ACTIVE DEBRIS REMEDIATION AND SPACE OBJECT MOBILITY USING ELECTROADHESIVE TECHNOLOGY

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Abstract—As the satellite industry transitions from disposable to sustainable space operations, new technologies are needed to extend asset lifetimes and optimize orbital resources. The Space Payload for Inertial De-spin Efficient Effects (SPIDEE) is an electroadhesion-based attachment platform that enables reusable on-orbit servicing without requiring pre-prepared surfaces. Built around Cambrian Works' eTAP™ (electrical Thin Attachment Payload), SPIDEE supports diverse missions from debris removal to scientific observatory preservation.

The technology's universal material compatibility—adhering to aluminum, composites, MLI, and solar panels—combined with low power consumption and demonstrated reusability positions it as critical infrastructure for sustainable space operations. Unlike traditional attachment methods limited by material constraints or mechanical complexity, electroadhesion provides reversible attachment that leaves no residue and causes no surface damage.

This paper presents comprehensive performance validation including capture of rapidly rotating objects, significant attachment forces, and enhanced performance in vacuum conditions. Testing at the Air Force Research Laboratory's Robotic Operations Center validated capture and detumbling of large masses at extreme rotation rates through controlled contacts without surface damage. The exceptional shear force capability enables robust attachment during high-rotation capture and propulsive maneuvers.

SPIDEE's modular architecture accommodates platforms from CubeSats to ESPA-class vehicles, integrating attitude control, propulsion, and mission-specific augmentation packages. NASA's selection of Cambrian Works, with partner Astroscale U.S., as a performer for the Swift Observatory servicing study validates the technology's readiness for operational deployment.

International collaboration opportunities span constellation maintenance, scientific asset preservation, and emerging space nations accessing on-orbit capabilities without launching new infrastructure. By enabling one servicing vehicle to address multiple targets, SPIDEE supports space sustainability through resource optimization. The platform transforms every spacecraft into a potentially augmentable asset, extending operational lifetimes and adding capabilities decades after launch. This paradigm shift from replacement to augmentation aligns with international sustainability goals while creating service-based business models that democratize access to advanced space capabilities.

Keywords—electroadhesion, active debris removal, on-orbit servicing, space sustainability, payload augmentation, detumbling

1. Introduction: The Imperative for Sustainable Space Operations

1.1 Background and motivation

The space around the earth, and especially Low Earth Orbit (LEO) is rapidly filling up with an exponentially increasing number of satellites, rocket bodies, and debris. Space is large, and there's still plenty of it available, but the chance of collisions and the occupation of useful orbits is impacting satellite design and operations.

Previously, the satellite development and launch paradigm was centered around "launch and forget", as technologies and access to space to provide upgrades, post-launch in-space mobility, and on-orbit servicing was limited. With new technology development in these areas, we have the opportunity to shift from "launch and forget" to "maintain and enhance".

The growing number of large constellations demand new servicing paradigms inspired by economic pressure to extend rather than replace assets and international recognition of orbital resource limitations. The shared orbital environment is a quintessential "commons" requiring international cooperation and coordination solutions to prevent a "tragedy of the commons" environment. Such coordination provides cost-sharing benefits for expensive servicing infrastructure, technology standardization opportunities, and the creation of a service-based economy accessible to all.

The Space Payload for Inertial De-spin Efficient Effects (SPIDEE) represents a paradigm shift in space attachment technology. By leveraging electroadhesion principles through Cambrian Works' electrical Thin Attachment Payload (eTAP™), SPIDEE enables secure attachment to virtually any surface encountered in the space environment—without requiring cooperative targets or prepared surfaces.

This universal attachment capability addresses both immediate operational needs and long-term space infrastructure development. Near-term applications include critical orbital debris removal missions to mitigate collision risks in congested orbits, life extension services for aging but functional satellites, and emergency response capabilities for spacecraft experiencing attitude control failures. Looking forward, SPIDEE enables transformative capabilities such as on-orbit assembly of large structures, reconfigurable satellite clusters that adapt to changing mission requirements, and autonomous servicing platforms that maintain entire constellations.

1.2 Problem statement and context

There are currently approximately 54,000 objects > 10 cm orbiting the earth, of which ~9,300 are classified as active payloads; most of the others have no ability to control their orbit [1]. This exponential growth from just a few years ago is spurred by mega-constellations such as Starlink (7,000+ satellites), OneWeb, Kuiper, and others, with the number of objects in orbit predicted to continue to grow as annual launch rates continue to increase [2].

This increase leads to four concerns:

1) Increase in the number of non-functional satellites that occupy valuable orbits
2) Risk of collision damage to functional satellites, with economic and national security implications
3) Potential for Kessler syndrome events that create unusable orbits
4) Sustainability concerns with respect to the expense of continuous satellite refreshes

These, in combination with increasing technological capabilities, have made the potential for providing on-orbit servicing economically feasible, both addressing the above concerns, as well as catalyzing an emerging market centered around sustainability.

1.3 The servicing technology gap

The on-orbit servicing market is predicted to reach $2-4 billion by 2030 [3], and several companies have started to provide solutions in this space to address the market demand from constellation operators and space agencies [4,5]. However, while the satellite busses for these missions are based on significant in-space heritage and well-understood mission parameters, the specific capture and/or attachment mechanisms are much more limited in terms of heritage and capability to attach to a wide diversity of objects, as the vast majority of objects in space were not designed with docking or attachment points [6].

Servicing solutions often fall into two camps: expensive, exquisite “universal” systems, or cheaper, specialized systems that are limited in the types of objects they can address. Rapidly tumbling, uncontrolled objects are especially challenging for both of these types.

Current attachment systems have limitations based on the types of objects and materials they can attach to: magnets (ferrous only), mechanical (prepared interfaces or complex mechanisms), and adhesives (typically single-use). There is a need for a universal, reusable, non-destructive attachment mechanism that handles the current multiplicity of in-orbit objects and supports the requirement for a flexible platform capable of addressing multiple mission types.

1.4 Literature review of attachment technologies

Spacecraft docking has been addressed through various approaches over the. Past decades. Mechanical systems, such as the Space Station Remote Manipulator System (SSMRS), provide strong, reliable attachment but require prepared interfaces on the target spacecraft. These systems work best with cooperative targets and precise control, limiting their applicability to smaller servicers.

Magnetic attachment systems are frequently used [6]; however, these systems can only attach to ferrous materials, excluding many modern spacecraft materials. In addition, their magnetic fields can interfere with spacecraft electronics and generate torques when interacting with the Earth’s magnetic field.

Adhesive-based capture systems provide secure attachment, but cannot generally be removed or reused, and may leave residue on the target surface [6]. They also tend to have temperature sensitivities that limit their utility in the space environment.

Gecko-like adhesive technologies have shown promise for reversible attachment [6]. These systems rely on van der Waals forces to provide attachment, however, require extremely clean surfaces, are difficult to manufacture at scale, and typically require a physical forcing or pressure to engage well on a surface.

