ELECTROADHESIVE TECHNOLOGY ENABLED CUBESAT MISSIONS

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Cambrian Works, Inc.

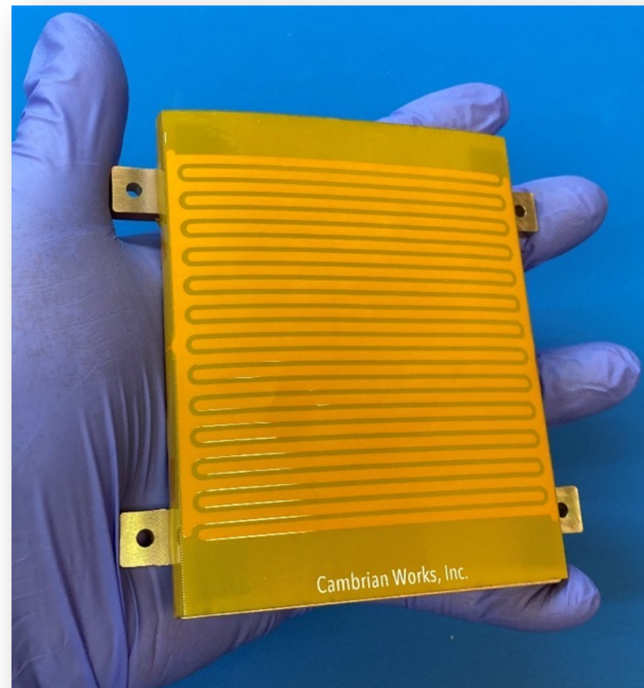
ELECTRODHESION

GENERAL ON-ORBIT ATTACHMENT TECHNOLOGY

- Electroadhesion uses an electric field to generate attractive force
- Attaches near-instantaneously to wide variety of surfaces
- Attaches to unprepared & non-planar surfaces
- Easily turned on/off & leaves no residue

Demonstrated successfully with:

Aluminum Alloys Anodized Al Steel Titanium	Glass Kapton Multi-Layer Insulation Composites



Cambrian Works' Electroadhesive Pad

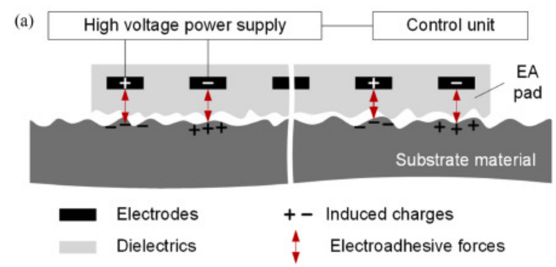
ELECTRODHESION OPERATING PRINCIPLE

Conducting Substrates

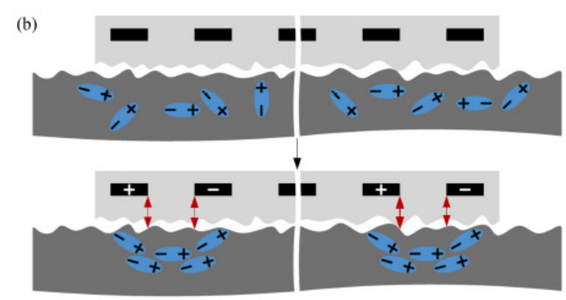
eTAP field mirrors charges in a substrate opposing the fields imposed on the substrate surface.
(Image courtesy Guo, et al. 2020)

Dielectric Substrates

eTAP field affects the polarization of molecules within the opposing surface.
(Image courtesy Guo, et al. 2020)



Electroadhesion with Conducting Substrate



Electroadhesion with Dielectric Substrate

Electroadhesion discovered ca. 1920 by Danish scientists researching how to make a better telegraph

