Testing Gecko-Inspired Adhesives With Astrobee Aboard the International Space Station

Readying the Technology for Space

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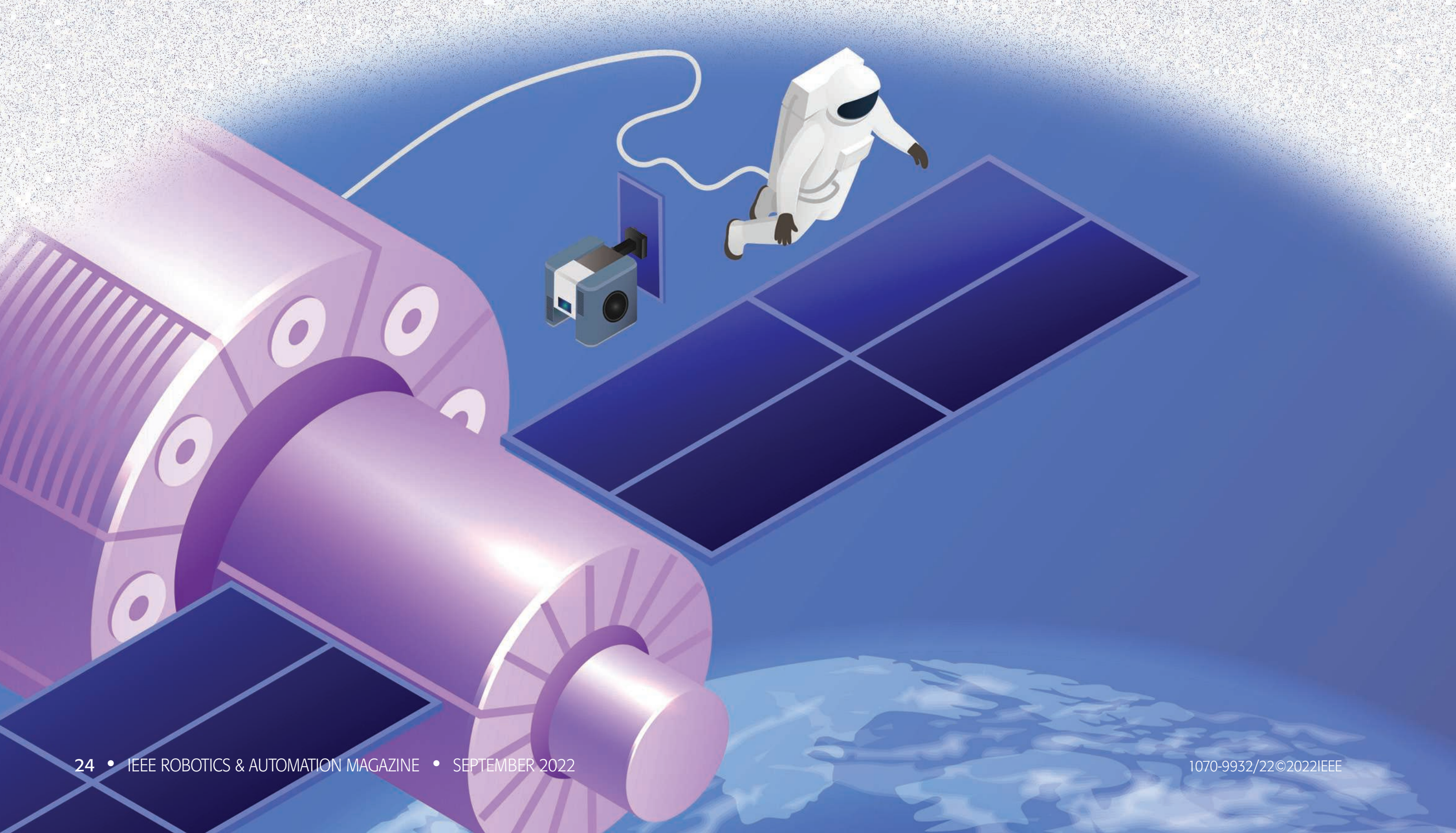
Gecko-inspired adhesives can allow free-flying space robots to grasp and manipulate large items or anchor themselves on smooth surfaces. In this article, we report on the first tests conducted using gecko-inspired adhesives on a gripper attached to an Astrobee free-flying robot operating inside the International Space Station (ISS). We present results from on-ground testing as well as two on-orbit sessions conducted during early 2021. Recorded data demonstrated that an adhesive gripper for Astrobee could provide 3.15 N of force for manual perching. The adhesives functioned as anticipated, despite a



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lengthy storage period. The results also highlighted some considerations for future adhesive gripping in space with free-flying robots. We discuss these topics along with system design considerations for successful implementation aboard the ISS, raising the readiness of this technology for a space-grade environment.

Overview

Gecko-inspired adhesives are a promising technology to enable free-flying space robots to grasp and manipulate large items or anchor themselves on smooth surfaces. They can function in vacuum, withstand extreme temperatures and radiation [1], [2], and allow robots to apply gentle forces to objects in orbit without having to enclose features as with a conventional gripper. Hence, they work on flat and gently curved surfaces that would otherwise be difficult to grapple. With these properties, they have been proposed as a solution for grasping and retrieving space debris. Grasping experiments have been conducted with simulated satellites floating on gas bearings in the Jet Propulsion Laboratory's Robodome and aboard the NASA zero-gravity parabolic flight airplane [3]. Additional terrestrial grasping experiments have been conducted in partnership with the Japan Aerospace Exploration Agency [4].

In this article, we report on the first tests conducted using gecko-inspired adhesives on a gripper attached to an Astrobee free flyer operating inside the ISS. The tests were conducted in March 2021, using grippers launched in July 2019, and kept in storage on the ISS.

We first provide a brief background on gecko-inspired adhesives and their applicability toward tasks carried out by assistive free-flying robots [or assistive free flyers (AFFs)]. We present the gripper design and requirements for gripping flat and gently curved surfaces with the Astrobee free flyer. We then present the results of tests conducted on ground and on orbit. The tests revealed that the adhesives functioned as anticipated, despite a lengthy storage period, but they also highlighted some considerations for future adhesive gripping in space.