The electroadhesion principle, first documented by Johnsen and Rahbek in 1923 for terrestrial applications [7], has seen limited use in space, despite significant advantages. Terrestrial applications in manufacturing [8,9] have validated the technology, and its specific characteristics make it particularly well-suited for space applications.

1.5 SPIDEE/eTAP™ as enabling infrastructure

Cambrian Works, Inc. (Cambrian) has developed the Space Payload for Inertial De-spin Efficient Effects (SPIDEE) to provide precisely that flexible platform capable of addressing multiple mission types with a cost-effective, reusable, universal attachment mechanism based on its eTAP™ technology. eTAP leverages electroadhesion to provide attachment to virtually all materials and is particularly well-suited to the space environment since it works best without the presence of humidity.

eTAP has the unique advantage of universal material compatibility, attaching to conductors, insulators, and dielectrics. It is reusable, with over 1000 attachment/detachment cycles demonstrated, as well as benign, leaving behind no residue or otherwise interfering with the surface it's attached to.

SPIDEE provides a scalable, modular architecture compatible with 3U to ESPA-class satellites and the ability to (1) attach, (2) augment, and (3) provide mobility. It can be implemented in a free flyer mode or integrated into other mobility platforms as a modular attachment subsystem. A representation in a CubeSat form factor is shown below in Fig. 1.

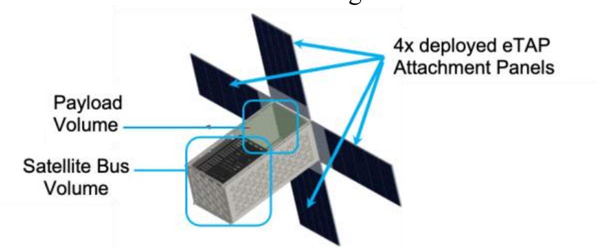

Fig. 1. SPIDEE-enabled CubeSat with payload volume for spacecraft mobility and enhanced capability

This flexibility was demonstrated via Cambrian's selection for the NASA Swift Observatory Re-boost mission study, which validated a partnership model with Astroscale U.S. to provide rendezvous, proximity operations, and docking, attachment, and mobility to a decaying scientific satellite. The study demonstrated commercial readiness of the technology and established a framework for rapid integration with existing servicing providers.

1.6 Paper objectives and organization

The objective of this work is to characterize electroadhesion's utility for on-orbit servicing, validate performance across different operational scenarios, describe various mission applications, including debris removal, satellite capability augmentation, and space mobility provisioning, and set the stage for international collaboration to ensure space and orbital sustainability.

The structure of this paper is Technical Foundation (Section 2), System Architecture (Section 3), Materials and Methods (Section 4), Results and Performance Validation (Section 5), Mission Applications and Analysis (Section 6), Discussion (Section 7) and Conclusion (Section 8).

2. Technical Foundation: Electroadhesion Theory and Modeling for Space Applications

Electroadhesion is an electric field-induced attraction mechanism that works on a diverse set of opposing substrates, providing material-agnostic adhesion to conductors, dielectrics, and insulators [7]. Voltage applied across opposing electrodes generates the attractive force, with voltages in the hundreds to thousands of volts range required for adequate attachment to most materials. Key benefits of electroadhesion-based attachment are that it is reversible, controllable, and provides contamination-free operation. Moreover, it achieves enhanced performance in low humidity and vacuum environments, making it especially well-suited for space.

2.1 Fundamental electroadhesion physics

Electroadhesion provides attachment to conductors, dielectrics, insulators, and composite materials. The mechanism for generating attractive force is different for each of these, with total achievable force per unit area dependent on material type.

Adhesion force is caused by multiple mechanisms. Coulombic attraction provides the primary force through direct electrostatic interaction between the charged electrodes and the induced charges in the opposing target substrate [7]. Charged particle mobility in conductive targets create strong attractive forces nearly instantaneously. For dielectrics, the relatively slower reorientation of dipoles caused by the applied electric field results in rise times on the order of a tenth of a second [8,9].

For semiconductors, the Johnson-Rahbek effect provides force enhancement through micro-scale contact area increases [7].

2.2 Shear force mechanisms

Unlike many other in-space attachment methods, electroadhesion has enhanced performance in the shear (sliding) direction, relative to normal (perpendicular) direction.

Qualitatively, the enhanced shear forces occur due to increased contact area under shear loading, field line concentration at surface asperities, mechanical interlocking at microscale, and charge accumulation in the shear direction.

2.2.1 Shear force calculations from detumble testing

Testing performed at Air Force Research Laboratories (AFRL) utilized the air bearing table at the Robotic Operations Control (ROC) Lab to characterize the performance for both de-tumble and free-flyer capture. Dozens of test runs were completed in total across many test configurations utilizing the facilities at the AFRL ROC Lab.

The testing performed at AFRL facilities encompassed rotational de-tumble testing and free-flyer capture testing using a zero-friction air-bearing table. Data from this testing was used to calculate effective shear force exerted by eTAP to detumble the craft.

The steps taken in analysis were as follows:

1) Identify the Z-axis angular rate of the client craft
2) Filter the magnitude of the angular rate
3) Identify each contact with eTAP in the data
4) Compute the magnitude of the angular rate reduction and the time over which the force was applied
5) Compute the delta angular momentum from each contact:

$$\alpha = \Delta\omega / \Delta t$$

6) Compute the resulting torque applied:

$$\tau = I\alpha$$

7) Compute the shear force and normalize against the contact area:

$$F_{shear} = \tau / r_{client}$$

$$F_{shear} = F_{shear} / A_{contact}$$

More detail and results are shown in sections below.

2.3 Space environment enhancement factors

The space environment provides significant performance advantages relative to terrestrial use. Vacuum enhancement follows the relationship:

$$F_{vac} = \alpha * F_{atm}$$

Where α ranges from 2 to 6 depending on material properties and surface characteristics.

In atmosphere, corona discharge events limit the maximum operating voltage and increase the potential for arcing, which is reduced or eliminated in vacuum, allowing for enhanced adhesion. In addition, the reduced air gap provides better contact and stronger forces. In vacuum, higher operating voltages are possible without breakdown concerns, allowing for mission-specific tuning of force relative to power usage.

2.4 Scaling relationships

Achievable normal force scales linearly as contact area between the electrode area and the target area. This linear scaling has been validated for arrays ranging from 16 cm^2 to 400 cm^2, enabling predictable force generation for different mission requirements. The modular nature of SPIDEE allows for flexible configuration of pad arrays to match target geometries. Temperature effects on adhesion force are minimal across the expected operational range of -40°C to 125°C.

3. SPIDEE System Architecture

SPIDEE (Space Payload for Inertial De-spin Efficient Effects) combines modular eTAP pad arrays with integrated attitude control systems and propulsion in an open-interface, easy-to-integrate payload. SPIDEE enables a multiplicity of missions focused on:

1) attachment to a tumbling, uncontrolled object
2) detumbling of the object
3) providing mobility to that object for orbit maintenance, raising and/or deorbit.

