Microspine Gripping Mechanism for Asteroid Capture

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Abstract

This paper details the development and early testing of a compliant suspension for a microspine gripper device for asteroid capture or micro-gravity percussive drilling. The microspine gripper architecture is reviewed, and a proposed microspine suspension design is presented and discussed. Prototyping methods are discussed, as well as testing methods and results. A path forward is identified from the results of the testing completed thus far. Key findings include: the microspine concept has been established as a valid architecture and the compliant suspension exhibits the desired stiffness characteristics for good gripping behavior. These developments will aid in developing the capability to grasp irregularly shaped boulders in micro-gravity.

Introduction

Recent exploration efforts have been focused on Mars and near-earth asteroids. However, current mobility technology (e.g., wheeled vehicles and touch-and-go probes) are inadequate for detailed exploration of sub-surface Martian caverns or the micro-gravity environment of asteroids [1]. Gravity-independent microspine grasping mechanisms have been demonstrated to have the necessary mobility to access these difficult terrains. Proof-of-concept robots such as SpinyBot and Lemur IIB have been shown to provide climbing capability and gripping force in the presence of gravity, and have additionally been demonstrated to function in inverted, harder-than-zero-g tests [2].

A central element of these systems is the mounting of spines to compliant suspensions that permits the system to conform to rough surfaces, placing a large fraction of many spines in contact with the surface [3]. Many microspine grippers thus far demonstrated have relied on polymer and elastomer flexure elements (the part of the suspension that deflects to achieve motion), which will not perform adequately in the space environment. To advance the technology and enable missions in space, the flexure components of the microspine must be converted to space-grade materials that will function robustly in the space environment.

This paper details the current state-of-the-art of microspine graspers, discusses the current proposed flexure system, and presents the testing methods used to validate the new flexure design. Results are discussed and design refinements are proposed.

Background

Microspine grippers seek to imitate insects and arthropods that use the large numbers of small spines to climb surfaces [3]. These spines engage with asperities on rough, hard surfaces to provide grip. Because the number of spines is large, the load can be distributed among the spines so that the load on an individual spine can be quite small and still in aggregate react large forces normal to the surface. In robots, these spines can are mounted on an architecture of hierarchical compliance: robotic arms position the gripper over the surface to be grasped, a linkage arm positions cassettes along macro contours of that surface, and microspines opportunistically grasp local surface asperities to provide grip. The motion of an individual microspine allows it to conform to small-scale surface roughness, and is provided by a compliant suspension.

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This concept was originally developed to provide the ability to climb porous and dusty vertical walls. It also has applications in exploring rocky or icy space environments. Since the microspine gripper does not rely on reaction forces from the surroundings to provide preload, it can be used in micro-gravity to provide reaction forces for other operations. For example, microspine grippers could be used in conjunction with a percussive impact drill, providing the necessary reaction force to hold the drill against a surface. Such a gripping mechanism could be used to retrieve a boulder from an asteroid.

Design Refinements

Development of this design is targeted on the objective of increasing the load capacity of the microspine gripping device. This follows two avenues: increase the number of microspines engaged in a given surface, and eliminate failure modes observed in the suspension. These failure modes include flexure pull-out and tangling. Subtle geometric changes in the suspension and gripper are being explored to increase the number of spines engaged with the surface. Alternative manufacturing methods may be able to mitigate the flexure pull-out, while more accurate manufacturing may reduce the tendency of the suspension to tangle with adjacent suspensions.

Gripper Design

This section gives an overview of gripper concept of operations (CONOPS) and summarizes some historical variations.

Gripper CONOPS

The microspine grippers that have been constructed at the Jet Propulsion Laboratory include a variety of architectures, but share several essential features. They all are used to provide reaction forces based on a rough surface. Operations proceed along a similar outline (see Figure 1).

