

INNOVATIVE ELECTROSTATIC ADHESION TECHNOLOGIES

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Synopsis:

Developing specialized Electro-Static grippers (commercially used in Semiconductor Manufacturing and in package handling) will allow gentle and secure Capture, Soft Docking, and Handling of a wide variety of materials and shapes (such as upper-stages, satellites, arrays, and possibly asteroids) without requiring physical features or cavities for a pincher or probe or using harpoons or nets. Combined with new rigid boom mechanisms or small agile chaser vehicles, flexible, high speed Electro-Static Grippers can enable compliant capture of spinning objects starting from a safe stand-off distance. Electroadhesion (EA) can enable lightweight, ultra-low-power, compliant attachment in space by using an electrostatic force to adhere similar and dissimilar surfaces. A typical EA enabled device is composed of compliant space-rated materials, such as copper-clad polyimide encapsulated by polymers. Attachment is induced by strong electrostatic forces between any substrate material, such as an exterior satellite panel and a compliant EA gripper pad surface.

When alternate positive and negative charges are induced in adjacent planar electrodes in an EA surface, the electric fields set up opposite charges on the substrate and cause an electrostatic adhesion between the electrodes and the induced charges on the substrate. Since the electrodes and the polymer are compliant and can conform to uneven or rough surfaces, the electrodes can remain intimately close to the entire surface, enabling high clamping pressures.

Clamping pressures of more than 3 N/cm² in shear can be achieved on a variety of substrates with ultra-low holding power consumption (measured values are less than 20 microW/Newton weight held). A single EA surface geometry can be used to clamp both dielectric and conductive substrates, with slightly different physical mechanisms.

Furthermore EA clamping requires no normal force be placed on the substrate, as conventional docking requires. Internally funded research and development has demonstrated that EA can function effectively in space, even in the presence of strong ultraviolet radiation, atomic oxygen, and free electrons. We created a test setup in an existing vacuum chamber to simulate low-Earth-orbit conditions. An EA mechanism was fabricated and installed in the chamber, instrumented, operated in a vacuum, and subjected to ultraviolet photons and free electrons generated by an in-chamber multipactor electron emitter.

Extensions to EA that can add value include proximity and contact sensing and transverse motion or rotation, both of which could enhance docking or assembly applications. Possible next steps include development of targeted applications for ground investigation or on-orbit subsystem performance demonstrations using low cost access to space such as CubeSats.

Background:

Since the beginning of the space program, a safe way of capturing and handling an object in space by another controlled vehicle has a subject of many studies and projects for many different missions. The earliest mission scenarios focused on disabled satellites tumbling in orbit to be picked up by a crewed capsule with some type of mechanism deployed out in front and roughly positioned by flying into close proximity and then “springing the snare”. Over the last 50-60 years, the “snare” has had many different configurations and capture methodologies including harpoons and spears thrust into a cavity or through part of the object, nets and bolos cast around the object, giant multi-digit grippers or bags to envelope and grasp the object, or even use wet adhesive strips or “globs” to wrap around or stick to the object. Many of these methodologies are derived from various methods for material handling employed used throughout the world by Mother Nature’s plants, animals, and mankind.

As NASA and Russia focused on get to the Moon and returning the crew safely, the need for a reliable docking method became a key requirement and the method selected was a probe on the front of the capsule flown into a cone for capture, requiring relative motion between the two vehicles to mechanically actuate the very reliable latches in the in-coming docking mechanism. This probe insertion method is still the baseline for the Russian docking port on International Space Station (ISS) and the new NASA Docking System has changed the “spear” into three conical segments with mechanical latches that are engaged by linear actuators performing a “lunge” maneuver to minimize the physical impact between the two vehicles during docking.

