CURB MOUNTING, VERTICAL MOBILITY, AND INVERTED MOBILITY ON ROUGH SURFACES USING MICROSPINE-ENABLED ROBOTS

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Three robots that extend microspine technology to enable advanced mobility are presented. First, the Durable Reconnaissance and Observation Platform (DROP) and the ReconRobotics Scout platform use a new rotary configuration of microspines to provide improved soldier-portable reconnaissance by moving rapidly over curbs and obstacles, transitioning from horizontal to vertical surfaces, climbing rough walls and surviving impacts. Next, the four-legged LEMUR robot uses new configurations of opposed microspines to anchor to both manmade and natural rough surfaces. Using these anchors as feet enables mobility in unstructured environments, from urban disaster areas to deserts and caves.

INTRODUCTION

Microspines were first developed for climbing rough vertical surfaces like brick, stucco, and concrete walls.[1] The technology was inspired by examples from nature; many insects climb using directional spines on the distal surfaces of their legs.[2] Microspines use sharp steel hooks to opportunistically grip small asperities on surfaces like bumps, pits, and ledges. Many microspines are fabricated with off the shelf hooks, like fly fishing hooks, surgical needles, or small brad nails. These hooks are embedded in a rigid frame with compliant flexures. When used in large arrays, as in the foot of a robot, the flexures allow neighboring hooks to displace relative to other microspines in the array. By dragging the array across a rough surface, hooks will catch on asperities and the flexures will stretch to allow other hooks to catch on other asperities further down the wall. In such a manner, a very distributed grip can be achieved without precise planning or control. Microspines are effective on rough surfaces and are robust to dust, fouling, and moisture. Recent efforts have applied microspines to natural surfaces as well, like rocks.[3] Several variations of microspines are shown in Figure 1.

Analytical models of microspines that explore the relationship between asperity size, hook size, and gripping forces can be found in prior work.[4,5] Generally speaking, the spine size is dictated by the asperity size and ease of manufacturing. Therefore the maximum loads that can be supported correlate to the number of microspines and the roughness of the surface. Intuitively, microspines support more load on rough concrete than on painted concrete where the paint may have filled in some of the smaller asperities. In rare cases, the surface strength becomes the fail

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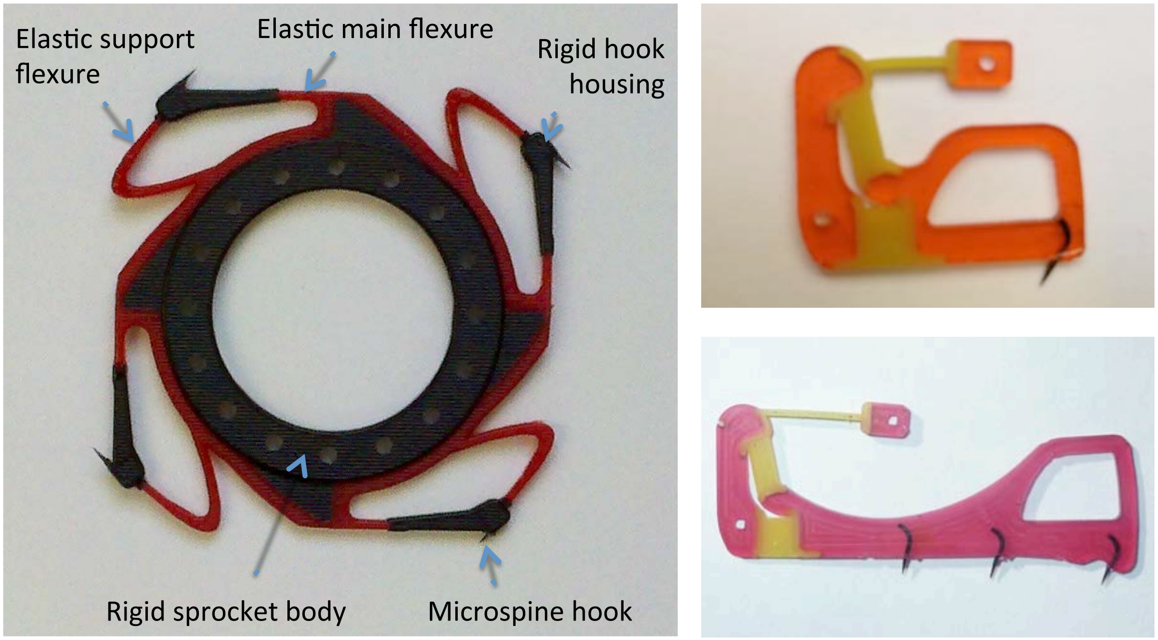