ELECTROADHESION ANATOMY

High Voltage Supply

1500V or higher

Electrodes

High-voltage electrodes generate the electric fields

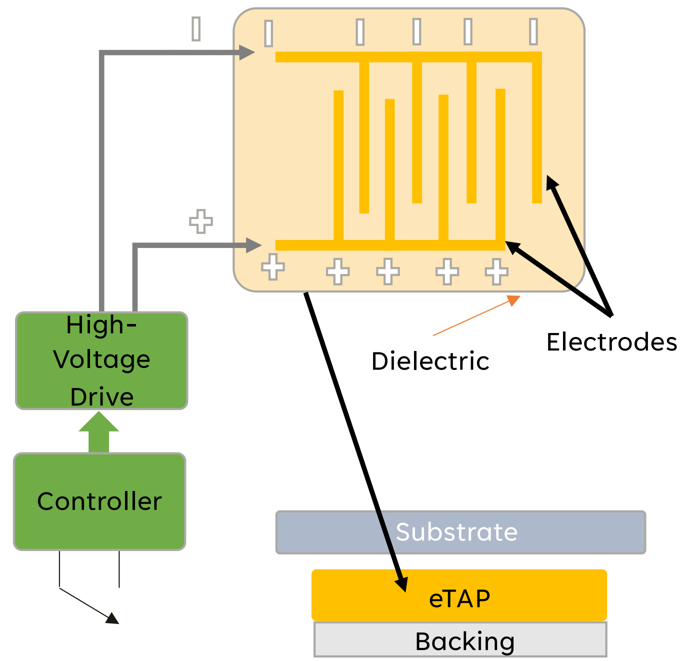
Dielectric

Electrodes encapsulated within a dielectric for safe handling

Very thin package possible (<0.2mm)

Substrate

Target surface for attachment



Electroadhesive force depends on ~20 parameters associated with the electroadhesive pad & driver alone

ELECTROADHESION FEATURES

Features	Description
Comprehensive	Attaches to conductors, dielectrics, and insulators
Generic	Requires no cooperation or special preparation from attached object
Flexible	Conforms to non-planar, rough, or protruding surfaces
Benign	No EMI/EMC effects and no residue left on attached object
High-performance	Generated forces strong compared to typical microgravity forces
Space-optimized	Operates better in vacuum than in air
Scalable	Size and generated forces can be scaled up or down
Reusable	Can be commanded ON and OFF repeatedly
Space-compatible	Is designed with space-rated materials
Low SWaP	Compact and uses milliWatts of power
Storable	Long shelf-life, minimal degradation over time
Operational relevance	Rapid mission flexibility and retargeting based on real-time needs

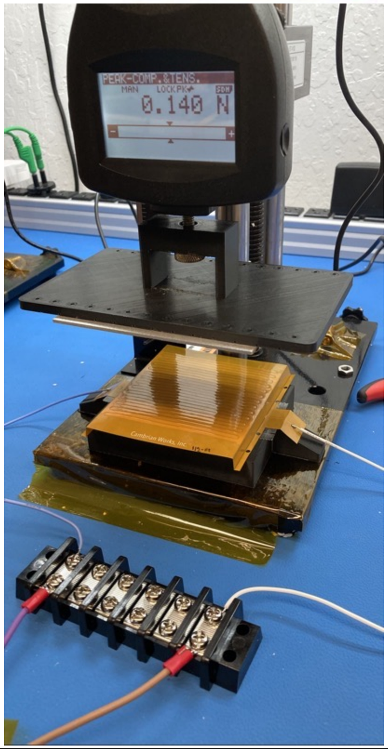
Compares favorably to other in-space attachment technologies:

- Mechanical grippers
- Electromagnets
- Laser ablation
- Adhesives
- Gecko-like adhesives

Unique set of features make it suitable for wide range of missions

PERFORMANCE CHARACTERIZATION

- Cambrian Works has conducted significant performance testing on our Electrical Thin Attachment Pad (eTAP™):
  - Normal force testing
  - Force testing in vacuum
  - Force testing against multiple substrate materials
  - 1D & 2D off-angle dynamic testing
- Upcoming testing:
  - Shear force testing
  - 2D dynamic air bearing testing

