Space Payload for Inertial De-spin Efficient Effects (SPIDEE) Enables Repeatable Orbital Debris Remediation Missions

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***Abstract*— The Space Payload for Inertial De-spin Efficient Effects (SPIDEE) is an electroadhesion-based general purpose in-space attachment payload ideally suited for docking, augmentation, mobility, and in-space assembly missions that does not require pre-preparation of the attachment surface.**

Built around eTAP™ (electrical Thin Attachment Pad), SPIDEE supports missions to attach to, detumble, and provide space mobility for defunct satellites or rocket bodies. eTAP's low power, reusability, and flexibility make it ideal as an all-purpose attachment and docking technology for the upcoming space challenge of reducing, reusing, and recycling in-orbit debris and/or assets.

Existing on-orbit attachment and/or docking methodologies tend to fall into two camps: either highly optimized for a single application (often requiring pre-planned docking points), or large and complex enough to handle the wide variety of resident space objects (RSOs) that may be of interest. eTAP occupies a unique middle ground: it is a simple, flexible alternative that adheres to virtually any space material, providing unique and complementary advantages to alternatives based on optical sensing, magnetics, "gecko" technology, adhesives, and/or mechanical grappling.

eTAP technology is a cost-effective, general attachment technology compatible with several types of surfaces, presenting unique opportunities for docking and proximity operations. eTAP adheres to virtually all materials that are used in space, can conform to irregular surfaces, is low power, requires no substrate preparation, has enhanced performance in vacuum, is temperature insensitive, and leaves no residue.

SPIDEE interfaces enable ease of integration to a wide variety of small satellite vehicles, from 3U CubeSats to ESPA class servicing craft. Such a vehicle that can attach itself to others becomes a reusable small satellite platform—limited only by its available propellant—with the capability to cost-effectively address orbital debris remediation, as well as extend the life of operational satellites. On-orbit missions planned include International Space Station-based (1) testing of eTAP coatings to demonstrate their ability to withstand atomic oxygen degradation in low orbits and (2) measurement of normal and shear gripping (attaching) forces generated in the on-orbit plasma environment.

Keywords—electroadhesion, space technology, orbital debris, satellite servicing, robotic end-effector, space docking, detumble, deorbit, space mobility

I. Introduction

The space industry is at an inflection point, transitioning from isolated satellite systems to interconnected on-orbit systems and capabilities. New technology for satellite servicing, space tugs, and removal of defunct satellites requires novel attachment methods for objects not previously designed to be touched on orbit. This paper presents the development and testing of electrical Thin Attachment Pad (eTAP™) technology as a solution to these challenges.

A. *Motivation*

As the satellite industry has progressed from fewer, exquisite, costly satellites, to more, lower reliability, low-cost satellites, the problem of orbital debris and derelict satellites has increased. As we leave the disposable, throw-your-litter-out-the-window phase of space development, new technologies and techniques are needed to not only clean up the litter, but also re-fashion it, where possible, into new uses. The current solutions for attachment to these satellites tend to rely on electromagnets, which require ferrous material, to robotic graspers, which are costly, complex, and typically require a "hard" mating feature.

B. *Contribution*

This paper demonstrates the feasibility of applying electroadhesion technology for space applications, specifically focused on attachment to uncontrolled RSOs for the purpose of detumble, deorbit, and/or orbital mobility through:

1) Quantitative characterization of attachment forces for typical aerospace materials,
2) Dynamic testing under representative orbital conditions,
3) Validation of capability for debris capture and satellite servicing missions.

II. Electroadhesion Fundamentals

A. *Principle of Operation*

Electroadhesion generates attractive forces between surfaces through applied electric fields. The eTAP technology uses inter-digitated electrodes activated by >1500V to create attractive forces via induced field and polarization effects. Gap spacing between electrodes is critical to balance higher achievable force levels against discharge (arcing) or corona events.

