REACCH - Reactive Electro-Adhesive Capture ClotH Mechanism to Enable Safe Grapple of Cooperative/Non-Cooperative Space Debris

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USC's Space Engineering Research Center (SERC) and the Jet Propulsion Laboratory (JPL) have created a unique "octopus" tentacle end effector for robotic systems that uses formable electro-adhesion (EA) and Gecko adhesion capture cloth material. REACCH, or Reactive Electro-Adhesive Capture ClotH, supports soft capture of objects of any size, shape, surface finish or material on-orbit. To-date SERC/JPL have developed initial tentacles and backing spines that can control the EA/G material. Prototypes with two tentacles have been demonstrated and tested on a 3-DOF air bearing device in 1g in one plane of grip. The results show promise to further develop this new type of grappling mechanism able to make first soft contact with an object, with a technology that merges compliance and control elements for future on-orbit servicing and assembly missions. This paper presents the initial design and test results on this type of system.

I. Nomenclature

Client	=	Satellite or Platform to be Serviced
Servicer	=	Satellite or Platform that provides Service
DOF	=	Degrees of Freedom
Base	=	Spacecraft with mounting ports to hold REACCH mechanism
Body	=	Reacch end effector responsible for performing operation

II. Introduction

The goal of the REACCH project is to create a simple, easily deployable, *smart* low mass/cost mechanism that replaces the need for very high cost/risk contact docking, to enable capture of any object (cooperative and/or non-cooperative) in space. REACCH utilizes low power high grip Electro-Adhesive/Gecko (EA/G) adhesion technology coupled with elastic substrates for ubiquitous geometric compliant grasping. Historically, capture is executed through pre-defined and mechanically fixed controlled contact methods or via uncontrolled methods such as nets. Our mechanism allows for a new solution that can accommodate any requirements for on-orbit servicing/construction and grapple. The proposed architecture, if employed, will be among the first technology to service satellites without the use of a pre-existing docking interface. The level of dynamic, flexible grip capability enabled by REACCH vastly expands the type of objects that can be captured, in their material composition, surface contiguity, and overall geometry, as well as in their orientation and attitude motion on orbit. The on-demand soft capture methodology through multiple contact arms would support a variety of distinct functions for safe space servicing including: contact/grapple of cooperative satellite Clients for hand off, object anchoring for temporary stability, and debris capture of selected Client bodies.

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A. Background

As the commercial space sector embark upon the advent of *servicing* activities in space, ubiquitous, easy to use and successful methods that enable safe *grasping* will be required [1, 2]. Multiple scenarios for *services* in space contemplate rendezvous and eventual *dock* or *contact* with another object, either cooperative or non-cooperative (i.e. working with a limited or non-operational satellite or object). Contact between two disparate entities in space has a higher than normal level of potential inadvertent mechanical contact risk because of the micro-gravity environment (as opposed to the ocean or air where there is still a medium to provide friction and thus a corresponding backing force). Current on-orbit operations that involve Rendezvous and Proximity Operations (RPO) resulting in contact are both an intensive activity from the ground and a costly one on spacecraft systems requirements for the *rendezvous-er*. The requirement to safely avoid collision requires this spacecraft to have complex attitude control systems, sensors, and dedicated proximity measurement devices. The operations themselves are labor intensive with checks and counter checks on the ground before the RPO event occurs. This is inefficient for non-cooperative rendezvous, which requires even more stringent requirements on the spacecraft control system. Attempting to dock with a slowly spinning and nutating body that has no control (as is the case with large dead satellites or rocket bodies, or future cargo containers that have lost control) is a very risky task. The closing spacecraft must not only have traditional rendezvous and proximity sensors, but it must also have the ability to match the nutation and specific rotation parameters of the Client object, thus expending even further fuel and requiring a level of robustness in attitude control in its own system to mitigate failures or offsets. To-date, *contact* solutions have focused on robotic elements that have levels of compliance relative to offsets in rotation or velocity between two objects. The torque and stress applied to the joints is sized to a rotation rate with compliance, which drives the mass of the overall robotic arm. If an object is rotating faster than the designed grasping specifications of the joints, the robotic arm cannot be used. Traditional docking/contact systems are mechanical; that is, they are designed to provide limited amounts of off-nominal compliance to errors in contact velocity or angle, and maximize control in the grapple/contact. *Compliance* is something assigned to the robotic arm that holds a mechanical contact, and is either software or hardware implemented.

A solution that addresses a number of challenges in rendezvous and docking would have as its primary attribute an ability to morph between pure compliance and pure control, as needed, depending upon the specific situation. This type of approach would help current challenges, for example to nullify the need for a Servicer to execute potential high risk/cost maneuvers for a spinning platform, lower the guidance requirements for very low error upon final approach, and have the ability to reach beyond a traditional mechanical contact arm before making final approach. This system would need to be flexible for multiple geometries, scaleable to different sizes, minimize power consumption, and be extremely compact to reduce weight and volume to pack on-board a spacecraft. For inspiration on such a system, we turned to biology.

B. Inspiration

While nature provides a plethora of interesting options to inspire a combined compliant/controlled mechanism, one particular natural element seemed to have the most flexibility and ability to realize in early engineering prototypes - that is the simple eight-limbed mollusc or octopus. Several depictions can be seen in Fig. 1.

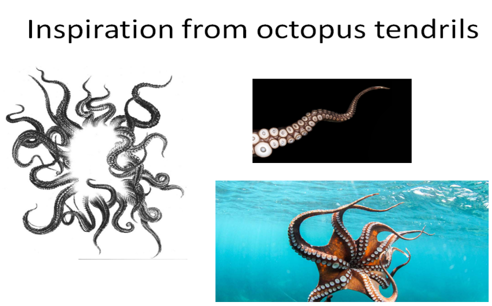


Fig. 1 Compliance and Control exhibited by Octopus Tentacles

The Octopus has a unique mechanism through its soft main body and 8 tentacles that provides both highly flexible movement and compliance to fit into tight spaces, and at the same time can control its tentacles to provide structural/mechanical rigidity for complex tasks of opening or gripping. It also has distinct features embedded in the tentacles for gripping through circular *suckers* that can serve as both sensing devices for the surface of an object it touches, and providing direct shear and normal force transference when engaged on a surface.