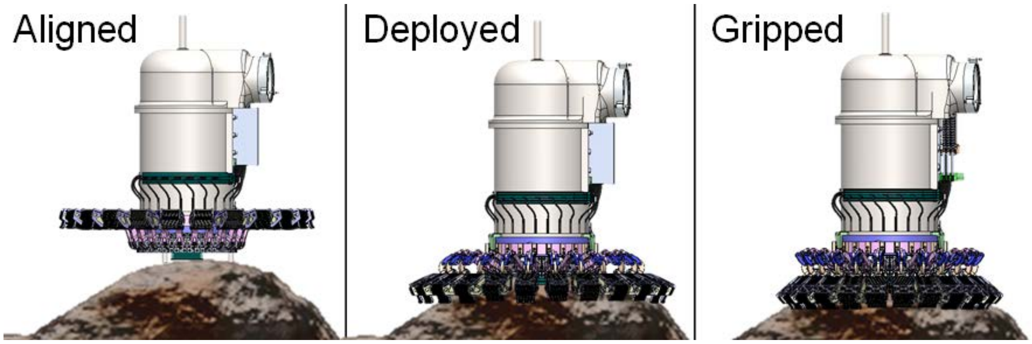

Figure 1. Illustration of gripper function, broken into three steps: alignment with the surface, deploying the microspine carriages, and gripping of the surface.

1. The gripper is placed in contact with a surface and aligned with the surface normal.
2. The microspines are dropped so that they make contact with the surface.
3. The mechanism applies tension to the microspines, so that all of the spines are dragged in towards a central axis.
4. The tool is now in the “gripped” state, and can be used to support various activities, including drilling, crew activity, towing or similar tasks.
5. Tension is unloaded in the system, bringing the tool to a “released” state.
6. The gripper tool can now be lifted away from the surface.

Historical Variations

This technology has been applied in many different configurations. Figure 2 shows a sampling of some of these designs.


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Figure 2. Examples of previous incarnations of microspine grippers. Top: NEEMO anchors. Upper middle: Lemur IIB climbing robot. Lower middle: Hand-actuated climbing paddles. (Parness and Discovery Channel, 2009) Bottom: Test grippers with elastomer flexures (left) and aluminum hoop flexures (right).

The following sub-sections describe functional elements common to all microspine gripper designs.

Spines

The spines on each gripper provide the surface interface. A variety of sizes and profiles have been investigated, but most systems have used #6 fish hooks, cut off to an appropriate length. Sizes from #4 to #26 have been used in various configurations. These hooks get mounted in the next assembly by pressing into a cavity, then potting with epoxy. The primary selection criteria for a given application are strength to support the estimated loads, and slenderness and sharpness appropriate to intrude into asperities expected to be present in the gripping surface. That is, smaller hooks can take advantage of finer asperities, larger ones can support more load on each hook.

Surface Conformance

The spines described above are mounted into a flexible element that provides a degree of conformance to the surface. This flexibility enables the hook to make contact with the surface while allowing other spines to continue moving towards the surface. The design goal is to maximize the number of hooks that make contact with the surface and establish a firm grip.

For cases where the microspines are grouped into “cassettes” or “carriages”, a roll degree of freedom was implemented to allow the group to conform to the bulk surface angle.

Load-Sharing

Similarly, as a groups of spines is dragged across the surface, some spines will catch in asperities before others. It is desirable that the spines that have not yet caught continue to move along the surface until they catch, or the mechanism end of travel is reached. However, compliance in this degree of freedom must produce high forces to provide grip.

Movement across surface/Application of Tension

Grippers have used a variety of sources for the primary tension that drags the spines across the surface. Some handheld units use the grip force of a hand to actuate. The ARM gripper will use a motorized tool drive on the spacecraft to drive a lead screw, producing motion across the surface.

This movement has also been transferred in a variety of ways among the historical examples shown in Figure 2. The Lemur and NEEMO grippers used a straight shaft pulled through a rotating barrel joint. The “Alien Wire Gripper” used compliant wires sliding through a 3D-printed channel.

Motion Takeup

The gripper is designed so that a single actuator applies the inward (x-direction) pulling force. However, the individual carriages may not all move inward the same amount. To absorb these differences in motion, the carriages are cable actuated with springs in series with the actuating cables. When a single carriage has a sufficient number of its microspines engaged with the rock surface, the cable spring will begin to deflect. This allows the actuator to continue to move or apply increasing force to the other carriages without over-actuating fully-engaged carriages.