B. *eTAP Design Architecture*

The eTAP (*Fig. 1*) is a pad (<0.1mm thick) made from space-rated materials and mounted on an aluminum baseplate. eTAP pads are scalable to almost any size; adhesive force is proportional to pad active area, with active area indicating the area covered by the electrodes that generate the electric field. Cambrian Works conducted tests with active areas of 40x40mm and 80x80mm to measure how force scales with pad active area.

Key design elements include:

- Thin (<0.1mm) pad construction
- Space-rated materials
- Scalable active area design
- Flexible conformability to irregular surfaces

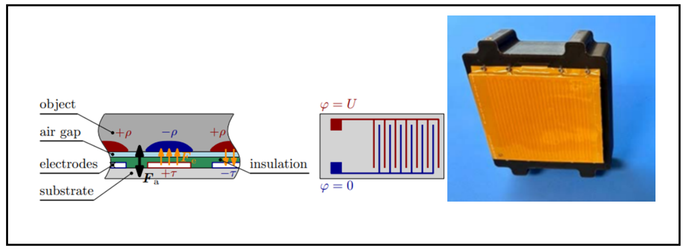

Fig. 1. Method of operation of eTAP™ gripper (left), and physical gripper (right)

C. *Space Environment Considerations*

eTAP performance enhancements in vacuum conditions:

- Enhanced attachment due to absence of air breakdown
- No dielectric breakdown constraints at elevated voltages
- Temperature-agnostic operation (-40°C to +85°C)
- Zero residue or contamination

III. Static Testing and Qualification

A. *Static Force Characterization*

The test configuration was designed to determine the normal force required to separate a substrate and a pad once adhesion had occurred. The eTAP 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 and the substrate (*Fig. 2*).

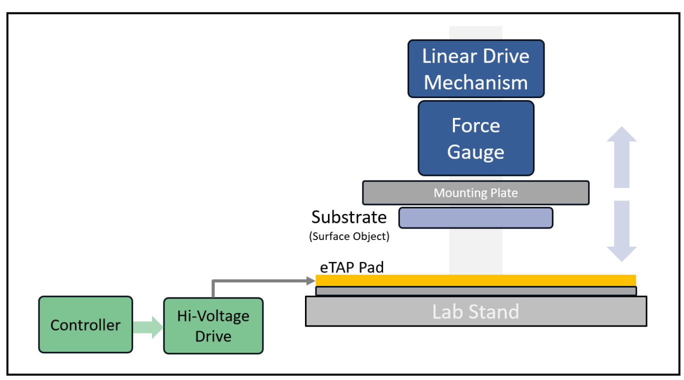

Fig. 2. eTAP™ Pad normal force test stand block diagram

With these test configurations we were able to measure eTAP attachment forces on these various substrates (*Fig. 3*). With the data collected from the conductive and insulative substrates, we can draw several conclusions about eTAP's performance with different types of substrate materials.

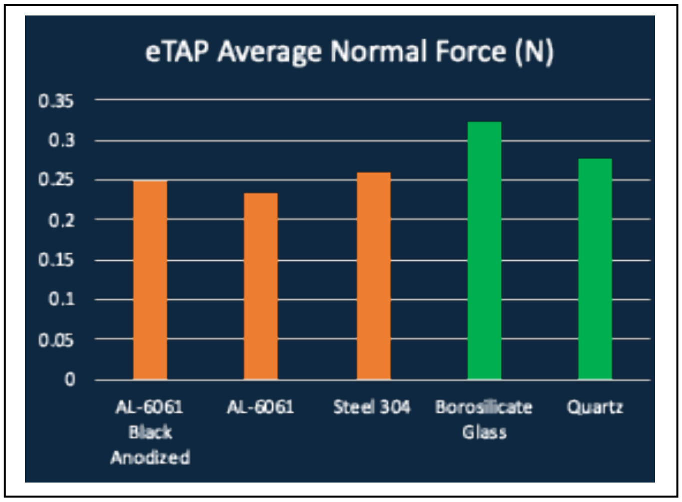

Fig. 3. eTAP™ Pad normal attachment force test results (ambient pressure)