To provide a drop-in replacement for the existing gripper, we designed an active system that uses a sensor to trigger a motor that loads the adhesives. It is important to load the adhesives only when all of the adhesive pads have established coplanar contact with a surface. However, in comparison to robot arms on a fixed base or even quadrotors on Earth, the ability of free flyers in microgravity to make final adjustments to velocity and orientation is quite limited. This limitation motivates our recommendation in the section "Conclusions and Future Work" that future adhesive grippers use passive suspensions and passively triggered grippers to align to a surface and load the adhesives for a firm grip.

Contributions

The contributions of this article are as follows:

1) The primary contribution of this article is to present a system that meets the requirements of being launched into orbit and integrated with the Astrobee free flyer.
2) We additionally report on tests conducted aboard the ISS both manually by astronauts and with Astrobee. In this respect, the work advances the technology readiness level (TRL) of gecko-inspired adhesives for deployment in space from TRL-3 (experiments from ground-based benchmarks) to TRL-5 (testing in a relevant environment).
3) As a result of the tests and the system development and integration challenges addressed, we present recommendations for future use of gecko-inspired adhesives on free-flying robots in microgravity.

Background

The grippers and experiments reported here take advantage of two technologies: gecko-inspired adhesives and free-flying robots for use in space. We briefly review them here with references to publications providing further details.

Gecko-Inspired Adhesives

Geckos are remarkable for their ability to run on vertical and even overhanging surfaces. To accomplish this feat, they use a hierarchy of features on the surfaces of their toes that terminate in tiny spatular tips less than 1 μm across. The dry adhesive features conform intimately to smooth and rough surfaces and achieve adhesion using primarily van der Waals forces. An important characteristic of gecko adhesion is that it is directional and, therefore, controllable. The gecko sticks only when its adhesive features are parallel to the gripped surface and from the gecko's palm out toward the tips of its toes (i.e., in the direction a gecko would load them when climbing up a wall). Relaxing the tangential load eliminates the adhesion and allows a gecko to lift its feet with low effort [5].

The same principle underlies directional synthetic gecko-inspired adhesives, albeit with less sophisticated terminal features. Figure 1 shows side views of the microwedge adhesives made of silicone rubber. These adhesives were used in prior work to explore space-related applications, for example, using planar robots floating on gas bearings [3], [6].

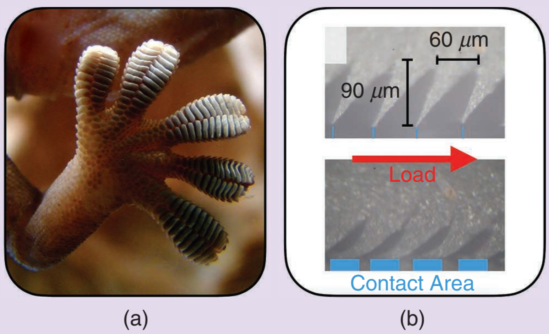
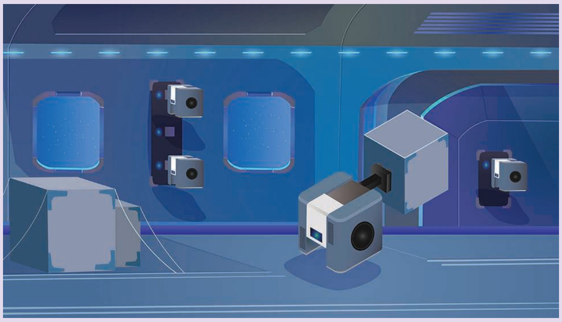


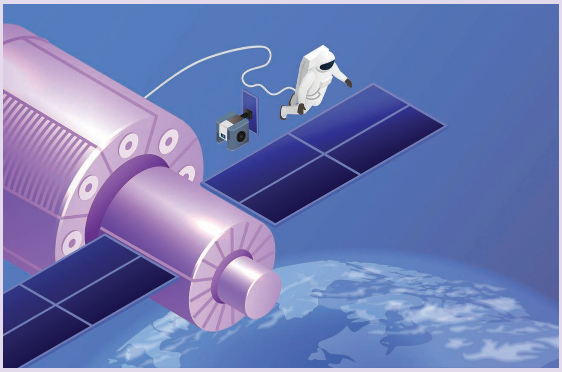
Figure 1. (a) Gecko toe and microscopic view of angled setal stalks with spatular tips (<1 μm across) [11]. (b) A microscopic view of silicone rubber synthetic adhesive; applying a tangential load causes the wedges to deflect and adhere because of the increased contact area.

Other examples of directional dry adhesives are provided in [7]–[9]. As seen in Figure 1, the adhesives have slanted triangular wedges with a length of about 100 μm, tapering to a sharp tip with a radius of $\approx$1 μm. In the unloaded state [the upper part of Figure 1(b)], only the tips of the wedges make contact with a surface, and adhesion is negligible; hence the adhesives are not sticky to the touch. Upon application of a shear force, the wedges bend and flatten, resulting in a large contact area so that van der Waals forces can produce adhesion. Relaxing the shear force allows the wedges to straighten, eliminating the adhesion. For the microwedge adhesives, typical maximum values of normal and shear adhesive stress are $\approx$20 kPa and $\approx$80 kPa, respectively [10], although these values depend on the mounting conditions and the type of silicone rubber employed.

Upon application of a shear force, the wedges bend and flatten, resulting in a large contact area so that van der Waals forces can produce adhesion.



(a)



(b)

Figure 2. Free-flying robots can work alongside astronauts to extend their capabilities and reduce the time required for simple tasks. (a) For intravehicular activities, they can save crew time by carrying out menial tasks, such as cargo retrieval. (b) For EVAs, they can assist in performing repair or inspection tasks. EVA: extravehicular activity.