Each stage of the system is designed to share load among an uncertain number of elements that are engaged with an unknown surface.

Microspine Suspension Design

Design Requirements

Design requirements were derived from previous experience using microspines in climbing and grasping robots. Approximately optimal stiffness values were found from prototypes using elastomer flexure elements; one key challenge was designing a metal suspension system that could match the low stiffness of the elastomeric versions. These design requirements are listed in Table 1. Z is the direction orthogonal to the surface to be gripped, and x is the radial direction.

Table 1. Key design requirements for stiffness and motion of the compliant suspension.

Metric	Value
k_z	0.005 N/mm
k_x	0.5 N/mm
Δz	0.010 m
Δx	0.012 m
Maximum rotation	15°
Maximum envelope	0.075 m x 0.075 m x 0.002 m
Factor of safety on material failure	1.25

In addition to the quantifiable design requirements listed above, several requirements were proposed that cannot easily be reduced to a single number. These are listed here:

- The mechanism should be simple to build in desired quantities
- The mechanism's x-direction stiffness should sharply increase at the extreme limit of travel
- The mechanism should be capable of nesting with itself to enable greater density of microspine placement
- The mechanism should, as much as possible, isolate x and z displacements

Design Overview

The key feature of the proposed design (shown in Figure 3) is that it achieves the required low-stiffness performance by utilizing metal ribbon flexures arranged to form two orthogonal parallel-guiding mechanisms. This serves the function of isolating the x and z stiffness values, allowing them to be independently tailored. Additionally, displacement is partially decoupled. Finally, the rotation of the end stage is inherently small.

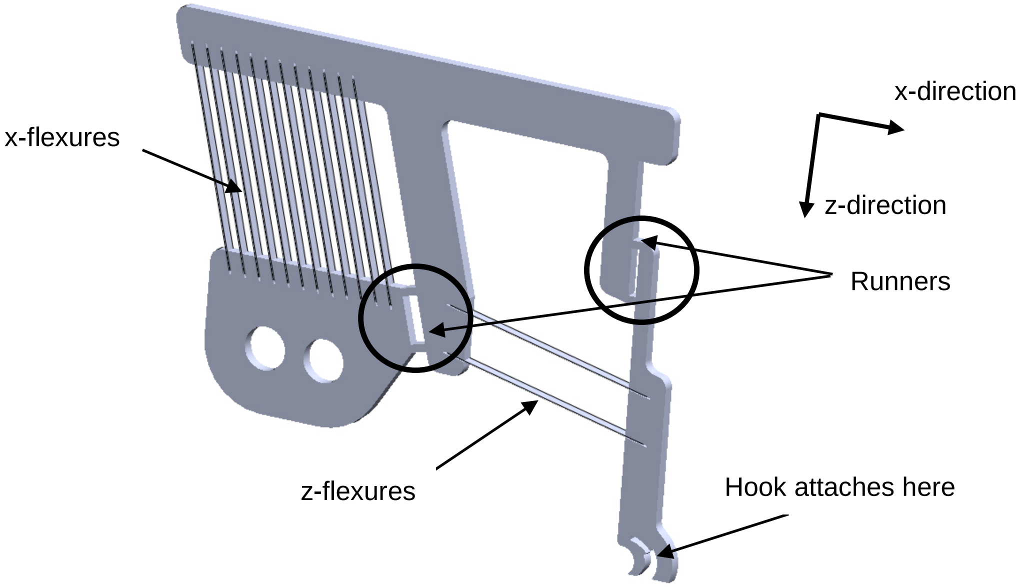


Figure 3. Rendering of CAD assembly model of microspine suspension indicating key design elements.

By mounting ribbons in a parent material instead of using the parent material itself, the combined mass is reduced and the target stiffness for each degree of freedom can be achieved more reliably. The slenderness of the metal ribbon provides the desired compliance while the parallel-guiding nature of the mechanism restricts its motion to the desired directions.

