Microgravity Coring: A Self-Contained Anchor and Drill for Consolidated Rock

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Abstract—**The Microspine Drill, a self-contained anchor and rotary percussive drill, is presented. The Microspine Drill can core in an inverted orientation into consolidated rock, a** *harder-than-zero-g* **proof of concept. The anchor extends the use of microspines to microgravity environments. Microspines, originally developed for climbing robots, use arrays of hooks with passive suspension structures to opportunistically grasp rough surfaces and share loads across many contacts. Utilizing radial arrays and hierarchical compliance, this new system creates omni-directional anchors. Prototypes have demonstrated anchoring strengths of >155 N tangent to, >150 N at 45° to, and >180 N normal to the rock surface. Using a weight-on-bit of ∼60N, 20 mm diameter boreholes were drilled 83 mm deep into vesicular basalt and a'a samples while retaining 12 mm diameter cores. The anchor-drill combination can be used to acquire samples and set up rope networks during future manned missions to near earth objects. The instrument also enables gravity independent sample acquisition from rock surfaces for science missions to asteroids, comets, or the walls and ceilings of lava tubes, craters, caves, and other extreme planetary terrains.**

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1. Introduction

Asteroids and Comets are uniquely of interest to the science, human exploration, and planetary defense communities, making technologies that can address gaps in our capabilities or enhance mission to these objects inherently cross cutting.

Asteroids and comets contain some of the most primitive material in the solar system that may date back to planetary accretion [1], [2], [3]. Sampling and analyzing the rock and regolith has the potential to answer longstanding questions about the formation of the solar system. Comets, in particular, also contain organic material that was identified in Wild 2 samples and through remote sensing observations[4], [5]. The Astrobiology Roadmap prioritizes the exploration of cometary material because this organic content may be related to the origins of life on Earth [6].