The Space Shuttle was conceived as a vehicle to retrieve as well as deploy satellites from the beginning and demonstrated this capability on its' second flight by reaching into the cargo bay to remove a small spacecraft and after moving it to various locations around the Shuttle re-stowed the spacecraft into its' cradle using the crew-operated Remote Manipulator System (RMS) using its' Grapple system that grabs the probe on the spacecraft or payload using the capture cavity with snare cables in the RMS end effector. Other spacecraft have been captured during Shuttle EVAs with various mechanical latches around protrusions, probes into rocket nozzles, or even three astronauts grabbing parts of a large satellite. The author knows of only one experimental spacecraft retrieval using a Magnetic End Effector (MEE) held by the RMS to attract and hold a soft iron plate on the spacecraft, impractical for many missions.

The re-supply of Space Stations is another orbital operational challenge solved first by the Russians whose unmanned Progress resupply vehicles have flown to and docked to three generations of Space Stations and both the MIR and the Russian side of ISS were assembled by the modules that flew up to and were docked for assembly. On the other end of ISS, the modules brought up by the Shuttle and the current resupply vehicles are grappled by the RMS and attached or berthed to ISS.

Currently no planned spacecraft capture or handling operations are planned using any methods other than mechanical docking or grappling or probes. If only we could build something like the **tractor beam** Gene Roddenberry created for his Starship Enterprise before man even went to the moon...

Flexible Electrostatic Tools for Capture and Handling (FETCH)

OK, OK. We don't have an electromagnetic beam that can extend out to another space object at kilometers or hundreds of meters and hold and tow them no matter what their composition. But we do have some new technologies when combined can begin to give us the capability to reach out meters with a lightweight retractable beam with an end-effector that can grip a smooth or more complex surface composed of just about any material or combination of materials and gently pull or push or release at speed of electricity. We will discuss each of these emerging commercial capabilities and their associated components and the combined effects on future space use and exploration. The end-effector for FETCH is a flexible electrostatic or electro-adhesion gripper pad. The retractable beam is an interlocking metallic band mechanism built for extreme commercial environments. And one video sensor can identify and calculate the 3dof poise of teachable outlines at 60 Hz and a simple lidar uses LEDs to provide overlapping angular arrays of 16 range measurements at 60 Hz to see the position and location of the elephant without having to know what it looks like beforehand. Combined, the FETCH system will be challenged to align to, synchronize with, and to capture and handle a spinning reactive orbital object simulator.

Changing the Physics of Space-Craft Docking and Capture

When we change the joining of two spacecraft from a mechanical jousting event into an electronic "reach and touch it" grappling, the physics of the process changes for both vehicles and objects as enumerated below

1. Docking defined as "Chase" Vehicle using their thrusters to move docking mechanism into capture envelope of Station mechanism (Controlled Collision with Impact Absorption) while controlling position and velocity in three translations and three rotations simultaneously with a complex thruster system.
2. Thruster, sensor, CG, GN&C, velocity errors in docking must be minimized or absorbed During Contact Dynamics
3. Docking contact dynamics can excite "water hammer" in chase vehicle and captured vehicle tanks which may require additional baffling if docking from an angle different from launch or after on-orbit re-supply
4. Berthing requires passive vehicle to be moved from station-keeping position into capture latch envelope by mechanism before hard contact
5. Station-keeping is less demanding on mechanisms, Attitude Control Systems, GNC; slower approach allows Control Moment Gyroscopes, simpler abort and Collision Avoidance maneuvers and operations, reduced plume impingement and contamination; Current baseline for Japanese and Commercial Cargo Resupply for ISS
6. Simple single actuator extendable mechanism with passive compliance extends to grapple & retract into capture envelope (for **Dexterous Docking** concepts)
7. Electrostatic adhesion Grippers work with various shapes and materials without special surface preparation for capture (Al, MLI, foam, composites, etc.)
8. Zero velocity Vehicle capture enables Scaling up to "Exploration" sized assembly and down to servicer vehicle to satellite capture, sample capsule return, or other activities
9. ES|EA grippers can be scaled down for cube-sat applications for attaching small vehicles to S/C or orbital objects and then deploying drag augmentation devices to de-orbit and captured vehicle de-orbit

ES\EA Principle of Operation:

Electrostatic attraction or Electroadhesion (EA) can enable lightweight, ultra-low-power, compliant attachment in vacuum by using an electrostatic force to adhere similar and dissimilar surfaces. When alternate positive and negative charges are induced in adjacent planar electrodes in an ES\EA surface, the electric fields set up opposite charges on the substrate and cause an electrostatic adhesion between the electrodes and the induced charges on the substrate. Used for years in the semi-conductor processing industry, ceramic chucks are used daily to grip semi-conductor, glass, and other dielectric substrates cleanly and precisely in ultra-hard vacuum processing. If the ES\EA electrodes are encased in a compliant polymer and can conform to uneven or rough surfaces, the electrodes can remain close to the entire surface, enabling high clamping pressures. As shown in Table 1, these compliant EA surfaces can conform to substrate surface irregularities and achieve adhesion to nearly any substrate material.

Clamping pressures of more than 3 N/cm² in shear (or 70-300 lb. by a 12x12 inch pad) can be achieved on a variety of substrates with ultra-low holding power consumption (measured values are less than 20 microW/Newton weight held). A single EA surface geometry can be used to clamp both dielectric and conductive substrates, with slightly different physical mechanisms. Clamping to virtually any substrate is enabled by different electrostatic attraction mechanisms using the same gripper structure: A) with conductive substrates, clamping is enabled through Coulombic forces (induced direct fields) across an insulator on the gripper, B) with non-conductive substrates, clamping is enabled through dielectric polarization forces. The charge induced between the clamping material and the substrate is generated by a power supply that provides a high voltage potential to the embedded electrodes. Although the ES\EA process typically requires a high voltage (on the order of 1–5 kilovolts), it requires very small amounts of current (on the order of 10–20 nanoamps per Newton of lateral force) due to the dielectric layer between the electrodes. Thus, current-limited, low-profile, low-power DC-DC converters can be used to activate the gripper. The ES\EA grippers are robust in hard vacuum and resistance to ultraviolet photons, atomic oxygen, and even RF fields used for substrate processing.

While have many good characteristics and capabilities in hard vacuum, some problems and challenges arise in the practical use and development of ES\EA grippers to get to space. A) To achieve flexibility and mechanical compliance in the gripper pad and harness, the thin conductors can be damaged by sharp bends without protection from a stiff insulator. B) To work in the humidity of a regular 1 atm. laboratory, the multi-phase high voltage power supplies require more complex gripper electrode layouts that increase the width and stiffness of the gripper pad and its' connecting flat conductor cable harness. C) To perform relevant vacuum chamber testing of the gripper pads used in laboratory, the same pad layouts needs to be used in the vacuum tests. D) Damage to the pad electrodes or the flat conductor cable is more likely to cause arcing, conductor etching, and power supply damage due to the high voltages used. E) Vacuum testing at less than 10⁻⁵ torr is required to prevent corona discharge and arcing or all high voltage conductors and connections must be potted and conformal coated for safe operations at higher partial pressures. F) Proper design of the support structure for ES\EA gripper pads is needed to enable sufficient compliance and flexibility of the gripper pads. G) ES\EA grippers are much weaker pulling perpendicular to the gripping surface than pulling across the gripping surface.

Table 1. Effectiveness of electrostatic adhesion on various materials.

Material	Mode of Manipulation		
	Pull	Shear	Twist
Sheet Metal	Poor	Exceptional	Exceptional
Painted Metals	Poor	Inconclusive	Inconclusive
Photovoltaics	Poor	Inconclusive	Inconclusive
MLI	Poor	Exceptional	Exceptional
Kapton/Mylar	Poor	Effective	Effective
Wood	Poor	Poor	Poor
Paper	Effective	Effective	Effective