These features of gecko-inspired adhesives make them an attractive technology for capturing and manipulating free-floating objects in microgravity environments. Free-floating objects in space are unpredictable and difficult to grasp, particularly when they are also tumbling [6]. With gecko-inspired adhesives, any relatively smooth surface, curved or flat, such as a solar panel or the outer body of a rocket, becomes a potential grasping location. The gentle capture and release of the objects is also very desirable in microgravity environments to prevent further complication of the dynamics.

The Astrobee Free Flyer

The second technology on which the reported experiments build is free-floating or free-flying robots for space. These robots have received a surge of interest in recent years as a platform that can work alongside and augment the capabilities of astronauts. As depicted in Figure 2, AFFs have the potential to reduce the time astronauts spend in performing repetitive tasks and on extravehicular activities (EVAs) as well as make human operations safer overall. To date, several AFF platforms have been developed for use in pressurized environments, such as the ISS [12], and have carried out planning and control experiments on orbit. However, one shortcoming of these existing platforms is that they lack the ability to interact with and manipulate the surrounding environment.

To this end, the Astrobee platform is a free-flying robot developed by NASA's Ames Research Center (ARC) with the goal of being able to carry out a rich set of grasping and manipulation tasks [13]. Astrobee is a six degree-of-freedom (6-DoF) holonomic robot powered by 12 independent thrusters drawing air from the surrounding environment. Astrobee additionally features a perching arm equipped with a gripper for grasping handrails and small objects (Figure 3) [14]. The perching arm allows Astrobee to remain stationary for extended periods of time when docked to a handrail, using the two arm joints for pan-tilt motion.

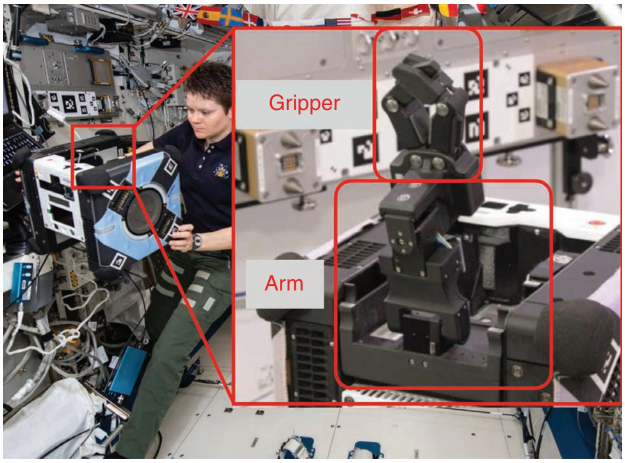


Figure 3. Astrobee uses a 3-DoF perching arm that folds into the top bay of the robot. The perching arm features an underactuated two-finger gripper to hold onto handrails aboard the ISS. (Source: [15]; adapted and used with permission.)

The Astrobee gripper is an underactuated two-finger mechanism driven by a tendon. Although this gripper can reliably grasp the handrails on the ISS for perching, it limits Astrobee to grasping targets with predefined features that it can pinch between the fingers. Thus, equipping Astrobee with a gripper that utilizes gecko-inspired adhesives offers the potential for increasing the range of grasping targets.

Design Requirements

Before proceeding to the details of the new design, it is useful to understand the main requirements necessary for the development of an end-to-end robotic system, including those arising from the adhesives, from Astrobee and its perching arm, and from the need to withstand a launch to orbit.

1) *Gecko-adhesive requirements*: To emphasize the adhesive gripping capabilities, we focus on grasping flat panels, which are ubiquitous in the ISS and cannot be grasped with a conventional gripper. To grasp such surfaces, the adhesives need to be loaded primarily in shear. As noted previously, the adhesives support a ratio of normal-to-shear loading of up to approximately 1:4 [10]. It is also important to prevent uneven loads that could cause the adhesive to peel from one edge and fail. One established solution is to mount the adhesives on small tiles that are loaded by pulling on a tendon, as shown in Figure 4 [3]. Pairs of tiles pull against each other parallel to the surface and together provide the ability to sustain a normal force pulling away from the surface. For the gripper reported here, we use two such pairs of tiles in a redundant configuration.
2) *Tile suspension requirements*: It is desirable to maximize the probability of tiles contacting the target surface at the moment of gripper activation. When using adhesives to lift objects on Earth, gravity can pull the tiles against a surface. Here, we use soft springs that Astrobee can compress. As the maximum thrust provided by Astrobee during experiments was ≈0.12 N, we employ compliant springs with a very low stiffness of ≈0.02 N/mm.
3) *Perching arm integration*: The gripper is designed as a drop-in replacement for the existing gripper, visible in Figure 3. Hence, it must integrate with the perching arm and its controller board. Thus, we select an active design where servos are used to engage the adhesive tiles and release them. A servo also locks and unlocks a pivoting wrist joint to accommodate angular misalignment on contact while providing a firm connection after grasping. The servos are chosen to match those used in the previous arm and gripper. In addition, the packet protocol definition for the gripper emulates the preexisting communication with the perching arm controller board.
4) *Launch requirements*: As a NASA payload, the gripper has to be robust enough to tolerate loads and stresses during rocket launch, and since it has to be unpacked and operated by an astronaut, it must meet all the necessary safety requirements, even in the case of component failure. Tests for vibration, heat generation and dissipation, and electromagnetic interference were required as part of the approval process. Heat is of particular concern because convective cooling is greatly diminished in microgravity (hot air does not rise). In addition, there must be no small parts that could come loose and no sharp corners. Materials should have low outgassing and low flammability, and they should not be prone to brittle fracture that could create sharp debris. For these reasons, the gripper is 3D printed using the same material (ULTEM 9085) as the existing Astrobee perching arm.

Gripper Design

The gripper system is designed to meet the foregoing requirements and consists of two subsystems: a lower assembly and an upper assembly; major components are highlighted in Figure 5(a). The lower assembly holds the adhesive tiles, which are suspended by preload extension springs and custom leaf springs, as shown in Figure 5(b). It also houses the servos and sensors controlling the engagement and disengagement functions of the gripper. The upper assembly houses the microcontroller printed circuit board (PCB) and an additional servo controlling the compliant wrist joint. The lower assembly is connected to the upper assembly via a ball joint and centering tendons, allowing it to rotate up to 10° in any direction. The wrist servo can tighten three pairs of tendons to bring the lower assembly to its center position and hold it in place. This enables the gripper to have rotational compliance to accommodate some angular misalignment as Astrobee approaches a surface and then hold Astrobee firmly in place after gripping.

