, *n*, *C*, *m* are material constants for the target aluminum (e.g., Al-2024 T3 typically used in satellites like Envisat).[18]

- Feasibility: Analyses indicate that a harpoon velocity of >50 m/s is often required to reliably penetrate dual-wall Whipple shields or honeycomb panels common on satellites like Envisat. This creates a dangerous trade-off: higher velocity ensures penetration but increases the risk of over-penetration (shooting through the target) or structural fragmentation.[18]

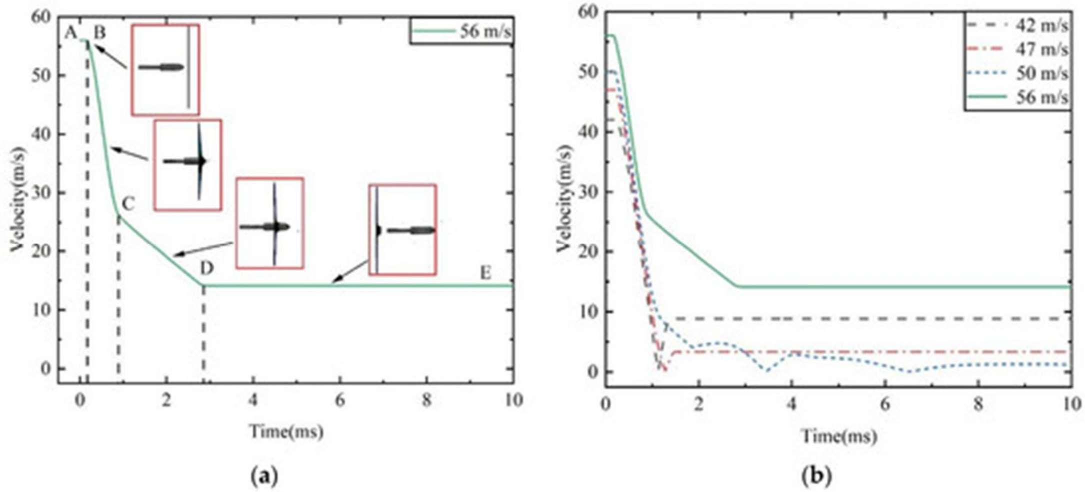

Figure 12: Velocity evolution curve. (a) Velocity evolution at 56 m/s of the initial velocity, and (b) velocity evolution at 42, 47, 50 and 56 m/s of initial velocities [18]

4) Robotic Contact and Impedance

For robotic capture, the contact force $\mathbf{F}_c$ is critical. Using Hertzian contact theory for a spherical end-effector on a planar target:

$$F_c = K\delta^{3/2} + D\dot{\delta}$$

where δ is the indentation depth and *K* is the contact stiffness.

- Impedance Control: To prevent the arm from bouncing off or pushing the target away, the robot controller must emulate a spring-damper system. The control law modifies the mechanical impedance of the arm:

$$M_d\,(\ddot{\mathbf{x}} - \ddot{\mathbf{x}}_d) + D_d\,(\dot{\mathbf{x}} - \dot{\mathbf{x}}_d) + K_d\,(\mathbf{x} - \mathbf{x}_d) = \mathbf{F}_{ext}$$

The chaser satellite must use its thrusters to counteract the reaction forces transmitted through the arm, essentially "flying" the end-effector to match the target's tumbling frame while maintaining a soft grasp.[26]