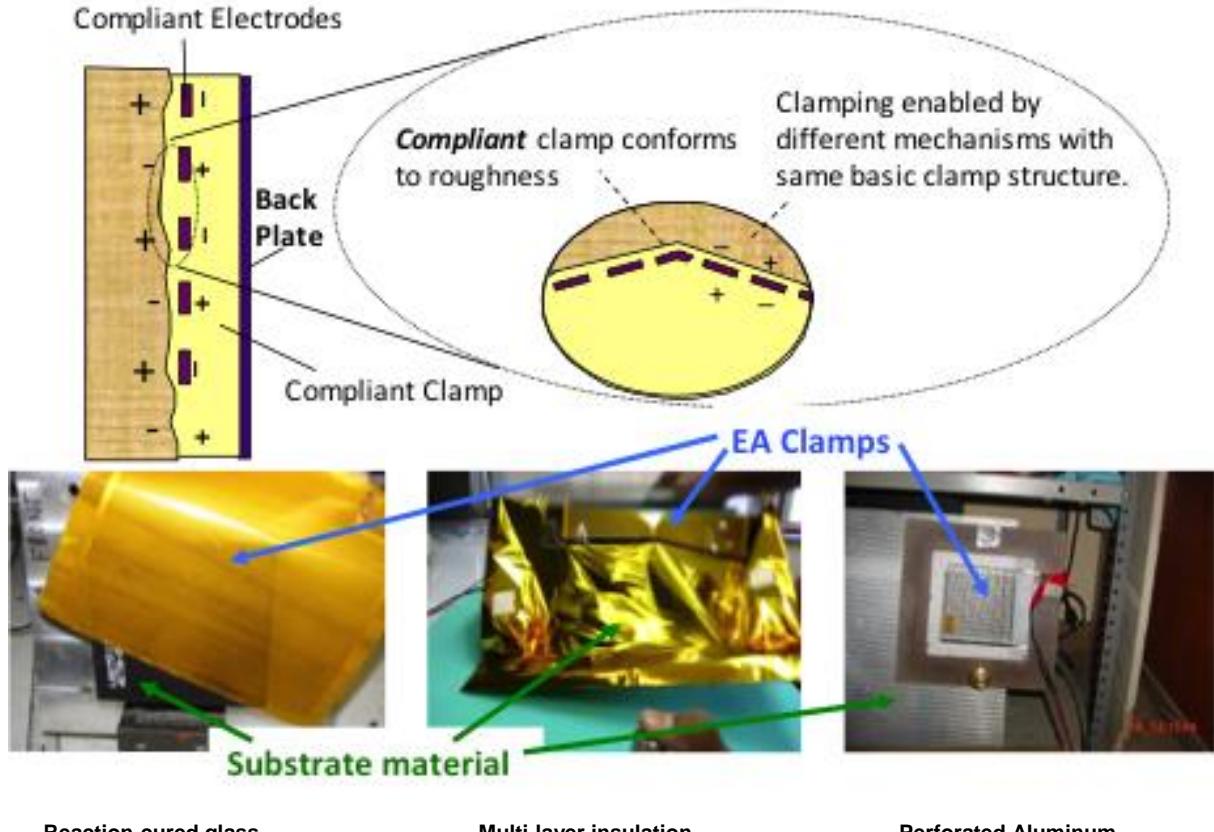


Figure 1. Electrostatic adhesion allows simple gripping to typical spacecraft surface materials

Industrial ES\EA grippers are currently used in various material handling applications, including picking and moving semiconductor and dielectric substrates for vacuum processing tasks, and picking, inspection, and placement of cloth and other flat, flexible materials for assembly tasks by two different companies. We are moving towards replaceable ES\EA gripper pads with custom shapes, sizes, & openings and that can be mounted & operated side by side like butterfly wings to wrap around various shapes for more compliance & higher grip forces.