The gripper is designed to align passively to a flat surface assuming a low approach velocity so that Astrobee can stop

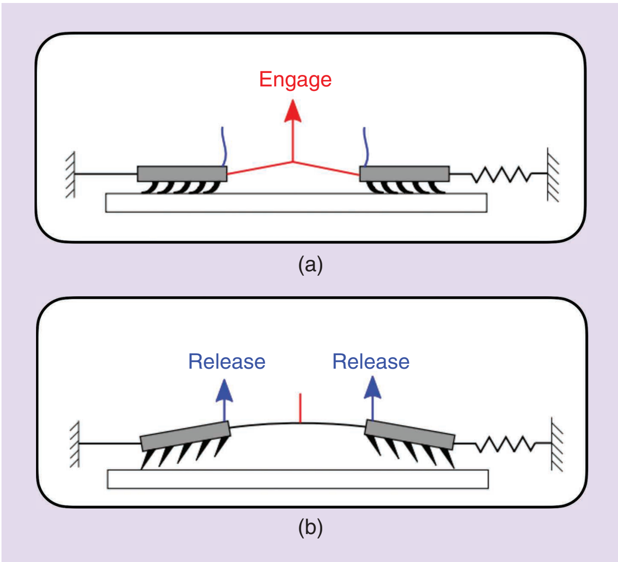


Figure 4. A schematic edge-on view of an adhesive tile pair indicating tendon topology and function. (a) The load tendon (red) applies an inward shear force engaging the adhesives; the tendon angle controls the ratio of normal-to-shear force. (b) To release, a second tendon (blue) pulls the tiles from one edge, causing them to peel.

and retreat if needed. The subsystem of tiles is on a floating suspension with 3 mm of travel perpendicular to a surface and approximately 0.174 rad to accommodate angular misalignment. The springs require just 0.6 N for a full compression of 3 mm. Given the low speed at contact (≈1 cm/s), this suspension provides enough time for the gripper to detect the collision and command the servos to engage the adhesives. After grasping, the suspension and pivoting wrist are locked.

Gripping is a timed sequence of actions. Astrobee first slows to 1–2 cm/s as it approaches a surface. In contrast to previous grippers using adhesive tiles (see, e.g., [16]), we cannot rely on gravity when placing the tiles on a surface before pulling the tendons, and we do not have a human positioning the gripper against a surface (see, e.g., [2] and [3]). Instead, we use a time-of-flight range sensor to indicate when the gripper has made contact, at which time we should tighten the adhesive engagement tendons [see Figure 5(b)]. This is done by applying finite differencing to the range measurements provided by the time-of-flight sensor to estimate the 1D velocity of Astrobee relative to the target surface. In practice, because there is some time delay, the process of tightening should begin shortly before the leaf springs are fully compressed. The time delay compensation is calibrated manually in testing, but ideally it should also depend on how fast Astrobee is moving. After gripping, the wrist servo centers and locks the wrist to hold Astrobee firmly in place.

The mechanical design presented in this section was designed around the existing platform of Astrobee while fulfilling all of the necessary design requirements of utilizing gecko-inspired adhesives. It provides a complete mechanical package of implementing a gecko-inspired adhesive gripper with another existing robotic system.

Control and Software Architecture

As noted earlier, the gecko gripper must serve as a drop-in replacement for the existing arm and gripper to more easily conduct testing with the Astrobee free-flying robot, both on ground and on orbit. This decision entailed a number of software integration efforts. An overview of the communication architecture is shown in Figure 6.