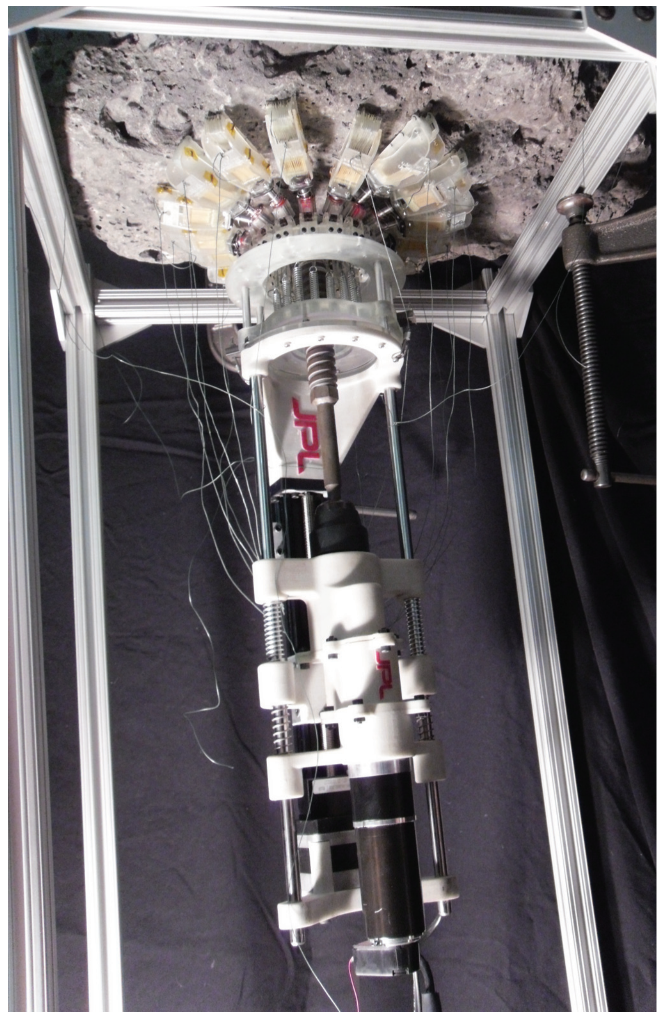

Figure 1. The Microspine Drill is an instrument capable of anchoring to and coring into consolidated rock regardless of the magnitude or orientation of a gravitational field (1g or less). The instrument is shown here coring into a piece of vesicular basalt in an inverted configuration on Earth. The instrument creates a 20 mm diameter borehole up to 82 mm deep in the rock while retaining a 12 mm diameter rock core sample. The Microspine Drill enables scientific missions to asteroids, comets, and extreme planetary terrains like the faces of cliffs and the ceilings of lava tubes where it can obtain rock cores for analysis or sample return. The instrument also has uses as a tool in manned NEO mission scenarios for setting up networks of ropes and anchor points that would enable astronauts to safely explore the surface.

[1] IEEEAC Paper #1335, Version 1, Updated 09/14/2011.

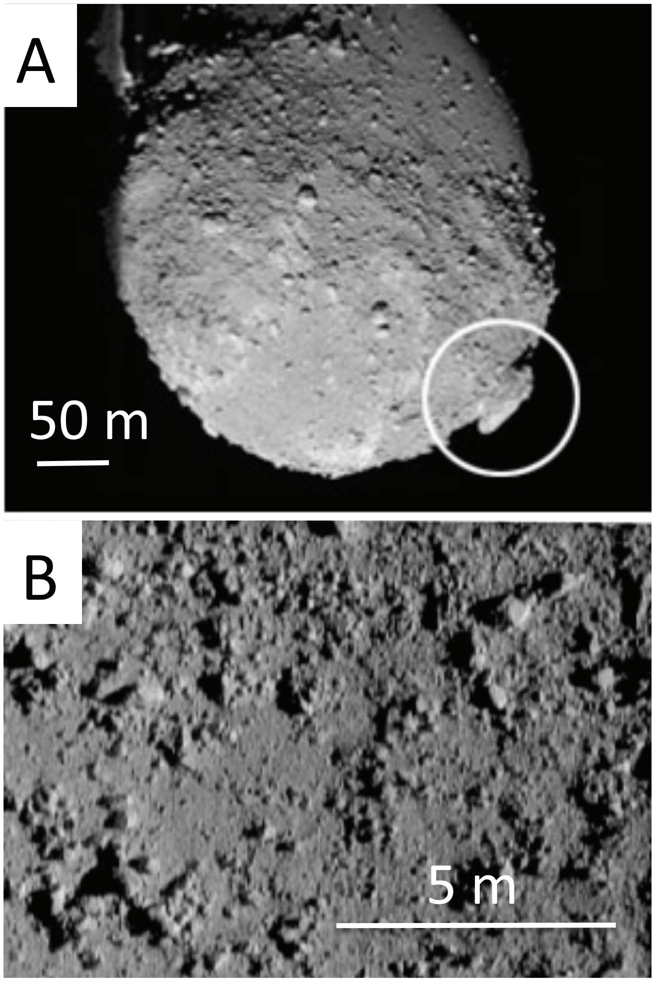

Figure 2. Large rocks can be seen in these close up images of A) Itokawa and B) Eros. The rock circled in the photo of Itokawa is approximately 50 m across. These rocks are targets for the Microspine Drill. Core samples from these kinds of rocks have a high scientific value and the rocks themselves have operational value as anchor points for spacecraft and/or astronauts.

Near Earth Asteroids are one of the commonly discussed destinations in the recent debate on targets for human exploration. President Obama, in his national space policy speech at Kennedy Space Center in April, 2010 [7], echoed the rationale to use NEO exploration as a stepping stone to Mars, a view put forth by the Augustine Commission Report [8]. Near Earth Asteroids allow for relatively short cruise times and overall mission durations that are much shorter than those for Mars, protecting Astronauts from potentially dangerous radiation doses. Near Earth Asteroids do not have significant gravity wells, which eases mass requirements because propellant is not needed to relaunch off the surface of the exploration target. However, this same lack of gravity necessitates more advanced technology to maneuver on and interact with the target. Little, if any, of the Apollo equipment development and surface operations lessons will be applicable.