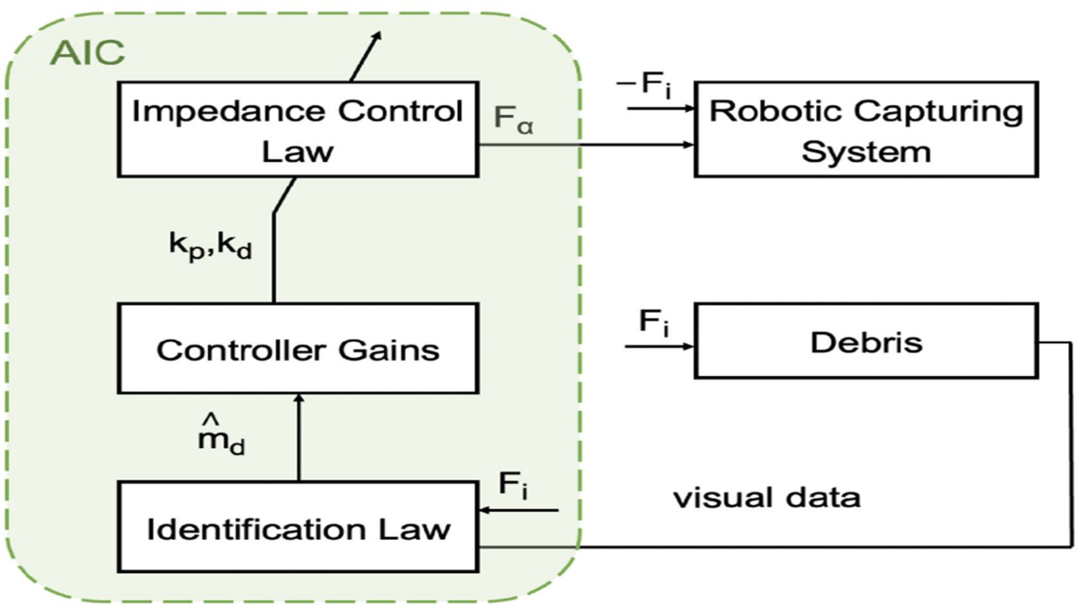

Figure 13: Block diagram of the adaptive control strategy. [27]

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V. DEPLOYMENT AND FAILURE MODE ANALYSIS

A robust mechanical design requires anticipating failure. This section applies a Failure Mode and Effects Analysis (FMEA) mindset to the three systems, identifying what can go wrong and the mechanical consequences.

A. *Net-Based Systems*

- Misdeployment (Deployment Phase): The most common failure mode is entanglement of the net with the chaser spacecraft immediately after ejection. If the corner mass ejectors do not fire synchronously, the net can tumble and collapse before reaching the target.
  - *Mechanism:* Asymmetric impulse causing angular momentum in the net bundle.
  - *Effect:* Mission loss; potential damage to chaser optics/sensors.
  - *Mitigation:* Pyrotechnic synchronization; separate "net container" ejection before deployment.
- Insufficient Closure (Capture Phase): The net may wrap around the target but fail to close securely if the target geometry prevents the drawstring from cinching (e.g., slipping off a smooth cylinder like Zenit-2).
  - *Effect:* Target escapes during towing; net becomes space debris.
  - *Mitigation:* Active closing mechanisms (motorized winches in corner masses) to mechanically force closure.[9]
- Tether Severance (Towing Phase): Sharp edges on the debris (e.g., broken solar panels, micrometeoroid shielding) can cut the net fibers during tumbling interaction.
  - *Effect:* Loss of target.
  - *Mitigation:* Multi-layer braids; abrasion-resistant coatings on net fibers.

B. *Tether-Harpoon Systems*

- Ricochet/Bounce-off (Capture Phase): If the impact angle is too shallow (obliquity >45°) or the target material is harder than predicted (e.g., hitting a titanium tank fitting instead of an aluminum panel), the harpoon may fail to penetrate.
  - *Effect:* Target escapes; harpoon recoil endangers chaser due to conservation of momentum.
  - *Mitigation:* Crushable nose cones to bite into surfaces; high-friction tips.[28]
- Over-Penetration (Capture Phase): The harpoon possesses too much kinetic energy and passes through the debris. If the toggle barbs fail to deploy or deploy inside a void, there is no mechanical hold.
  - *Effect:* Weak connection; pull-out during towing; internal damage to target (potentially causing explosion).
- Fragmentation (Impact Phase): The high-energy impact generates a cloud of secondary debris (ejecta) from the target surface.
  - *Effect:* Damage to chaser sensors/solar panels; pollution of orbit.
  - *Mitigation:* Debris shields on chaser; optimization of impact velocity.[19]