These two attributes translated into a combined compliance and control mechanism for investigation into satellite grasping and gripping, which formed the basis for REACCH.

C. New Research Domain

A combined compliant/controlled gripper requires new methods for a set of consistent metrics to show value or gauge its effectiveness. Figure 2 shows a preliminary conceptual attempt at applying metrics to existing robotic grippers that begin to explore how to value a morphing compliant/controlled gripper relative to others.

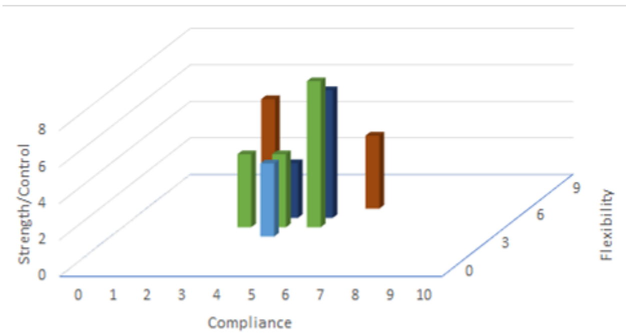


Fig. 2 First look at metricizing the Compliance/Control domain

Just as an octopus uses its tentacles in a multitude of applications, a morphing compliant/controlled mechanism for Space should have flexibility to move within the fully compliant and fully controllable spectrum. While normal to define each in singular values (i.e. length of stretch or amount of area a system can cover for compliance, or force required to maintain control), it is possible to consider a combined metric that also meausures one additional variable in addition to *compliance* and *control*. Much of the data that was gathered in testing the first iteration of a REACCH type system was in an attempt to develop appropriate metrics and thus be able to compare the system against other grippers/grabbers/docking systems that use robotic arms. The premise is that by having a robotic system that can connect soft compliant and stretchable contact structures to a body in orbit, with the ability to rigidize that contact upon command or sense, then it could greatly expand the ability to safely and effectively execute structural manipulations and RPO/docking options on-orbit.

III. Initial Concept of Operation

REACCH is expected to complement an existing spacecraft servicing mission through a flexible design compatible with existing robot servicing arms. It is comprised of a Body - Base structure that operates as an end-effector tool for robotic operations. The *Body* housing would contain all required electronics such as the high voltage modules, relays, power and communication systems, and a control system. Individual power and data lines will run along each tentacle to connect tiles and sensors back to the centralized control system. Here the *Base* would stay affixed to the robotic arm, and the body would detach from the base and extend out to an object using its cold gas thrusters, a tether module will be used to connect the two via a kevlar line. The Base housing, still attached to the robotic arm, would then be able to reel in the tentacle Body module attached to the Client object. On reaching the Base, the tentacle arms will retract to release the Client object. The primary robotic arm would then stow the REACCH mechanism in its payload bay and grab onto the Client object to initiate servicing through traditional direct robotic controlled connection, as seen in Fig. 3. The EA/G technologies are placed strategically in the form of tiles throughout the tentacle arms embedded with elastic stretch sensors to provide feedback on load values at each anchor point, thus allowing for smart controls on their connection to any surface.

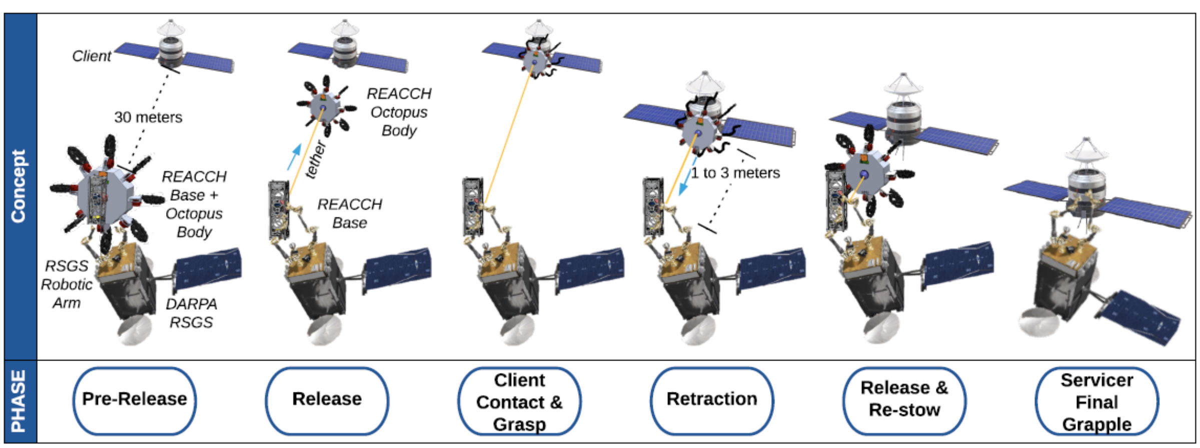


Fig. 3 REACCH employed by the RSGS platform (artists concept)

IV. Design and Initial Prototype

Figure 4 shows the initial design for the full system envisioned at project start. As described above, the REACCH system uses a *base/body* approach. An initial study was executed to examine the most likely contiguous and non-contiguous surfaces expected for a servicing gripper, which defined the initial sizing for length of tentacles. The number of tentacles selected for this design was 8, which offered dedicated pairs of grasping planes which could support varying geometries. The size and length of the tentacles themselves can be defined by the specific objects designated for capture, and we sized our initial prototype based on the SERC's testbed of a Servicer and a Client spacecraft (see IV.C). The three key attributes that make up the REACCH technology are described in the following subsections.

