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Demonstrating New Attachment Technology for On-Orbit Docking

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ABSTRACT

Cambrian Works has developed eTAP (electric, Thin Attachment Pad) based on the principle of Electroadhesion (EA) as a general attachment technology particularly suitable for the space environment. eTAP addresses multiple in-space applications such as docking, in-space assembly, transportation, refueling, and orbital debris removal. These objectives have received significant attention in recent years, with many new space companies and business models receiving large government contracts and private funding. In this paper, Cambrian Works demonstrates the feasibility of eTAP to support these various missions by 1) examining the quantitative attachment force levels achievable with common aerospace materials under laboratory conditions, and 2) demonstrating a docking and capture scenario using a linear axis air track (1D) and a two-axis air bearing table (2D) to simulate in-space approach and attachment to a target object under representative dynamic conditions.

MOTIVATIONS FOR GENERAL ATTACHMENT

The space industry is at an inflection point, as it transitions from isolated satellite systems to a more interconnected set of on-orbit systems and capabilities. New technology, applications, and practices in the areas of satellite servicing, space tugs, and removal of defunct satellite objects in desirable orbital paths are required for the development of a robust, interacting space systems environment. New space business models addressing these applications must all address the problem of in-space attachment. A major challenge for companies is developing attachment methods for satellites and orbiting debris that were never designed to be touched once on orbit. Satellites in general are not designed with mechanical docking capabilities and can be covered with multi-layer insulation blankets (MLI) and/or solar cells which further impede attachment. 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. Beyond the initial docking/attachment, the satellite servicer also requires a general workspace and surface on which to place tools and materials during the servicing process. eTAP, based on EA, neatly addresses all these needs, and overcomes many of the limitations of other attachment technologies. eTAP attaches to commonly used aerospace materials (including conductors, insulators, and dielectrics), has low power consumption on the order of milliwatts, attachment does not require a previously prepared attachment point, can be turned off and on like a switch, and can flexibly conform to non-uniform surfaces, allowing a general attachment mechanism for various phases of an in-space servicing mission.

ETAP STATIC ATTACHMENT FORCE

On-Orbit Workspace and Docking Application

eTAP surfaces may be used as a general mechanism for on-orbit workspace management, allowing tools and parts needed for assembly or disassembly to be temporarily held in position in the work area for ready access.

As a means for making initial contact and/or docking with a target object, we must understand the achievable adhesion force levels that eTAP can apply to an object. We measure the adhesion force normal to the pad surface as representative of the common attachment scenario where eTAP attaches to large orbiting bodies that have surface areas significantly larger than the eTAP's attachment surface or where objects are placed onto an eTAP work surface. In either of these cases, attach and detach forces are normal to the surface rather than in shear. This in-space scenario is different than current (terrestrial) use of EA in robotic applications where it is common to grasp small objects, as is shown in Figure 1, resulting in more reliance on shear attachment forces. The likely targets for eTAP are large orbiting bodies that have surface areas significantly larger than the eTAP's area, thus making normal forces more operationally useful and limiting the use of shear forces. Achievable EA force levels are greater in shear than in normal configurations, making the characterization of EA force levels at 90º (normal) to the pad surface critical for understanding this technology's application to in-space use[1].

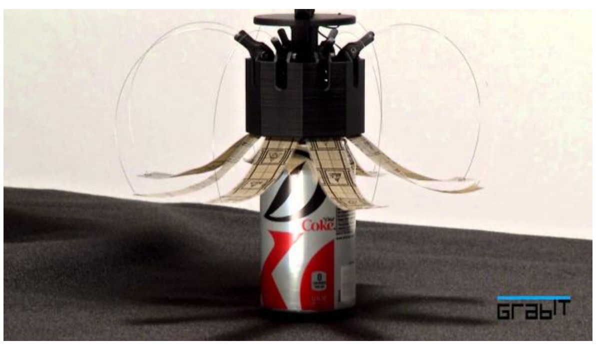

Figure 1: Current terrestrial use of EA technology targets small objects which is different than the large debris in space. (Credit: GrabIT)

eTAP Design and Configuration

The eTAP shown in Figure 2 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. The larger pad (80x80mm) is shown in Figure 2.