Asteroids and comets are important to the defense industry because of the threat of a collision with Earth that might cause extensive damage and loss of life, and in the worst scenarios, could trigger human extinction. The recent IAA Planetary Defense Conference identified 350 near earth objects with a small but non-zero probability of impact this century [9]. NASA was ordered by the US Congress to create a catalogue of these potentially hazardous objects, and while that survey is nearing its goal of 90% completion, technologies to alter the trajectory of an object are still immature [10].

While small bodies can vary widely, the portfolio of objects that have been visited by spacecraft is growing and shows several commonalities. JAXA, ESA, NASA, and Roscosmos have all flown or have plans to fly to comets and/or asteroids. Unilaterally, on every object that has been visited, large consolidated rocks have been observed. Examples of these can be seen in Figure 2. (Pictures of Itokawa excerpted from [11] and of Eros from [12].) These rocks are important for two primary purposes. First, rock cores from these sites can provide additional scientific information that cannot be obtained from regolith samples or small rock fragments including essential contextual information as well as geological features like grain boundaries. Regolith samples from the surface will also be skewed to minerals that can survive the radiation exposure and may lack soft minerals that weather faster and may only be present beneath the weathering rind of a rock. Second, large rocks provide an operational asset to missions that wish to anchor and interact with the surface for sustained periods of time. These large rocks offer the most secure anchor points on the bodies, even (especially) for so-called rubble-pile asteroids. However, existing microgravity capabilities are limited to 'Touch-and-Go' techniques. The self-contained Microspine Drill presented in this paper is the first instrument that has demonstrated a gravity-independent method to anchor to these rocks. The Microspine Drill has also demonstrated acquisition of rock cores regardless of the orientation or presence of a gravity vector. In future mission scenarios – expansion bolts could be placed in the borehole after a sample has been acquired to provide a permanent anchor point, allowing the Microspine Drill to acquire a new sample and establish a new anchor.

2. Instrument Design

The Microspine Drill is a sample acquisition instrument designed to obtain a subsurface core from consolidated rock without requiring any external reaction forces. The instrument is self-contained and reacts all of the forces required to drill into the rock, including hole start, with a microspine anchor. It can be seen drilling into a piece of vesicular basalt in an inverted configuration in Figure 1.

The first microspine anchor developed for natural rock is detailed in [13], and uses approximately 200 microspines. Microspines were invented at Stanford University in 2003 [14] for use on climbing robots like Spinybot [15] and RiSE [16], [17]. They are manufactured using a semi-rapid prototyping process called Shape Deposition Manufacturing [18] that can create multi-material parts with embedded components through an iterative series of material addition and removal steps. Microspines are comprised of steel hooks embedded in a rigid frame with a compliant suspension system. By arraying tens or hundreds of these parts, large loads can be supported and shared between many attachment points. Since each spine has its own suspension structure, it can stretch and drag relative to its neighbors to find a suitable asperity to grip on a rough surface. The hooks can attach to both convex and concave asperities like pits, protrusions, or even sloped rock faces [19]. The suspensions also work to passively distribute the overall load across an array of toes [20].

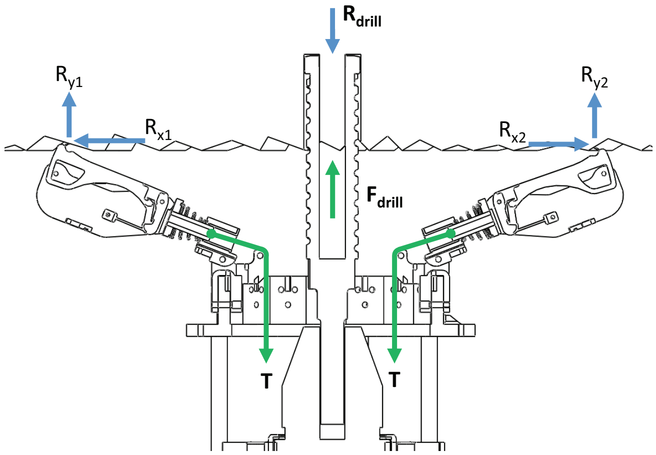

Figure 3. Two dimensional free body diagram of the microspine anchor and drill system. The reaction forces are shown in blue, and the internal forces are shown in green. Clearly, the maximum weight on bit is limited by the strength of the anchor.