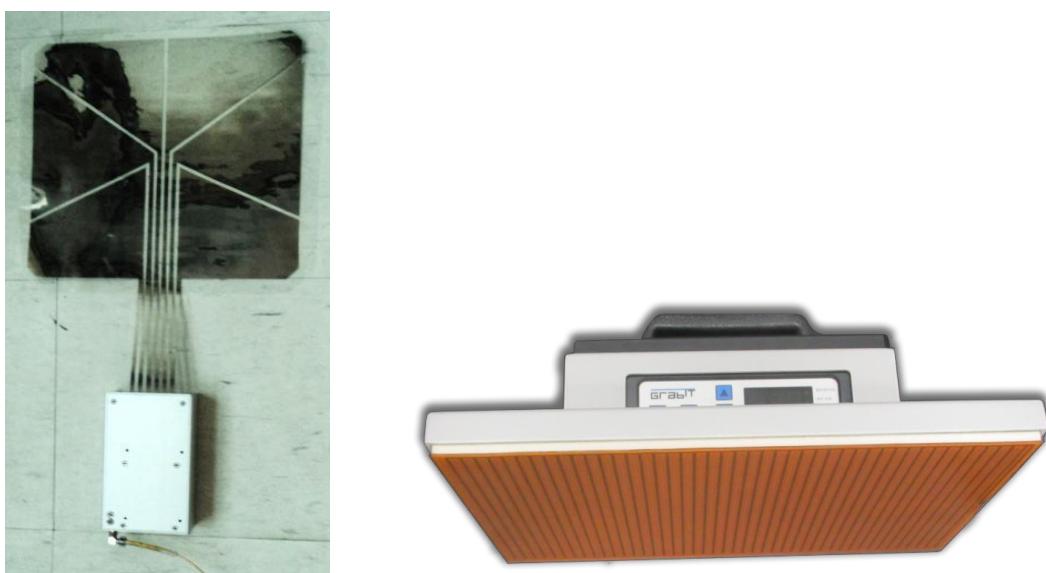


Figure 2. Industrial ES\EA grippers from ElectroGrip, Co. and GrabIt, Inc.

Strong Compact Retractable Boom

To achieve the reliability and mission adaptability for a compact retractable beam that once attached between the chaser vehicle and the orbital object can maintain relative separation and position, several choices are available commercially. Retractable booms have been used throughout the Space program from moving Skylab film cartridges and Vikings' Mars sampling arms to solar array booms for Hubble Space Telescope and ISS, and many were bi-metallic ribbons that employed shape memory to form a curved cross section when extended and were flattened and rolled up for storage. Advances in materials have improved the basic bi-metallic ribbon booms such as composition ribbons that when deployed curl into a circular cross-section but has a natural stable flat profile when stored without using a restraining retraction mechanism. Another metallic boom consists of a coiled stainless steel vertical ribbon with holes along each edge and a horizontal band that looks like a toy Slinky with teeth around the outside edge that interlocks the bottom of one turn of the steel ribbon with the top of the next turn as guides on the core of the extension/retraction mechanism screws the flat outside ribbon and inner interlocking spider extended out together or retracted into separate rolls. This industrial compact boom has a retracted to extend ratio of 1:12 and a weight to load ratio 1:40 with few moving parts and is designed for low maintenance. We incorporate a smaller boom model driven with a small electric motor and two scissor mechanisms for end effector plate stabilization and that was mounted onto a heavy duty DC pan & tilt unit to assemble a retractable X, Y, Z manipulator arm for laboratory testing. Future plans may use two retractable boom mechanisms driven in parallel to stabilize each other without the scissor mechanisms with a simpler tilt plate for the shoulder.

The I-Lock 75



Figure 3: Compact Retractable Interlocking Metallic Beam Design:

Operational Sequence and Comparison for FETCH:

The requirements for the overall Flexible ES Tools for Capture and Handling are most easily derived by first examining the operational sequence of a chaser vehicle parked at a safe distance, capturing a typical orbital object (either stable or spinning) using a boom mounted ES|EA gripper. Advanced optical sensors can enable the following FETCH operational sequence with poise detection from a safe, stable station-keeping point and minimize disturbances from both sensor and positioning errors. Temporary gripping for relative dynamics control is possible with fast ES|EA activation and rapid retraction, enabling the possibility of de-spinning objects before capture.