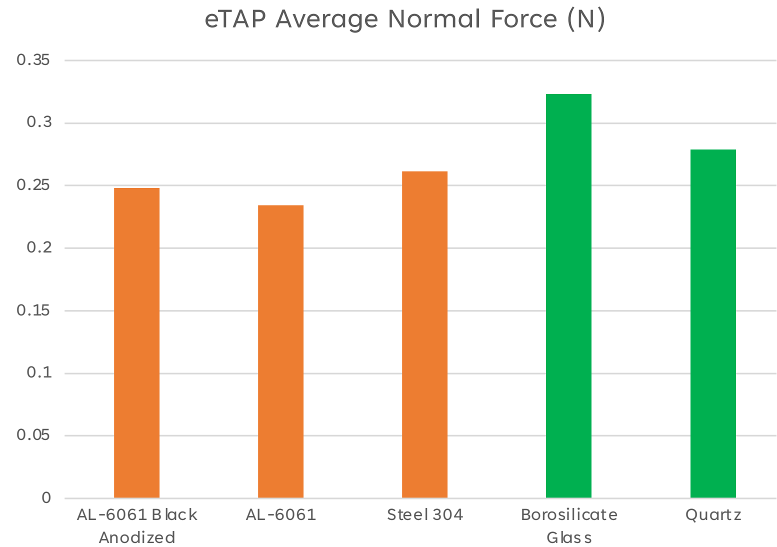


Normal Force Testing Setup

Designed from the ground up for on-orbit use—validated and tested for in-space performance

STATIC TESTING RESULTS

- Normal attractive forces are ~15 mN/cm^2 at ambient pressure
  - Normal force scales linearly with the attached area
  - Insulator substrates have slightly higher normal attachment force than conductors
- Thin non-conductive coatings on conductive material do not affect attachment force
- Mechanical design and mounting of the pads has a significant impact on the maximum attachment performance
- Normal force attachment is significantly higher in vacuum than at ambient pressure
  - Ranges from 2x to 6x higher, depending on material

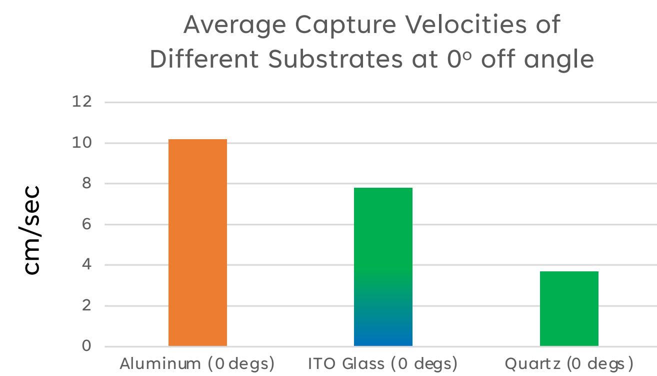


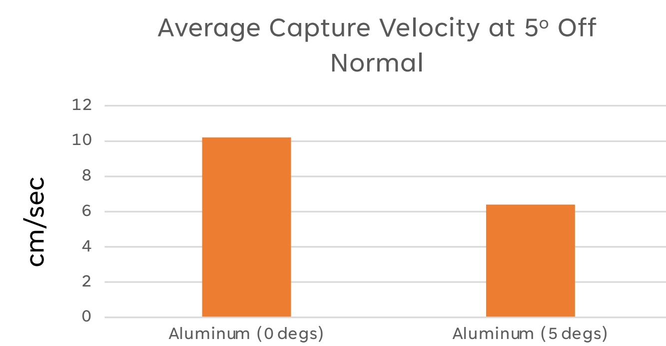
Measured Normal Force of 16 cm2 eTAP Pads at Ambient Pressure

Significantly improved performance in vacuum makes this an ideal technology for in-space use

LINEAR VELOCITY CAPTURE RESULTS

- Conductive substrates have a slightly faster electrical response time (0.02 s) compared to dielectric materials
  - Thus eTAP is able to capture conductive objects with a higher velocity
- Dielectric substrates coated with a resistive layer (e.g. Indium-Tin Oxide, as on solar cells) behave more like conductive materials
  - This allows capture at higher velocities than without a resistive layer
- eTAP conformability enables off-normal contact angle capture
  - However, as off-normal contact angles are increased, maximum capture velocity decreases





Off-angle & maximum capture velocity heavily dependent on eTAP packaging and mounting

