Gravity-Independent Mobility and Drilling on Natural Rock Using Microspines

Aaron Parness, Matthew Frost, Nitish Thatte, and Jonathan P. King

***Abstract*—To grip rocks on the surfaces of asteroids and comets, and to grip the cliff faces and lava tubes of Mars, a 250 mm diameter omni-directional anchor is presented that utilizes a hierarchical array of claws with suspension flexures, called microspines, to create fast, strong attachment. Prototypes have been demonstrated on vesicular basalt and a'a lava rock supporting forces in all directions away from the rock. Each anchor can support >160 N tangent, >150 N at 45°, and >180 N normal to the surface of the rock. A two-actuator selectively-compliant ankle interfaces these anchors to the Lemur IIB robot for climbing trials. A rotary percussive drill was also integrated into the anchor, demonstrating self-contained rock coring regardless of gravitational orientation. As a harder-than-zero-g proof of concept, 20mm diameter boreholes were drilled 83 mm deep in vesicular basalt samples, retaining a 12 mm diameter rock core in 3-6 pieces while in an inverted configuration, literally drilling into the ceiling.**

I. INTRODUCTION

Previous NASA missions to Mars have been limited by the mobility of surface rovers. The Mars Exploration Rover (MER), Opportunity, viewed stratified bedrock in the crater wall at Victoria Crater, but was unable to access the samples despite the efforts of the rover drivers [1], [2]. The 6-wheeled rocker bogie architecture can overcome large obstacles, but using this architecture on Mars limits rovers to slopes of ~25°. Repelling robots offer a more attractive approach for certain scenarios like crater walls [3], [4], but lack the flexibility to deal with highly variable terrain with roughness at multiple spatial scales and may lack critical capabilities like lateral movement and the ability to resist the forces of sampling. Robots with these capabilities are highly desirable for exploring lava tubes, crater walls, and cliffs that are approached from below. In the search for life on Mars, extant or extinct, the surface may be only the beginning. The surface of Mars is cold, dry, and subjected to heavy doses of radiation, making it an unlikely environment for current life. However, as noted in the Planetary Decadal Survey [5], "*Mars's subsurface appears to be more hospitable.*" The recent potential of liquid brines that may have subsurface sources makes the search for life underground even more compelling [6]. The anchors presented in this paper allow a robot to secure itself to a rock surface regardless of the presence or orientation of a significant gravitational field. This enables a rover to enter the subterranean realm of Mars through the vertical entrance lava tubes observed by orbital imagers [7], [8], [9], as well as gain access to steep terrain like crater walls and cliff faces.

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Fig. 1. The LEMUR IIB robot [10] hanging by a single microspine anchor on a vertical vesicular basalt wall (total weight of 130 N). A robotic ankle allows the robot to engage and disengage the gripper.

Asteroids and comets are another high priority target for future missions, in part, due to the presence of pre-biotic material that scientists suspect had a role in the formation of the primordial soup on early Earth [11], [12]. This interest has led to at least 17 missions to these bodies by the international community, but to date, only remote sensing data has been collected, and none have successfully anchored, sampled, or maneuvered on the surface. Because of the microgravity environment found on asteroids and comets, traditional mobility methods like wheeled driving are not feasible due to 1) a lack of the necessary normal force on the wheels that creates the friction to move and 2) the dangers of accidentally reaching escape velocity and jettisoning the rover into outer space (for example, Itokawa, the asteroid visited by the recent JAXA mission, has 3μg of equatorial surface gravity and an escape velocity <0.5 mph [13]).

JPL's gravity-independent anchors enable an entirely new mission capability for microgravity targets. By developing self-contained compact anchors, future rovers like Lemur IIB [10], [14] will be able to move efficiently and safely across the surface of these bodies because each foot will be able to react the forces of locomotion that could be generated in any direction, and also resist the sampling forces created by coring drills and other potential instruments that interact with the surface. Also, because this technology scales well [15], anchors could also be fabricated for astronauts and entire spacecraft. The anchors described here have the additional benefit that they do not require any preload to engage, just brief contact, an especially useful trait when establishing the first anchor. While asteroid and comet rock friability is not well characterized and likely varies widely [16], gripping onto a large boulder like those seen on Itokawa [17], [18], [19] and Eros [20] will allow drilling and sample analysis to be performed regardless of the system-wide consolidation, even with so-called rubble pile asteroids and high-porosity comets.