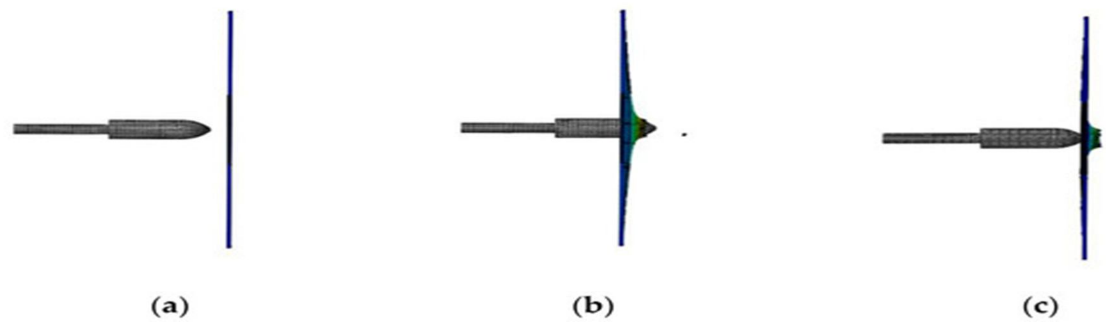

Figure 14: Simulation results for a launch speed of 42 m/s: (a) before penetration; (b) penetrating; (c) no penetration. [18]

C. *Robotic Arm Systems*

- Singularity/Joint Limits (Capture Phase): While tracking a tumbling target, the arm may reach a kinematic singularity or joint limit, losing the ability to apply necessary force or follow the motion.
  - *Effect:* Loss of capture; collision due to control lag.
  - *Mitigation:* Redundant degrees of freedom (7-DoF arms); optimized path planning algorithms that predict target motion.[29]

- Contact Instability (Grasping Phase): Upon contact, the sudden exchange of momentum causes the chaser to recoil. If the chaser's Attitude Determination and Control System (ADCS) cannot compensate fast enough, the arm may be wrenched free or damaged.
  - *Effect:* Structural damage to arm; collision.
  - *Mitigation:* Compliance/Impedance control; flexible joints; reaction wheels with high torque authority.[7]

VI. COMPARATIVE MECHANICAL TRADE-OFF ANALYSIS

This section synthesizes the mechanical data into a comparative framework. The selection of a capture mechanism is fundamentally a trade-off between structural complexity, control authority, and risk.

A. *Comparative Matrix*

The following table summarizes the key mechanical characteristics of each system:

Feature	Net-Based System	Tether-Harpoon System	Robotic Arm System
Mechanical Complexity	Medium (deployment/closing mech)	Low (simple ballistic mechanism)	High (multi-joint articulations)
Control Difficulty	Low (ballistic phase, passive capture)	Low (ballistic aiming)	Very High (6-DoF active tracking)
Target Requirement	Low (agnostic to shape)	Medium (requires penetrable surface)	High (requires rigid grasp point)
Debris Generation Risk	Low (unless net tears)	High (impact ejecta)	Low (controlled contact)
Tumbling Handling	High (can wrap tumbling objects)	Medium (tether wrap risk)	Low (limited by joint speed/torque)
Rigidity of Connection	Low (flexible tether)	Medium (flexible tether)	High (rigid linkage)
Scalability	High (larger nets for larger debris)	Medium (limited by recoil/penetration)	Low (arm mass/power scales poorly)
Reusability	Low (single use typically)	Low (single use)	High (multi-mission capable)
TRL (Technology Readiness)	TRL 7-8 (RemoveDEBRIS tested)	TRL 6-7 (Ground/Flight tested)	TRL 9 (Servicing arms exist)