New versions of these anchors use a hierarchical compliance system to conform to the surfaces of unknown rocks that have roughness at multiple length scales [21], [22], [23]. The microspine anchor used in this instrument has 16 carriages of microspines that conform to cm-scale roughness. Each carriage contains 12 microspines, which conform to mm-scale roughness and below. The carriages of microspines are arrayed around a circle with a single actuator that pulls each carriage towards the center of the circle, creating an anchor that can resist forces in any direction. The center of this housing was kept clear so that the drill could be deployed through the center of the circle. The forces of drilling and sample acquisition are reacted by the anchor. A simplified two-dimensional free body diagram of the anchor and drill system is shown in Figure 3 to illustrate the relationship between the gripping carriages and the preload that is applied to the drill bit. The weight-on-bit is directly proportional to the strength of attachment between the microspines and the rock.

$$\mathbf{R_{drill}} = \mathbf{R_{y1}} + \mathbf{R_{y2}} \tag{1}$$

$$\mathbf{R_{x1}} = \mathbf{R_{x2}} \tag{2}$$

where R_{y1}, R_{y2}, R_{x1}, R_{x2}, and R_{drill} are the reaction forces of the rock acting on the Microspine Drill instrument.

A close up view of a single carriage of microspines is shown in Figure 4. A cable with a series elastic element is used to load each carriage of microspines. Each carriage is attached to a dowel pin that is free to slide within a sleeve bearing. A conical spring returns the carriage to fully extended between each application. By applying tension to the cable, the microspines are dragged along the surface of the rock giving them opportunities to catch on asperities (small pits, bumps, and slopes on the surface of the rock). This tension also creates a moment about he pivot point where the carriage is connected to the instrument housing, pushing the microspines into the rock surface during engagement. A torsion spring around this pivot point biases the carriages into the rock surface so that the spines will contact the surface even in zero gravity or inverted configurations. By varying the length of

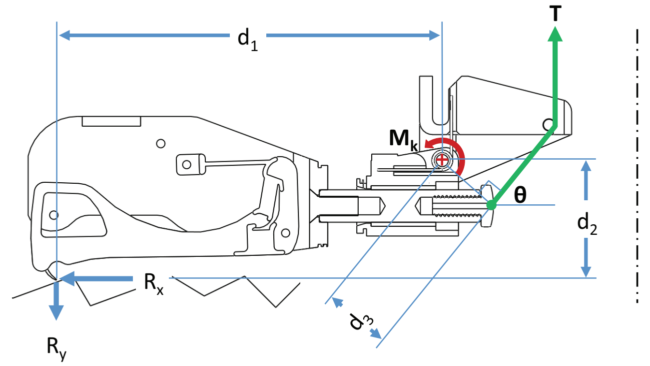

Figure 4. Free body diagram of the carriage subsystem assuming a fixed instrument outer housing. The angle, θ, that the cable is pulled and the length of the dowel pin can be designed to influence the reaction forces at the hook tip.

the dowel pin and the angle at which the cable pulls on the carriage, the magnitude of these two effects can be traded against one another. The relationship is described by:

$$\sum \mathbf{M_+} = \mathbf{M_k} + \mathbf{T} * \mathbf{d_3} - \mathbf{R_x} * \mathbf{d_2} - \mathbf{R_y} * \mathbf{d_1} \tag{3}$$

where T is the tension in the cable, M_k is the moment created by the torsion spring, R_x and R_y are the reaction forces of the rock acting on the hook, and d_1, d_2, and d_3 are the lengths of relevant moment arms.