A primary objective of a new mission to the surface of a small body or to the surface of Mars will be mineralogical analysis and the study of any organic material that is found. Generally, subsurface cores are favored over surface regolith because the rock has been protected from weathering. Drilling a core sample on a body with no gravity, however, is a significant challenge. On Mars, drilling into a vertical wall or into the ceiling of a lava tube presents similar obstacles. A method to react the forces of drilling locally is required. The anchoring system presented below, presents one path to maneuvering on and sampling from these desirable locations.

II. DESIGN METHODOLOGY AND FABRICATION

A. Omni-directional Microspine Gripper

Microspine toes (shown in Figure 2) were originally invented at Stanford University in 2003 [21]. Through the last eight years of development, these toes have evolved into a mature technology that has been demonstrated on RiSE [22] and several other climbing robots [23], [24], as well as on the landing gear of unmanned air vehicles [25], [26], and on human climbing paddles [15]. Microspine toes consist of one or more steel hooks embedded in a rigid frame with a compliant suspension system. By arraying tens or hundreds of these microspine toes, 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. The hooks

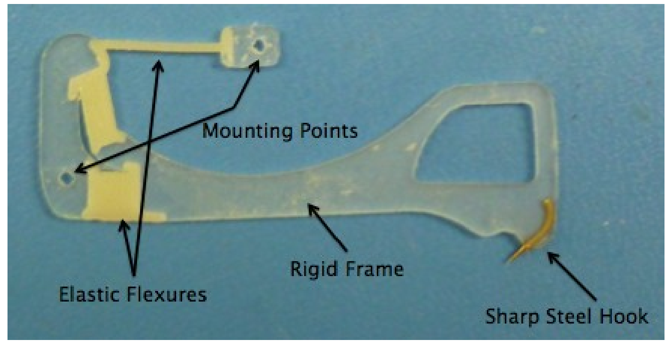

Fig. 2. A Microspine Toe consists of one or more steel hooks embedded in a rigid frame with a compliant suspension system. By arraying tens or hundreds of these microspine toes, large loads can be supported and shared between many attachment points.

can attach to both convex and concave asperities like pits, protrusions, or even sloped rock faces [27]. The suspensions also work to passively distribute the overall load across an array of toes [28]. This allowed robots like RiSE [29], [22] and Spinybot [23] to climb flat, rough, vertical surfaces such as exterior brick and stucco walls.

As discussed in [30], two main advances must be made for microspine technology to be effectively used on natural rock.

1) *use configurations that can resist forces in any direction*
2) *comply to the large-scale roughness and variation of rock surfaces*

To meet these requirements, JPL's omnidirectional anchors seen in Figures 3 and 4 use a radial arrangement of microspines with a centrally tensioning degree of freedom. A torsion spring biases each of these carriages into the rock face regardless of gravitational orientation so that the toes will drag across the rock surface and establish a grip, even in an inverted configuration. The radial configuration creates a secure anchor that can resist forces in any direction away from the surface. A hierarchical compliance system was developed that contains 16 carriages of microspines that conform to cm-scale roughness. Each carriage contains 12 microspines, which conform to mm-scale roughness and below. This hierarchical system can be seen in Figure 3 conforming to both the large and small variations on the surface of a basalt rock.