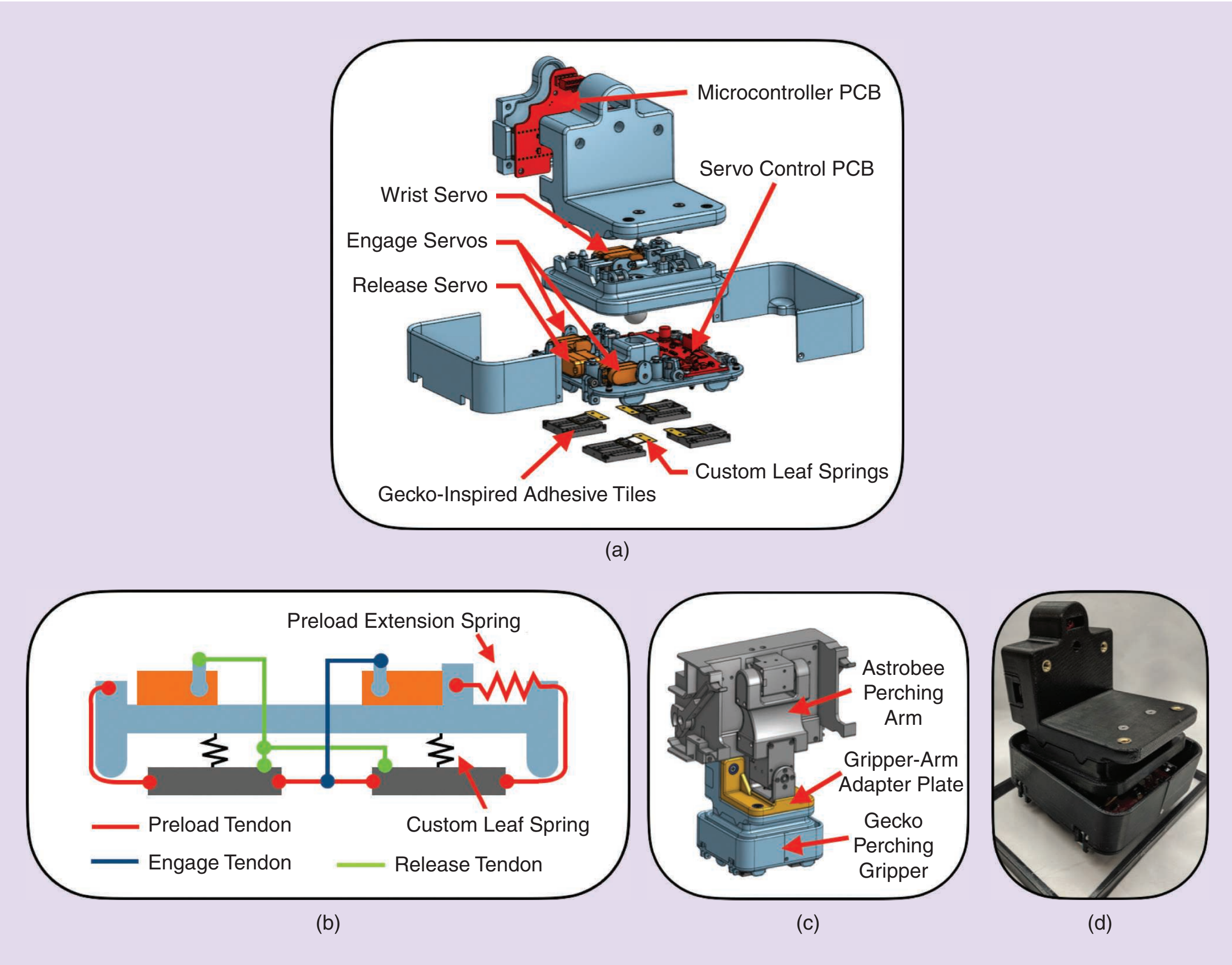


Figure 5. Mechanical systems of the adhesive gripper. (a) A partial exploded view of the mechanical and electrical components. (b) A schematic view of floating adhesive tiles with preload extension spring for lateral positioning and custom leaf springs for normal compliance. (c) Gecko perching gripper interfaces with the Astrobee perching arm through an adapter plate. (d) An assembled gripper unit. PCB: printed circuit board.

Flight Software Integration

Astrobee has three main flight computers: a low-level processor (LLP) that commands the propulsion system, a mid-level processor (MLP) that is responsible for running the primary flight software, and a high-level processor (HLP) that is used for relaying and processing guest science commands. Both the LLP and MLP run Ubuntu Linux, and the HLP is an Android computer. The three flight computers communicate internally over Ethernet. The flight software utilizes the Robot Operating System (ROS) middleware framework, which uses a publisher–subscriber architecture for asynchronous message passing among all three flight computers. Additionally, Astrobee uses PIC microcontrollers for running, among other subsystems, the perching arm control firmware.

For the gecko gripper, the firmware for the base PCB is written using the Teensyduino variant of the Arduino Integrated Development Environment. The gripper firmware receives and interprets commands to engage and disengage the adhesive, toggling between manual and perching modes, and is responsible for file input–output for the onboard Secure Digital card used to record data (see [17] for a full overview of the avionics commands). The PIC microcontroller for the Astrobee perching arm serves as the interface between the gecko gripper and the MLP.

For the MLP, the primary focus for integration is on modifying the flight software to accommodate the additional commands required for engaging and disengaging the adhesives and locking the compliant pivot. These commands are integrated into the existing perching arm interface.

During on-orbit experiments, Astrobee is operated through a ground control station that is set up for guest science researchers. The HLP serves as the interface between Astrobee and the ground control station as it receives commands from the ground station and sends back real-time telemetry being recorded on the MLP. A custom Android application is developed for this purpose. The Astrobee ground control station software is accessible as a custom GUI developed by the Astrobee group.

The code for the Android Package Kit running on the HLP, flight software for the MLP, and firmware running on the gecko gripper is publicly available at https://github.com/StanfordASL/astrobee and https://github.com/StanfordASL/astrobee gripper.

Gripper Commands

The gripper has two primary modes of operation: manual and automatic. In the manual perching mode, ground station operators issue commands for engaging (disengaging) the gecko adhesive tiles and locking (unlocking) the wrist servo. In the automatic mode, the gripper uses an on-board time-of-flight sensor to measure the distance to a target surface. When the target surface appears in the line of sight of the sensor, a simple linear interpolation scheme is used to estimate the time-to-contact delay with this target surface, and the gripper adhesives are engaged and the wrist servo locked after this delay period. As noted in the section "Main Experimental Insights," this estimated delay is a limitation of the current system, with implications for future adhesive docking of free-flying systems.

In this section, we detailed the integration efforts necessary to provide end-to-end control of the gecko gripper being developed for Astrobee. As detailed in the next section, this software integration effort was a necessary step for enabling on-ground and on-orbit system-level testing.

System Validation and Testing

After finalizing the perching gripper design, the next step in raising the TRL of this technology is to conduct extensive testing, following the timeline summarized in Figure 7, to verify the safety, performance, and functionality of the gripper units. The tests include qualifications necessary to launch a payload to space, test the performance of the gecko adhesives, and perform full system testing of the gripper with Astrobee.

Flight Qualification

Prior to launch, extensive testing of two flight gecko gripper units was conducted in early 2019 to validate their ability to survive launch and operate safely on board the ISS. To assess structural integrity, vibration testing was conducted at NASA ARC. This test involved simulating the representative loads that could be expected on a launch vehicle using a shaker table. Further electromagnetic interference (EMI) and acoustic testing were conducted at NASA's Johnson Space Center (JSC) (Figure 8) to ensure that the gripper units could be powered safely in the presence of astronauts.