The x-flexures and z-flexures provide motion in the x- and z-direction, respectively. The stiffness of these two flexure systems must be dramatically different – by two orders of magnitude. This stiffness difference is accomplished using two strategies. First, the x-flexures are much thicker than the z-flexures. Second, as the upper limit of thickness was approached in the x-flexures, more flexures were added. This addition of flexures increased stiffness without increasing maximum stress.

The proposed parallel-guiding design was initially analyzed using the pseudo-rigid-body model approximation [4], and then the design was analyzed using finite element analysis in the commercial package ANSYS. The finite element model is shown in Figure 4. For simplicity, these models only analyze the flexures; the rigid sections are neglected.

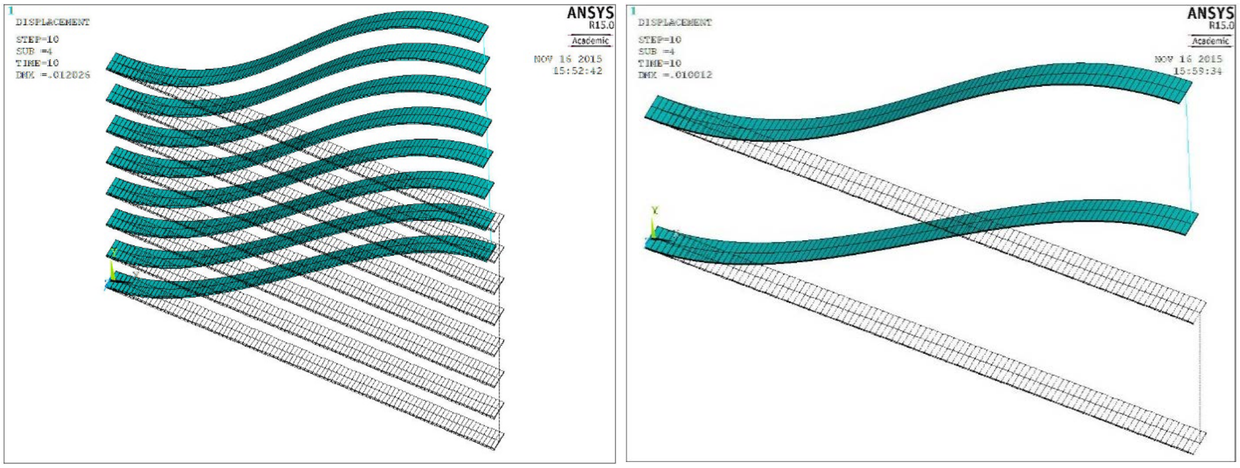


Figure 4. Finite element models of the x-direction flexures (left) and z-direction flexures (right). Green elements are the displaced state; outlines show the initial state.

It was found that neither wire electro-discharge machining (EDM) nor water-jet cutting would be able to fabricate extremely slender flexures. If these manufacturing methods were used, thicker flexures would have to be employed. With thicker flexures, the flexure would need to be unacceptably long to avoid material failure and would violate the envelope restrictions. Thus, the complexity of affixing metal ribbon flexures was deemed acceptable due to the significant performance advantage.

Design Details

Refer to Figure 3 during the following explanation of design features. Two candidate materials were considered for the flexures. 1095 spring steel at a full hard temper is available in a range of standard thicknesses and has a high yield strength. Alternatively, the class of alloys known as metallic glass offers high performance, but alloys available in ribbon or sheet form are limited, and low-quantity production of custom alloys is expensive. However, metallic glass is a superior choice for the flexure material because of its high S_y/E ratio. Finite element models and preliminary testing showed that the steel flexures would yield slightly if taken to the full displacements in the x- or z- directions. The low cost of steel made it acceptable for prototyping, but superior performance is predicted if the challenges of procuring metallic glass ribbon can be overcome.

To simplify fabrication, the rigid three sections are all cut from the parent material as one piece. Connected by runners, these sections are to remain together until the flexures are fixed in place. Then the runners can be severed, allowing the mechanism to move freely.

The hook attachment is accomplished first by harvesting the tips off of commercially fishhooks, then pressing the hook into the hook attachment geometry. The gaps are then filled with aerospace epoxy, which is allowed to cure. When the design enters production, it is intended that hook tips can be specially ordered to eliminate the harvesting step.