Table 2: Orbital Object Capture Sequence using Electrostatic-Adhesion Compared to Docking

FETCH Flexible Capture	Hard Docking
At 10m, Chaser Vehicle <u>Station-keeps</u> at port with thrusters (& CMGs)	At 20m, Align to Docking Port and Enter into Approach Corridor
Pose Sensor: 3-6 DOF, 1-5Hz, ~10m range [TOF 3D Camera, simple LED Lidar]	Pose Sensor: 6 DOF, 5-20 Hz, 0.5-20m Range [VGS type]
Use 3D Camera & <u>ES Gripper Proximity Sensor</u> to Steer Extendable Boom (or 9 RMS joints)	Use Pose Sensor Feedback to Thrust into Docking Port [6 DOF Thruster Control]
<u>ES Gripper Flexes at Contact to Align to Target</u>	Avoid Contact before Soft Latch
Both Vehicles usually separated by meters during Flexible Capture	Control Docking Impact (& Water Hammer by Reverse Thrusting or pushing)
Contact force controlled by Boom Extension & <u>ES Gripper flexure</u>	Mechanism must absorb or Withstand Docking Collision
Chaser vehicle can align to center of rotation of Spinning Orbital Objects during simple Station-keeping and the Gripper pad spun up with simple motor and slip-ring at the end of the Boom	Spinning Orbital Objects Require Chase Vehicle to match body rotational rates before capture, such as ramming probe into rocket nozzle

ES\EA Orbital Capture Mission Specific Sensor Suite

Beside the speed and joint feedback for controlling the end position of the boom, the position and poise of the orbital object relative to the chaser vehicle is needed. For un-stabilized target orbital objects, real-time multi-pixel range data is needed to measure and track the rotational and translational position and dynamics of the targeted orbital object data to position the chaser vehicle at a safe position relative to either the axis of rotation or the planned capture gripper site. The number of industrial time-of-flight and stereo optical sensors for outdoor use is growing as are the number and capability of video sensors that can track not only the X & Y position of a designated arbitrary marking on the target object, but the rotation angle at speeds up to 50 Hz. With this type of sensors, the chase vehicle can approach the target object to safe distance and center itself along the best rotational centerline of the target. With additional short range sensors, the ES\EA gripper pad can be spun-up and moved into close proximity to the target surface before ES\EA gripper activation and surface contact & compliance. Because of the stable separation to the target orbital object, the chaser vehicle can check and re-assess the relative dynamics before and after initial contact and safely re-position the ES\EA gripper if needed.

ES\EA Orbital Capture Evaluation and Testing

This research project (which means we don't really know what we are doing yet) is to evaluate the capability of ES\EA gripper technology for capture and handling of various types of orbital objects built or composed of various materials with a three prong project approach as described below.

- A. Laboratory feasibility simulations of proposed orbital capture scenarios will use scaled mechanisms, optical 3D sensors, manual sensor & boom & gripper control, and a 5 axis air-bearing target simulator. In MSFC's Flat Floor Robotics Lab, 1) a re-configurable Reactive Satellite (orbital object) Simulator (RSS) has been assembled from a spherical air-bearing (3 DOF) supported on a planar air-bearing platform (2DOF), spun-up by air jets, and supporting a spacecraft mock-up with re-configurable material capture panels. The Reactive Satellite Simulator is design to move dynamically in response to torques and forces from off-axis contact forces. Along with the reactive spacecraft simulator, we have 2) a large chase vehicle simulator with self-contained power, propulsion, GNC, and support capability to position the ES\EA gripper boom system in a safe station-keeping position above the dynamic spacecraft simulator. Mounted to the large chase vehicle simulator will be 3) the compact retractable boom system using a heavy duty DC pan & tilt unit pointing a smaller boom model driven with a small electric motor and two scissor mechanisms for end effector plate stabilization, 4) one or two ES\EA gripper(s) are mounted with a compliant hinged attachment on a spin-table mechanism with slip-rings and a limited-slip spin-motor and 5) a suite of time-of-flight and video sensors a] to enable centering the orbital capture arm above the spinning dynamic spacecraft simulator, b] measuring and matching the S/C spin-rate, c] positioning the ES\EA gripper pad in close proximity to S/C before activation and d] captured S/C simulator de-spin dynamics.
- B. Vacuum chamber testing in various small facilities will continue to evaluate different ES\EA pads' sensing and gripping performance with different materials with the three mechanical manipulation tests as shown in

Table 1. The materials and shapes of the test panels will be based on scenarios from laboratory simulations and material & shape configurations derived from orbital objects.