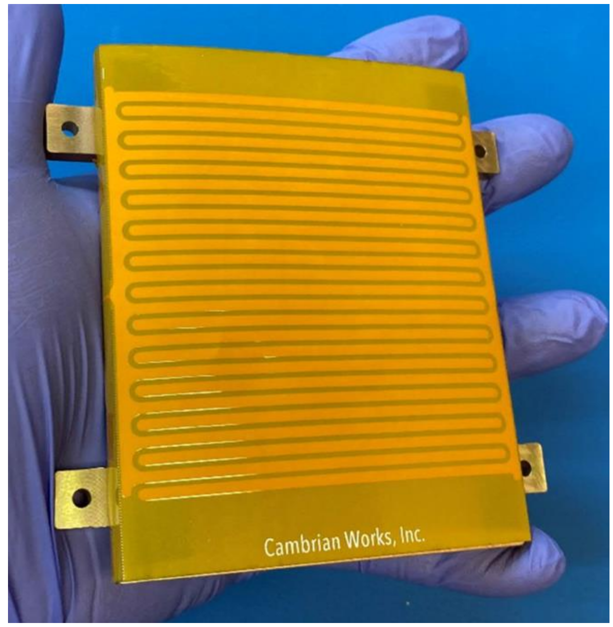

Figure 2: A thin eTAP with an 80x80mm active surface area made from space-rated materials.

The block diagram in Figure 3 illustrates the internal workings of the pad. eTAP consists of two sets of inter-digitated electrodes. Gap spacing between electrodes is critical to balance higher achievable force levels against discharge (arcing) or corona events. The high-voltage driver circuit provides the 1500V or greater required to generate an electric field that will interact with the target object (referred to here as *substrate*). The electrodes are encapsulated in a suitable insulator to prevent discharges and allow for safe handling even when energized.

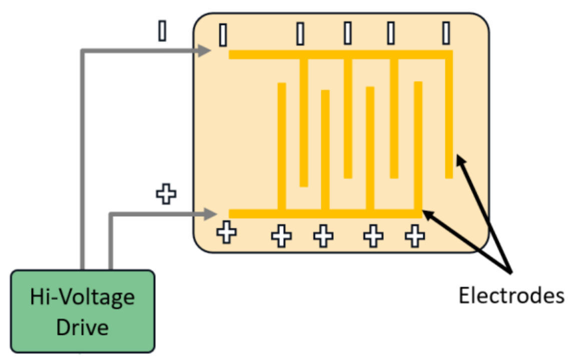

Figure 3: eTAP functional diagram

Substrate Types

Materials suitable for eTAP attachment include common space materials such as aluminum, solar cell cover glass, titanium, mylar, steel, etc… Here Cambrian Works shows test results with aluminum, glass, and quartz to confirm eTAP performance on conductive and insulative materials. Typical space coatings were also tested to better simulate materials found in space and confirm that the coatings do not degrade eTAP performance. Cover glass with an indium-tin oxide (ITO) coating was chosen to test as a proxy for solar cell panels.

Table 1: Commonly used aerospace materials tested with eTAP

Substrate Material	Use of substrate materials in space
Aluminum 6061	A common structural material that makes up most satellites because of its excellent strength-to-weight ratio.
Aluminum 6061 Black Anodized	Aluminum can be processed with a protective layer to prevent corrosion (typically 0.12). This outer layer is non-conductive.
Glass with ITO Coating	An Indium Tin-Oxide coating is applied to the surface of solar cells cover glass as a resistive layer to mitigate charge build-up.
Quartz	While not a common space material, quartz was selected as a representative insulator material.

Overall Test Configuration

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 Figure 4. The Figure 5 block diagram illustrates the key components of the test stand and its operations. 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. After allowing several seconds for the eTAP and substrate to adhere, the test stand is activated to pull the substrate upwards to detach it from the pad.