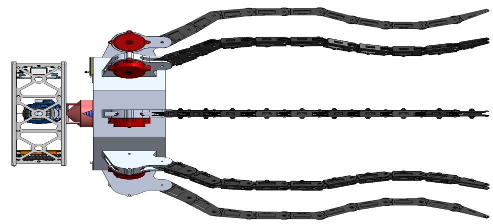
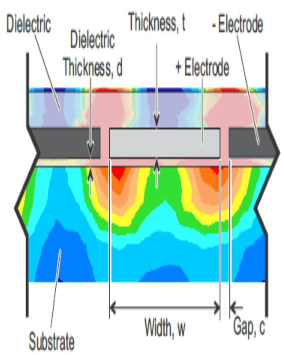


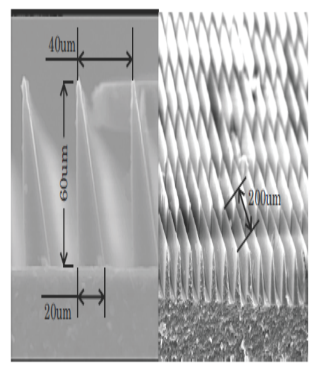
Fig. 4 Initial Configuration of REACCH End Effector (left is Base, right is extended tentacles from Body)

A. EA/G Tiles

Electrostatic adhesives function on the principle of utilizing a controlled electrostatic field to generate surface polarization to provide a weak attractive force within a wide variety of substrates. Alternatively, Gecko-like adhesives utilize the principle of Van der Waals to create inter-molecular attraction forces based on the generation of a high real-area-of-contact. Figure 5 shows examples of both the active (electrostatic) and passive (Gecko-like) adhesive technologies that were used to created the tiles [3].



(a) EA cross sections



(b) Gecko cross sections

Fig. 5 Comparison of EA and Gecko adhesive cross sections

EA functions by utilizing a high voltage differential across a set of inter-digital electrodes to generate a strong local electric field. This electric field polarizes the surface material creating a surface charge buildup and thus adhesion [4]. EA is used in the semiconductor industry, the printing industry, in the food and painting industry for powder coating, and in the robotics industry as attachment mechanisms [5]. The advantage of electrostatic adhesion is that it generates an adhesive force on a wide variety of surfaces ranging from glass and steel to rougher surfaces such as wood and concrete. This is in contrast to other adhesion methods such as micro-spines, suction, electromagnetic, and others techniques that can be very surface specific [6–8]. The disadvantages of electrostatic adhesives are that the adhesion level is relatively weak and is highly dependent on the separation gap between the adhesive and target substrate. EA is shown to be one of the more robust attachment mechanisms since it is both controllable and effective over a variety of surface roughness-es and compositions including conductors, semi-conductors, and insulators. Electrostatic adhesives are especially promising for space applications because they can operate in a vacuum, do not utilize chemical bonds, and require no preload force on the target surface.

Gecko or dry adhesives are based, literally, on behavior traits of geckos [9]. The adhesive consists of a micro-structure surface which is used to create a large real-area-of-contact with a substrate and generate adhesion through Van der Waals forces. Two different varieties of dry adhesive generally exist; non-directional and directional dry adhesives. Non-directional dry adhesives typically consist of micro-scale straight vertical stalks with a mushroom shaped tip to provided improved contact area. They typically generate high adhesion on very smooth surfaces but are not controllable

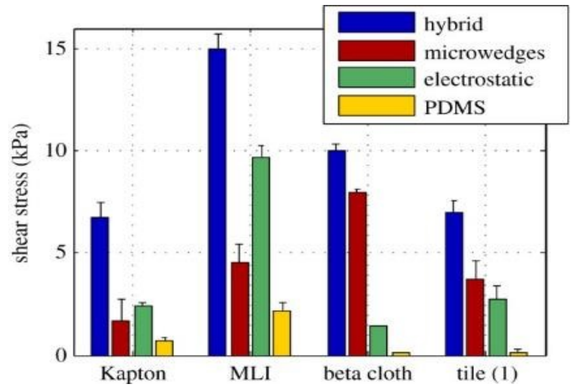


Fig. 6 Comparisons of EA, Gecko and Hybrid Experimental Results

and lack confirmation rough surfaces. Directional gecko-like adhesives, on the other hand, are typically asymmetric structures which deform to provide geometric local compliance with the target surface and generate adhesion when loaded in a preferred direction. Load sensitivity of the adhesive provides a form of ON/OFF control and greater micro-scale surface conformation. The directional dry adhesive to be used in the proposed work has been developed at JPL and consists microscopic triangular wedges about 20 µm wide at their base, 60 µm - 70 µm tall, and about 200 µm long. The adhesive or wedges have directionality in that they use asymmetric micro-structured hairs (the wedges) that bend to create a high area of contact when loaded in preferred shear direction.

To utilize the best of both adhesion mechanisms, a hybrid combination of Electrostatic adhesion (or EA) and Gecko-like adhesion has been shown to increase shear force applied to any object and multiple substrates. The electrostatic adhesive provides initial clamping to the target surface and allows for macro scale surface conformation due to the generated attraction force and flexibility of the EA film. This high surface contact then allows a significant percentage of the gecko-like adhesive hairs to engage with the target substrate when loaded. As the gecko-like adhesive hairs engage the micro-scale surface conformations they reduce the gap distance between the EA and substrate, further increasing its effectiveness. This interaction provides the synergistic effect that enables greater overall adhesion, which is often greater than the sum of the individual adhesives. Figure 6 shows a measured increase shear stress with the EA/G relative to the EA, Gecko adhesive, and a plain silicone polymer sheet on a variety of materials, including some commonly found on spacecraft. This effect will be taken advantage of with REACCH to allow expanded effectiveness on wide range of target substrate materials.