A second implementation of the anchor was constructed using the principles of microspine attachment (independent conformation, load sharing, opportunistic attachment via drag over a rough surface), but using metal spring elements and containerizing the mechanism within a central housing. This implementation is more similar to an anchor that could eventually fly on a mission because it does not rely on elastomeric polymers that are unsuitable for the very cold temperatures of space, and because it shields the compliant mechanisms from debris and secures moving parts within a protected shell. However, with this design, only 80 potential attachment points were realized, and only a single level of

Fig. 3. Close up of an anchor gripping a vesicular basalt rock. Both the cm-scale conformation of the carriages, and the mm-scale and below confirmation of the microspine toes can be seen.

compliance was achieved. The microspine version of the anchor achieved two levels of compliance, and 192 potential attachment points. Future anchors will try and capture the strengths of both of these approaches.

B. Robotic Ankle

A key component of a future microspine-based rover will be the ankle used to interface the anchor to the robot. The ankle‘s purpose is twofold: 1) to allow the gripper to conform to the rock so a higher percentage of microspines attach to the surface, and 2) to neutralize torques that may dislodge the grippers from the wall. The ankle must also house both the engagement and disengagement actuators, and interface with the robot, in this case LEMUR IIB [10]. The engagement actuator loads all of the carraiges of microspines towards the center of the housing via a cable drive system. Each carriage has a series elastic spring that begins to stretch once 2 or more microspine hooks have achieved a grip. A torsion spring biases the carriages into the rock surface so that the engagement actuator always drags the spines across the rock. The disengagement actuator overcomes this torsion spring bias, and lifts all of the carriages up and away from the surface of the rock. A high torque brushed DC motor was chosen for the engagement actuator and a 2 inch linear actuator was chosen for the disengagement actuator in the first prototype.

To address the issues of compliance and torque neutralization, the ankle system contains a set of gimbals, which can be seen in Figure 4.The gimbals are composed of two concentric rings mounted on orthogonal axes. They allow the gripper to rotate around all axes so that when pushed against the rock wall, the gripper can passively comply to the surface. Additionally, the gimbals do not transmit torques through their axes, which helps prevent the microspine toes from dislodging from the walls. Rotation about the normal axis to the wall (yaw) was discovered to be the most threatening to an anchor‘s grip. Since the robot kinematics will impart a

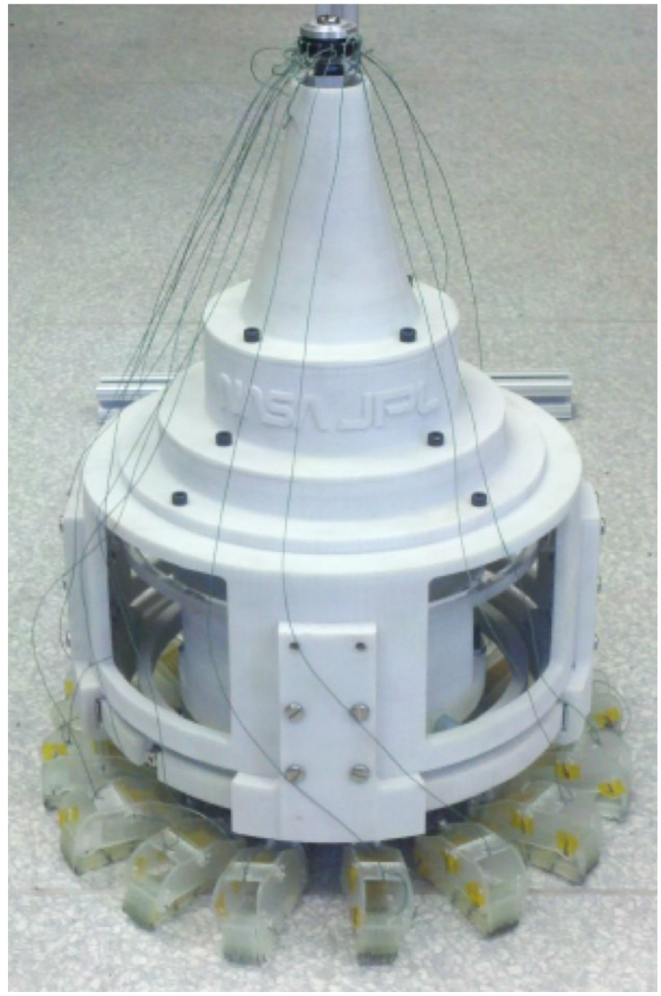

Fig. 4. A prototype two-actuator ankle that interfaces a microspine anchor to the LEMUR IIB robot. Gimbals allow the anchor to conform to the surface of the rock, and a free-spinning yaw joint allows the robot to take a full step without imparting any twist to the anchor.