Extra payload space is available for additional mission needs, such as sensors, comms, or power systems. SPIDEE is designed to provide mission-specific sizing with modular interfaces that enable rapid design, prototyping, integration, and launch. Power and control electronics are integrated, payload volume is available for augmenting capability, and standard interfaces for various host vehicles support 3U CubeSats to ESPA-class spacecraft.

3.1 Space-optimized design features

eTAP has several space-optimized design features:

- Flexible form factor conforming to curved surfaces
- Minimal thickness (<0.5mm) and mass impact
- Low power consumption enabling long-duration operations
- Thermal stability across orbital temperature ranges (-40°C to +125°C)

3.2 System overview and specifications

System specifications are mission-dependent, but typical values are as follows:

- Power: <1W (eTAP), subsystem power dependent on mission-dependent ADCS and propulsion
- Attachment force: 1-100N (scalable)
- Operating temperature: -40°C to +85°C (electronics), -40°C to +125°C (exposed parts)
- Attachment cycles: >1000
- Compatible vehicles: 3U CubeSat to ESPA-class

3.3 eTAP subsystem design

The eTAP subsystem has been designed with modular, scalable pads, making integration and scaling for diverse missions possible without additional NRE. Fig. 2 shows a single eTAP tile unit, while Fig. 3 gives an example of how these tile units can be used on irregularly shaped areas without custom design.

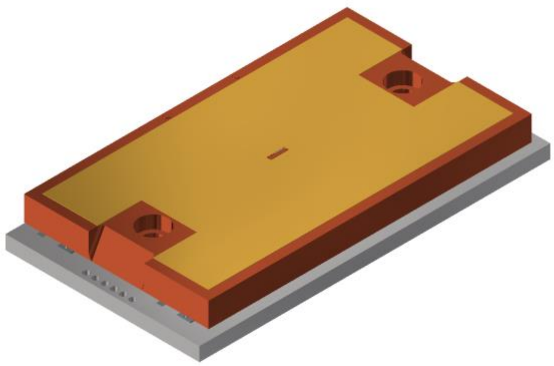

Fig. 2. eTAP tile unit

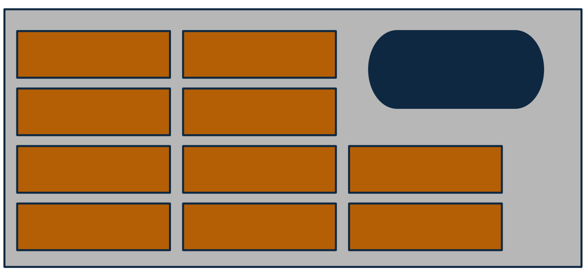

Fig. 3. eTAP tile units tiling irregular shaped area

3.4 Control and power electronics

Several tile units are driven by a single provided eTAP driver with 5-28V DC input as shown in Fig. 4. This driver provides a high-efficiency converter to generate the required high voltage for the eTAP pad (700-3000V). This voltage is provided at very low current and designed to ensure no risk to surrounding electronics or spacecraft. eTAP drivers are modular and stack to scale to the number of desired eTAP tile arrays (Fig. 5**).**

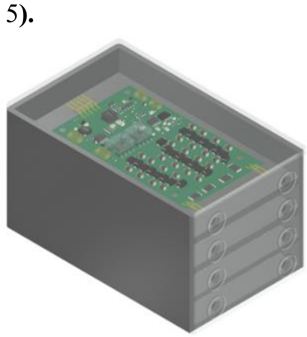

Fig. 4. 4 stacked eTAP drivers provide power for 4*4 = 16 eTAP tiles

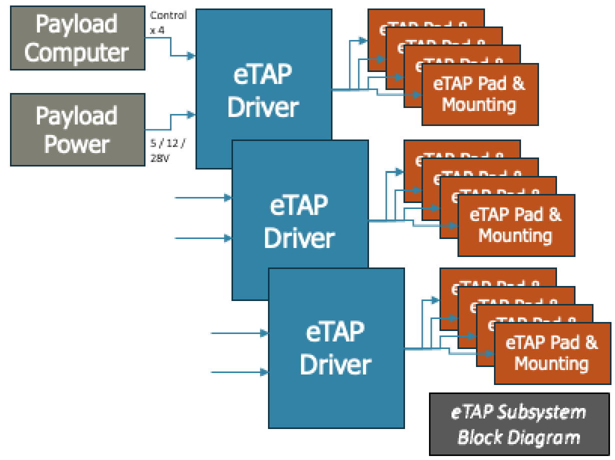

Fig. 5. eTAP subsystem block diagram

3.5 Integration architecture

SPIDEE has been designed to be compatible with typical small satellite interfaces for ease of integration:

- Mechanical interfaces: standard CubeSat/ESPA mounting
- Electrical interfaces: 5-28V input, digital I/O for commanding
- Thermal management: passive (conductive paths)
- Augmentation payload volume:
    - 3U config: 1U available
    - 16U config: 8U available
    - ESPA-class: 100+ kg capacity

4. Materials and methods

Cambrian has conducted numerous tests and experimental setups to validate eTAP and SPIDEE’s performance under various conditions and suitability for in-orbit use. These experiments fall into three categories: Static Force Tests, Dynamic Tests, and Environmental Qualification Tests.

4.1 Static force measurement setup: Normal

The test configuration was designed to determine the normal force required to separate a substrate and a pad once adhesion had occurred. To measure the normal force, a force gauge was attached to both manual and automated test stands like the one shown in Fig. 6. The Fig. 7 block diagram illustrates the key components of the test stand and its operations. The eTAP pad is mounted to the base of the test stand while a substrate is attached to the test stand using a hanging mount that fits the hook attachment of the force gauge. After the substrate mount is placed on the hook, the force gauge is tared, the eTAP is activated, and the test stand is set to the correct reference position to make contact between the active eTAP pad and the substrate. After allowing several seconds for any transient contact behavior to settle, the test stand is activated to pull the substrate upwards to detach it from the pad.

Fig. 6. Automated normal force test stand

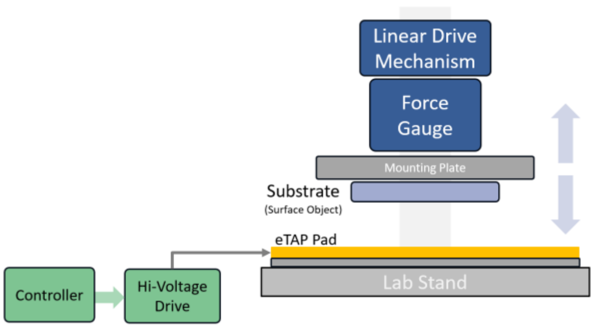

Fig. 7. Automated normal force test stand block diagram

Different sized pads were tested to determine the relationship between area and measured force.