Prototype Fabrication

While much information on the stiffness and displacement behavior of the compliant suspension can be discovered from finite element modeling, the gripping behavior and interactions with neighboring microspines is difficult to model. Therefore, several rounds of prototyping were employed to investigate the behavior of the suspension.

To lower costs and reduce lead time, initial prototypes were laser cut from 1.6-mm-thick acrylic sheets. They were built at 1:1 scale. Flexures were cut from steel shim stock of the appropriate thickness using hand shears. The shearing operation imparted significant curvature to the flexures, which was removed by plastically deforming the flexures to straighten them. The flexures were then cut to length and fixed to the acrylic cut-outs with cyanoacrylate. These prototypes are shown in Figure 5. In early versions, the fishhook was omitted to decrease prototyping time and improve safety.

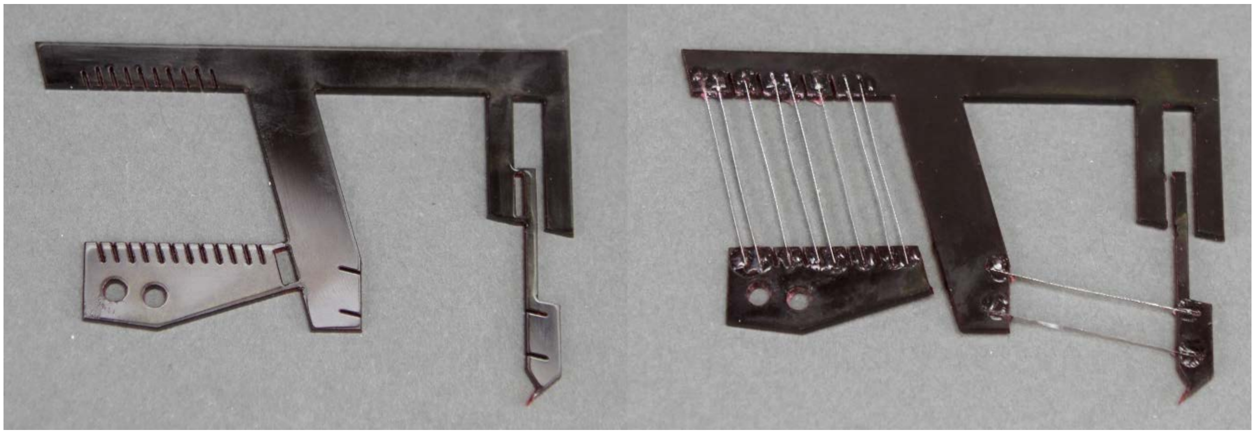


Figure 5. Acrylic-steel prototypes in two stages of production. On the left is the acrylic suspension body before the addition of steel flexures. Note that the three independent sections are held together with runners. On the right is the completed prototype with steel flexures embedded and runners removed.

These acrylic-steel prototypes were subjected to the stiffness testing described in the next section. Once the accuracy of the finite element model was established, additional prototypes were fabricated to observe their behavior as an array. In this iteration, steel hooks were included to facilitate initial tests of grasping ability.

The behavior of these acrylic-steel prototypes was sufficient to warrant further investigation and aluminum-steel prototypes were built. The aluminum was cut from 1.6-mm (1/16th-inch) 6061 aluminum sheet material on a waterjet cutter. Future versions could be cut using a wire EDM to improve machining precision, or using waterjet to do most of the cutting and then using EDM to cut the finer details such as the channels where the flexures attach. A waterjet-cut blank is shown in Figure 7.