B. *Vacuum Performance Testing*

To ensure eTAP utility in space conditions, vacuum chamber testing was conducted to measure attachment performance in vacuum. This testing demonstrated:

- Normal force enhancement of 2x to 6x vs. ambient pressure conditions
- Reliable operation at <= 10^{-5} Torr
- No dielectric breakdown at elevated voltages
- Consistent performance across temperature range

C. *Material Compatibility Results*

Static testing of eTAP with a variety of materials demonstrated:

1) Excellent attachment to common space materials (aluminum, titanium, MLI, solar cells)

2) 15%-20% higher force on insulators vs. conductors (insulators achieve higher attachment force)

3) Negligible performance degradation from common coatings (anodization, ITO on class)

4) Linear force scaling with active area ($40mm^2$ to $80mm^2$)

5) Shear (sliding) attachment forces significantly stronger than normal attachment forces.

With the data collected from conductive and insulative substrates, we can draw several conclusions about eTAP's performance. A 40x40mm pad produces approximately 0.25N of force, which translates to about 15.6 mN/cm^2. This is several orders of magnitude stronger than typical small satellite electric propulsion subsystems like Empulsion's Micro R3, which delivers a nominal thrust of 0.001N.

Scaling to 80x80mm increased active area yielded a 4.8x force increase for aluminum and 4.3x for glass. The larger eTAP achieved >1N of normal force, showing the direct linear relationship between active area and achievable force.

IV. DYNAMIC TESTING AND VALIDATION

A. *1D Linear Air Bearing Testing*

Linear motion testing utilized a 1D Air Track with adjustable spring plunger to impart controlled velocity to a satellite mass simulator.

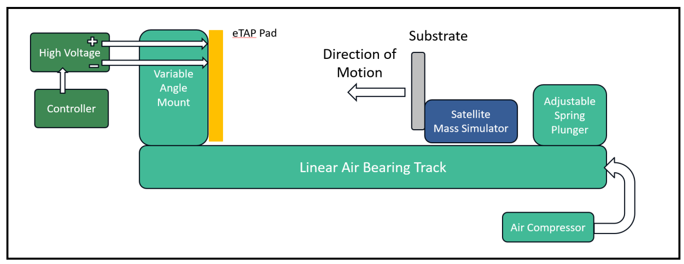

Fig. 4. eTAP™ 1D air track block diagram testing

Results (*Fig. 5*) demonstrated:

- Maximum capture velocities ranging from 6-10 cm/s (with materials showing difference in performance)
- Material-dependent performance (conductive materials allow faster adhesion)
- Off-normal angle effects (40% reduction at 5° offset for aluminum)

There is a clear difference in maximum capture velocity between different materials. Conductive materials can be captured at higher velocities due to faster generation of electroadhesive force through increased charge mobility.