4.2 Static force measurement setup: Shear

Shear force is known to be especially strong for electroadhesive attachment. The test setup shown in Fig. 8 below was constructed to quantitatively measure these forces against several target materials. The goal was to measure shear force under applied load. The eTAP pad was mounted on a custom 3D-printed holder and a pulley-force system was connected to the force gauge. Care was taken to maintain the pull force between the eTAP pad and substrate in a planar position. The baseline sliding friction was measured with eTAP inactive. Then eTAP was activated and the shear force was measured again. Net force was calculated by subtracting the baseline sliding friction from the activated eTAP shear force. Brass, aluminized Mylar, and Kapton/Mylar with gold coating were tested.

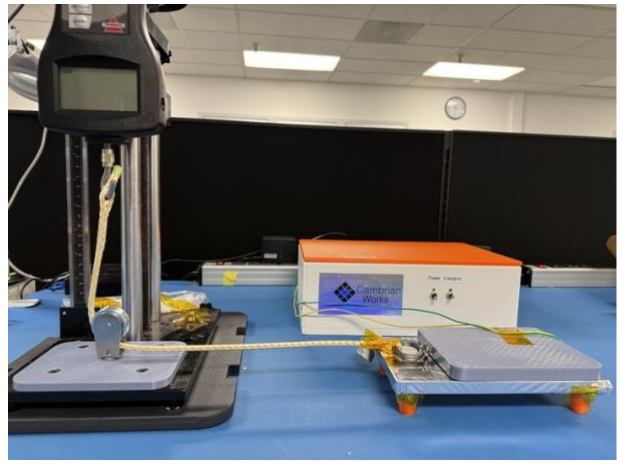

Fig. 8. Shear force test setup

4.3 Dynamic capture testing (1D & 2D)

Dynamic capture testing was also conducted in order to validate eTAP performance in dynamic on-orbit situations when approach velocities and angles are varied. To simulate realistic in-space servicing dynamics, a 1D air track (Fig. 9 and Fig. 10) was assembled with a moving satellite mass simulator to allow repeatable testing of different target substrates, relative velocities, and off-normal offset angles. A spring plunger was used to impart a controlled velocity to the mass simulator. Approach velocities up to 10 cm/s and off-angle approaches up to 5° were tested.

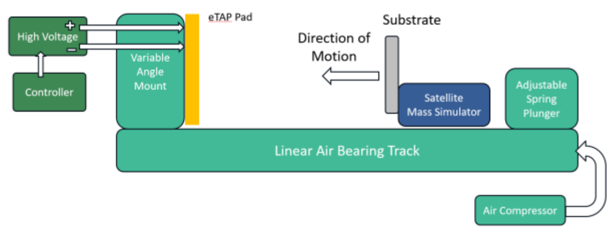

Fig. 9. 1D air track block diagram

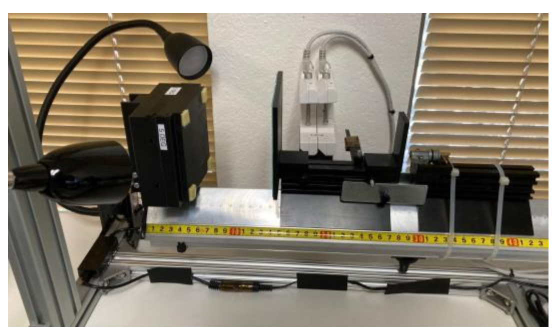

Fig. 10. 1D air track for repeatable velocity capture testing

To more realistically demonstrate capture of an object in a dynamic impulsive event, a 2D air bearing table was constructed to more realistically simulate a satellite docking maneuver. The 2D Air Bearing table shown in Fig. 11 allows a circular disk to float on a cushion of air. The target substrate, glass with an ITO coating in this case, is mounted to this circular disk and launched by the electronic ejector shown at the bottom of the figure. The electronic ejector is controlled by a variable power supply that allows the ejector speed and velocity imparted to the disk to be varied. As the disk and substrate are launched towards the statically mounted eTAP shown at the top of the figure, an armature attached to the disk will pass over two optical sensors. Using the optical sensor position and the relative time measured, we were able to calculate the velocity of the disk and substrate.

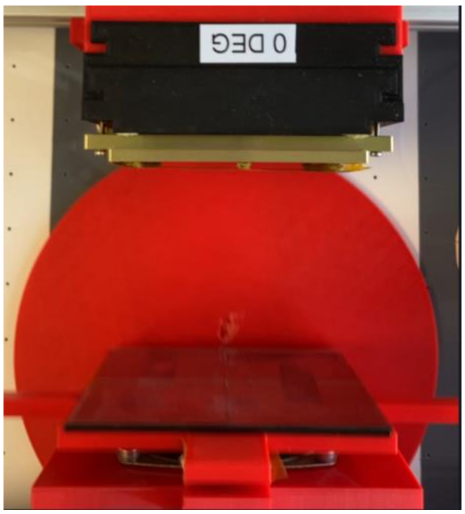

Fig. 11: 2D Air Bearing table configuration

4.4 Rotational dynamics testing

Rotational testing at the AFRL Robotic Operations Control lab used a 3x3 meter granite air bearing table to provide near-frictionless rotation. Spacecraft analogues with mass simulators of 45.8 kg and 124.7 kg were used as test articles.

The test configuration mounted various substrate materials on these rotating platforms to test eTAP adhesion to different materials, including MLI, bare aluminum plates, cover glass, and standardized docking plates. The contact areas ranged from 8.0×10^{-3} to 2.3×10^{-2} m².

Testing covered rotation rates up to 30°/s, exceeding typical debris rotation rates. eTAP was configured as shown in Fig. 12, Fig. 13, and Fig. 14 below to make contact with the substrate material once per rotation. Testing was conducted with eTAP both powered and unpowered in order to subtract out the effect of simple friction. Changes in rotational rate of the spacecraft analogues were measured and used to calculate the effect of eTAP at slowing the craft rotation.