EMI testing ensures that equipment is electrically compatible with ambient avionics and does not impede the functionality of critical systems, such as onboard computers or radio frequency communications [18]. For EMI testing, the flight gripper units were installed on an Astrobee unit, and the

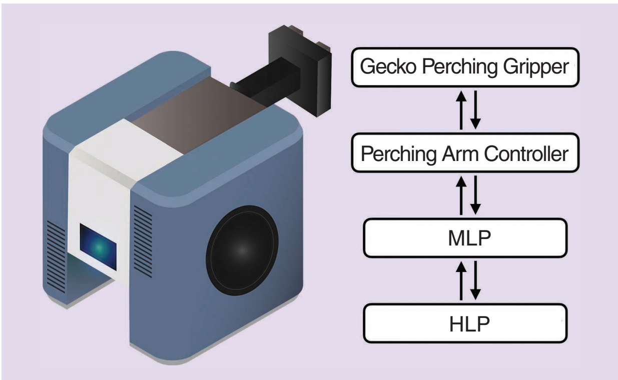


Figure 6. The communication chain for sending and receiving data required flight software integration with multiple flight computers on Astrobee. Ground station commands are received by an ROS node on the Android HLP and then are relayed to the Linux MLP providing the critical flight software functionality. These commands are then interpreted by the MLP and sent to the perching arm controller via serial communication. A microcontroller on the gripper finally receives and processes the data from the perching arm controller. ROS: Robot Operating System; HLP: high-level processor; MLP: midlevel processor.

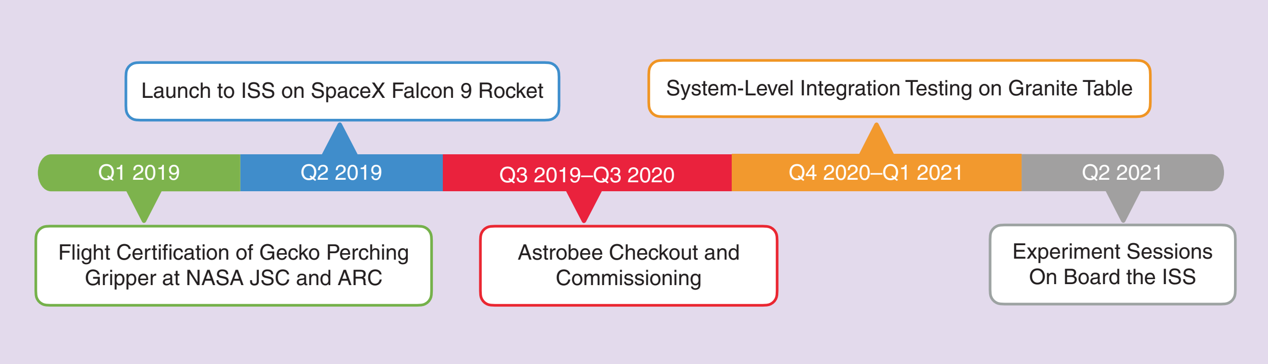


Figure 7. Development and testing was a multiyear effort. Two flight units were launched in July 2019 alongside Astrobee flight units that underwent commissioning through 2020. Further system-level ground testing was conducted in the fall, with detailed experiment planning in early 2021. Two experiment sessions were completed in April 2021. Q1: first quarter; Q2: second quarter; Q3: third quarter; Q4: fourth quarter; JSC: Johnson Space Center.

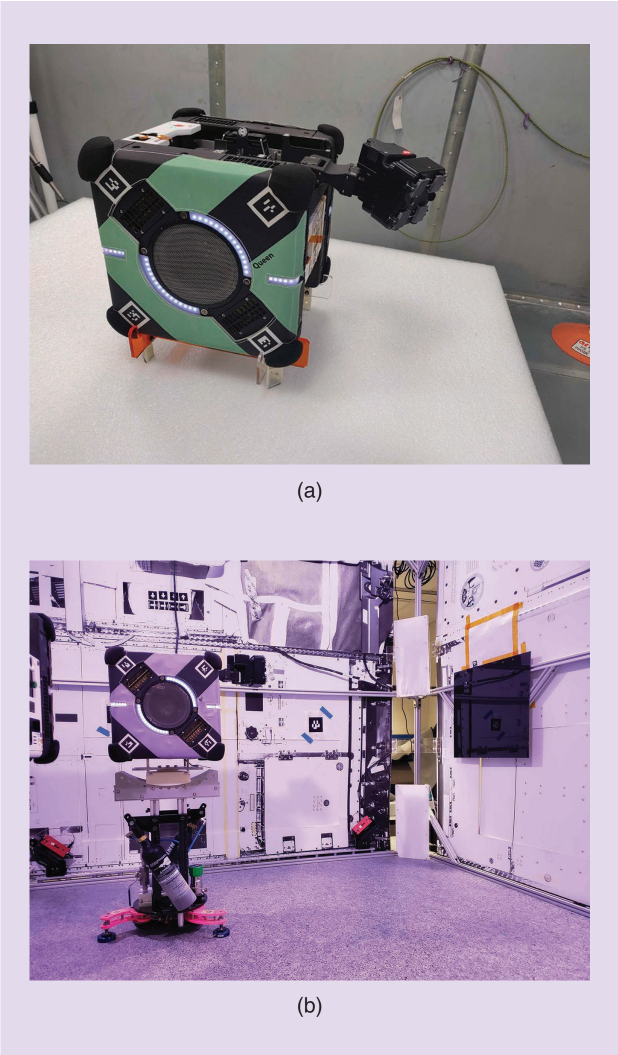


Figure 8. Flight qualification of the gecko perching gripper was accomplished through integrated, system-level testing of the flight gripper units and Astrobee. (a) EMI testing at NASA JSC to ensure electronic compatibility of the hardware with avionics aboard the ISS. (b) Functional testing of the gecko perching gripper and Astrobee on the NASA ARC granite table, a testbed that simulates a 2D microgravity environment.

robot and gripper were powered on. The gripper was then cycled through the full concept-of-operations (ConOps) commands to measure peak loads. Acoustic testing was also conducted in an anechoic chamber at NASA JSC. This test involved cycling through the ConOps commands with only the gripper powered.

Functionality Testing

Benchtop testing was conducted to validate and verify the adhesive performance. An identical ground unit was modified to be powered and controlled without the need for an Astrobee. A polished aluminum plate, similar to one of the panels tested in the ISS, was mounted to a six-axis force/torque sensor. The gripper was brought into contact with the surface, and the adhesive engage command was issued by pressing a button. Then the gripper was pulled away from the surface until the tiles released. Forces and moments were recorded, and the magnitude of the peak force was calculated for each trial. The force data are shown in a boxplot included in Figure 9 for comparison with data from tests conducted aboard the ISS.