B. Compliance Mechanism - Design and Validation

Space suitable fabrics were surveyed to identify an appropriate material for prototyping and testing the flexible spine, based on their ability to stretch, to deform, and their space heritage. Spandex and Dacron were chosen as principle materials for our first consideration as the elastic material to merge with the adhesive technology. The team created multiple swatches of stretchable material with different geometries of tiles attached in the stretch and cross stretch area. In addition, we reached out to a commercial company, StretchSense, to merge their unique sensing techniques into the fabric swatches.

To mimic actual deployment on a Client surface, we created a simple benchtop test layout to test and validate swatches. In this layout, a glass surface was setup to be the test surface, a pulley was used to enable vertical loading, a single axis load cell was used to measure line load, with masses hung from the line to load the swatches. To load the fabric swatch, a metal bracket was manufactured and riveted onto its base, a hook would then run a line from the bracket, over the pulley connecting the load cell. A total of five different swatch configurations were designed and manufactured, each having a different number and arrangement of tiles on the flexible surface. The objective with the varied design was to identify a suitable pattern for placement of tiles and to compare overall performance of a given swatch design.

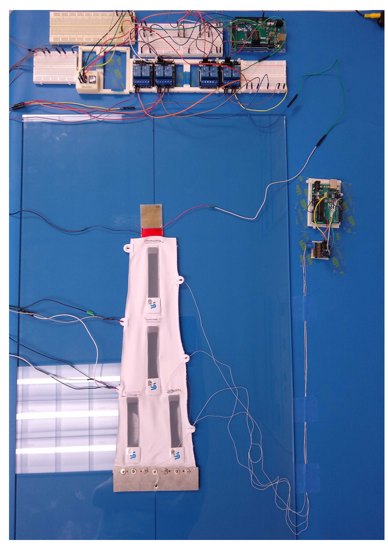


Fig. 7 A Swatch on the experimental platform under test

A common trend observed during initial integrated swatch (stretchable fabric with EA/G tiles) research testing was that the tiles on the bottom (closest to the bracket and load) would fail first. This occurred because they would bear most of the applied load, thus preventing an equal distribution among the other tiles. This behavior suggested progressive load transfer, that is, tiles lower in the chain would fail prior to ones higher up in the chain, and led us to alter the tile layout to distribute the load. This would more evenly spread the load and thus take advantage of the compliance in the stretchable material.

The phenomenon is depicted in Fig. 8, which shows that tiles 3 and 4 fail first, transferring all of the load to tile 2, where the load value is much higher than its threshold and causes it to fail almost immediately. Tile 1 then fails in a similar fashion, causing the swatch to lose adhesion from the test surface. Our observation validated that arranging tiles column-wise, in a series arrangement, does not offer passive distribution of load. Instead, a row-wise arrangement offers reasonable elastic isolation and is more effective in providing a stronger adhesion, and consequently a better grasp of an object.

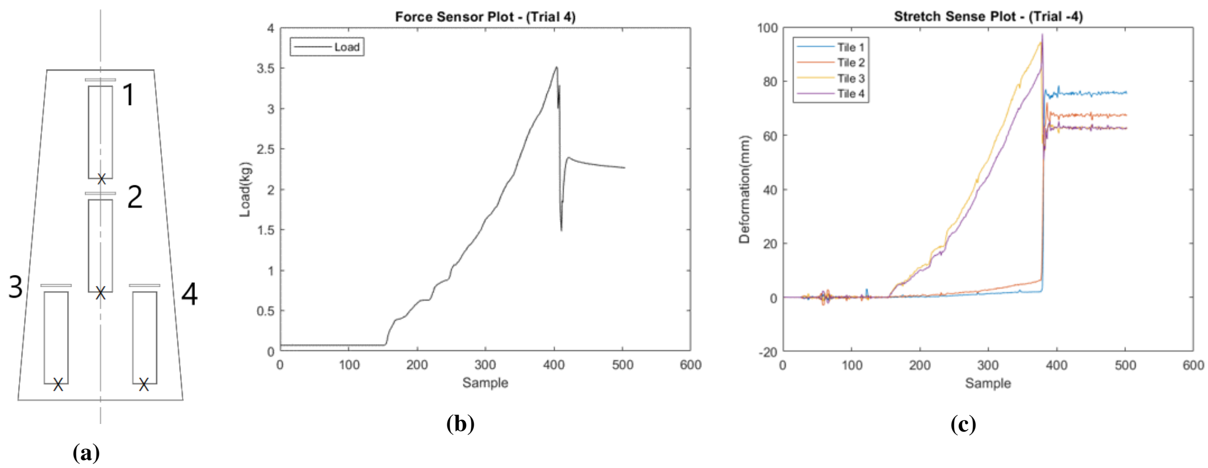


Fig. 8 Progressive load transfer seen at max load of 3.6 kg, where tiles 3 and 4 fail first, followed by failure of tile 2, and then of tile 1.

Due to the extensive number of possible tile arrangements on each tentacle, a computer simulation was created to explore a wider variety of patterns and inform design selections. Initial results created a baseline for three tiles arranged in parallel vs series, with results similar to experimental findings, providing validation that a parallel configuration is superior. In addition, through simulation, we were able to model the added dynamics associated with flexible fabric attached to the tiles on the spines. The simulation is described in more detail in section IV.E.

C. Spine for Compliance Control - Robotic Gripper Design(s)

To provide the control and support to the flexible swatch tentacles the team settled on utilizing an in-extensible *spine* for each tentacle that can accept the connection of the EA/G tiles embedded in REACCH fabric to its front face. Below are the two main requirements established for the tentacle/gripper arm design:

- Require the use of a backing element to provide effective load transfer from each individual EA/G tile to the base of the tentacle.
  - Serve as both actuation and retraction mechanisms
- Require a stretch sense element between each tile and the spine to allow for load sharing from tile to tile while also enabling force sensing when used with the stretch sense elements.
  - Be in parallel compliance for maximum shear transfer
  - Be in series compliance to overcome load sharing challenges

To achieve these requirements, two prototypes were made: a film-based structure termed the *continuous* gripper and a set of jointed rigid mechanical links termed the *segmented* gripper. Each provide a unique grip, adhesive platform, and implementation attribute which led to the concurrent development of both designs during the project. Table 1 below is a brief overview of some the identified pros/cons for each tentacle design.