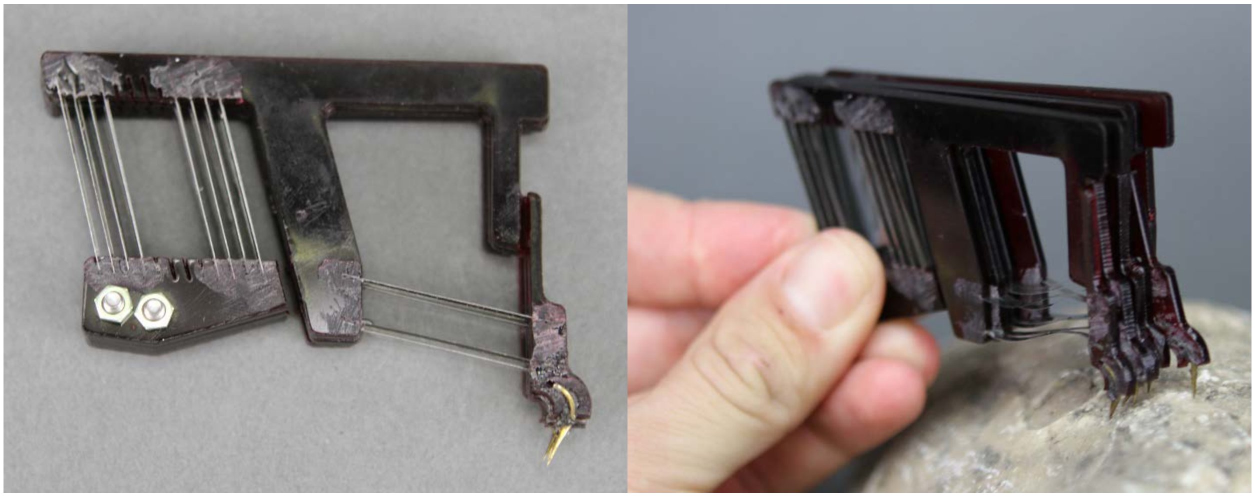


Figure 6. An array of acrylic-steel prototypes.

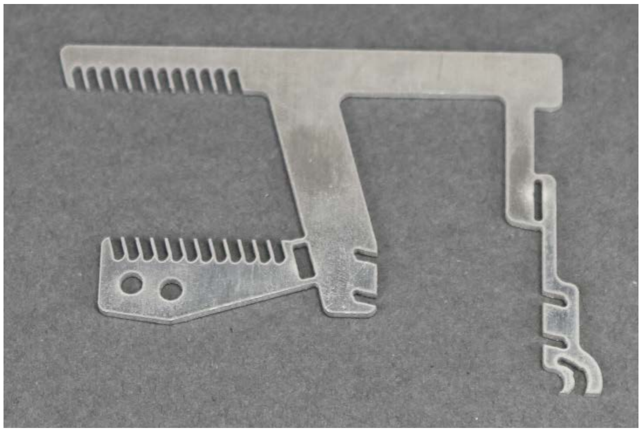


Figure 7. An aluminum blank into which steel flexures will be bonded.

After cutting on the water-jet, the blanks were de-burred. Because of the large kerf of the water-jet, the flexures were fixed in place with adhesive tape prior to bonding. The tape was arranged to form pockets into which epoxy was injected, bonding the flexure to the aluminum. This process was labor intensive; future iterations will be altered to avoid the painstaking application and removal of the tape. Alternatively, Teflon fixtures could be designed to contain the epoxy and hold the flexures during curing. In all, 24 aluminum-steel prototypes were built and tested. These were assembled into the test gripper and loaded. Testing is further described in the following section.

Testing

At this point the design is currently undergoing testing and design refinement. Initial testing separately measured stiffness of the suspension along each desired motion direction. Then a sufficient number of prototypes were built to allow for a gripping capacity test to be conducted on natural rock surfaces using a test stand. The maximum load supported by eighteen microspine suspensions and spines in a test gripper was measured; results indicate that the design merits further testing and refinement.

Stiffness Testing

To confirm that the new suspension design met stiffness targets, individual suspensions were tested in a force-displacement jig. A known displacement was applied and the resulting force was measured. This testing is shown in Figure 8.