yaw rotation of this kind on the order of 90 $^\circ$ with each step during a normal gait, a free-spinning bearing was constructed within the gimbal system. The outer ring of the gimbal was able to slide within C-shaped clamps that attach the gimbals to the outer housing of the ankle. These clamps fit loosely around the outer ring and are lined with Teflon. This ensures that the gripper can spin freely when the robot takes a step, while generating minimal torques on the microspine toes. The pitch and roll gimbals were found to be largely redundant with the compliance in the upper level of hierarchy on the gripper, and will likely be eliminated in future iterations of the design.

C. Self-Contained Coring Drill

Drilling requires a minimum preload force that pushes the drill bit into the surface, called Weigh-On-Bit (WOB). On Mars or the Moon, this WOB can be reacted by the gravitational force acting on the rover or lander if drilling downwards. On an asteroid or comet, the minuscule gravitational field makes this impossible. As a best-case example, to create a 50N WOB on Itokawa requires a lander mass of 500,000 kg (Itokawa has an equatorial surface gravity 0.0001 m/s2 [17]). Clearly, this is out of the scope of current spacecraft architectures. Drilling into the ceiling of a lava tube or the side of a cliff on Mars presents similar challenges for resisting the WOB. The omni-directional self-contained anchor solves these issues and has been used to react the WOB of a rotary percussive coring drill, see Figure 5.

Rotary percussive drills are a natural choice for rock surfaces because of their ability to fracture the rock, making them more efficient than rotary drag drills. A rotary percussive drill was selected for use on the Mars Science Laboratory [31]. Similar reasons drive their popularity for masonry applications in brick, stone, and concrete. To demonstrate coring in an inverted position, a harder-than-zero-g proof of concept, an off the shelf Bosch Hammer Drill was repackaged and integrated with the microspine anchor. A brushed DC motor was coupled to the hammer mechanism to provide improved drill control and accurate position estimates using an encoder. A linear slide and stepper motor served as the deploy/retract mechanism. A set of two guide rails and four compression springs maintained a constant WOB and reduced the tendency for the percussion motion to loosen the grip of the microspines. The design of the drill system leveraged previous work by the Mars 2018 mission development team [32], [33], expanding this architecture for use in microgravity or on inverted rock surfaces.