Table 1 Gripper prototype design tradeoffs

Spine Type	Pro	Con
Continuous	Made from primarily *soft* elements Tugs and pulls target into gripper Potential for compact stowage if rolled onto a drum	Lower overall surface conformation Adhesion is only at the end pad Complex stowage mechanism required to effectively allow deployment and actuation
Segmented	Excellent conformation to centi-meter scale surface geometries High overall grip strength	Many mechanical components Required constant cable tension to keep cable on pulleys Can push away from target when perpendicular to large flat surfaces

1. Continuous Gripper-Arm or Tentacle

The continuous tentacle design consists of a flexible but in-extensible plastic film that is actuated by a thin super-elastic metal wire. It is possible that future versions would use a flex PCB circuit in place of the film to provide both support and electrical wire routing throughout the structure for signal and high voltage.

Version 1: To prototype the concept, a quick mock-up of a flexible tentacle with segmented tubing to route a flexible, extensible rod from one end to the other was created. By varying the distance between the tubing and tentacle substrate we found that we can tune the stress/strain profile and thus the curling angle of the tentacle. This proved out the general concept and enabled more detailed prototypes.

Version 2: The latest version uses a 3-level hierarchy of wire springs and spring-loaded films combined with a large end *pad* similar to a long squid tentacle. The pad on the end was then outfitted with tiles in a parallel geometry to enable a much higher end grip shear force applied to a surface. The stiffest wire generates curling of the lower half of the tentacle and serves to force the end pad to engage with the target surface. In, operation the tentacle is effectively a bimorph material, where the Polyethylene terephthalate (PET) base substrate material (clear/white) is inextensible while the wire increases in length by sliding extra wire through the guides secured to the tentacle substrate and placing the substrate in tension. Due to this action, the tentacle is forced to curve as a result.

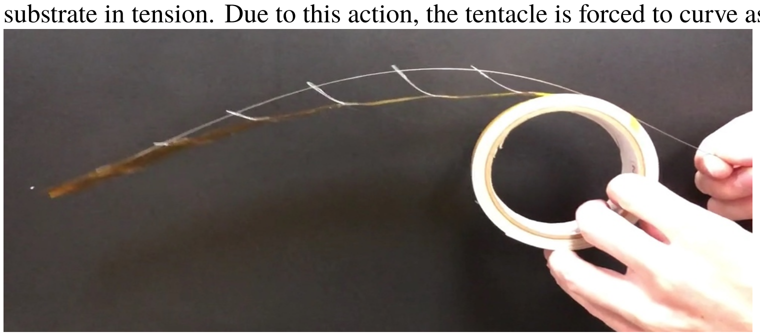


Fig. 9 Flexible film actuation by nitinol wire, where length of support tabs connecting wire to Kapton film allow tuning of resultant curvature profile.

A softer pair of wire springs enable the flared pad of the tentacle to conform to a range of surfaces topology. These softer wires connect the tip of the toe to the stiffest wire, and extension of the stiffest wire also causes the softer wires to tension the toe and further pressing it into any nearby surfaces. Finally, the softest pair of wire springs is used to spring-load adhesive flaps that will eventually hold the EA/G material. This allows individual flaps to better conform to a surface.

2. Segmented Gripper-Arm or Tentacle

The segmented tentacle spine design consists of a set of rigid links connected by pin joints to create a highly compliant structure in spite of using rigid elements. For movement, through careful design of the internal pulley configuration, the tentacle can be actuated with a base-to-tip unrolling action while also retracted with a tip-to-base action. This allows the tentacle to unroll and conform to surface along the way while also being able to naturally roll back up for stowage. To assist with design, optimization, and fabrication of the segmented tentacle, the primary design parameters were calculated within a MATLAB script. This script is used to design the storage spiral of the tentacle (see Fig. 10), the pulleys in the transmission responsible for gripping and retracting, and the key link dimensions necessary to package the transmission. The designer populates arrays of major design variables such as link length, pressure into a surface, center of pressure, transmission packaging and manufacturing limits, etc. The script then evaluates a free body diagram of the system and calculates the tentacle specifications required to meet the design requirements. The script populates a design table in Solidworks that is used to auto updates the CAD design. This work flow allows quick updates to CAD as the mathematics driving the design evolve.

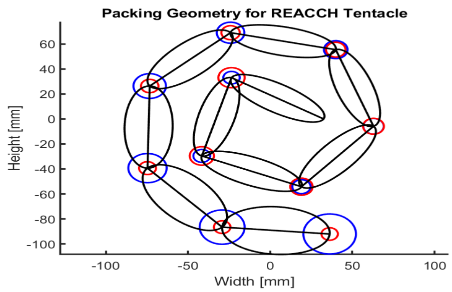


Fig. 10 Matlab Simulation used to design segmented gripper

This design process was established early on and continuously refined throughout the project. Three primary versions of the segmented tentacles were prototyped using this development approach with significant improvements over the course of each iteration.

Version 1: The first iteration of the Hirose-based tentacle acted as an initial proof concept (Fig. 11). It was able to demonstrate the basic concept of unrolling deployment and generic surface conformation but exhibited a number of issues which prevented it from being truly functional. Most critically, the spring retraction proved to be too weak and did not provide sufficient force to roll up the tentacle. This limited us to testing only the engagement capabilities. Also, the internal pulleys were all the same diameter causing uneven surface force and buckling of the tentacle after making full contact. Finally, the fabrication approach proved insufficient as only plain bearings were used with relatively flexible links. This caused the tentacle to exhibit excessive deflection under gravity while the joint friction limited actuation effectiveness.