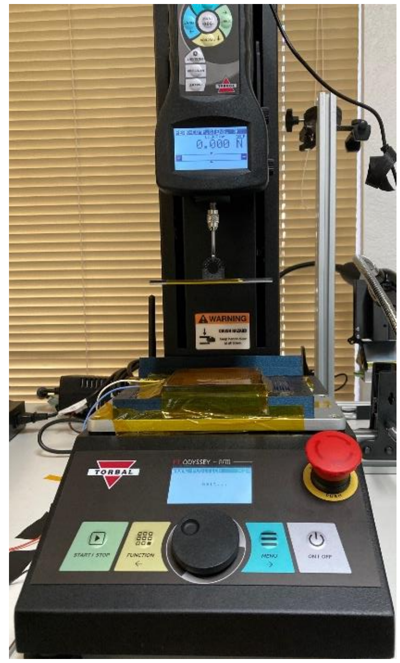

Figure 4: Automated normal force test stand

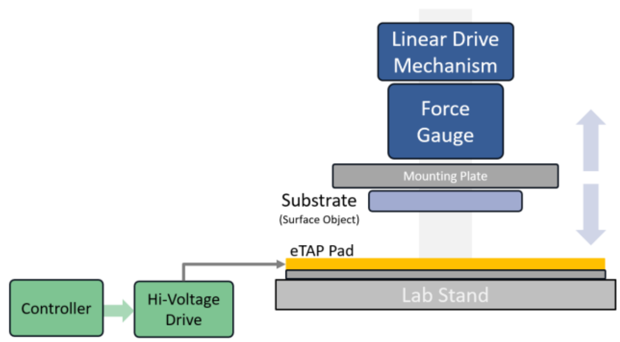

Figure 5: Normal force test stand block diagram

Detachment Force Required to Separate eTAP from Different Substrate Materials

With these test configurations we were able to measure eTAP attachment forces on these various substrates (see Figure 6). 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.

First, eTAP attaches well to several substrates representative of common space materials, and with sufficient force to support a variety of applications. While adhesive force in the normal direction varies with different substrate materials, a 40x40mm pad produces approximately 0.25N of force, which translates to about 15.6 mN/cm^2. This is significant when considering that 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[2]. Therefore, it is possible for objects attached to a small 40x40mm eTAP to remain attached while a satellite is under constant thrust from its propulsion system. More broadly speaking, these force levels are of sufficient magnitude to exceed the force levels needed for several types of in-space applications.

Second, insulators in general have a higher achievable attachment force than conductive materials; this difference is on the order of 15-20%.

Third, commonly used coatings such as anodization and ITO on glass do not hinder performance.

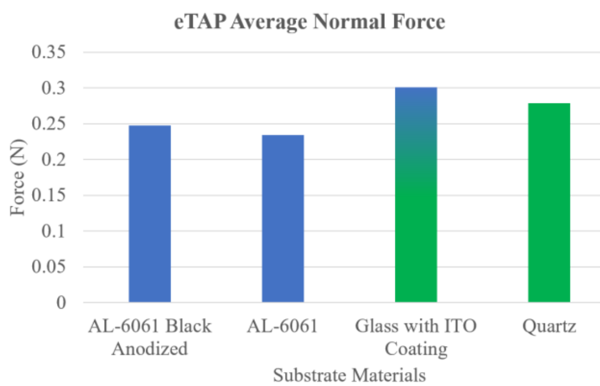

Figure 6: Achievable adhesive force for 40x40mm eTAP, with respect to several representative space materials

Attachment Forces Scale Linearly with eTAP Size

To determine eTAP active area effect on adhesive force levels, we doubled the eTAP edge dimensions to 80x80mm. This larger eTAP was tested with two representative substrates: Aluminum 6061 and Glass with ITO coating. As shown in Figure 7, the average forces achieved were 1.14N and 1.30N respectively. This increase in force indicated that a 4x increase in active area yielded a 4.8x force increase for aluminum and 4.3x for glass. The force increase was in line with our expectations of a direct linear relationship of 1:1 between active area and achievable force. The data shown in Figure 7 show a slightly better than 1:1 area-to-force increase. We attribute the slight discrepancy to measurement uncertainty and the difference in fringe effect between pad sizes as a percentage of the total area.