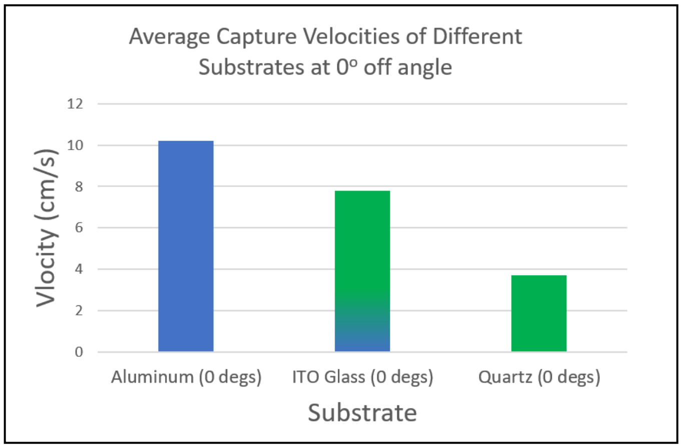

Fig. 5. eTAP™ 1D air track maximum capture velocities

B. *2D Air Bearing Docking Simulation*

Cambrian Works and Astroscale US performed 2D air bearing testing at an air bearing facility to verify eTAP performance in realistic on-orbit mission scenarios (*Fig. 6)*. Note that this testing was in ambient pressure, and thus we expect in-space forces to be 2x-6x to those achievable in this testing. The 2D Air Bearing table provided the opportunity to explore the impact of a rotational degree of freedom on the ability for eTAP to capture a satellite that is moving at a constant velocity. Enhanced testing with rotational freedom showed:

- eTAP ability to capture rapidly rotating, high mass objects (initial contact causing reduced rotation rate that settles with full contact)
- Successful attachment settling dynamics in representative docking scenarios

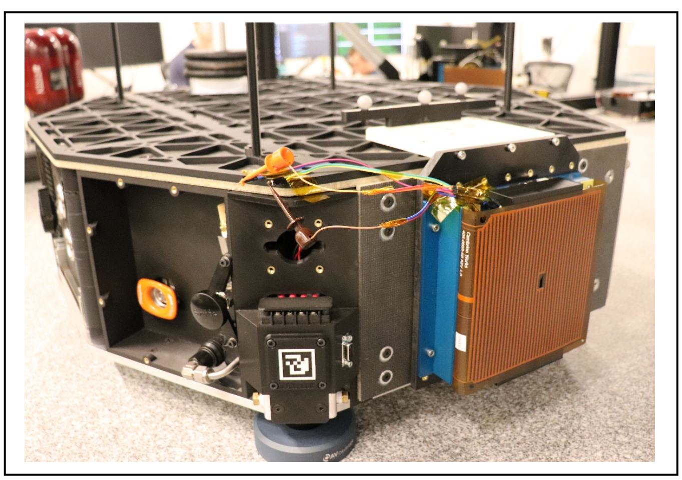

Fig. 6. eTAP™ Pad installed on air bearing craft

C. *RSO Detumbling Experiment*

Electroadhesion was used to demonstrate the ability to act as a momentum exchange brake and successfully arrest high momentum rotating objects (*Fig. 7*):

- Successfully arrested objects rotating at 30° per sec (*Fig. 8*)
- Demonstrated controlled torque application for detumbling
- Provided gradual energy dissipation through eTAP shear forces
- Measured forces provide ability to scale performance analysis for larger debris objects

