Foot design and integration for bioinspired climbing robots

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ABSTRACT

Climbing animal's feet use combinations of interlocking and bonding mechanisms in a staggering array of designs. The most successful climbers' feet exhibit a complex hierarchy of varied mechanical structures at multiple scales, combining small appendages that generate shear or adhesive forces with compliant suspension systems that promote intimate contact with surfaces. Recent progress is presented in mechanical and materials design that integrates novel dry adhesive and microspine structures mounted on passively compliant suspensions into successively improved generations of feet targeted at the RiSE (Robots in Scansorial Environments) family of climbing robots. The current version can ascend 90^{o} carpeted, cork covered and a growing range of stucco surfaces in the quasi-static regime. Specifications of a "public interface" for integrating a broad range of synthetic appendages into the foot assemblies are presented in the hopes of encouraging as large as possible a community of MEMs and Nanomaterials designers to submit adhesive or friction enhancing materials for operational tests using the robot.

1. Introduction

Robots capable of climbing a wide variety of surfaces would be useful for surveillance, hazard removal, maintenance in difficult to reach locations, and disaster relief applications. Previous robots have climbed walls using magnets [1, 2], suction [3, 4, 5], or adhesives [6, 7, 8]. These solutions work well on well characterized and specialized surfaces such as glass windows or metallic surfaces. However, they are not appropriate for dry, dusty, exterior walls comprised of materials such as stucco, brick, concrete, or stone. Recently, researchers have developed a wheeled robot that can climb glass and brick surfaces by creating a negative aerodynamic lift via a controlled vortex [9]. The solution works well on flat surfaces such as the walls of some buildings, but is limited on curved or rough surfaces such as a tree. In contrast, the RiSE (Robots in Scansorial Environments) family of hexapod legged robots takes cues from scansorial (adapted to climbing) animals and uses combinations of dactyls, compliant toes with embedded spines, and adhesive patches to climb a wide variety of surfaces (see Figure 1).

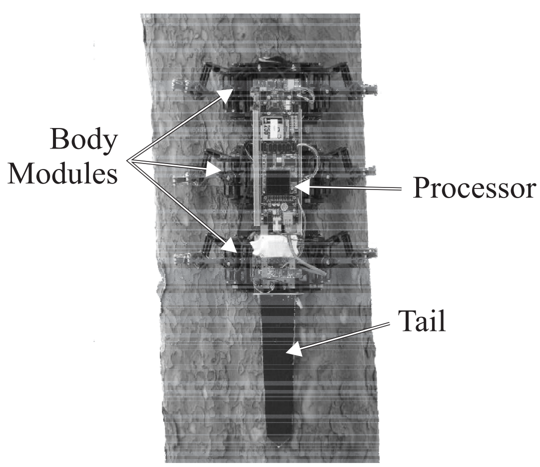

Figure 1: RiSE climbing a tree with dactyls

Scansorial animals have developed several strategies for adhering to a wide array of surfaces. One common theme among successful climbing animals is a hierarchy of varied mechanical structures at multiple scales. For example,

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geckos commonly have both nano-structured hairs for adhesion and claws for gripping. This paper reviews animal foot design strategies and details how they have been incorporated into the RiSE family of robots. The most recent version of the robot is capable of climbing a variety of carpeted, cork covered, and a range of stucco surfaces at 90° as well as smooth surfaces such as glass at 55°. The paper details ongoing work involving the integration of novel microstructured adhesives into the robot for increased adhesion. It concludes with specifications of a "public interface" designed to encourage the community of micro- and nanomaterials designers to submit materials that would yield increased friction or adhesion over conventional materials.

2. Animal Locomotion

Climbing is defined as locomotion on a vertical or steeply sloped surface [10]. Scansorial animals are capable of, but not limited to, a climbing mode of locomotion, as opposed to arboreal animals that are obligate tree climbers [11]. Locomotion in a scansorial environment requires the ability to move horizontally, vertically, laterally, or while inverted. It is independent of the gravity vector.

Climbers must meet at least three physical challenges [12]. First, oscillating fore-aft ground reaction forces must sum to equal the body weight over a step to maintain constant average climbing speed. Second, development of effective ground reaction forces for climbing requires rapid engagement of an attachment mechanism. Third, the natural pitching moment rotating the animal's head away from the vertical surface must be stabilized.

2.1. Attachment Mechanisms

In order to avoid falling while moving over any surface (flat or sloping), legged animals must generate vertical ground-reaction forces at least equivalent to that of gravity. This poses a problem on steep or vertical surfaces because vertical forces tend to cause slipping rather than provide support. There are two classes of attachment mechanisms that can potentially solve this problem: interlocking and bonding [10].

Interlocking mechanisms generate nonvertical contact surfaces to resist gravity and inertia [10]. Examples include claws and spines that can apply large forces per unit area to penetrate soft surfaces during climbing. Interlocking mechanisms may also rely on mechanical engagement of a rough substrate rather than deformation of a soft substrate. Claw-based attachment is highly dependent on the interaction of claw and substrate; failure of attachment may be due to bending, yielding, or fracture of the claw or substrate.

While claw morphology has received considerable attention (e.g. [13-15]), there are relatively few studies on the mechanics of claw function (e.g. [16-18)), and there is currently no dynamic model integrating elastic and plastic deformation of both claw and substrate. When claw bending or failure is not the limiting factor, microscale claw sharpness may be of greatest importance in penetration-based attachment. This is indicated by the fact that reducing tip radius at the microscale level has the greatest effect on attachment strength of steel claws [16].