B. *Discussion of Trade-Offs*

- Structural Complexity vs. Control Difficulty: Robotic arms represent the pinnacle of control difficulty. The mechanical requirement to track a tumbling object like Envisat (spinning at ~3°/s with a mass of 8 tons) places immense torque requirements on the joint actuators. The chaser satellite must be nearly as massive as the target to prevent being thrown around by the arm's reaction forces.[15] In contrast, nets shift the complexity from control to the mechanical deployment. The chaser does not need to match the spin exactly; it only needs to place the net in the correct intercept path. The flexible nature of the net mechanically integrates the energy dissipation (friction/deformation) that the robotic arm must simulate via complex control algorithms.
- Capture Reliability vs. Risk: Harpoons offer the highest "locking" reliability once embedded, as the connection is a mechanical interlock with the structure. However, the *probability* of a successful latch is lower due to material uncertainties (e.g., hitting a fuel line or strut). Nets have a high probability of initial contact and envelopment but a lower certainty of a "hard" lock—the debris might slip out during towing if the closing mechanism isn't perfectly secure.[20] Robotic arms offer the lowest risk of generating new debris (no impact ejecta) but the highest risk of catastrophic collision if the control loop becomes unstable during the grasp phase.

1) *Scalability*

For massive debris like Zenit-2 stages, robotic arms become prohibitively heavy and power-hungry. A net system scales much more favorably; a larger net adds relatively little mass compared to the structural reinforcement required for a larger robotic arm. This makes nets the preferred mechanical solution for the largest class of debris.

2) Conclusion on Optimization:

No mechanism is universally optimal.

- Robotic Arms are best suited for controlled, high-value targets or those with low tumble rates where precision is required (e.g., servicing missions, ClearSpace-1).
- Nets are optimal for large, tumbling, non-cooperative debris where target integrity is not a priority and geometry is complex/unknown.
- Harpoons are niche solutions for specific structural targets (e.g., rocket upper stages with known tank wall thicknesses) where simplicity is paramount and debris generation is an acceptable risk.