- C. Generate a comprehensive database and mock-up panel collection of surface shapes and materials of orbital objects and suitable ES\EA gripper pad configurations for vacuum chamber tests and scenario simulations.

This research approach of performance testing of the ES\EA gripper to verify the required function determined from laboratory simulations of Orbital Capture scenarios is aimed at raising the TRL of this technology and has already shown needed changes to the first generation of Flexible ES\EA gripper pad cabling. Both Vehicles usually separated 10m during Flexible Capture



Figure 4. Reconfigurable Reactive Spacecraft (Orbital Object) Simulator



Figure 5. Flexible ES\EA Tool for Capture and Handling (FETCH) simulator under construction!

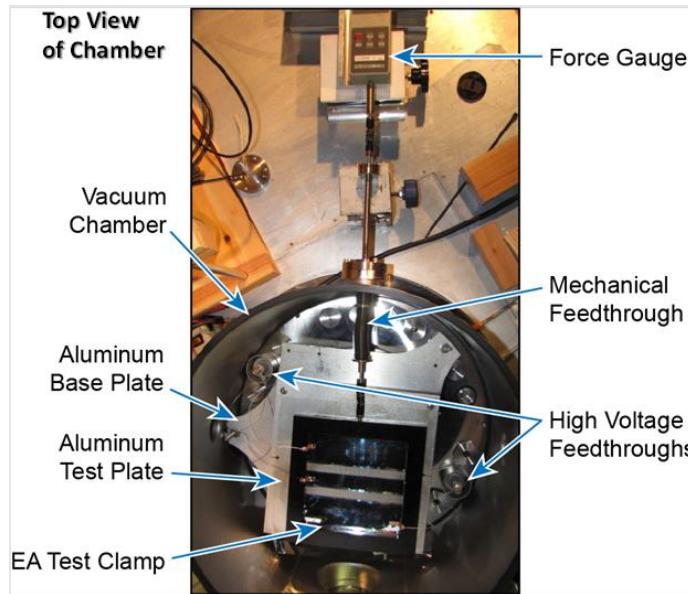


Figure 6. Electrostatic Adhesion Mechanic Grip Testing in a small SRI Vacuum Chamber

Current ES\EA Research Project Status and Future Plans

The author of this paper has been honored and humbled by the work and diligence of two teams of summer college interns from the NASA Robotics Academy in taking the vague ideas and assortment of pieces and parts that the author and mentor was able to purchase, build, and scrounge with the research & development funds for this ES\EA technology development and simulation project. The 2014 intern team of B. R. Leung, N. R. Goeser, L. A. Miller, and S. Gonzalez demonstrated the first full-scale small satellite Capture and Handling on the MSFC Flat Floor with a Flexible ES\EA gripper documented their work in their paper entitled Validation of Electro[static]adhesion as a Docking Method for Spacecraft and Satellite Servicing". The 2015 team of J. M. Kepron, C. M. Stelly and L. A. Marinello designed, fabricated, and assembled the re-configurable Reactive Satellite Simulator as a spinning target for the retractable boom arm and ES\EA gripper spin table and support structure, as documented in their intern report: "Universal Satellite Capture Arm and Reactive Satellite Simulator". I am proud to report that these young engineers and scientists made the vendor calls, performed the research and tests, and assembled parts into laboratory equipment that the Author will finish-up and use to perform further vacuum chamber tests and Flat Floor reactive satellite capture simulations. Once the retractable capture arm is complete and integrated into the large chaser vehicle simulator with the re-furbished dual flexible ES gripper pads, tests will determine good mounting positions for the TOF and 3D optical sensors for target satellite alignment as well as ES\EA gripper pad and proximity sensor placement on the end of the retractable boom arm. The small test vacuum chamber will be equipped with mechanical motion pass-throughs from the remaining R&D funds to allow the ES\EA gripper performance with parallel and perpendicular pull testing as well as rotational grip tests with different materials and shapes. Further activities and plans beyond those discussed above are indefinite, but the author looks forward to the next group of summer interns or cooperative students that become available.