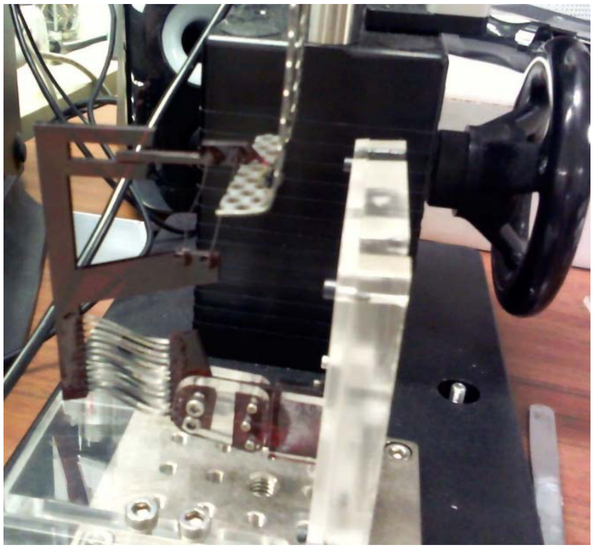


Figure 8. Stiffness testing of the x-direction suspension. This prototype was constructed from laser-cut acrylic (1.6-mm thick), with steel shim stock for the flexures.

Grip testing

Figure 9 shows the test equipment used to obtain data on the gripping capabilities of the microspine flexures.

Figure 9. Testing on the microspine gripper in a test fixture. Top: The entire test fixture, with independent x- and z- stages to test gripping force in each direction (the rock is scoria). Bottom: Close-up view of microspines during testing (the rock is rhyolite).

The purpose of grip testing is to quantify the force a given microspine design can support. The rig shown in the top half of Figure 9 is able to measure the forces in the x- and z- directions independent of one another. Although the x-direction force may not seem to contribute to the vertical load capacity, there is a relationship between the load capacities in the x- and z- directions. This test setup gives more repeatable results more rapidly and requires fewer microspine specimens than other testing techniques that consist of attempting to lift large rocks.

Results

The most important design function is to provide a large reaction force. Therefore, the gripping force in the x and z directions was measured as the critical performance metric. Figure 10 shows a plot of force testing data with x-direction force plotted on the x-axis and z-direction force plotted on the y-axis. This single carriage of microspines is generating nearly twenty newtons of vertical reaction force. Used in an array, as is typical for this architecture, the total vertical reaction force could reach hundreds of newtons.

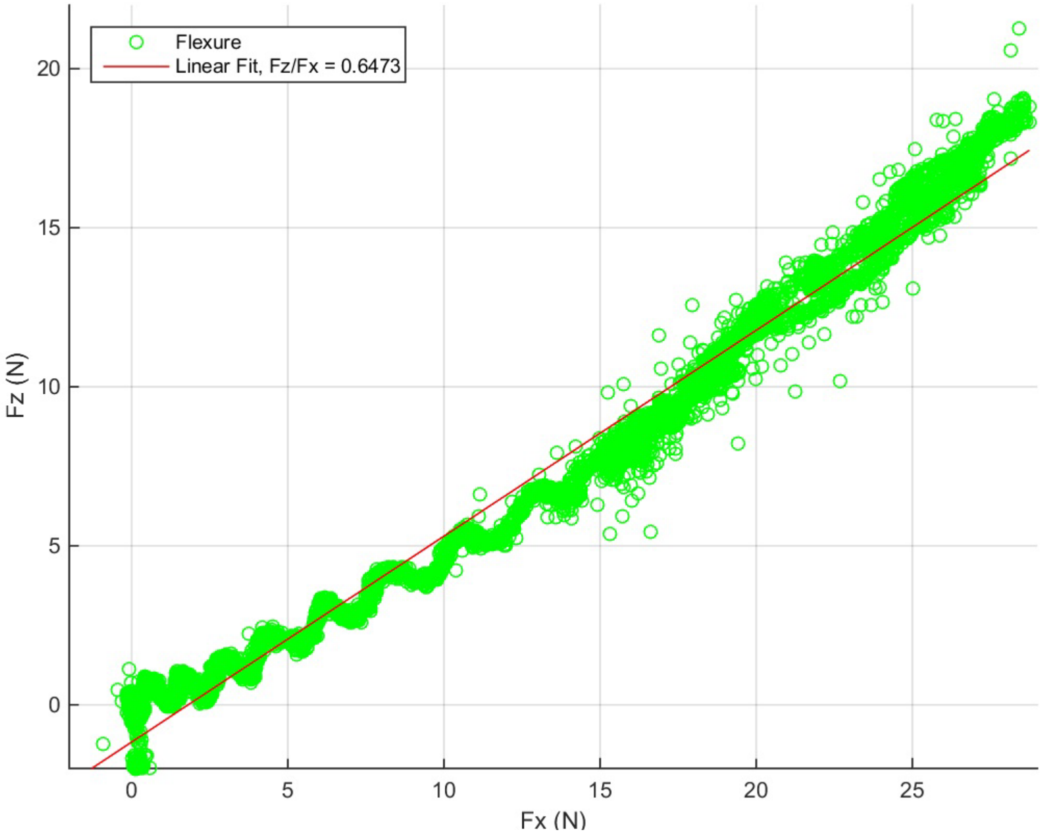
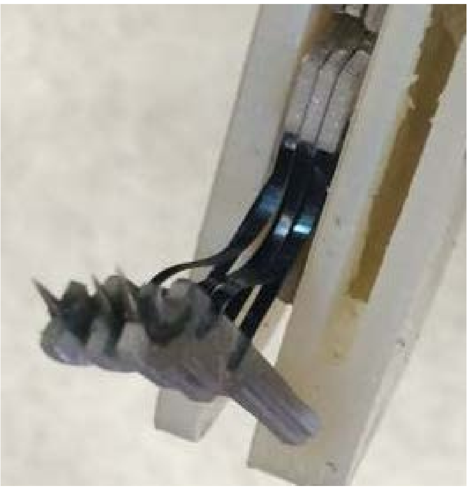