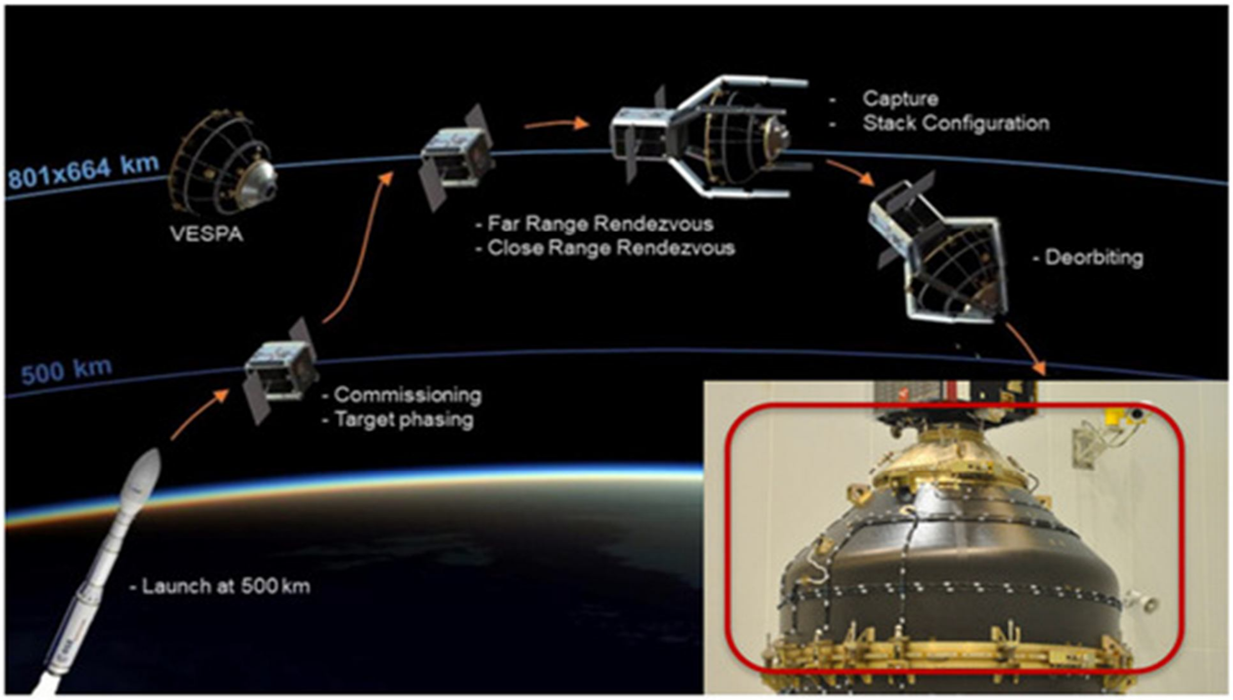

Figure 15: ClearSpace-1 mission overview. [32]

VII. FUTURE MECHANICAL CHALLENGES AND RESEARCH DIRECTIONS

The field of ADR mechanics is rapidly evolving. Several key areas require further research to mature these technologies for operational deployment.

A. Adaptive and Reconfigurable Mechanisms

Future robotic grippers are moving toward bio-inspired "soft robotics" and gecko-adhesion technologies. These systems use Van der Waals forces or electrostatic adhesion to grasp smooth surfaces (like solar panels) without requiring high normal forces, bridging the gap between the compliance of nets and the precision of arms. [30] Research is also needed into "morphing" nets—smart structures that can actively change their mesh geometry or stiffness upon contact to better secure irregular targets.[17]

B. Lightweight and Smart Materials

The mass of the tether or arm is a parasitic load on the mission. Development of Carbon Nanotube (CNT) tethers or ultra-high-molecular-weight polyethylene (UHMWPE) composites with embedded fiber-optic strain sensors would allow for real-time monitoring of towing loads and vibration suppression.[8]

C. Integrated Mechanics and Control (Co-Design)

The separation of mechanical design and control system design is a legacy approach. Future ADR systems require **co-design**, where the mechanical compliance is tuned specifically to aid the control system. For example, designing robotic joints with variable stiffness actuators (VSA) that can mechanically absorb impact shock, reducing the bandwidth requirement on the control loop.[31]

D. Ground Testing Limitations

A major hurdle remains the inability to replicate 6-DoF microgravity dynamics on Earth. Air-bearing tables are limited to planar motion (3-DoF), and neutral buoyancy tanks introduce fluid drag that dampens vibrations unrealistic for space. High-fidelity Hardware-in-the-Loop (HIL) simulators combining robotic motion platforms with complex contact dynamic models are essential to validate failure modes before launch.[32]

VIII. CONCLUSION

The active removal of space debris is not merely a trajectory problem; it is a profound mechanical engineering challenge characterized by high-energy interactions, uncertain physical properties, and the unforgiving environment of microgravity. This comparative study has highlighted that the "best" capture system is heavily context-dependent.

Net-based systems excel in capturing large, tumbling, and irregular objects like Envisat due to their inherent mechanical compliance and generous capture envelope, though they face challenges in simulation reliability and post-capture securing. Tether-harpoon systems offer mechanical simplicity and robust towing connections for rocket bodies like Zenit-2 but carry significant risks of debris generation and require precise target characterization. Robotic arms provide the highest level of control and reversibility, making them ideal for servicing or stabilizing widely tumbling objects, yet they are penalized by high mass, complexity, and strict operational limits on target spin rates.

Ultimately, effective debris removal architectures will likely evolve into hybrid systems or specialized fleets. The success of future cleaning missions—such as the upcoming ClearSpace-1 and the operational follow-ups to ADRAS-J—will depend less on conceptual novelty and more on robust mechanical design: the ability of a mechanism to absorb shock, tolerate uncertainty, and maintain structural integrity under worst-case dynamic loads. As the orbital environment grows more congested, the mechanical engineering community must prioritize these "nuts and bolts" realities of contact dynamics to ensure the sustainable use of space.