Figure 1: Examples of Microspines

ure mode and pieces of the surface will break off (weakly glued stucco is the only common example).

Microspines have been successfully employed in several robotic applications. SpinybotII was the first microspine climbing robot, and demonstrated vertical climbing on rough walls.[6,7] These microspines were later modified and enlarged for the RiSE climbing robot, which performed an untethered vertical climb of a 3-story building.[8,9] Large paddles of microspines were constructed that supported the weight of human climbers, and were used to climb a 5-story building for the Discovery Channel show, *Prototype This!*[10] Microspines have also been used as landing gear for fixed wing airplanes, enabling perching on vertical walls. [11,12]

This paper extends this body of prior work by using microspines in two novel configurations. First, rotary microspines are presented that implement the principles of microspines in a wheeled configuration. Using a wheeled platform enables several advantages over previous linear microspines that were deployed on legged platforms. This includes the ability to mount curbs and stairs, integrate onto existing deployed military platforms, and improved robustness to impacts and overturning. Second, opposed microspines are presented that can be used to maneuver on inverted surfaces like cave ceilings and the awnings of roofs.

ROTARY MICROSPINES

All previous microspine applications have used a linear motion, engaging the hooks through a dragging motion tangent to the surface. This has led to legged architectures with multiple degrees of freedom in each leg, limiting climbing speed based on the inertia changes required to cycle the legs back and forth. By overcoming the challenges of a rotary implementation, a wheeled microspine robot can be realized that can move at much higher speed with many fewer degrees of freedom. Two-wheeled robots can also transition from horizontal to vertical surfaces using the symmetry of the wheels, as demonstrated with magnetic wheeled robots.[13] Further, this symmetry allows two-wheeled robots to drive when overturned or perform simple righting maneuvers.

Similar to linear microspines, rotary microspines use a suspension feature that enables each microspine hook to engage the surface independent of adjacent hooks, and allows it to remain engaged through a large range of motion as the rotary microspine spins. Figure 2 shows multiple iterations of the rotary microspine design.

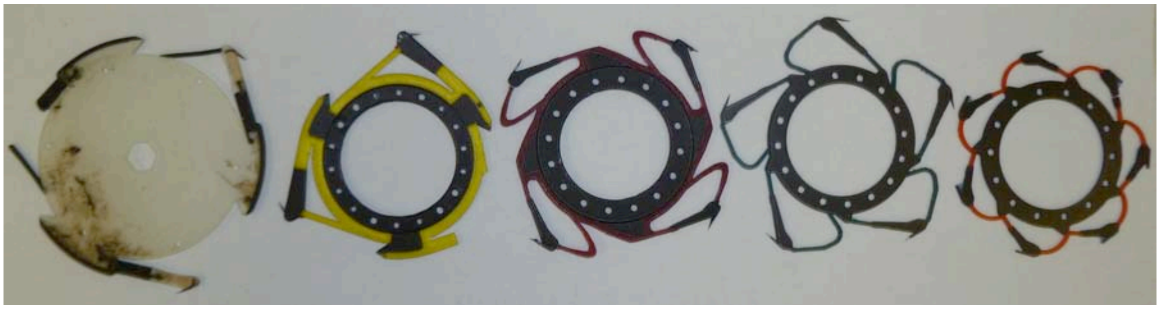

Figure 2: Iterations of rotary microspines.