Version 2: The next iteration, V2, corrected many of the issues found in the V1 design and proved to be the first truly functional prototype. Most notably, a much stronger return spring mechanism was designed using rotor spring to allow proper retraction of the tentacle. Rigid hard stops were added for retraction to allow the tentacle to curl up in an organized spiral pattern for its fully retracted state. The goal was to have the segmented tentacle deploy from base to tip, retract from tip to base, and provide even surface pressure when deployed.

Version 3: The most recent version saw the introduction of an overhauled mechanical link design that proved a much higher stiffness and introduced low friction shield ball bearings at all of the joints. This significantly reduced jointed friction which improved actuation and retraction consistency. Additionally the out of plane stiffness was greatly enhanced allowing longer lengths (currently 65 cm) to be used under 1G conditions.

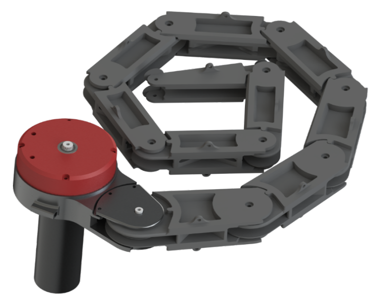


Fig. 11 Initial Hirose segmented design

D. Tether Module Design

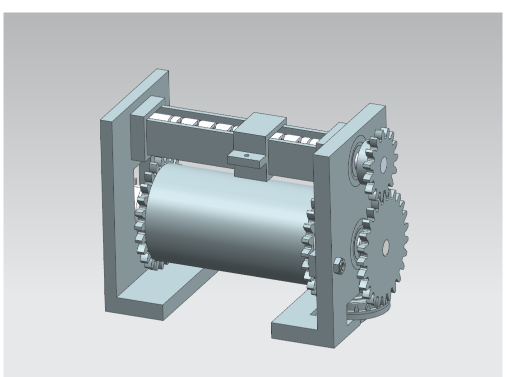


Fig. 12 Preliminary tether module design

To retract the REACCH Body mechanism back to it's Base after successfully contacing the Client, a motorized tether module was designed to support very low acceleration force application. The initial design, as seen in Fig. 12, uses a motorized shaft mounted on a pedestal to apply a torque, a level wind screw to manage spooling of the line and appropriate gear heads to transfer power. This module will share electronics and power with the robotic arms, corresponding lines will run from the aft section of the Servicer spacecraft to the location of our control system. A kevlar line with a high strength to weight ratio is envisioned to be used as the tether. Preliminary calculations were made to predict the force required to begin an acceleration with a commensurate velocity for a 2000 kg Client object in space, as an example. A base reel would need only micro-Force to initiate acceleration that maintains a very slow velocity movement from Client to Servicer. The next requirement it would have is an automated slack sensing system to avoid increasing the force through micro-accelerations or *tugs* as it reels in. An additional construct of *frictionless payout* may be required as the Body moves away from the Base on the way to the Client, where the reel should not impose friction or drag on its movement. This may require an autonomous payout system that constantly extends more line than the current range from the Base and Body are, until it slows at the Client. These types of requirements would include in future work on the REACCH tether system.

E. System Level Simulation

A kinematic simulation was created in MATLAB – Simulink, modeling all the swatch elements to be a simple translational mechanical system. EA/G tiles were set with a predefined failure point based on threshold values obtained from experimental tests carried out by Ruffatto et al, [10]. In this model, the stretchable material was modeled as a nonlinear spring with a polynomial characteristic function, results from our bench-top tests were overlaid and a polynomial regression scheme was used to generate the characteristic function.

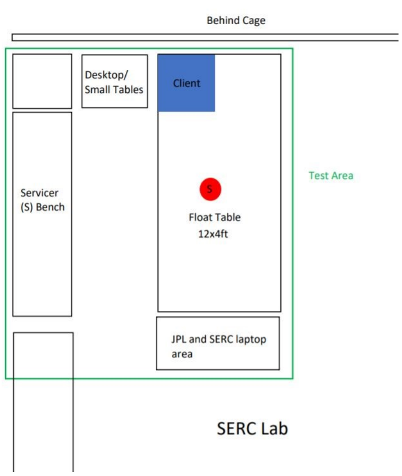
To replicate experimental loading conditions, a time-varying ramp force input was implemented. This model was run to test new swatch arrangements and validate previous experimental results, and was particularly useful in confirming that a parallel arrangement of tiles was beneficial for our application. However, some limitations are that it assumes the tiles operate under low pressure; that is, the spine on which they are situated functions in a gradual/gentle manner. Also, this model does not consider the geometry/surface contour of the Client object. For these reasons, it was attempted to extend this work to a robust three-dimensional simulation.

Project Chrono [11], an open-source physics engine, was used to model the flexible fabric swatch with all its elements in six degrees of freedom. Following established cloth simulation research by Wu et al [12] and Thomaszewski et al [13], we modeled our tentacle as a mesh of connected Euler beams with suitable material properties to simulate spandex like material [14]. Like our Simulink model, the tiles were modeled as static/fixed nodes in the mesh with a preset threshold value. To simulate the swatch as if it were deployed in Space, all nodes, except for those acting as tiles, were set to be unconstrained and have no additional force acting on them. In this scenario, the fabric, after deployment, would eventually try to wrap around itself and return to a wrinkled, elongated shape. This can be attributed to the internal dissipation of energy within the fabric as it is trying to get to a state of lowest potential energy, synonymous with a protein strand folding into a neutral position [15]. A version of the above work can be found and accessed on GitHub [16].

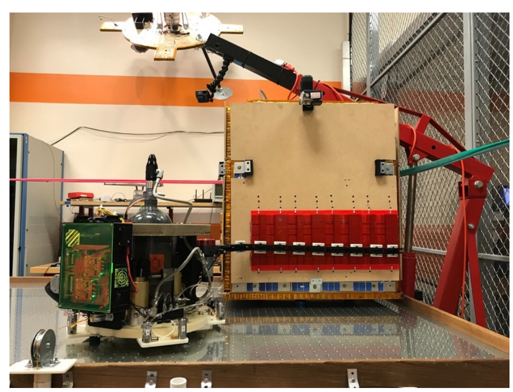
These findings were made after the initial 3-DOF testing of the two mechanical arms. As a result, it encouraged the team to pursue a rigid mechanical implementation and avoid inherent complications with the flexible spine. Future work on the simulation will help create a metric to characterize the effectiveness of the REACCH mechanism.