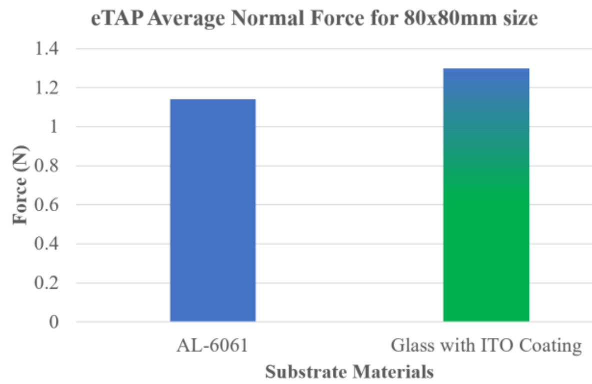

Figure 7: An 80x80mm eTAP achieves >1N of normal force.

ETAP DYNAMIC ATTACHMENT DEMO

In-space Capture Application

The above results show normal adhesive forces achievable in a static configuration. However, approach velocities and angles are also an important part of any in-space dynamic situation, such as an approach to dock. To demonstrate eTAP performance in this type of dynamic configuration, we explored the dynamic arrival, capture, and arrest phase of a docking maneuver, i.e., when a satellite is heading with a known velocity to a target object. In this scenario, we want to understand the importance of approach velocity and angle on eTAP attachment. To simulate realistic in-space servicing dynamics, Cambrian Works outfitted a 1D Air Track for testing of eTAP attachment with a moving satellite mass simulator. This 1D Air Track allows repeatable testing of different target substrates, relative velocities, and relative off-normal offset angles.

Configuration for 1D Track

Figures 8 and 9 show the 1D Air Track and a block diagram of its components.

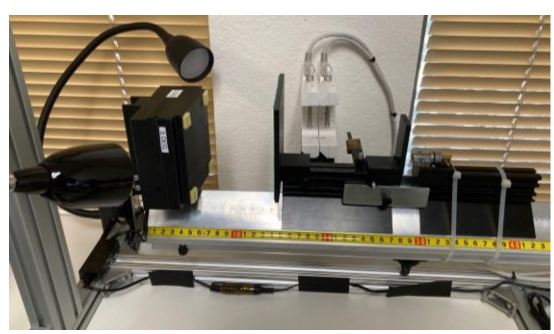

Figure 8: 1D Air Track for repeatable velocity capture testing

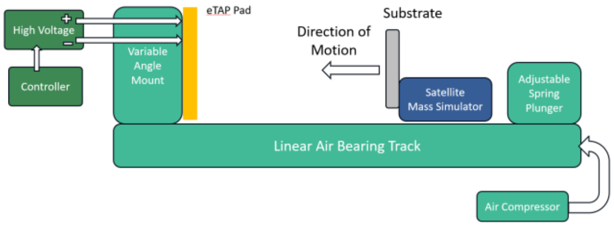

Figure 9: 1D Air Track block diagram

Satellite Mass Simulator: The maximum payload mass that the linear air track can handle is approximately 0.2kg. The substrate is mounted on the satellite mass simulator and is interchangeable to allow for testing with multiple simulated satellite materials. The adjustable spring plunger described below imparts velocity to the mass simulator, which moves on the low-friction track to collide with the eTAP.

Linear Air Track: The linear, or 1D, Air Track is a machined piece of aluminum with pre-drilled holes that allow for uniform airflow from the air compressor that is attached to the end of this track. The uniform airflow creates a low-friction track representative of the floating, frictionless, micro-gravity environment.

Adjustable Spring Plunger: This mechanism uses a spring plunger mechanism to impart a controlled velocity to the mass simulator. The plunger force is adjustable to vary the velocity imparted to the mass simulator.

Variable Angle Mount: This provides the static mounting point for the eTAP. The angle of the mount is selectable to allow testing of satellite approach at off-normal angles. 0^o is the reference position where the eTAP pad is parallel to the approaching substrate, and thus yields the maximum normal force attachment.