A rotary percussive drill with a modified coring bit was chosen because of its ability to core into all types of rock and acquire samples. Rotary percussive drills are commonly used on rock (especially hard rocks) because the percussion fractures the rock [24]. This makes percussive drills more efficient than rotary drag drills. A rotary percussive drill was selected for use on the Mars Science Laboratory [25], and similar reasons drive their popularity for masonry applications in brick, stone, and concrete on Earth. An off the shelf Bosch rotary hammer drill [26] was selected based on its successful use in prototype development for the Mars 2018 mission's sample acquisition and caching subsystem [27], [28]. In fact, the housing for the drill mechanism and the motor interface parts were build-to-print based on drawings provided by the Mars 2018 sample acquisition and caching task of their early-stage prototypes. Leveraging this architecture will allow future versions of this instrument to integrate with the current state of the art sample caching systems [29].

The sequence of assembling the drill subsystem can be seen in Figure 5. First, the clamshell housing was separated exposing the hammer mechanism. These parts were removed from the housing and separated from the commercial electronics and control system. The mechanism was repackaged in a more compact housing (fabricated using selective laser sintering), and a brushed DC motor was connected to the input of the mechanism. A precision rotary encoder attached to the DC motor allows more precise control of the drill than is possible with the commercial off the shelf electronics.

The drill subsystem rides on a linear slide that can deploy the drill after an anchor has been established. Two guide rails

Figure 5. A commercial rotary hammer drill mechanism was repackaged with a DC motor to provide a higher degree of precision control. This sequence shows that repackaging process. The repackaged system rides on two rails and uses a motorized dovetail linear slide and a set of springs to provide the weight-on-bit to the drill bit.

hold sets of compression springs that dampen the percussive loads that are reflected back to the anchor and also serve as visual indicators of the magnitude of preload the linear slide is providing. For this proof of concept prototype, a commercial slide was purchased from Velmex Inc that provided up to 200 mm of travel and could apply a maximum of greater than 100 N of force [30]. The linear slide mounts directly to the microspine anchor, and was designed to retract the drill bit 50 mm away from the nominal surface of the rock during anchor engagement, and extend the drill up to 100 mm into the rock surface while maintaining a preload on the bit.

3. Testing Methods

It is difficult to test a device for zero gravity on Earth. Neutral buoyancy tanks and aircraft flying parabolic trajectories can simulate wieghtlessness in certain situations, but are costly and have additional constraints like the duration of test and the need to hermetically seal electronics. Rather than trying to accommodate these constraints and use funds for such testing, the Microspine Drill project embraced the philosophy that performing anchoring and drilling tests in an inverted configuration constitutes a *harder-than-zero-g* test. Gravity is essentially less than zero because the vector is away from the surface of the rock. To perform these tests, various rocks were strapped to a testing stand constructed from aluminum extrusion. The face of the rock was left exposed so that the Microspine Drill could anchor and drill as if it were doing so on the ceiling of a cave. Various rock types were tested to span a range of hardness, friability, and surface roughness.

Drilling tests were also performed on the vertical face of a large rock. However, in this configuration the microspine anchor was unable to react the large moment created by the mass of the linear slide and drill subsystem hanging several inches off the surface of the rock. In this case, a fishing line tied to a ladder overhead was used to react this moment. All the forces of drilling and necessary weight on bit were reacted by the microspine anchor. In a multi-legged robotic configuration, this moment would not present a problem because it could be resisted by the other feet in contact with the surface.

For all drilling tests, power was supplied by a remote power supply sitting on the ground. While the drill and linear slide were capable of operating with a relatively lightweight battery ($\sim$ 1 kg), the burden of charging and replacing this battery during long test periods was undesirable. This battery represents less than 10% of the total mass the microspine anchor is capable of supporting. The tests presented here were all performed in a teleoperation mode. Future work will implement closed loop control around the weight on bit using the compression springs as the sensor input.

The microspine anchor was also tested independently using a cable ratchet system to apply a load to the anchor at a various angle away from the rock surface. A load cell was placed in series with the cable so that the strength of the grip in that specific direction could be measured. The full range of angles from pure shear (tangent to the rock) through 45 degrees and up to pure normal (directly away from the rock) were tested on a variety of rock surfaces for multiple prototypes of the microspine anchor, as described more thoroughly in [21].