UPCOMING DYNAMIC TESTING

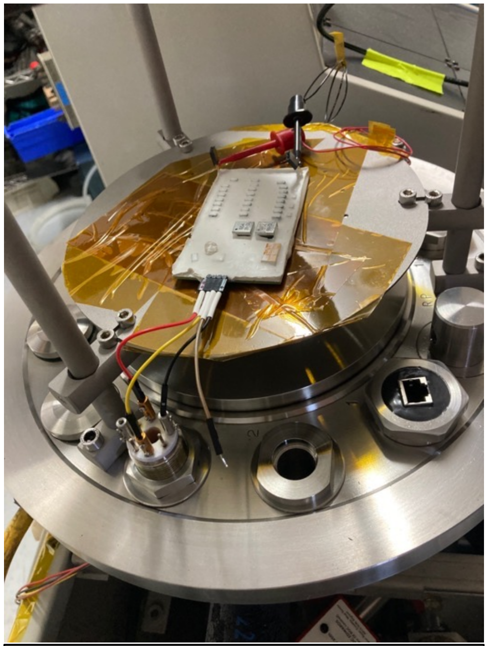
- Collaboration with Astroscale & AFRL ROC lab will allow us to see how eTAP performs in realistic conditions (July 2024)
  - Force that eTAP can exert on a spinning object
  - 2D dynamic approaches at multiple angles & velocities between eTAP and a simulated satellite

European Space Agency Orbital Robotics Lab (representative of dynamics testing setup)

Simulations & linear track testing are useful, but there's nothing like real dynamic testing to understand how eTAP will perform during on-orbit operations

SPACE QUALIFICATION PROGRESS

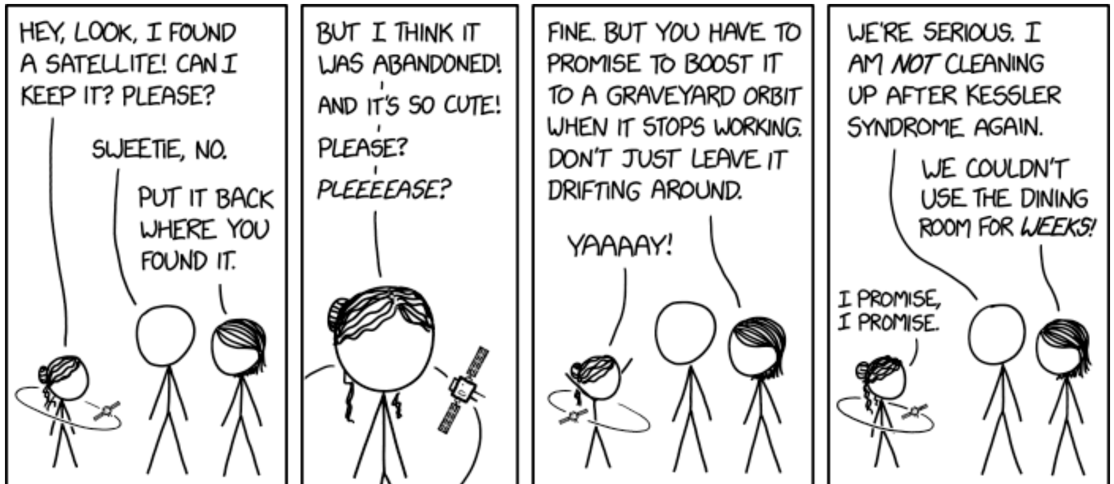
- eTAP has been designed from ground-up for space suitability
- eTAP driver circuit and pads have successfully undergone vacuum testing
- Upcoming testing will confirm eTAP suitability for space via:
  - Thermal testing
  - Vibe testing
  - EMI/EMC testing



High-Voltage Driver Circuit in Vacuum Test Chamber

Materials & circuit design choices based on components and principles with long on-orbit heritage

ADDRESSING ORBITAL DEBRIS



Credit: xkcd.com (https://xkcd.com/license.html)

- eTAP technology well suited for active debris remediation:
  - Attachment without need for prepared surfaces or attachment points
  - Wide variety of attachment surfaces
  - Reusability