The primary consideration when designing rotary microspines was the engagement angle of the microspine hook with respect to the climbing surface, denoted as theta in Figure 3. An engagement angle of between 30° and 45° is preferable to maximize the ratio of climbing force (F_c) to adhesion force (F_a).[14] Because the motion of the rotary microspine results in a continually changing hook angle, the overall design of the climbing mechanism was greatly influenced by the need to constrain the hook engagement angle. Setting θ =30° and l_t and h such that the maximum rotation of the hook housing is limited to 15° created the desired range of hook angle of between 30° and 45° throughout the rotation of the rotary microspine. The rotation of the rotary microspine disengages the hook from the surface by applying a force through the main flexure that rotates the hook housing, causing a decrease in hook angle theta and eventual release. Disengagement occurs at significantly higher forces in rotary microspines than linear microspines because the hook is being forced off the wall in its preferred direction rather than being released by moving the foot back up the wall, as in linear instantiations. For this reason, the flexures for rotary microspines must be made slightly thicker to withstand the detachment forces.

Rotary microspines use a pattern of mounting holes that allows the hooks to be arrayed evenly around the wheel so that hooks are continuously being presented to the surface. This near-continuous arrangement was empirically determined to be more effective than rows of hooks spaced at intervals of 15 or 30 degrees around the wheel.

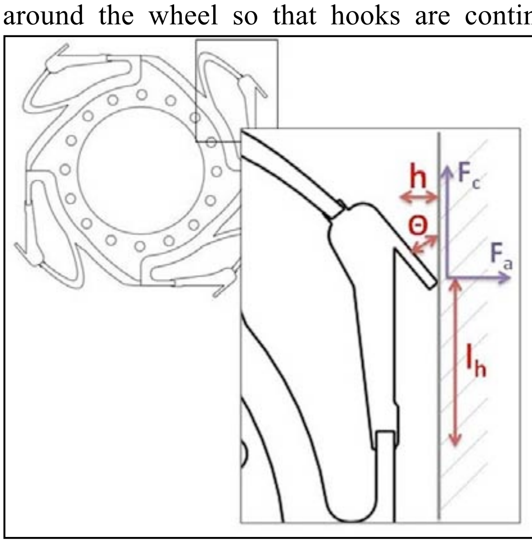

Figure 3: Hook design parameters

Rotary microspines were designed to maximize the likelihood of hook engagement, transfer the load to the robot appropriately, and prevent tangling or fouling of the hook elements during repeated use. Flexure shape and stiffness were improved through empirical testing using groups of 5 or 10 rotary microspines on a vertical test apparatus with linear slides for repeatability. The side-by-side arrangement and angular variation of the rotary microspines were determined in a similar fashion. For initial prototyping, two materials were considered for the flexure segments, one of hardness shore 20A and the second of hardness shore 60A. Testing of several designs resulted in the selection of flexures of shore 60A hardness. Using this rotary microspine design, several side-by-side arrangements were tested to reduce issues such as entanglement and twist. Entanglement was the tendency of hooks to extend and engage adjacent hooks, greatly hindering the probability of engagement with the climbing surface. Twist was the tendency of the hook housing to rotate out of the plane of the rotary microspine. This effectively eliminated any possibility of engagement as the hook would often end up parallel to the surface instead of in the desired perpendicular orientation. These issues were resolved through the combination of an exaggerated support flexure, the C-shaped segment at the top of the hook housing, and by the inclusion of dividers between each microspine to constrain the motion of the hook housing to the plane.