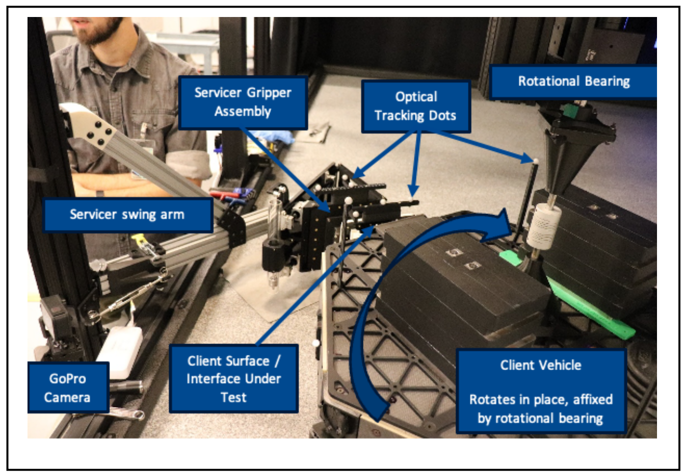

Fig. 7. Rotational air bearing test rig as assembled for testing

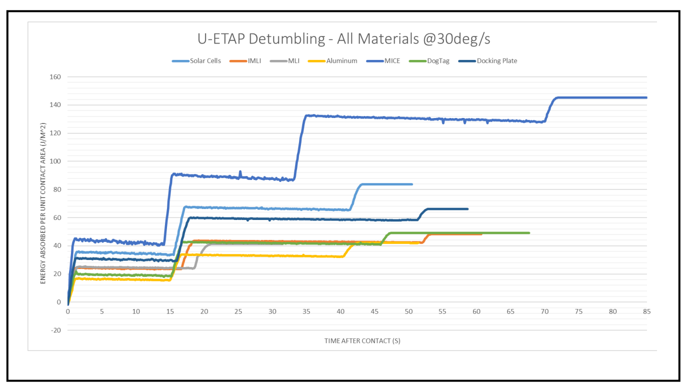

Fig. 8. Comparison of detumble performance across all materials, scaled for surface contact area

V. Mission Applications

eTAP's versatility as a an in-space attachment technology occupies a unique middle ground: it is a simple, flexible alternative that adheres to virtually any space material, providing unique and complementary advantages to alternatives based on optical sensing, magnetics, "gecko" technology, adhesives, and/or mechanical grappling.

A. *Debris Capture and Detumbling*

Force levels sufficient for:

- Capturing 3000kg+ objects
- Counteracting propulsion forces
- Active detumbling of rapidly rotating objects
- Momentum transfer efficiency >85%

B. *Satellite Servicing and Docking*

Capabilities for:

- Tool placement and workspace management allowing tools and parts needed for assembly or disassembly to be temporarily held in position in the work area
- Surface attachment without damage
- Reversible and reusable adhesion
- Precision alignment maintenance during servicing
- Multi-point attachment for stable docking

C. *In-Space Assembly Support*

Applications demonstrated:

- Temporary part fixturing during assembly
- Robotic end-effector enhancement
- Deployable "sticky" surfaces for workspace organization

VI. Rendezvous and Proximity Operations (RPO) Modeling

Cambrian Works will carry out extensive modeling of rendezvous and proximity operations for the purposes of providing RSO detumble and in-space mobility. This modeling, in conjunction with measured attachment force performance parameters, verifies eTAP's ability to attach to much larger, rapidly spinning objects. Inclusion of propulsion and/or ACS subsystems further enables detumble and orbital mobility.

A. *Dynamic Interaction Modeling*

Comprehensive modeling of eTAP forces during rendezvous of an eTAP-equipped "chaser" with unprepared rotating targets will provide:

- Multi-body dynamics simulation of chaser-target interaction
- Calculation of normal and tangential force requirements
- Prediction of attitude control system (ACS) interaction with electroadhesion
- Time-dependent force profile during initial contact and settling

RPO modeling will focus on representative unprepared docking targets, such as a defunct Space Development Agency (SDA) satellite and a tumbling rocket body. Sensitivity analyses associated with varying RSO mass and rotation rates will provide required electroadhesive force for the chaser vehicle to successfully achieve docking.

B. *Integrated System Performance and Space Mobility and Logistics Applications*

Integrating attitude control and/or propulsion with the eTAP-equipped chaser enables modeling of:

- eTAP force profile during docking sequence
- Thrust vectoring assistance for maintaining attachment
- Detumbling trajectory optimization
- Deorbital burn maintenance under varying loads

System modeling will demonstrate capability for attaching a payload to an unprepared RSO in order to provide:

- Controlled detumbling while maintaining attachment
- Orbital plane changes with attached payload
- In-plane circularization maneuvers
- Station-keeping operations

SPIDEE interfaces enable ease of integration to a wide variety of small satellite vehicles, from 3U CubeSats to ESPA-class servicing craft. Such a vehicle that can attach itself to others becomes a reusable small satellite platform—limited only by its available propellant.

Modeling and analysis will evaluate the feasibility and/or time required to detumble and/or alter system orbit based on various propulsive and ACS technologies such as: magnetic torquers, reaction wheels, electric propulsion, cold gas thrusters, etc.