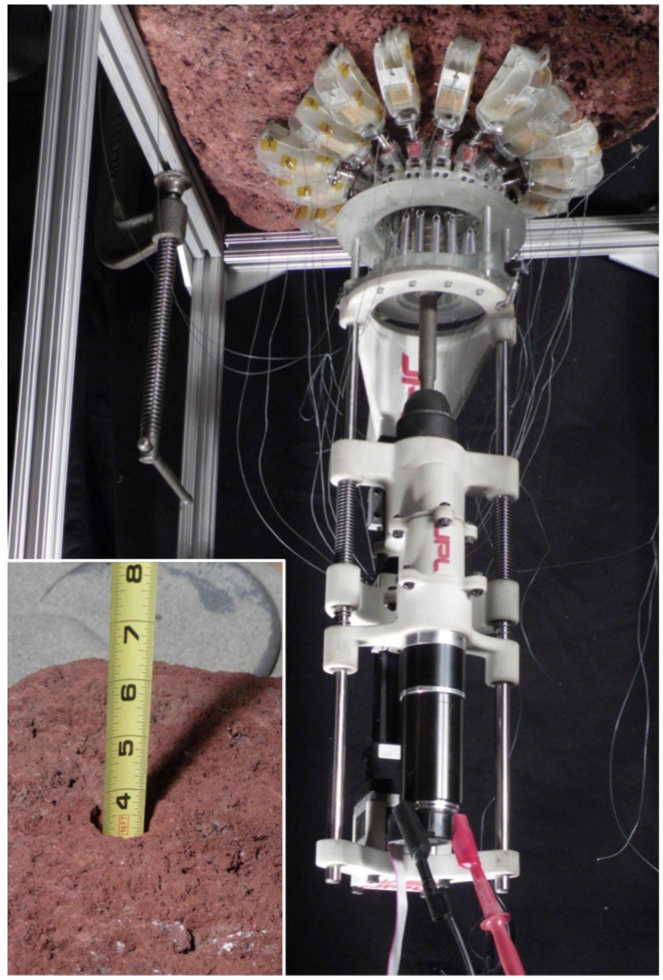

Fig. 5. The microspine anchor latches onto a piece of vesicular basalt and resists the weight-on-bit required to drill a 20 mm diameter borehole and retain a 12 mm diameter rock core sample.

III. RESULTS

A. Omni-directional Microspine Gripper

The microspine anchor was built with an interface that would allow it to be operated manually, or by the robotic ankle. The latest anchor was able to support >160 N tangent, >150 N at 45°, and >180 N normal to the surface of the rock. Figure 6 shows this testing. This is strong enough to support the weight of the LEMUR IIB robot with only one anchor in Earth's gravity. The anchors were successfully engaged and detached more than 100 times, and were tested to failure of the grip nondestructively. To date, only strong, consolidated rock has been used for testing, but future experiments will also test on friable and weaker rocks to characterize performance.

B. Robotic Ankle

To test the ankle-anchor system, the ankle was mounted to an aluminum arm that counteracted the pitch-back moment. On a full robot with multiple grippers, the pitch-back moment would be balanced by the other grippers in contact with the wall. In addition, two different attachment points for the arm were tested. The first attachment point is the top, center of the outer housing. This attachment point is 24cm from the wall and therefore creates a large pitch-back moment. The advantage of this attachment point is that it is coaxial with the gripper, creating a symmetric force distribution path back to the robot. The second attachment point is on the side of the ankle and closer to the wall, 8cm. This attachment point produces a smaller pitch-back moment, but does not load the ankle axially on horizontal ground. Tests show that the microspine gripper and ankle system can support 85 N in the shear direction to a rock wall when the arm is mounted at the upper attachment point and 129N when the arm is mounted on the side of the ankle

The ankle's ability to neutralize torques about all its axes was tested by manually rotating the arm. When the arm was turned and torques were applied to the ankle, the gimbal mechanism effectively compensated, as microspine disengagement was minimal. The ability of the ankle to rotate about the normal axis to the wall (yaw) without compromising load bearing ability is especially important, as a climbing robot will need this capability while taking a step. To test this feature, the arm attached to the ankle was rotated roughly 90°, during which only a few microspines detached from the wall, but quickly regained grip. Even after undergoing a 90° simulated step, the ankle and gripper were still able to support 125 N, showing that rotation does not compromise load bearing ability.

Fig. 6. A tension sensor were used to measure the anchoring strength of each prototype at various angles away from the rock surface. The flight-like prototype is shown here supporting >130 N tangent, >150 N at 45°, and >140 N normal to the surface of the rock. Scale readings are in lbf.

C. Self-Contained Coring Drill

The drill-anchor system demonstrated inverted rock coring on vesicular basalt, a harder-than-zero-g proof of concept. A 20 mm diameter borehole 83 mm deep can be seen in Figure 7 from one such inverted test. Including hole-start and core removal, the drilling sequence takes 3-10 minutes when drilling in very hard, lava rocks like vesicular basalt and a‘a. A 12 mm diameter rock core is retained with stratigraphy in ~3-6 pieces in each case. The Mars 2018 technology development team has created a sample caching system that can encapsulate and containerize many rock cores [34]. Such a system could be modified for use with this drill on future asteroid, comet, or Mars missions.