4. Results

The Microspine Drill successfully cored in an inverted configuration on multiple rock types including vesicular basalt and a'a. The speed of drilling varied with the applied weight on bit and the rock type, but nominally ranged from 15-45 mm/min. A 20 mm diameter borehole was created using a concrete and rebar coring bit with solid carbide teeth. The retained rock core was 12 mm in diameter and generally broke into multiple pieces within the drill bit. While this slightly decreased the scientific value of the sample, it alleviated the need to perform a core break-off maneuver. The Mars 2018 Sample Acquisition and Caching task is researching such active break-off mechanisms [29]. A picture of the retained core from a 25 mm depth drill sequence can be seen in Figure 7.

Inverted drilling experiments were performed to depths of 25 and 82 mm. The sequence of operations was to:

1. establish the anchor using the microspine anchor
2. deploy drill into rock with $\sim$60N weight on bit
3. begin drilling
4. drive drill into the rock using linear slide
5. retract the drill bit after desired depth
6. cease drilling
7. evaluate retained core sample and shavings

The residual borehole from 25 mm trials can be seen in Figure 6a and 6b, and from an 82 mm trial in Figure 6c. The surface

Figure 6. Drilling tests were performed on a variety of rock types in both inverted and horizontal configurations. The microspine anchor conformed to rocks with roughness at multiple length scales. Drilling was effective on all forms of rough, consolidated rock, including very hard vesicular basalts. The borehole is 20 mm in diameter for each picture. The hole depth is 25 mm for the pictures on the left and center and 82 mm on the right.

roughness of the rock at multiple length scales can also be seen in the photos. The target drill site was not preselected – the Microspine Drill was attached to the underside of the rock in approximately the middle of the exposed surface.

Not surprisingly, the most difficult portion of sample acquisition was often the hole start. The drill bit wandered on the surface of the rock in several trials before establishing a good hole start, and on at least one occasion, slipped into a preexisting depression after significant weight on bit had been applied. Drill bit wandering is hard to prevent because of the compliance that is intentionally built into the Microspine Drill's anchor subsystem. However, this compliance also allows for the system to maintain its anchor, despite the amount and magnitude of vibrational forces that occur during hole start and drilling. Once hole start was complete, drilling proceeded with significantly lower vibration levels and could be preformed at higher speeds.

Successful drilling demonstrations were performed into vertical rock faces in a gravity-offloaded configuration to a depth of 15mm, as shown in Figure 8. Similar hole start behavior and drilling speeds were observed in these trials.

The anchoring subsystem was also tested independently from the drilling subsystem. As described in [21], the microspine anchor supports >155 N in pure shear (tangent to the rock surface), >150 N at 45°, and >180 N normal to the rock surface. A more flight-like mechanism has also been built that uses the principles of microspine anchoring (independent conformation, load sharing, opportunistic attachment via drag over a rough surface), but replaces the elastomeric material with metal extension springs that are containerized inside a central housing. This prototype had a larger volume per hook ratio, but was able to support similar loads due to the higher spring constants of the metal extension springs.

5. Conclusions

An instrument capable of drilling rock cores in microgravity, the Microspine Drill, was presented. The instrument uses a microspine anchor to apply weight on bit to a rotary percussive drill. 20 mm boreholes were drilled into hard rocks in inverted and vertical configurations up to 82 mm deep. 12 mm rock cores were retained inside the drill bit in several pieces with maintained stratigraphy. The instrument has applications to science missions to asteroids, comets, and extreme terrain on Mars, the Moon, or other planetary bodies. The Microspine Drill could also assist astronauts in manned NEO mission scenarios where a robot might place a network of ropes on the surface of the body prior to the astronauts' arrival, or where the instrument could be used in real time by an astronaut as a hand hold or sample acquisition tool. Expansion bolts could easily be placed into the boreholes left after drilling, creating permanent attachment points to the most solid portions of the NEO, the boulders.

Figure 7. Preserved 12 mm diameter rock core from a 25 mm depth drill test on vesicular basalt. The stratigraphy of the core is maintained within the drill bit, and the percussion action of drilling tends to break cores into approximately 10 mm long segments. Result is typical of other tests.