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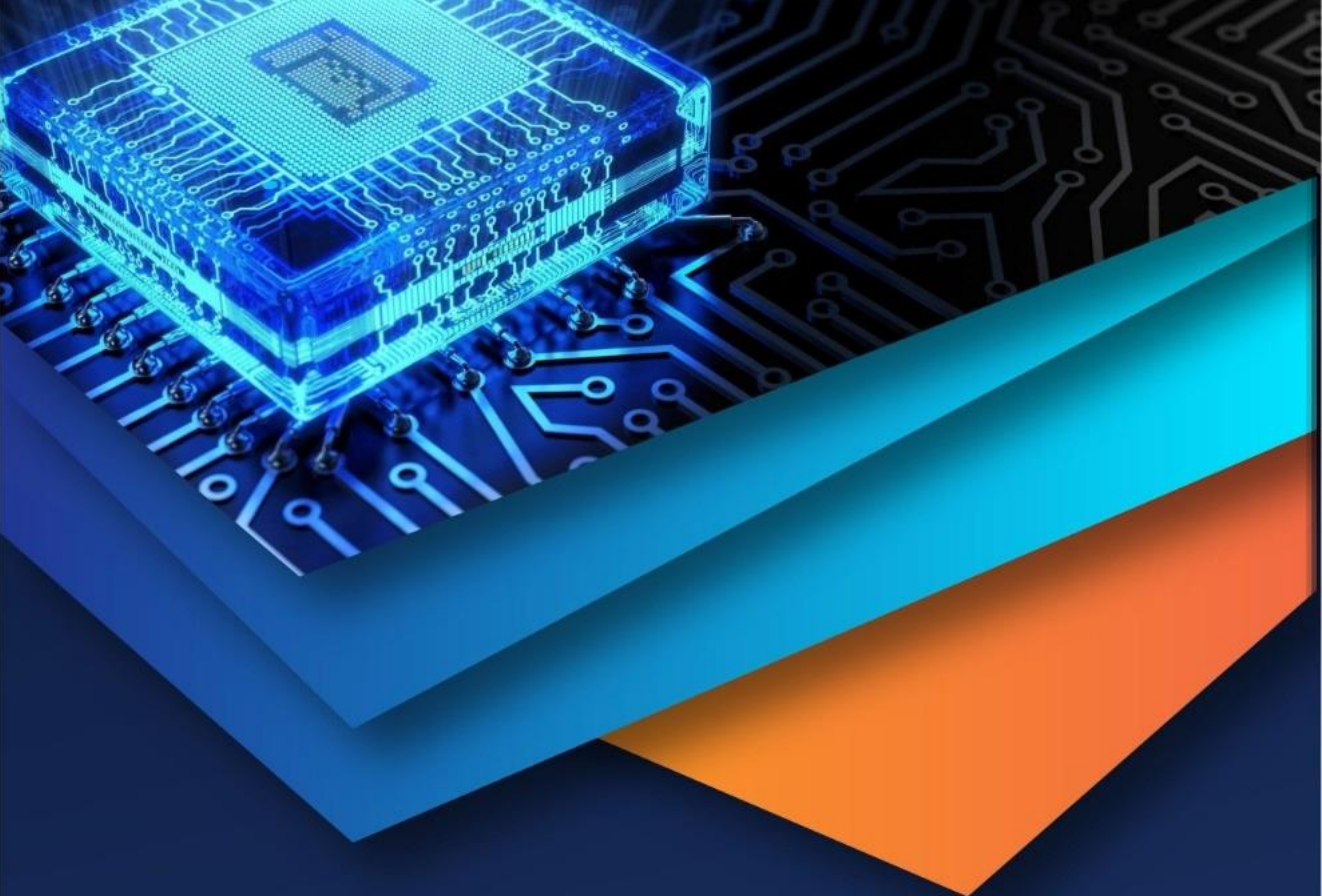

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