V. Dynamic Testing on 3-DOF frictionless Testbed

For testing of the prototype REACCH system, the SERC lab created an experimental frictionless testbed – an air bearing table that allows motion in 3-DOF, allowing planar translation and a single rotation about the out of plane axis. This allowed the team to test out a single plane of the REACCH mechanism.



(a) Layout of the Test Setup for REACCH



(b) First iteration of floating Servicer platform outfitted with REACCH tentacles, attached to a floating Client

Fig. 13 Dynamic Experiment Test Layout - Schematic and Image

The major components for the test set up are as follows:

- A Servicer that holds the prototype tentacles
- A Client of representative size/shape with various mountable surfaces that represent materials commonly found on space vehicle exteriors. The different materials/configurations used in actual testing are listed in Table 2

- A Testbed, modified to enable both approach and pull on the Client at multiple angles from different anchor points on the side of the table.

A floating air bearing platform from a previous SERC project was utilized as the Servicer, as seen in Fig. 13b. An initial prototype was sent to JPL to outfit with necessary fixtures to support the prototype tentacles and electronic control box. The Servicer was controlled wirelessly to actuate the prototype and collect relevant data, and had onboard power to provide to the REACCH mechanisms.

A representative satellite model at the SERC was also outfitted with pneumatics to act as a Client in a frictionless capability on the table, with swappable side panels to represent different materials and surface geometries. Table 2 shows the different surfaces and materials used. For the capture experiment, the Servicer would approach the Client with the surface material for the trial, grab the object, and then a load would be applied on a tether to the Servicer while the Client is anchored in place. This load could be applied at a variety of angle offsets from the centerline of the Servicer/Client interaction. The intention was to induce off-axis forces on the REACCH Servicer gripping the Client, imparting a difference of shear pull in the two tentacles. This served to examine the resulting behavior between differing forces applied to each tentacle.

Table 2 Test Surface Materials, selected to simulate grapple on space vehicle exteriors

Smooth Surfaces	Rough/Textured Surfaces
Kapton	3D printed large/small humps covered in kapton
Pyralux	
Acrylic	Solar Cells (Dormant) in Flat Array
Carbon fiber	MLI Blanket (with Poly-Fil)

Testing was executed in two phases, to allow the team to standardize procedures and develop the prototype and surfaces. The first phase used an alpha version of the tentacles employing only gecko adhesion of tiles on the two tentacle arms. This phase enabled validation of the tentacle methodology and provided initial test results to define a quantitative/qualitative metric for performance of both tentacles against various material configurations.

A. Phase 1: Test Results for Tentacles Utilizing Gecko Only Adhesive Tiles

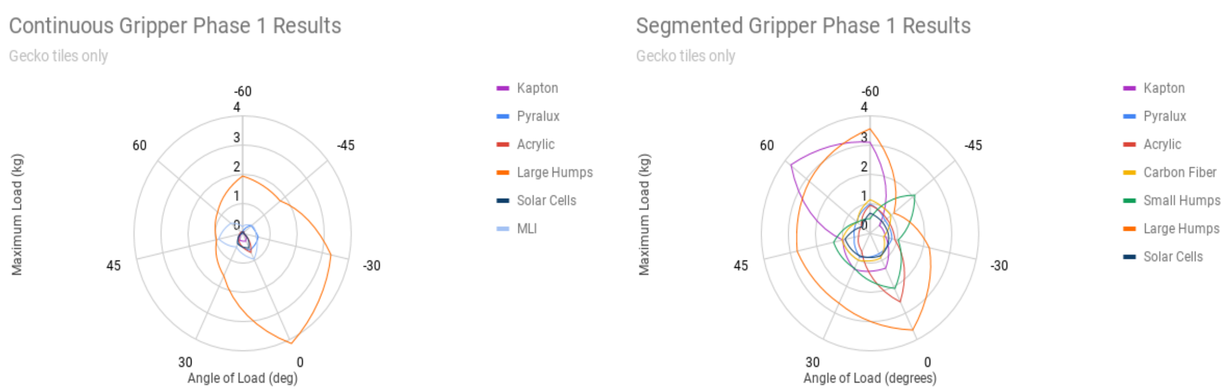


Fig. 14 Comparisons of Continuous vs Segmented Gecko Tentacle designs

Comparisons of the load-bearing capacity of the Phase 1 version continuous and segmented tentacles are shown in Fig. 14. As depicted, the segmented tentacles generally exhibited a stronger grasp on the Client surface, which we believe is due to the rigid anatomy of mechanical linkages that can provide direct force onto the tiles, whereas the continuous tentacles use a simple spring loading mechanism prone to grip failure when not actuated correctly. Both tentacles showed better performance on rougher surfaces, particularly on our large hump design because of inadvertent correspondence between the length of the links and peak width of the humps. Kapton and other flat surfaces like acrylic showed nominal performance. It should be noted that both arms were tested without an active control system, employing simple logic to control the motor drivers. It is planned to implement a robust and autonomous system to manage grip, orientation, and position of Client objects using feedback from our various sensors. The next subsection presents our results from the most recent iteration featuring a suite of control sensing equipment.