D.R.O.P. THE DURABLE RECONNAISSANCE AND OBSERVATION PLATFORM

Figure 4: DROP robot

The first robot to utilize rotary microspines was DROP, Figure 4, which used a two-wheel plus tail architecture previously demonstrated in robots such as JPL's AXEL[16] and ReconRobotics' Scout platform,[17] although it is seldom seen in climbing robots. The use of a two-wheeled design creates a unique set of criteria, which needed to be accounted for in the body design. See Figure 5 for parameters. Two criteria needed to be met for climbing to occur:

$$\mathbf{F}_{a;max} \geq \mathbf{F}_r \qquad (1)$$

$$\mathbf{F}_c > \mathbf{F}_{mg} \qquad (2)$$

The torque exerted by the motors causes the tail of the robot to rotate into the surface being traversed. Without this reaction, F_r, the body of DROP would spin freely in place. During climbing, however, this reaction force has the potential to pitch the robot off the climbing surface. The length of the body, l_t, and the radius of the rotary microspine, r, were adjusted to account for this and provide a balance of horizontal and vertical mobility. Expanding F_r in Equation 1, Equation 3 displays the inverse relationship that exists between the maximum adhesion force generated by the microspine hook, $F_{a,max}$, and the body length, l_t.

$$\mathbf{F}_{a,max} \geq ([\mathbf{F}_{mg} * \mathbf{r} + \mathbf{T}] / \mathbf{l}_t) \qquad (3)$$

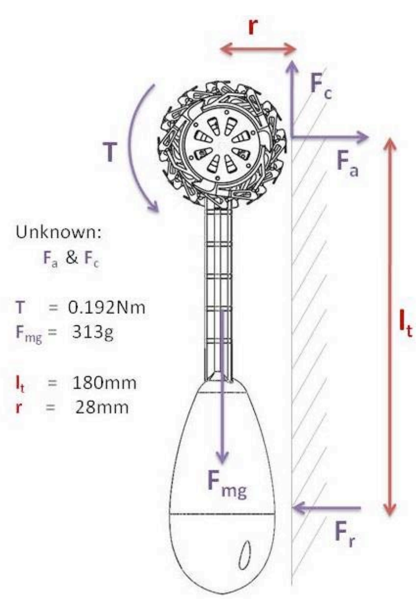

Figure 5 DROP parameters

Increasing the body length, l_t, improved climbing by virtue of reducing the necessary adhesion force, but inversely impacted turning ability and ground travel. While the radius of the rotary microspine has an effect on the reactions seen on the tail, F_r, it was more important in determining the climbing force produced by the microspine hook, F_c. Eq. 2 can be rewritten to show this relationship:

$$[T / r] > F_{mg} \qquad (4)$$

Future iterations will largely address these design considerations of the body to improve performance by reducing the pitch-back moment reflected to the spines during climbing.

The current DROP prototype has the ability to transition from horizontal to 90° vertical surfaces, travel at a ground speed of 45 cm/s, and climb vertical cinder block walls at 25 cm/s. To date, vertical climbing is sporadic, usually resulting in a fall after 3 or 4 body lengths of climbing. DROP can survive impacts from 3 meters, i.e. driving off of rooftops. The platform can turn in place on flat ground and can travel at headings up to 20° off of vertical on walls. A related video publication shows these achievements.[15]

Horizontal to vertical surface transitions were achieved with a high degree of repeatability, see Figure 6. These transitions were possible at a variety of speeds, including full throttle. Transitions from vertical to horizontal, however, were only partially successful with the current body design. The mass of the controls at the end of the tail in conjunction with the stiffness of the tail prevented DROP from moving its center of mass over the lip of the wall to transition onto the roof. A softer tail, lighter controls, or higher torque motors will address this issue.

Figure 6: DROP making horizontal to vertical transition

The climb speed of 25cm/s is more than 5x that of RiSE (4cm/s) and more than 10x that of Spinybot (2.3cm/s) on vertical surfaces. The 45cm/s ground speed of DROP is also a rate unseen in other microspine climbing robots. DROP displayed high maneuverability on horizontal surfaces with the ability to turn in place (turning radius of 0) and overcome small obstacles with ease.