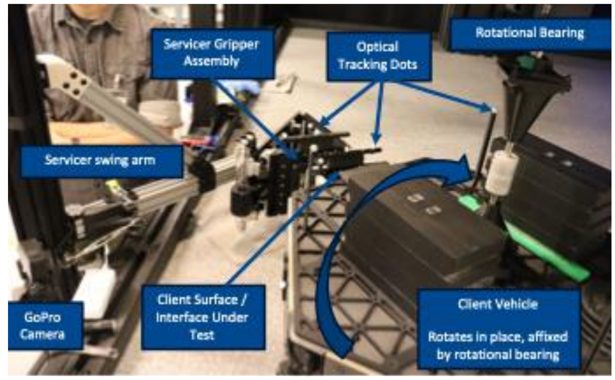

Fig. 12: Rotational air bearing test rig as assembled for ROC lab testing

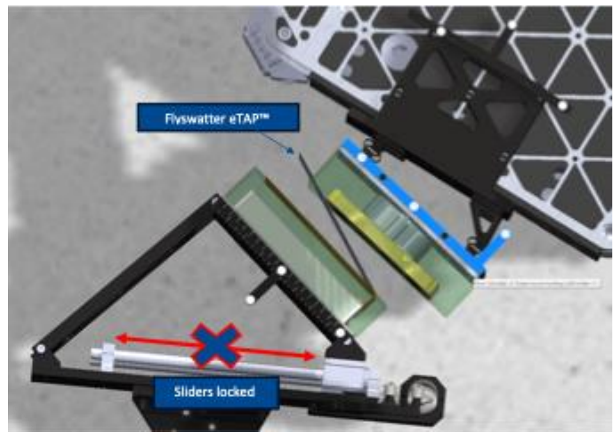

Fig. 13: CAD of locked eTAP configuration (view from above)

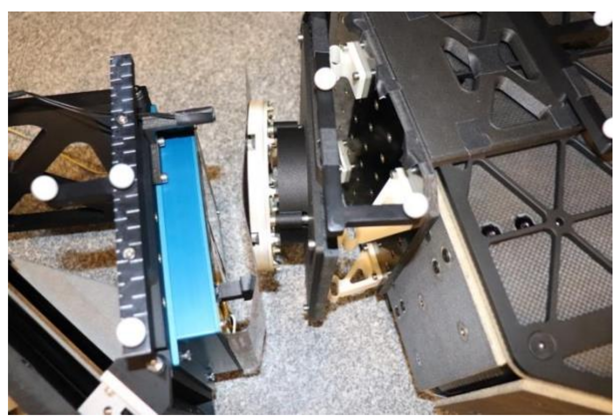

Fig. 14: eTAP used to stop rotation of test rig

4.5 Environmental qualification

Environmental testing followed GEVS standards to ensure space readiness. Thermal cycling was conducted at -40°C to +85°C, with functional testing at temperature extremes verifying performance across the operational range. Thermal vacuum testing at 10^{-6} Torr and vibration testing were conducted, with eTAP successfully maintaining operation during and/or after each of these tests.

5. Results and Performance Validation for Operational Scenarios

The experimental methods detailed in the previous section have been used to test and validate eTAP and SPIDEE performance in various realistic scenarios, representative of on-orbit use. A summary of the validated performance characteristics include:

- Normal forces: 15+ mN/cm² (scalable with area)
- Shear forces exceeding normal (critical for operations)
- 2-6x force enhancement in vacuum
- 1000 reusability cycles demonstrated

5.1 Static force measurement results: Normal

Static normal force measurements across a variety of materials were performed according to the test configuration described in Section 4.1. Results are shown in Fig. 15 below at ambient pressure.

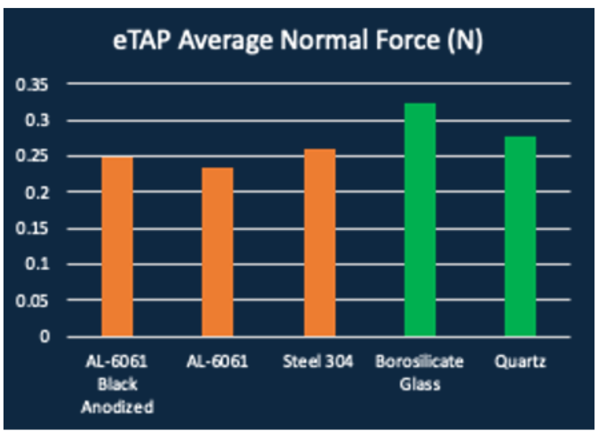

Fig. 15. Measured normal force of 16 cm^2 eTAP pads at ambient pressure

Additional testing was performed in a 10^{-5} Torr or better vacuum environment with a similar test setup. Results showed forces 2-6 times greater than at ambient, depending on material.

Testing confirmed that force is dependent on the attachment area of the substrate and eTAP pad. Normal force was found to scale linearly with area, with an average of ~15 mN/cm^2 across all materials.

5.2 Static force measurement results: Shear

Static shear force measurements across a variety of materials were performed according to the test configuration described in Section 4.2. Results are shown in Table 1 below at ambient pressure.

Table 1. Shear force testing results

Substrate Material	Unpowered Shear Force (N)	Enabled Shear Force (N)	Net Shear Force (N)
Brass (unfinished)	0.1	7.2	7.1
Mylar (silver) (aluminized, reflective)	0.09	12.99	12.9
Mylar (gold) (Kapton/mylar, gold coating)	0.09	3.69	3.6

Shear force testing confirms measured shear forces are approximately 2-3 times normal forces for the same materials. Minimal baseline friction (<0.1 N) ensures clean release. Mylar/MLI materials show exceptionally strong performance, which is notable given the difficulty of other attachment methods to adhere to this material. Shear force performance is particularly relevant to attachment and/or detumbling of a rapidly rotating space object.

5.3 Dynamic capture performance

Using the 1D air track described in Section 4 above, linear velocity capture of various substrates at 6-10 cm/s was demonstrated (Fig. 16). Results showed that conductive materials can be captured at higher velocities.

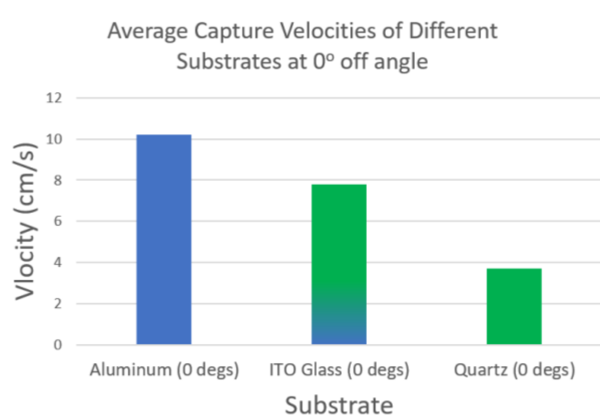

Fig. 16. Maximum capture velocities for different substrates

As anticipated, it is harder to capture objects approaching at off-normal angles. The maximum achievable capture velocity was lower when the substrate and eTAP were configured at a 5deg off-normal angle. In this configuration, approximately 50-60% of the eTAP pad contacts the substrate, which aligns with the observed decrease in maximum capture velocity of approximately 40% (Fig. 17). Note that in an actual dynamic on-orbit situation, neither craft is rigidly constrained as in this test, providing more opportunity for a larger contact area to occur.