Drilling into the face of a vertical rock wall was also successfully demonstrated in a gravity-offloaded position, see Figure 8. Similar to the discussion on the ankle test arm, pitch back moments cannot be effectively reacted by a single gripper, but a fully equipped robot like LEMUR IIB would neutralize these moments with other contact points. To mimic this scenario, the drill system was supported with guide wires to react this moment. However, the anchor reacted all of the forces of drilling.

Fig. 7. A borehole and retained rock core from an inverted drill test on vesicular basalt.

IV. CONCLUSIONS AND FUTURE WORK

This paper presents a repurposing of microspine technology that widens its applicability to natural rock and frees it from gravitational constraints. Anchors that can withstand >150N in any direction were formed by orienting microspines in a hierarchical, radially symmetric configuration. A flight-like implementation of this system was also built and tested with similar results. Using two actuators, one to engage by pulling carriages of microspines towards a centeral housing, and one to disengage, by pulling carriages up and away from the surface, a robotic ankle demonstrated use of the anchor by a robot, LEMUR IIB. The ankle joint has a free spinning yaw degree of freedom that allows the anchor to remain stationary as the robot moves along the rock. A rotary percussive drill was demonstrated with the microspine

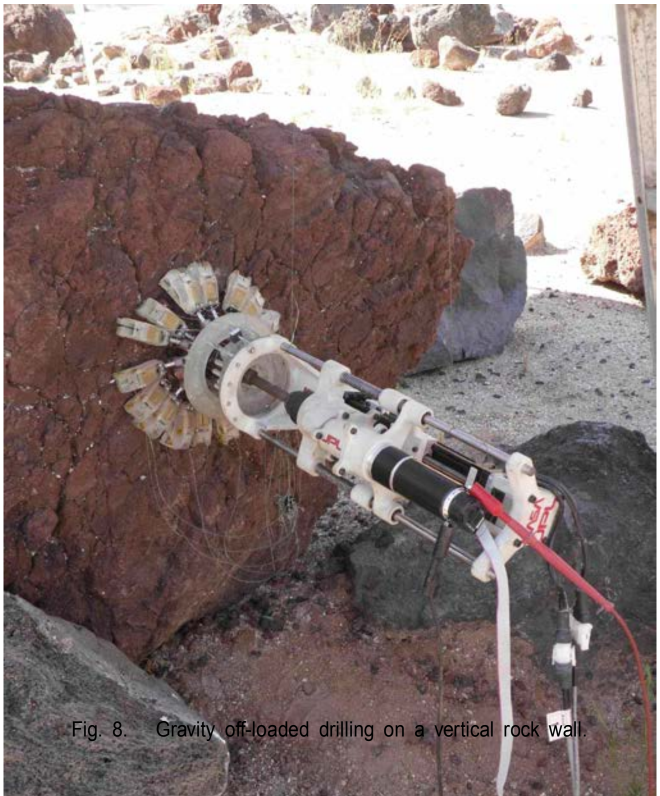

Fig. 8. Gravity off-loaded drilling on a vertical rock wall.

anchor coring into hard, vesicular basalt to a maximum depth of 83 mm. A 20 mm diameter borehole was created and a 12 mm diameter rock core was retained by the drill bit in a stratigraphy-preserving sleeve.

Future work will focus on refining the ankle design and fabricating four ankle-anchor systems so that climbing trials can be performed with the LEMUR IIB robot. A legged robot like LEMUR IIB has applications to asteroids and comets where there is very little gravity, and to vertical cliff walls and the ceilings of lava tubes on Mars, where high value scientific samples reside. The anchor and drill are also relevant to manned missions to Near Earth Objects, as proposed by president Barack Obama [35]. Astronauts will encounter similar mobility challenges on the surfaces of these microgravity objects, and a precursor robot or an anchoring tool could provide additional capabilities to a manned mission in go-ahead and real time scenarios.

V. ACKNOWLEDGMENTS

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Additional thanks to the JPL Office of the Chief Scientist and Chief Technologist and NASA Education Office.

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