ORBITAL DEBRIS MITIGATION

- Cambrian Works' Space Payload for Inertial Despin Efficient Effects
- eTAP-enabled CubeSat can be deployed from a larger mothership to attach to debris, with options to:
  1) Apply drag via electroadhesion to slow down debris rotation
  2) Actively de-spin via use of magnetorquers, active thrusters, atmospheric drag sail, or electrodynamic tethers
  3) Attach docking plate to serve as a later attachment point for another craft
  4) Attach a tag to mark debris
  5) Attach IMU to determine and broadcast the object rotation rates for other debris retrieval servicers

6U SPIDEE™ Mockup

SPIDEE™ CONCEPT OF OPERATIONS

ChatGPT-Generated Image of SPIDEE™ Mission

SPIDEE™ is deployable and recoverable from a larger servicing mission, providing re-use potential

ELECTROADHESION-ENABLED WORKSPACES & DEPLOYMENT

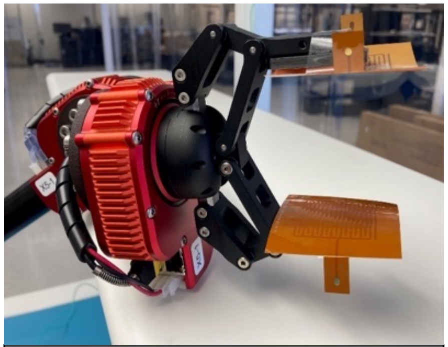
- Tool and component management (eTAP Wall™)
- Workspace augmentation (camera mounts, anchor points, etc.)
- Controlled deployment/detachment of subsystems

eTAP Wall™

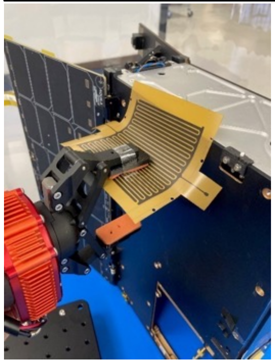
Credit: xkcd.com (https://xkcd.com/license.html)

ELECTROADHESION-ENABLED IN-SPACE ASSEMBLY MISSIONS

- Telerobotic and Servicing Assistance
  - Attractive “touch” – pull objects in, and absorb incoming momentum
  - Augment existing mechanical graspers for in-space assembly
- In-Space Assembly Line
  - Easily controllable “stickiness”
  - In-orbit assembly debris capture
  - Double-sided “Oreo filling” between items
  - Easily enables modular assembly approach



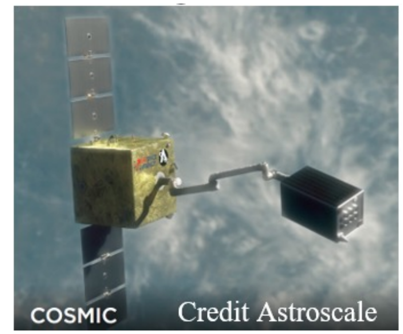
eTAP-Augmented Robotic Hand

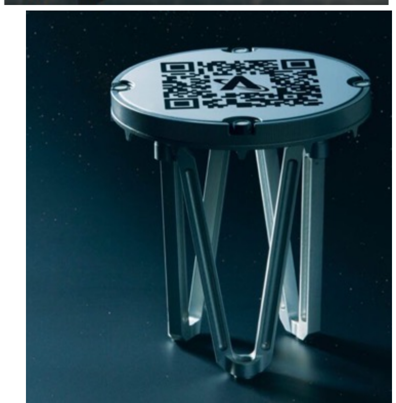


"Goldilocks” technology: not too strong, not too weak
Tunable for specific mission parameters

DOCKING AND REFUELING MISSIONS

- Unprepared/non-responsive docking
  - Soft docking/berthing
  - Repeatable release and re-dock
- Low profile & extremely versatile topography
  - eTAP technology allows for arbitrarily shaped passthroughs, allowing wiring, cameras, refueling ports, etc.
- Compatible with other types of mechanisms for redundancy
  - Magnetics, mechanical grapplers