Future work will focus on redesigning the instrument to be more robust, and integrating it onto a climbing robot platform, Lemur IIb [31], [32], shown in Figure 9. A robot like LEMUR with four microspine anchors and at least one Microspine Drill could be used for science applications in

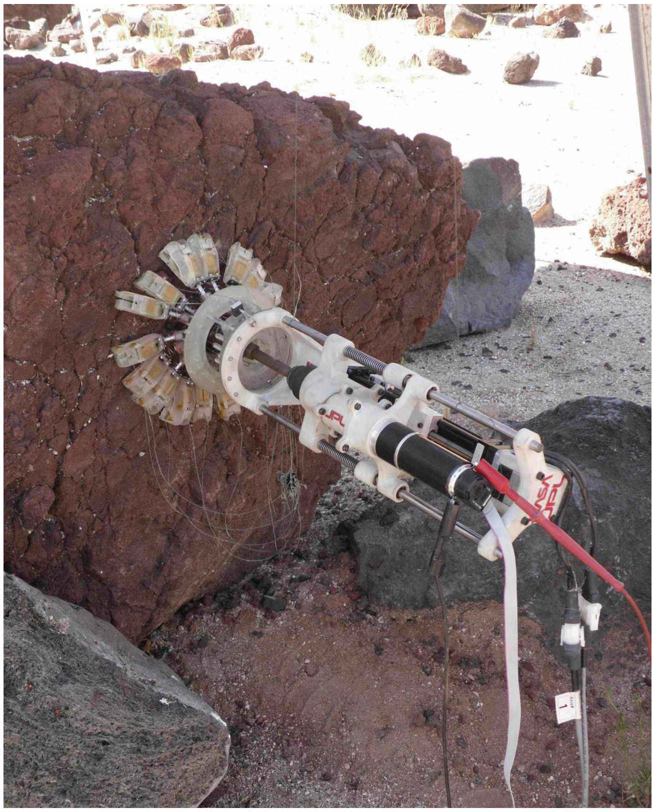

Figure 8. Horizontal drilling tests were performed in a gravity offloaded configuration. A single microspine anchor can support forces in any direction, but is unable to support the moments created by the center of gravity of the system being offset from the rock while in a horizontal configuration. However, these moments can be reacted on a multi-legged robot. Fishing line was used to react this moment during these tests while the microspine anchor reacted all the forces of drilling (i.e. weight on bit, vibrational loads, etc.).

Figure 9. The LEMUR IIb robot hanging inverted from a piece of vesicular basalt supported by the drilling test frame. With four microspine anchors and at least one Microspine Drill, the robot could explore the insides of caves and lava tubes on Earth as an analog to future asteroid, comet, and Mars extreme terrain mission possibilities.

caves and lava tubes on Earth, and as a test platform for future mission technology development.

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BIOGRAPHY

Aaron Parness received his B.S. degrees in Mechanical Engineering and Creative Writing from MIT in 2004 and a Ph.D. in Mechanical Engineering from Stanford University in 2010. He is a member of the Robotic Vehicles and Manipulators Group at the Jet Propulsion Laboratory in Pasadena, CA. Dr. Parness is the Principal Investigator for the Gripping Foot Mechanisms project that did the research presented in this paper. His research interests include all forms of robotic attachment mechanisms for space including microspines for rough surfaces like rock and gecko-like adhesives and electrostatic methods for smooth surfaces like the exteriors of spacecraft. Dr. Parness also leads work on small, reconnaissance robots for terrestrial applications.

Matt Frost received his B.S. degree in Mechanical Engineering from the University of California at Los Angeles in 2002. From 2002-2007 he worked at Evolution Robotics designing development robots for both internal and external use, and later at Evolution Robotics Retail as Senior Mechanical Engineer for the Lanehawk visual scanner project. In 2007 he transitioned to JPL where he currently divides his time between Lead Mechanical Engineer duties on the NASA Exploration Technology Development Program's ATHLETE (All-Terrain Hex-Limbed Extra-Terrestrial Explorer) as well as providing his mechanical design skills to the Gripping Foot Mechanisms project. His interests include quick turn prototyping, efficient structures and mechanism design and synthesis.