Impact testing was performed by driving DROP off of a one-story rooftop. The platform survived these falls of 3 m, and was also thrown from the ground onto the roof to demonstrate one potential deployment strategy. From higher rooftops, DROP failed consistently with a crack to the unprotected edge of the plastic coupling between the motors and the rotary microspines. Redesigned couplers with additional protective damping material are currently in fabrication, and should improve impact resiliency.

CURB MOUNTING AND STAIR CLIMBING

Rotary microspines were also implemented on the ReconRobotics' Scout Platform. Scout is a durable, throwable robot that enables video reconnaissance in both indoor and outdoor environments. It is currently deployed both with the military and in police forces across the country. The stock wheels were removed from a Scout platform and replaced with arrays of rotary microspines. This robot was then tested in urban outdoor environments.

Figure 7: Curb mounting

Figure 8: Stair climbing; overlaid video frames

Figure 7 shows the rotary microspine Scout mounting a concrete curb with a height more than 3x the diameter of the wheel. Curb mounting was reliably performed on a wide variety of concrete curbs across the JPL campus. However, this ability was significantly diminished on heavily painted curbs (i.e. fire lanes) where the paint had filled in many of the asperities where the microspine wheels commonly attach. New tail designs that provide improved friction on the ground contact may allow climbing these painted curbs, even with the limited number of asperities.

Figure 8 shows the rotary microspine Scout climbing a set of concrete stairs. Stair climbing was successful on sufficiently rough materials like concrete and wood. Some stairs are built with slightly overhanging steps (95° and 100° are common). On overhanging stairs, the robot's ability was somewhat diminished. Improved performance is expected through modifications to the tail where the ground contact was often observed to be slipping.

INVERTED MOBILITY

Both linear and rotary microspines rely on gravitational forces to engage the microspine hook with the surface. Extending microspine technology to inverted surfaces requires that this loading force be created internally rather than through the natural weight of the robot. An omnidirectional anchor was created by using a radial arrangement of linear microspines with a tensioning mechanism that loads the microspines towards the center of the anchor.[18,19] A hierarchical system was used in the anchors where 16 microspine toes were mounted in a single carriage. 16 carriages were arranged radially around the anchor. This allowed the microspines to conform to both mm-scale roughness (through the spines' independent motion) and cm-scale roughness (through the carriages' independent motion). A torsion spring at the pivot point of each carriage biases the carriage into the surface regardless of gravitational orientation. The ability of this hierarchy to conform to natural rock surfaces can be seen in Figure 9.

Figure 9: Inverted gripping with microspines

Inverted, steep slope, vertical, and overhanging mobility demonstrations are currently being conducted using these anchors on the LEMUR IIB robot, see Figure 10.[20,21] The robot uses two actuators to control each gripper, and a rotary quadrupedal gait that ensures the stability of the robot. Since each gripper can support more than 160N, and the robot's weight is only 140N, a high factor of safety is also realized.