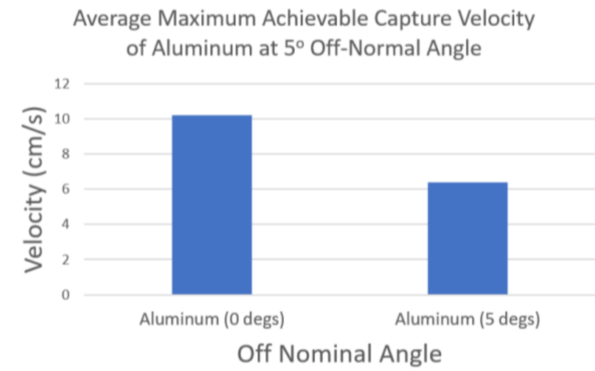

Fig. 17. Capture achieved at off-nominal angles albeit at reduced maximum velocity

5.4 Rotational capture results

5.4.1 Successful attachment at extreme rotation rates

Capture of high-angular-rate targets as detailed in the test configuration described in Section 4.4 above simulated the use of eTAP to slow and stop uncontrolled, rapidly tumbling debris. Even at the maximum rotational rate (30°/s) and mass (124.7kg) of the spacecraft analogue, eTAP was able to successfully bring the target to a stop with only 6 contacts.

These results dramatically expand the target debris population addressable with on-orbit servicing. Traditional robotic grappling systems are limited to approximately 4-5°/s. This testing indicates eTAP's ability to successfully capture objects rotating at much higher speeds that are currently unaddressable at reasonable cost points.

5.4.2 Progressive detumbling performance

Table 2. Angular Rate Reduction per Contact

Run #	Mass (kg)	Initial Rate (°/s)	Substrate	Contacts	Final Rate (°/s)
48	124.7	30	DogTag	6	0
47	124.7	25	DogTag	5	0
45	124.7	15	DogTag	2	0
40	124.7	15	Al Plate	2	0

Complete detumbling was achieved with a maximum of 6 contacts, with typical contact duration between the eTAP pad and the target of approximately 2-3 seconds. This rapid momentum transfer enables efficient detumbling operations, minimizing the use of propulsion.

5.4.3 Material performance comparison

Different surface materials showed varying effectiveness for rotational capture, with eTAP absorbing different amounts of energy at each contact as shown in Fig. 18. Aluminum plates provided excellent adhesion with fewer contacts needed for complete detumbling. DogTag surfaces (painted aluminum tags) demonstrated reliable performance across all rotation rates tested. IMLI surfaces were successfully captured at 10°/s, though with slightly reduced momentum transfer per contact. MICE (Mechanical Interface for Capture at End-of-Life) interfaces proved effective at 10-15°/s, validating compatibility with standardized docking interfaces.

The consistency across material types confirms eTAP's versatility for addressing the diverse population of space objects, from bare aluminum rocket bodies to MLI-covered satellites.

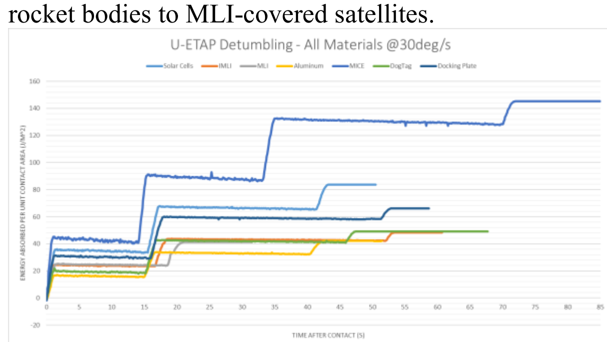

Fig. 18. Energy absorption per contact for different substrates

5.4.4 Shear force during rotational contact

Dynamic shear force measurements during detumbling operations revealed critical performance characteristics for maintaining attachment during high-rate rotation. Measured forces ranged from 1.0 to 1.65 N during active detumbling operations, with force magnitude scaling proportionally with both contact duration and angular rate of the target. These measurements, obtained through synchronized force sensors, confirm that electroadhesion maintains consistent attachment throughout the momentum transfer process.

Importantly, post-test inspection revealed no surface damage across all tested materials despite dozens of contact cycles at various rotation rates. This non-destructive attachment is critical for servicing missions where preserving the target spacecraft's surface integrity is essential for continued operations or subsequent servicing missions. The absence of surface marring, scratching, or material transfer validates electroadhesion as a benign attachment method suitable for high-value assets.

5.5 *Rotational capture results with shear force validation*

5.5.1 *Correlation between static and dynamic shear measurements*

The relationship between static laboratory measurements and dynamic operational performance provides critical validation of force margins for mission planning. ROC Lab testing measured shear forces of 0.2-2.4 N during actual rotational contact events, with contact areas ranging from 0.008 to 0.023 m². This translates to normalized shear force densities as shown in Fig. 19, representing the actual forces experienced during detumbling operations.

Comparison with static test results reveals substantial performance margins. Static tests using similar contact areas demonstrated shear force capabilities of 3.6-12.9 N as shown in Table 3, depending on substrate material.

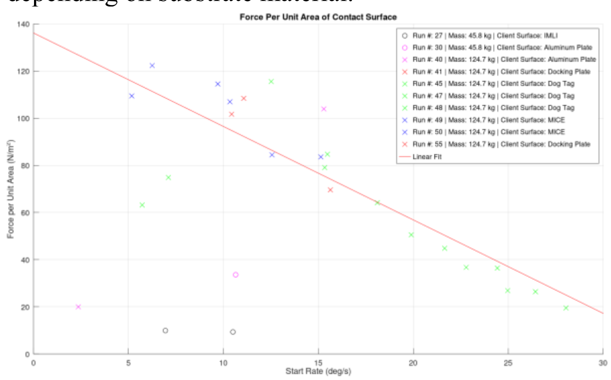

Fig. 19. Normalized shear force densities vary with rotational speed (time of contact)

Table 3. Static Shear Force for Brass and Mylar

Substrate Material	Unpowered Shear Force (N)	Powered Shear Force (N)	Net Shear Force (N)
Brass (unfinished)	0.1	7.2	7.1
Mylar (silver) (aluminized, reflective)	0.09	12.99	12.9
Mylar (gold) (Kapton/mylar, gold coating)	0.09	3.69	3.6

5.5.2 *Implications for detumbling operations*

The large shear force margins validated through testing have profound implications for operational mission design. The validated force margins enable progressive detumbling strategies where multiple brief contacts can be used to gradually reduce rotation rates without risk of attachment failure. This approach minimizes propellant consumption for the servicing vehicle, as it doesn't need to maintain continuous thrust to counteract separation forces. The demonstrated safety of multiple contact-release cycles, validated through over 1000 attachment cycles without degradation, enables flexible mission planning where servicers can attempt multiple capture attempts if initial contacts are suboptimal, or deliberately use a series of brief contacts to manage momentum transfer while maintaining servicer stability.

5.6 *Reliability and durability results*

Environmental and life testing demonstrated durability with over 1000 attachment/detachment cycles completed. Visual inspection revealed no wear, delamination, or other physical degradation.

Environmental testing validated space readiness across all conditions. Thermal cycling, vibration testing, and thermal vacuum testing were successfully completed with eTAP functioning within parameters during (as applicable) and after each test.