VII. SPACE PAYLOAD FOR INERTIAL DE-SPIN EFFICIENT EFFECTS (SPIDEE) PAYLOAD

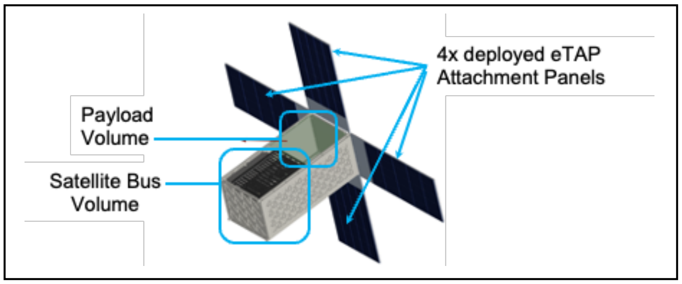

Fig. 9. SPIDEE-equipped 16U spacecraft with volume for additional payloads

A. *Architecture and Design*

SPIDEE (Space Payload for Inertial De-spin Efficient Effects) is a complete space-qualified payload system based on eTAP technology. SPIDEE features (*Fig. 9*):

- Standardized physical interfaces compatible with 3U CubeSats to ESPA-class spacecraft
- Modular design allowing flexible configuration of eTAP arrays
- Built-in power conditioning and control electronics
- Open communication protocols for integration with host vehicle systems

SPIDEE system components (*Fig. 10*):

- Control unit: containing logic circuitry and a switching module to generate and time the polarity reversals
- Sensing unit: containing optional sensing circuitry to analyze and report attachment status
- Power drive circuit: supplies high-voltage (e.g., ±1500V) to electroadhesive pad(s)
- Electroadhesive pad(s): contain electrical traces embedded in dielectric material that generates an attractive force to an opposing surface when a high voltage is applied)

Operational method: enables a two-stage cycle — (1) activation for attraction and attachment; (2) deactivation for detachment.

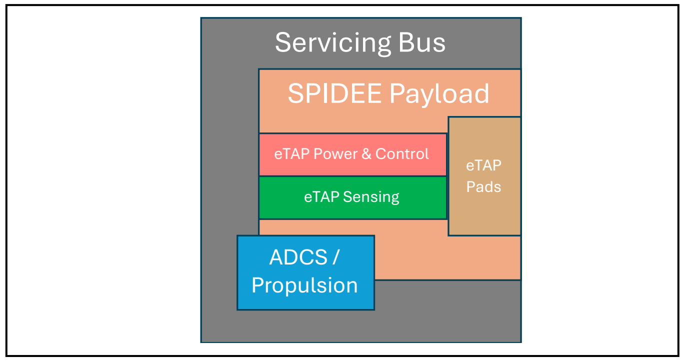

Fig. 10. SPIDEE system component block diagram

B. *Payload Capacity and Integration*

SPIDEE accommodates various host vehicle configurations or enhancements:

1) *Propulsion Integration:*
   - Support for cold gas, chemical, or electric propulsion systems
   - Thrust vectoring capabilities for maintaining attachment during burns
   - Propellant capacity for extended orbital operations

2) *Attitude Control Integration:*
   - Compatible with reaction wheels, thrusters, and magnetic torquers
   - Real-time force feedback for coordinated control
   - Autonomous detumbling algorithms

3) *Mission-Specific Payloads:*
   - Additional sensor packages
   - Communication systems
   - Scientific instruments
   - Refueling or repair mechanisms

C. *Concept of Operations*

SPIDEE enables a flexible approach to mission design and on-orbit servicing. At its simplest level, the CONOPS consists of:

1) Delivery to the Resident Space Object (RSO) via a larger bus mechanism or as a free-flying smaller satellite
2) eTAP attachment
3) Support for mission payload (e.g. space domain awareness sensor, communications upgrade, etc.)
4) Optional support for RSO detumble and/or orbit change
5) eTAP deactivation or detachment
6) Retrieval or orbital change to await next mission (reusable).