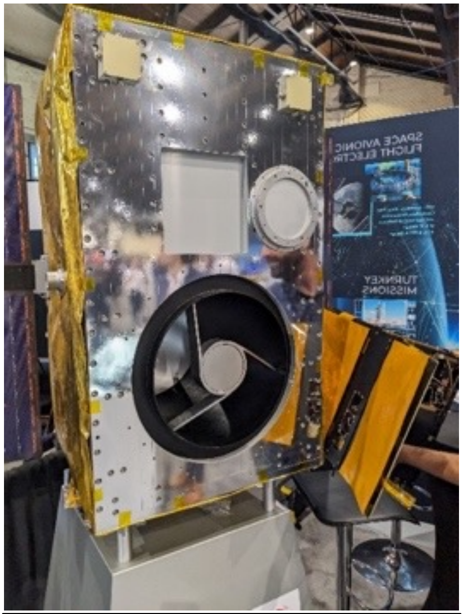

Astroscale Docking Plate

eTAP suitable for stand-alone docking or augmenting existing docking solutions

MODULAR PAYLOADS

- Attach a fully functional modular payload to existing satellites
  - eTAP compatible with power, data, and heat transfer
  - CubeSat payload deliverable via mothership, e.g. Space Logistics' Mission Robotic Vehicle
  - Add capability: space domain awareness, computational payloads, imaging payloads
  - Add comms and/or other services: comms terminal, PNT payload, propulsion module

- Someday...
  - Satellites designed for upgradeability will enable evolving missions
  - Intra-satellite wireless comms and modular power supplies will allow for deep integration of new capabilities

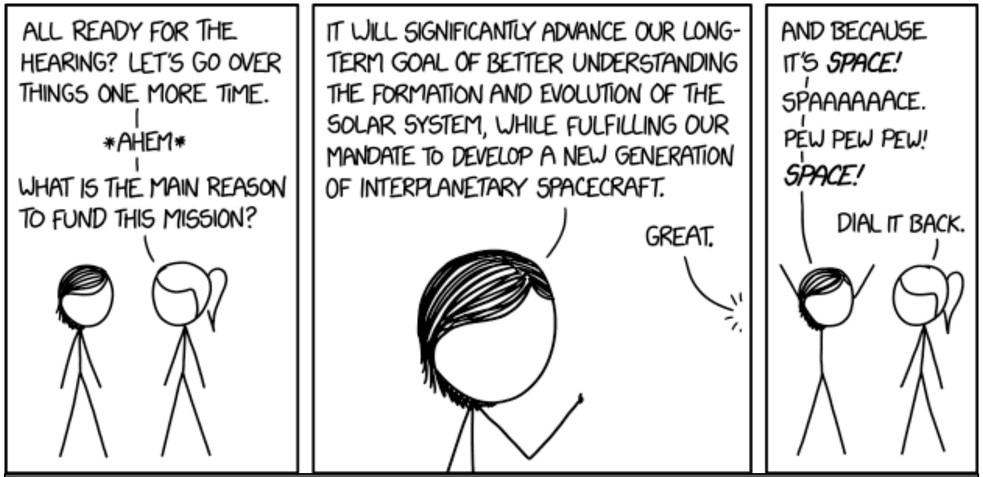


eTAP-Enabled CubeSat "Docking" with Larger Spacecraft

eTAP's ability to dock with non-prepared surfaces makes it possible to add payloads to virtually any satellite

ELECTROADHESION-ENABLED MISSION DESIGN PRINCIPLES

- Understand mission parameters:
  - Likely attachment surface(s)
  - Required shear and/or normal forces
  - Approach angles, speeds, and relative masses
- Tune for desired attractive force:
  - Attracts to all surfaces, but difference in quality
  - Scales with attached area and voltage applied
  - Best to design for a minimum required force
- Design mission CONOPs to play to electroadhesion strengths:
  - Shear force many times stronger than normal
  - Flexibility & pad conformance useful to minimize elastic collisions



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Electroadhesion's unique set of qualities, low SWaP, and ease of use make it perfect for your next CubeSat mission!

QUESTIONS?

Cambrian Works is actively seeking partners to develop eTAP Missions—come talk to us!

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