6. Mission Applications and Operational Analysis

Experimental test results inform the types and parameters of missions addressable by SPIDEE. This section addresses the operational envelope validated thus far and several mission types enabled by this technology.

6.1 *Concept of Operations*

SPIDEE's operational flexibility accommodates various mission architectures. For small debris, SPIDEE-equipped CubeSats deploy from larger hosts, approaching multiple targets sequentially. For large debris or operational satellites, ESPA-class vehicles incorporate SPIDEE as the primary attachment mechanism.

The baseline concept consists of four phases: (1) rendezvous and attachment at <10 cm/s relative velocity with eTAP activation during final approach, achieving attachment without surface preparation; (2) stabilization and control, including momentum exchange for detumbling through superior shear force capability; (3) orbital maneuvering for deorbiting, boosting, or station-keeping based on mission objectives; (4) detachment and retargeting with clean separation enabling progression to the next target limited only by available propellant. The system's reusability supports multiple servicing missions per deployment.

6.2 *Active debris removal and constellation management*

The proliferation of large constellations in LEO creates urgent needs for rapid debris removal capability [1,2]. Failed satellites in operational shells pose immediate collision risks to functioning constellation members. SPIDEE enables rapid response with minimal custom development, scaling effectively to objects exceeding 1000 kg validated through force scaling analysis.

Beyond debris removal, SPIDEE enables proactive constellation management and de-orbit as a service. Rapid defunct satellite removal prevents collision cascades affecting entire orbital planes. Emergency stabilization for satellites experiencing attitude control issues eliminates complex robotic grappling requirements. Collision avoidance augmentation provides additional maneuvering capability, enabling threatened satellites to perform avoidance maneuvers without depleting onboard propellant—potentially extending mission life by years. Sequential multi-target servicing missions maximize value, with a single ESPA-class servicer addressing 5-10 targets depending on orbital spacing and propellant allocation, transforming constellation maintenance economics from reactive replacement to proactive management.

Maintaining attachment during thrust operations presents unique challenges SPIDEE successfully addresses. Shear force validation demonstrated 12.9N capability versus 1.5N requirement for typical electric propulsion systems. This margin ensures secure attachment during chemical thruster burns (100-500N), electric propulsion operations (0.01-1N), and momentum wheel desaturation events. The high shear-to-normal force ratio proves critical as thrust vectors create moments about the attachment point, with enhanced shear capability preventing slippage.

6.3 Payload Augmentation Services

SPIDEE enables transformative augmentation of existing spacecraft capabilities. For satellites with depleted propellant, cold gas systems deliver 50-100 m/s ΔV for station-keeping, extending mission life by several years. Attitude control augmentation addresses common failure modes through reaction wheels providing 3-axis stabilization and magnetic torquers enabling momentum management without propellant consumption.

Beyond basic bus functionality, SPIDEE enables sophisticated capability additions: sensor packages for space domain awareness, Earth observation sensors on GEO communication satellites, modern transponders with higher data rates, deployable solar arrays addressing degradation, and edge AI/ML processing reducing downlink requirements. These upgrades can add decades to spacecraft originally designed for 5-7 year missions.

6.4 Emerging applications

Electroadhesion's integration into robotic systems enables new paradigms. As an end-effector, eTAP provides scalable force at low power, enabling tool use on unprepared surfaces. For in-space assembly, the 12.9N holding force exceeds typical assembly loads while allowing repositioning through controllable, reversible attachment.

Formation flying benefits from physical connection between spacecraft maintaining structural rigidity during differential drag compensation and coordinated maneuvers. CubeSat clustering allows multiple small satellites to function as a single platform, with over 1000 attachment cycles enabling adaptive mission operations.

SPIDEE's rapid attachment capability enables emergency response to spacecraft anomalies. Capturing tumbling spacecraft at up to 30°/s exceeds most failure mode rotation rates. Off-nominal approach capability ensures successful attachment despite imperfect geometry, potentially saving missions worth hundreds of millions of dollars.

7. Enabling Sustainable Space Operations Discussion

7.1 Technical performance validation

The comprehensive testing campaigns establish SPIDEE's transformative capabilities. Rotational dynamics testing demonstrated capture of a 124.7 kg mass at 30°/s—fundamentally changing the serviceable spacecraft landscape. Complete angular momentum dissipation within 5-6 contact cycles minimizes structural loads, with no specific pre-contact orientation required.

Shear force testing revealed exceptional tangential load capacity unique to electroadhesion. With shear forces 15-28 times greater than normal forces, the 12.9N capability ensures robust attachment during extreme dynamics. This enables tangential approaches, sliding capture maneuvers, and maintained attachment during propulsion—capabilities impossible with other methods.

Material compatibility spans aluminum alloys, titanium, composites, MLI, and solar cells with consistent performance regardless of surface condition. Scalability from gram-scale demonstrations to 125 kg masses, combined with over 1000 reuse cycles, confirms deployment readiness. By addressing 95% of LEO debris (acknowledging GEO debris at 400°/s remains challenging), SPIDEE eliminates pre-detumbling requirements for most targets.

Table 4 demonstrates electroadhesion's unique position: the only solution combining universal material compatibility, high reusability, minimal power consumption, and exceptional shear force performance. With core technology at TRL 6+, modular interfaces enable rapid integration while proven partner collaboration through Astroscale positions SPIDEE for near-term deployment.

Table 4. Attachment Technology Comparison

Type	Material Compatibility	Reusability	Power	Shear / Normal
Electro-adhesion	Universal	>1000	<1W	15-28x
Magnets	Ferrous only	Yes	0-10W*	<1x
Mechanical	Prepared	Variable	Variable	Variable
Adhesive	Most	No	0W	~1x
Gecko	Clean surfaces	Limited	0W	~2x

*Permanent magnets require no power; electromagnets require continuous power

7.2 Sustainability impact and economic value

SPIDEE directly addresses space sustainability pillars. Each life extension eliminates a replacement launch, reducing environmental impact and orbital congestion. Removing failed satellites before fragmentation provides proactive debris mitigation. The non-destructive attachment preserves spacecraft value for future servicing. With over 1000 reuse cycles, a single platform services multiple targets, embodying circular economy principles aligned with UN guidelines for long-term space sustainability.

SPIDEE enables fundamental economic shifts through service-based revenue models replacing spacecraft sales. Pay-per-use augmentation democratizes advanced capabilities for emerging space nations. Insurance markets recognize life extension value through premium reductions. The addressable market, estimated at \$2-4 billion by 2030 [3], represents only the beginning. The comparison between \$15-20 million for augmentation versus \$500 million for replacement illustrates compelling value, particularly for scientific missions.

7.3 International collaboration framework

The Swift Observatory concept study with Astroscale U.S. demonstrated effective risk-sharing, with partners contributing specialized expertise. Rapid mission architecture development proved agile partnership viability for urgent servicing needs.