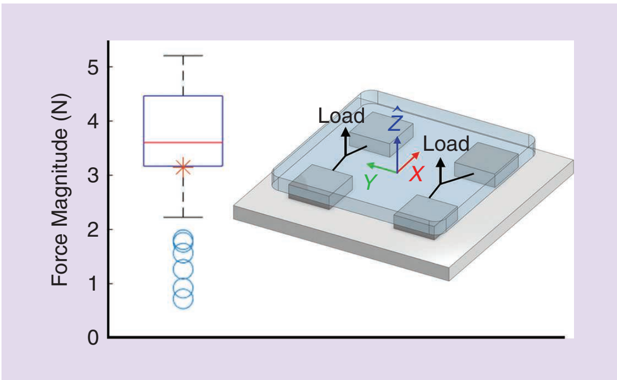


Figure 9. Pull-off force tests: ground testing data are plotted with the boxplot; blue circles represent data points collected during ISS Session 1 using the initial unit of the gripper with one pair of damaged tiles; red asterisk represents data from Session 2 with the second unit. The force magnitude measurements correspond to the $\hat{Z}$-axis direction illustrated on the right.

System Testing

Prior to on-orbit experiments, the functionality of the gripper integrated with Astrobee was tested using a third gripper unit. This ground unit allowed for continued flight software refinement and development of the flight ConOps. These tests were performed on the NASA Ames spacecraft robotic test bed, which is a 3 m × 3 m granite table that is precisely calibrated with a flat and level surface to simulate a 2D microgravity environment. Astrobee was placed on a carriage structure that floats on the table using frictionless air bearings [visible in Figure 8(b)]. The granite table platform allowed for full walkthroughs of the flight ConOps with the gripper integrated onto Astrobee and ground station control software being used by the Astrobee operator.

As flight software integration proceeded for the integrated gripper/Astrobee system, each integration milestone was validated through granite table testing. This allowed for modular testing and verification of communication between particular subsystems, e.g., verifying commanding and telemetry information between the perching arm Teensyduino microcontroller and the perching arm PIC microcontroller.

The floating air bearing tests provided some initial indication of the need to calibrate the time delay between the last available measurements from the time-of-flight distance sensor to the command to tension the cables. For a planar system, there is only one DoF for angular misalignment, and errors were small enough that grasping occurred reliably. As noted in the next section, the alignment challenges with 6 DoF can lead to unreliable autonomous perching.

The integration and validation efforts described in this section were necessary for the gecko-inspired adhesives and gripper to be approved for launch to the ISS. They provide a basis for raising the TRL of the adhesive technology and enabling future robotic manipulation experiments.

Experiments on the ISS

On 27 July 2019, two flight units of the gripper, alongside a force gauge and a flat aluminum plate serving as the baseline for adhesion testing on orbit, were launched to the ISS with the Dragon space capsule on SpaceX Commercial Resupply Services-18 mission. Because of a shortage of available crew time, the payload stayed in storage until early 2021 before two experiment sessions were scheduled for March 2021. The goals of each session were as follows:

1) *First session*: Check out one of the gripper units and perform manual testing to verify the functionality of the gripper and establish a baseline for adhesive performance, measured using the force gauge.
2) *Second session*: Attempt autonomous perching at preselected locations inside of the ISS to demonstrate the capability of the gecko-inspired adhesive with Astrobee in a zero-gravity environment.

Each session was allocated approximately 2 h of experiment time, resulting in about half a dozen perching attempts after accounting for time resetting the robot, cleaning test surfaces, and accounting for loss of communications with the ISS.

Experimental Setup

To facilitate the experiments, a ground control station was set up at the Stanford Autonomous Systems Lab to monitor live telemetry and video, securely communicate with the experiment team, and send commands to Astrobee as necessary. Ground station operators included researchers from Stanford, an Astrobee operator responsible for sending commands to the robot, and the operations engineer responsible for communicating with the astronaut. Each experiment session involved a single gecko perching gripper unit installed on Astrobee and an astronaut involved to support the activity.

Commands issued from the ground station were sent to the ISS via the Tracking and Data Relay Satellite system, and these commands were then processed by a workstation on board the ISS. The workstation relayed these commands to Astrobee over the onboard wireless network. The Android HLP received these commands, which were then sent along the MLP, perching arm PIC microcontroller, and gecko gripper firmware chain detailed earlier. To account for the delay in communication between the ground station and the ISS, our command sequence was consolidated into higher level routines sent to the robot, which were then processed by the robot state machine to execute the desired behavior.

ISS Experiment Session 1

On 5 March 2021, the first ISS experiment session was supported by astronaut Dr. Kate Rubins. The first unit of the gecko perching gripper, along with the force gauge and testing surface, was unpacked, and the gripper was installed onto an Astrobee perching arm. As shown in Figure 10(a) and (b), this session entailed measuring adhesion forces of the gecko perching gripper using the test surface and force gauge setup. The recorded data allowed for verification of the adhesive performance, following nearly 20 months in storage on the ISS. The forces recorded in this experiment session are included in Figure 9, plotted as blue circles.

Compared to ground testing results, the forces recorded were approximately half that expected for an intact gripper, indicating damage to one of the pairs of tiles. Upon visual examination provided via video feed, one pair of tiles was indeed found to be damaged.

ISS Experiment Session 2

Six days later, the second ISS experiment session was conducted by Commander Victor Glover, Jr. [Figure 10(c)]. Because of the observation of the damaged adhesive tile in the first session, a decision was made to unpack and use the second gripper unit. There was very limited astronaut time, so it was decided to focus on manual perching tests rather than autonomous Astrobee-controlled perching. The 3.15-N measured force for manual perching, included in Figure 8(b), fell within expected values from ground-based testing, indicating that the unit was not damaged. Once manually perched, Astrobee was also able to perform a pan-tilt maneuver.