Test Results at Normal (0^o Approach Angle)

The 80x80mm eTAP was tested on the linear Air Track with various substrates and approach velocities. Tested velocities began at 2cm/s and were gradually increased until the eTAP was no longer able to capture the approaching 200g satellite mass simulator. Previous experience with eTAP had shown there is a difference between conductive and insulative materials in terms of time required for maximum adhesion. Thus, this test focused on comparing aluminum, quartz, and ITO-coated glass in order to characterize any difference in maximum capture velocity between conductive, conductive/insulative hybrid, and insulative materials.

Figure 10 shows the maximum velocities at which the eTAP was able to successfully capture the satellite mass simulator outfitted with each of the three substrates. While the eTAP was able to arrest and capture all three substrates in this dynamic configuration, there is a clear difference in maximum capture velocity between the different materials. We find that materials with greater conductive materials can be captured at higher velocities. This is an interesting result as the static normal force tests described above show that insulative materials had ***higher*** adhesion. Cambrian Works hypothesizes that increased charge mobility in conductive materials allow for faster generation of electroadhesive force. Figure 11 (with eTAP offset at a 5^o angle) shows the eTAP pad being attracted to the substrate within 0.02s after initial contact.

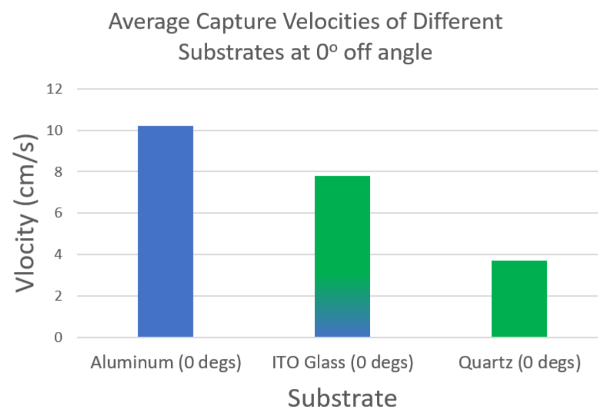

Figure 10: Maximum capture velocities for different substrates

Figure 11: Attachment occurs faster for conductive materials.

Test Results at 5^o Off-Normal Approach Angle

After testing at normal approach angles, the variable angle mount was set to provide a 5^o off-normal angle for simulating off-normal satellite approaches. As expected, the off-normal angle resulted in less attractive force, and thus a decrease in the maximum achievable capture velocity. Figure 12 shows the difference in achievable capture velocity for aluminum at 0º and 5º offset angles. Figure 12 shows a decrease in achievable capture velocity from 10cm/s (0º) to 6cm/s (5º). Figure 13 shows an image of the 5º offset angle configuration, where it can be seen that, since the eTAP is constrained from moving, the offset angle prevents the full eTAP from contacting the substrate. Approximately 50-60% of the eTAP can contact the substrate in this configuration, which aligns well with the observation from Figure 12 that the capture velocity has decreased by approximately 40%.

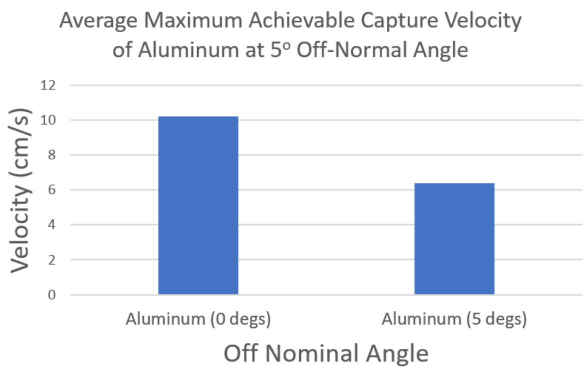

Figure 12: Angling the satellite mass simulator with respect to the eTAP shows maximum achievable capture velocity is reduced as eTAP contact area with substrate is constrained.

Figure 13: eTAP contact area with satellite mass simulator reduced to approximately 60% at 5º offset angle.

This test setup constraint is not representative of an actual in-space attachment maneuver that would not constrain the eTAP from rotating to make better contact with the substrate. Thus, these measurements can be considered a worst-case, or conservative, attachment scenario.