Figure 10. Representative plot of x- and z- directional forces.

In these early stages of testing, we discovered many design issues that must be addressed. Figure 11 shows several of the most common or serious issues that arose.

The original test gripper experienced interference with the rock sample, necessitating a redesign that provided adequate clearance.

If an x-direction compression load is exerted on the z-direction flexures, this crimping failure can result, indicating the need to protect the flexures from compressive loads.



The flexure arrays being bolted too tightly into their carriages caused this binding/tangling failure. Here, the flexures are only undergoing elastic deformation and can be untangled without loss of performance.

This photo shows a hook that has shifted in its mounting epoxy due to a high transverse load.

Another binding/tangling failure. Layering thin Teflon sheets between the microspines has been proposed as a solution to the tangling problem, and it may also alleviate the binding issue.

Pullout failure of the z-direction flexure due to overload in the x-direction. This failure must be guarded against with better surface preparation of the flexure material.

Test run incorporating divider sheets to reduce tangling.

Figure 11. Several design issues that came to our attention during testing.

Design Changes

One of the most important shortcomings in the suspension design was the susceptibility to tangling. To remedy this, divider sheets were included between neighboring microspines. Other problems revealed included susceptibility to binding, flexure pull-out, and flexure crimping. The binding and crimping problems are being addressed through changes in the carriage design that prevent pinching and x-direction compressive loads. Flexure pull-out will be addressed by using better surface preparation and high-quality epoxy that is not past its shelf life.

Conclusions

This work presents the development of a compliant suspension for a microspine gripper assembly suitable for use in space as a drill anchor or as part of an asteroid-capture mission. A brief overview of the microspine architecture has been presented, along with the design details for a compliant parallel-guiding suspension system. The testing method has been outlined and results summarized.

It has been shown that the proposed design has potential to provide adequate gripping force in asteroid-capture or micro-gravity drilling application. The critical issues of tangling, binding, and flexure pull-out appear solvable and are currently being addressed. With additional design, prototyping, and testing, the microspine architecture could provide a reliable, scalable, space-capable anchoring system.

Lessons Learned

- The microspine architecture can be effectively translated into space-grade materials.
- The rock surface-microspine interaction is complex and stochastic, making modeling difficult. Therefore, extensive prototyping and testing is necessary to understand performance.
- Proper use of inexpensive prototypes can speed development compared to purely analytic or numeric models
- Proper consideration should be given to all stages of manufacturing and assembly to produce meaningful test specimens.

Acknowledgements

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