Beyond bilateral partnerships, SPIDEE enables diverse frameworks. Technology licensing allows regional operations while maintaining sovereignty. Consortium approaches enable nations to share infrastructure costs and benefits. Emergency response networks provide mutual aid for critical assets. These flexible models accommodate varying participation levels from technology transfer to joint development programs.

The universal nature of electroadhesive attachment creates standardization opportunities. Common interfaces enable any servicer to assist any spacecraft regardless of origin. Standardized protocols across space agencies reduce complexity while improving safety. Common certification frameworks accelerate market development while ensuring responsible operations.

7.4 Development roadmap

While SPIDEE's capabilities exceed alternatives, several limitations bound operations. eTAP is less resistant to peeling than normal or shear pulling. Heavy contamination can degrade adhesion, though most space-weathered surfaces remain operational. The <1W continuous power requirement necessitates budget allocation for extended operations.

Continued advancement addresses limitations while expanding capabilities. Advanced electrode materials promise higher force density. Autonomous control systems incorporating AI-guided attachment simplify operations. eTAP sensing provides attachment validation without mechanical switches.

The deployment pathway follows systematic progression: Cambrian is preparing for atomic oxygen exposure testing in the summer of 2026. Additionally, preparations are underway for long-duration LEO exposure testing and dynamic performance measurement of normal, shear, and rotational forces in LEO for 2027.

Demonstrated capability and planned on-orbit validation is informing engagements with multiple commercial providers to demonstrate Cambrian attachment units on-orbit in 2027.

8. Conclusions: A Foundation for Collaborative Space Sustainability

The Space Payload for Inertial De-spin Efficient Effects (SPIDEE) and its electroadhesive technology represent a critical breakthrough enabling sustainable space operations through international collaboration. This paper presented comprehensive validation of technology that fundamentally transforms on-orbit servicing, life extension, and debris mitigation approaches.

8.1 Validated technical foundation and international collaboration

Testing campaigns established electroadhesion as a universal attachment solution requiring no surface preparation, adhering to any spacecraft material from pristine solar panels to decades-old degraded MLI. The technology demonstrates exceptional performance with normal forces exceeding 15 mN/cm² and shear forces 15-28 times greater—capabilities unmatched by alternatives. Validated 30°/s capture expands the serviceable population, bridging the gap between limited robotic arms and uncontrolled capture methods. Over 1000 attachment cycles without degradation, combined with 2-6x vacuum enhancement, confirms space environment readiness.

NASA's Swift Observatory concept study selection validated technical merit and feasibility for servicing unprepared, decades-old spacecraft. Rapid mission architecture development with Astroscale U.S. established eTAP as credible for challenging scenarios, demonstrating flexibility and ease of integration. The modular architecture accommodates diverse collaboration frameworks through common, standards-compliant interfaces—addressing shared orbital challenges while enhancing sustainability. The global market development roadmap, with ISS demonstration in 2027 and commercial operations by 2028, provides clear opportunities for international participation through various engagement models.

8.2 Transforming space sustainability

eTAP enables fundamental shift from "launch and replace" to "maintain and enhance." Every life extension eliminates replacement launches, directly reducing environmental impact. The technology transforms liabilities—tumbling satellites and debris—into opportunities for resource recovery and reuse. One servicer addressing multiple targets supports transition to a circular space economy where assets are maintained, upgraded, and recycled rather than abandoned.

These operational models inherently promote sustainability: shared servicing infrastructure reduces redundant launches, life extension preserves economic and scientific investments, and removing failed satellites before fragmentation protects the orbital environment. These capabilities directly support UN guidelines and create economically viable pathways for all nations to participate in responsible operations.

8.3 Path forward

With flight demonstrations planned on ISS in 2027 and continued engagement with commercial and government partners, the SPIDEE concept will transition from validated technology to operations delivering capabilities for prepared and unprepared spacecraft augmentation, orbit maintenance, and enhanced robotic capability. The Swift study provided invaluable insights strengthening our approach for future opportunities where electroadhesion's advantages—particularly universal material compatibility—are mission-critical. The growing $2-4B servicing market presents numerous opportunities where traditional approaches fail.

As the space community grapples with increasing debris populations and sustainability needs, SPIDEE offers a proven, practical solution. By transforming every spacecraft into a potentially serviceable and augmentable asset, this technology enables inherently sustainable, economically viable, and accessible space operations for all nations. The successful validation of electroadhesive attachment represents not just technical achievement, but a critical enabler for collaborative international effort required to preserve the space environment while maximizing benefits for humanity.

Acknowledgements

This material is based upon work supported by the Air Force Research Laboratory under agreement number ASUS-PRO-01024. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Air Force.

References

[1] ESA Space Debris Office, "ESA's Annual Space Environment Report," European Space Agency, Issue 6, April 2022.
[2] Liou, J.-C., "An Active Debris Removal Parametric Study for LEO Environment Remediation," Advances in Space Research, Vol. 47, No. 11, pp. 1865-1876, 2011.
[3] Northern Sky Research, "In-Orbit Servicing Markets, 4th Edition," NSR Report, 2021.
[4] Long, A.M., M.G. Richards, and D.E. Hastings, "On-Orbit Servicing: A New Value Proposition for Satellite Design and Operation," Journal of Spacecraft and Rockets, Vol. 44, No. 4, pp. 964-976, 2007.
[5] Saleh, J.H., E.S. Lamassoure, and D.E. Hastings, "Space Systems Flexibility Provided by On-Orbit Servicing: Part 1," Journal of Spacecraft and Rockets, Vol. 39, No. 4, pp. 551-560, 2002.
[6] Shan, M., J. Guo, and E. Gill, "Review and Comparison of Active Space Debris Capturing and Removal Methods," Progress in Aerospace Sciences, Vol. 80, pp. 18-32, 2016.
[7] Johnsen, A. and K. Rahbek, "A Physical Phenomenon and Its Applications to Telegraphy, Telephony, etc.," Journal of the Institution of Electrical Engineers, Vol. 61, No. 320, pp. 713-725, 1923.
[8] Shultz, C.D., M.A. Peshkin, and J.E. Colgate, "Surface Haptics via Electroadhesion: Expanding Electrovibration with Johnsen and Rahbek," IEEE World Haptics Conference, Evanston, IL, pp. 57-62, 2015.

[9] Monkman, G.J., "Electroadhesive Microgrippers," Industrial Robot: An International Journal, Vol. 30, No. 4, pp. 326-330, 2003.
[10] Lee, S., et al., "Demonstrating New Attachment Technology for On-Orbit Docking," Proceedings of the 37th Annual Small Satellite Conference, SSC23-XIII-02, Logan, UT, August 2023.
[11] NASA, "NASA Explores Industry Possibilities to Raise Swift Mission's Orbit," National Aeronautics and Space Administration, Washington, D.C., 2024. Available: https://www.nasa.gov/missions/swift/nasa-explores-industry-possibilities-to-raise-swift-missions-orbit/ [Accessed: Sep. 27, 2025].