2D Air Bearing Table

The 1D Air Track limited the degrees of freedom to a single dimension. We were able to demonstrate that eTAP can capture an object in a dynamic impulsive event representative of a satellite docking maneuver. However, the 1D Air Track overly constrained the eTAP rotation, thus limiting eTAP attachment likelihood by limiting the dynamics. To get around this testing limitation, we configured a 2D Air Bearing table, which allows more rotational freedom for an incoming object.

2D Air Bearing Table Configuration

The 2D Air Bearing table shown in Figure 14 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 Cambrian Works' designed 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 can calculate the velocity of the disk and substrate.

Figure 14: 2D Air Bearing table configuration

Test Results from the 2D Air Bearing Table

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 towards a targeted object. The initial results, using a 140g moving object, show the rotational dynamics on the 2D Air Bearing table. Specifically, if there is an angular deviation from a normal angle of approach, the resulting initial contact causes the approaching object to start rotating, i.e., some of the incoming energy is converted to angular rotation.

As expected, the 2D Air Bearing table testing showed better attachement at off-normal angles, given the increased rotational freedom of the moving object. Figure 15 shows a time sequence of capture at an off-normal angle of approximately 3º. At T+0.00sec, the disk and substrate have just made contact with the eTAP. The adhesive force of the eTAP causes the incoming substrate to rotate and make better contact with the eTAP. There is a rocking motion that can be observed at T+0.03 and T+0.06 secs that ultimately settles with the substrate and eTAP in full contact.

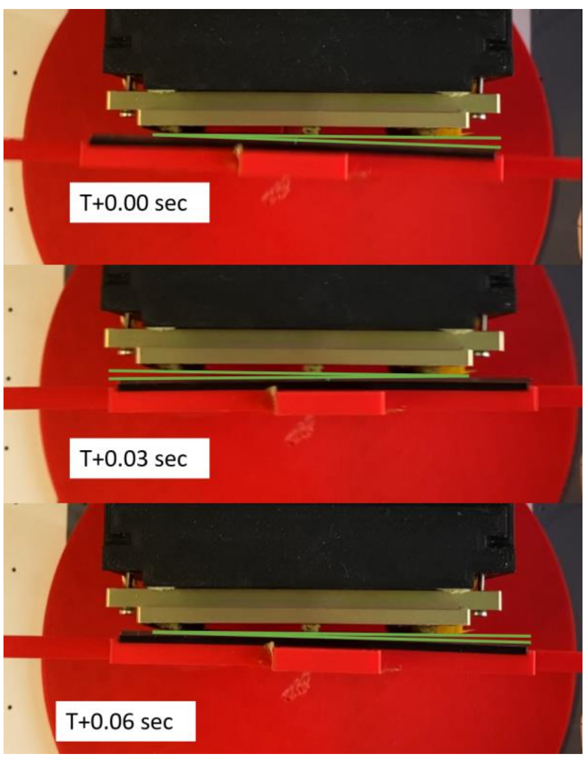

Figure 15: The 2D Air Bearing table allows the eTAP to make full contact with an approaching off-normal substrate. The green lines show the angular rocking as the substrate settles onto the pad due to its attraction.

CONCLUSION

The eTAP technology developed by Cambrian Works shows significant promise as a generalized in-space attachment technology. 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. In addition, eTAP has two control variables or “knobs” that allow the force being generated to be adjusted or selected to support missions – the force varies with both area and applied voltage, allowing greater flexibility in control of attachment than with alternative technologies. Finally, because eTAP is non-damaging, capable of switching on and off adhesion, and leaves no residue, it provides a highly desirable alternative to many alternatives that rely on glues or inter-locking mechanisms or prepared surfaces.

Cambrian Works is partnering with several companies to provide eTAP as a solution for application in the areas of orbital debris removal, in-space servicing, and in-space workspace management. The eTAP results reported in this paper demonstrate force levels higher than those needed for these types of applications, as well as showing how even larger forces can be achieved by scaling up the eTAP active area. In addition, dynamic testing conducted thus far shows eTAP’s ability to perform in dynamic scenarios representative of those needed for the complex in-space servicing missions envision for the near future. 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.

ACKNOWLEDGMENTS

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