By testing the integrated gecko gripper with the Astrobee AFF, this on-orbit testing successfully raised the TRL of the gecko gripper technology from TRL-3 (experiments from ground-based benchmarks) to TRL-5 (testing the module in a relevant environment).

The Main Experimental Insights

In general, the adhesive materials performed as anticipated on smooth surfaces, matching force results previously obtained in ground-based testing. However, the tests also revealed some considerations for future work. First, as noted, one of the gripper units was damaged, despite careful packing and handling. Fortunately, the design incorporated two sets of adhesive tiles in redundancy; thus, the experiments were able to continue. Nonetheless, this issue points to a need for robust and redundant designs. Damage will occur, and tiles should be easy to replace in future iterations—something the current design does not permit because the tendons are tied and glued in place.

A second issue arose in testing with Astrobee. The fundamental requirement is that gecko adhesives need to establish intimate contact over the whole contact area immediately prior to applying loads. The solution consisting of adhesive tiles and tendons works well in terrestrial pick-and-place applications where gravity holds each tile against a surface before applying tension to the tendons. The tendons subsequently ensure a proper ratio of normal to tangential forces to remain within the adhesive limit surface [3]. For perching unmanned aerial vehicles (UAVs), the tendon/tile solution also works, when combined with substantial passive compliance and damping to absorb kinetic energy at contact [19]. In that case, the UAVs used an accurate offboard motion capture system and were capable of aggressive late-stage maneuvers to ensure alignment.

The situation for free-flying robots in space is different. For Astrobee, the large mass (10 kg, 0.15 kg/m^2 inertia) combined with gentle thrusters (0.06 N, max) limits angular accelerations to approximately 0.2 rad/s^2. This comparatively low actuator authority, combined with uncertainties of up to 3 cm in localization due to the use of onboard vision, means that the final approach of Astrobee toward a surface is essentially without an ability to make final adjustments in velocity and orientation. Therefore, in the next section, we present recommendations for future application of gecko-inspired adhesives on free-flying robots in space.

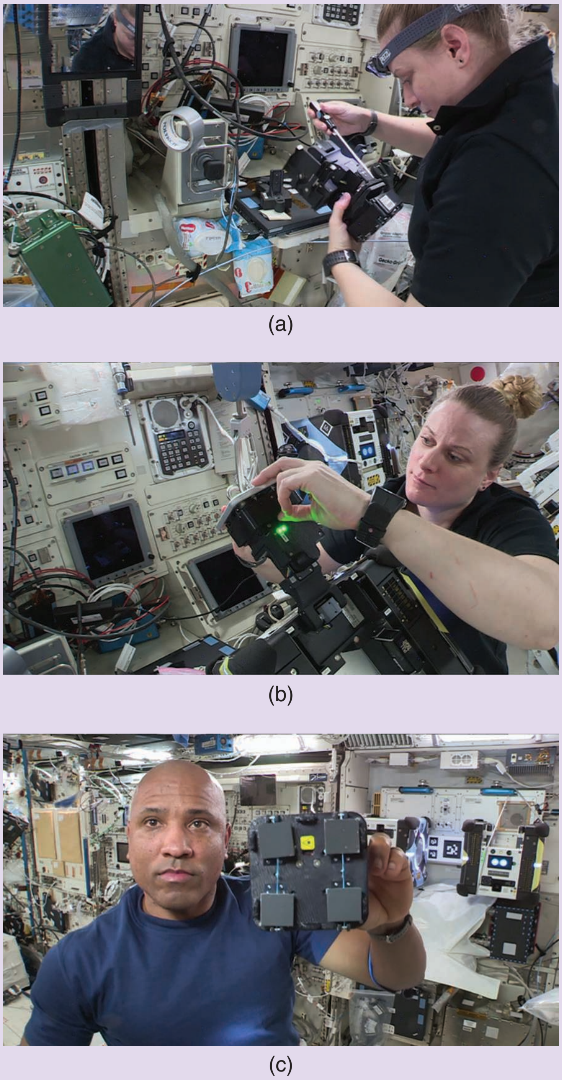


Figure 10. (a) and (b) Astronaut Kate Rubins performs manual tests of the undamaged gripper tiles against a smooth aluminum plate, triggering the gripper to attach and release. A gauge attached to the plate with a carabiner records the pull-off force. (c) Astronaut Victor Glover holds the second gripper for visual inspection of the adhesive tiles before testing in Session 2.

Conclusions and Future Work

We have presented a system that allows a free-flying robot to attach to surfaces using gecko-inspired adhesives in space. The system was compatible with the rigors of launch and use inside the ISS and survived in storage for more than a year. In tests it produced levels of adhesion comparable to those obtained in ground-based testing.

The tests also revealed some insights for future applications of gecko-inspired adhesives for free-flying robots in space. For example, while the inertia and actuation numbers given previously apply specifically to Astrobee, future free flyers for intravehicular activities or EVAs are likely to have similar limitations on acceleration and final course correction. Thus, an insight from the project is that future gecko grippers should be capable of absorbing kinetic energy and accommodating angular misalignment internally, without relying on control of the robot. Moreover, grippers should have sufficient sensing to determine when all tiles are in coplanar contact with the intended grasping surface so that they can apply tension at the right moment. A single range finder, as used in the current gripper, only gives an average distance measurement and, moreover, does not work when the distance drops below 20 mm. The resulting perch strategy is not robust because it relies on a calibrated time delay (which depends on the Astrobee velocity) between the last available distance measurement and an estimate of when to tension the tiles.

An alternative solution is to design a system that provides passive alignment and grasping, using the kinetic energy of the free flyer. This solution would require that the free-flyer approach the surface at a velocity of several centimeters per second, so that it has enough kinetic energy to align and trigger a gripper and load the tiles.

Another promising extension for future work is to employ hybrid electrostatic/gecko tiles [20], [21]. A Maxwell stress of about 2 kPa at 3 kV can gently pull the tiles against a surface, effectively taking on the role of gravity in terrestrial pick-and-place operations. However, this solution may not be desirable for grasping of solar panels or other electronic items.

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