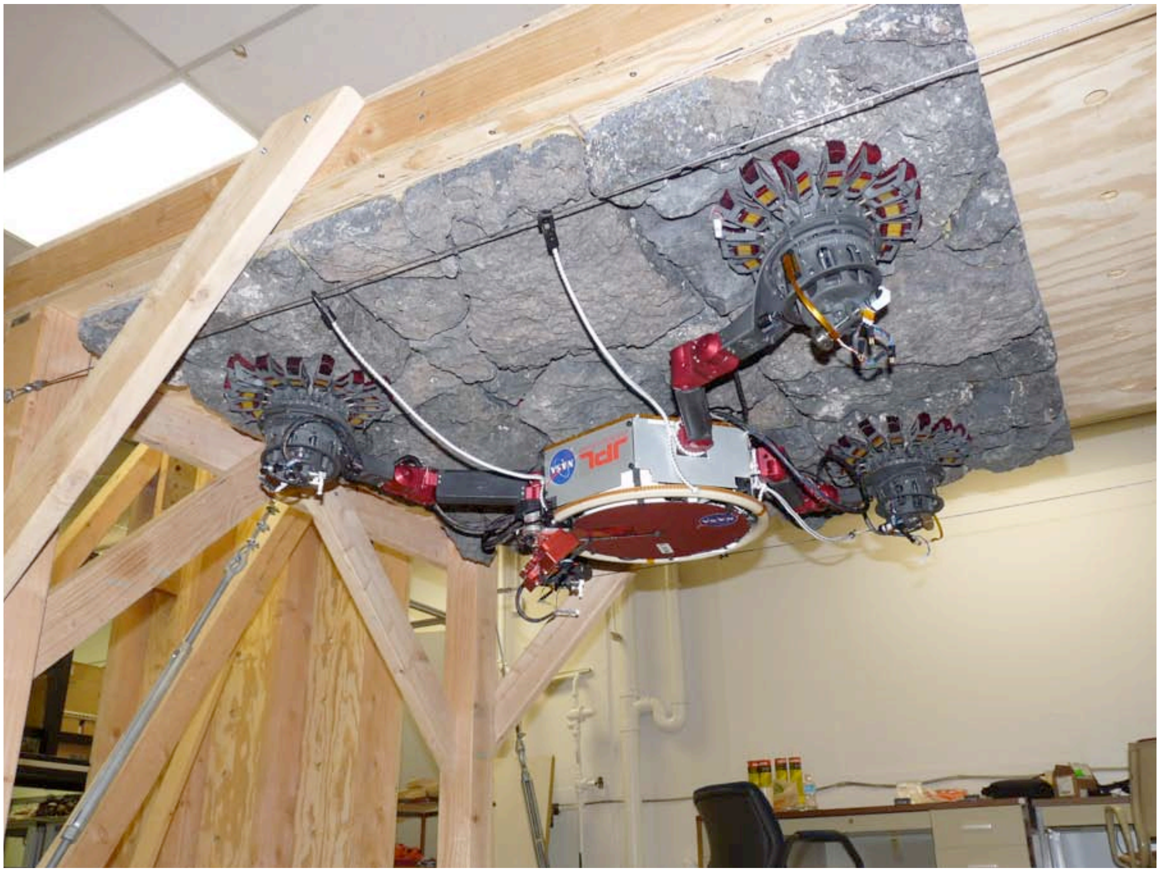

Figure 10: Inverted mobility test with LEMUR IIB robot

LEMUR is a 12 kg, four-limbed robot with 3 degrees of freedom per limb. As such, it is kinematically constrained to planar mobility demonstrations. Future upgrades to the robot will provide 5 or 6 DOF limbs so that the robot can access virtually any rocky surface regardless of shape or gravitational orientation. As a concept for future operations, LEMUR has stereo video cameras that could be used for reconnaissance or autonomous operations. Additionally, a rotary percussive drill has been demonstrated inside one of the grippers, validating the potential for the robot to obtain rock samples that would be relevant to resource exploration or scientific studies.[22]

CONCLUSION

Several extensions of microspine technology were shown. First, a rotary microspine was presented that used the same principles of previous linear microspines, opportunistic grasping and distributed load sharing, in a circular form factor. Rotary microspines enable wheeled microspine mobility, as demonstrated on the DROP robot and the commercial ReconRobotics Scout platform. With these platforms, rapid horizontal to vertical transitions, vertical mobility, curb mounting, and stair climbing were demonstrated.

Inverted mobility was also demonstrated using the LEMUR IIB platform and omni-directional microspine anchors. By arranging the microspines in a hierarchical, circular configuration and loading the spines towards the center of the anchor, a single anchor is able to support the entire robot's weight. This provides a high factor of safety when walking inverted with a rotary quadrupedal gait.

Each of these platforms has the potential to provide new capabilities for reconnaissance and sample acquisition. Future work will focus on refining the designs and testing on a wider variety of surfaces.

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