B. Phase 2: Test Results for Tentacles Utilizing Both Gecko and EA Adhesive Tiles

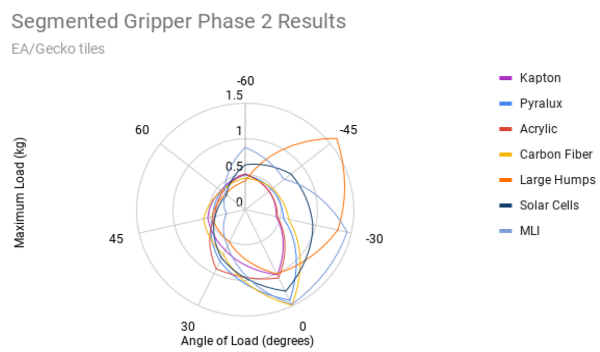


Fig. 15 Segmented Tentacle performance with EA/G tiles

In this second phase of tests, both types of tentacles (segmented and continuous) were equipped with EA/G tiles where the continuous design had Stretch Sensors anchored to the base of each tile. Additionally, a tile contact estimation board was fit on the continuous tentacles to detect percentage of contact on the Client surface, through capacitive sensing. Generally, the segmented tentacles exhibited a more consistent behavior as compared to Phase 1 tests. This can be attributed to the additional EA capability in this iteration, which allowed for a better grasp on Client surfaces. Within this phase, the tentacles performed better on bumpier surfaces than flatter ones, showing maximum load on MLI and large hump panels.

Overall, however, it is not possible to draw a direct comparison between the performance of the gripper in Phase 1 and in Phase 2. In particular, the tile mounting for the gecko only tiles in Phase 1 is more compliant than the mounting utilized in the EA/G tiles in Phase 2. Phase 1 exclusively utilized a foam mounting system which enables approximately 2mm of stretch. This mounting mechanism was not possible for Phase 2 at this time since the EA high voltage wiring contacts required a secure connection. Since the EA/G tile is more rigidly attached, there will be less tile to tile load sharing. This mounting mechanism can be improved upon in future work.

The Phase 2 testing of the continuous tentacles showed slightly diminished performance, likely owing to additional hardware mounted on the back side of tentacles, adding additional weight to the tentacle arms and shifting the location of grasp. We observed nominal performance on smooth surfaces such as kapton and carbon fiber panels, where the tentacles took up to a kilogram of load.

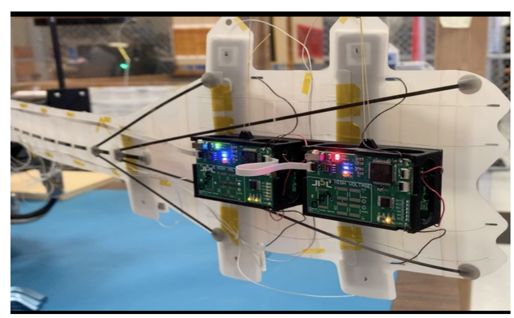


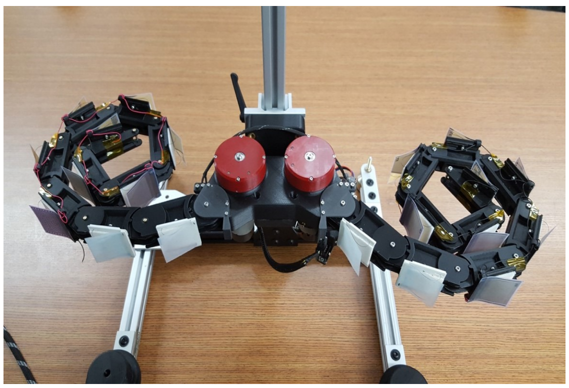
Fig. 16 Continuous Tentacles with EA/G tiles and control sensors

Unlike the segmented gripper, it was more challenging to test this version on bumpier surfaces. Updates to the test setup to accommodate the new hardware on the continuous tentacles will occur going forward. In addition to load cell data, we collected capacitance values from the Stretch Sensors and contact estimation boards. Overlaying all of that data helped understand how load was being distributed on the tentacles. The team is also working on establishing a relation between the two capacitance values obtained from the sensors, the relation we expect will form the basis for the development of a new metric in the field of EA/G grippers. The continuous tentacles with the new control sensing equipment - the Stretch Sensors and contact estimation board is pictured in Fig. 16

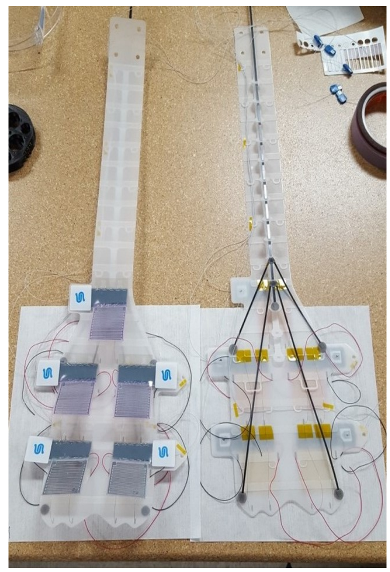
VI. Conclusion

The initial research and testing to create a robotic grasping tool able to operate freely between a fully compliant and fully controlled domain shows strong promise. The REACCH project testing validated that load versus deformation using elastic material is able to provide a level of multi-directional compliance upon contact, and proved that merging EA and Gecko adhesive tiles onto a stretchable substrate allows load transfer to take advantage of the elasticity of stretchable fabric. Various layouts in 2-dimensions showed that tiles could be applied that supported an increasing load path in parallel, and with judicious placement in serial path are able to catch a slipped panel after initial grip is lost. Two separate gripper structures or spines were demonstrated to provide the backing and control to the elastic and compliant tiles, and each shows unique attributes in behavior toward different materials and geometries. Figure 17 shows the final configurations of segmented and continuous tentacles tested.

Overall, the first iteration of the REACCH project showed great promise to develop a variable compliance/control device able to be used in the free-Space environment to provide a soft initial contact, yet retain strong grip for capture, grapple, and standoff hold.



(a) Segmented design with EA/G tiles



(b) Continuous design with EA/G tiles and stretch sensors

Fig. 17 Most recent iteration of segmented and continuous tentacle designs

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