D. *Operational Capabilities*

SPIDEE will enable comprehensive orbital service operations:

- Docking with targets rotating up to 30 deg per sec
- Active detumbling while maintaining secure attachment
- Orbital transfer maneuvers with attached payloads
- Station-keeping and formation flying operations
- Multi-target sequential servicing missions

E. *System Performance*

We anticipate SPIDEE system specifications (scalable to other ranges with addition of modular pads) such as:

- Maximum attachment force: >11N (configurable with multiple pads)
- Power consumption: <1W for continuous operation of eTAP
- Operating temperature range: -40°C to +85°C
- Attachment reliability: >95% across all qualified materials
- Reusability: >1000 attachment/detachment cycles

The SPIDEE system represents the first commercially available general-purpose attachment solution designed specifically for uncontrolled target spacecraft servicing and orbital debris mitigation missions.

F. *Example Advantages over Traditional Methods*

Aspects of this method of docking include:

- Controlled electroadhesive attachment and detachment
- No mechanical parts needed for retention or release
- Method enabling predictable, repeatable, force-free docking in zero-g
- Ability to attach to virtually all common materials used in space without requiring surface pre-preparation
- Integrated attachment sensing
- Drive options to trade off force and power constraints
- Ability to detumble previously unrecoverable rapidly spinning spacecraft

Aspects of this method of docking include:

- Prevents motion disturbances from mechanical attachment and detachment
- Provides ability to attach to previously unserviceable spacecraft with no preprepared surfaces, or rotational rates that are too high for other docking or servicing
- Reduces astronaut effort and tool handling time
- Allows repeated use without wear or degradation
- Improves reliability and safety for robotic and crewed operations
- Is benign to attaching surfaces; has no EMI effects and leaves no residue
- Integrated attachment sensing

TABLE I. ADVANTAGES OVER TRADITIONAL METHODS

Technology	**Limitation**	**eTAP Advantage**
Electromagnets	Requires ferrous material	Any surface material, low power
Mechanical grappling	Requires prepared docks	No preparation needed, low power
Gecko technology	Complex design	Simple operation & compatible with more materials
Adhesives	Leaves residue, generally not reusable	No contamination, reusable
Thrusters	High fuel consumption	Continuous attachment

In addition, eTAP technology is complementary, allowing integration with one or more of the docking technologies listed in Table 1, and thereby providing additional capability and/or risk reduction to a docking procedure.

VIII. Conclusions and Future Work

The development and testing of Cambrian's eTAP technology demonstrates significant potential for addressing critical space industry challenges. Results show:

1. Force levels exceeding requirements for multiple applications
2. Compatibility with diverse materials and conditions
3. Scalability and controllability through design parameters
4. Successful integration with attitude control systems for complex maneuvers

The eTAP technology developed by Cambrian Works shows significant promise as a generalized in-space attachment enabler. Specifically, it produces forces that are of sufficient magnitude to be significant in the micro-gravity environment of space, and sufficient to counteract forces such as those expected from actuators such as thrusters.

eTAP provides a highly desirable alternative to many alternatives that rely on glues or inter-locking mechanisms or prepared surfaces. eTAP's ability to adhere to a wide variety of materials and unprepared surfaces opens up new options for in-space servicing missions not yet considered possible.

Future work will focus on:

- Extended environmental testing
- Increased pad area scaling
- Integration with complete servicing systems
- Validation of multi-body dynamics models through on-orbit testing

A. *Future Demonstrations*

Planned missions:

- ISS-based testing of eTAP coatings to demonstrate ability to withstand atomic oxygen degradation in low orbits
- Measurement of normal and shear forces generated in the on-orbit plasma environment
- Free-flyer demonstration mission to demonstrate approach, attachment, and control of a target unprepared RSO.