Bonding mechanisms generate forces normal to the substrate that resist gravity and inertia during climbing. Physical processes utilized for bonding in climbing animals include *suction* [19-22], *chemical adhesion* [23-25], *capillary adhesion* [20-22, 26-28], and *van der Waals adhesion* [30, 31]. Animals climbing with bonding mechanisms can run while vertical or inverted on a wide variety of substrate materials. However, bonding mechanisms can fail if a barrier that sloughs or flows is present, such as water, dust, or wax crystals on plant leaves [32-36].

2.1.1. Integration of Interlocking and Bonding Mechanisms

Climbing animals use combinations of interlocking and bonding mechanisms in a staggering array of designs [37]. Insects use claws to climb rough surfaces and hair-like structures on the arolium or pulvilli to climb smoother surfaces. Orthopterans climb with claws and adhesive pads that are composed of dense pillars covered with a compliant layer as well as secrete a glue-like lipid [38, 39]. Lizards (geckos, skinks, anoles) [40, 41] and spiders [42-45] have independently evolved an elaborate lamellar pad structure supporting microscopic setae that allow attachment on surfaces too smooth or hard for claw attachment. Interestingly, the dynamics of attachment of lizard adhesive pads are similar to those needed to attach a claw: first a small perpendicular preload is needed to initiate contact, and then a micrometer-scale shear drag in a proximal direction bends the setae to allow attachment of the spatular tips [46-48]. Finally, passive mechanisms in ants [49] and flies [50] deploy adhesive pads whenever the insect's claws fail.

2.1.2. Compliance Hierarchy

Interlocking and bonding mechanisms are of little use if they never encounter the substrate, attach inappropriately, or fail to detach readily. This is a particular challenge when the substrate is sufficiently rough. Alignment mechanisms in the form of a hierarchy of compliant suspension elements supporting the interlocking or bonding structure are common evolutionary themes in climbing animals (see Figure 2).

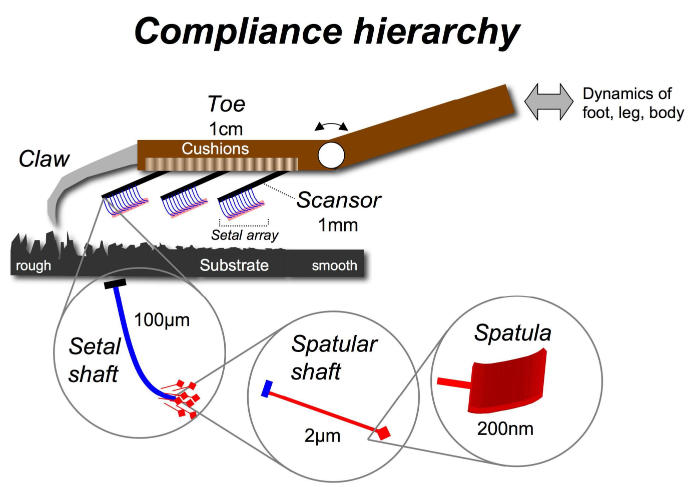

Figure 2: Schematic of compliance hierarchy of the gecko adhesive system. For review, see [30, 51]

We hypothesize that a matching of compliance exists from the nanoscale spatular branches, to setal arrays, scansors (lamellae), and toe cushions, so that the entire compliance hierarchy enables maximum suspension travel without overloading the adhesive setae [48]. This hypothesis remains to be tested.

2.2. Foot Design

Animals living in environments with mainly smooth (low fractal dimension) surfaces may not need toes. For example, tiny arboreal salamanders climb slowly on smooth leaf surfaces with suction-cup-like feet that lack developed digits [20]. However, toes provide redundant contact points and allow opposing shear forces to couple so that a grip is formed. Geckos can spread their toes to a total angle of more than 180 degrees. In many species the toes are asymmetrical, increasing the spread of the outer digits [52]. Geckos of the genus *Ailuronyx* have a unique asymmetry of their digits [53]. The inner three digits of both the hands and feet are curved inwards towards the body axis, and the outer two digits curve outward. In *Ailuronyx*, the inner three digits can operate as a single unit separate from the two outer digits. This allows *Ailuronyx* to grasp protrusions on the substrate in a viselike grip as well as stick to flat surfaces.

In geckos, mechanisms exist to decouple attachment and detachment from the center of mass [12]. Detachment is accomplished by digital hyperextension [51, 54, 55], a mechanism apparently similar to the peeling of tape from a surface [56, 57]. Toe peeling appears to greatly reduce the force required for detachment. Since the muscles responsible for digital hyperextension (*interossei dorsales*; [55]) are located in the toe, detachment does not have to be coupled mechanically to the center of mass, as would be the case if the gecko only used its leg musculature to break the adhesive bonds in the foot. However, single setae can be detached without added force by increasing the angle between the setal shaft and the wall [48]. If the geckos increased the setal angle rapidly in all attached setae during toe peeling, detachment forces would be low or immeasurable.

Animals can cling to objects using friction if they can grasp by producing an adduction force at a sufficient central angle [10, 58]. Static analyses suggest that attachment by gripping with claws or friction pads requires that the legs pull toward the body's midline [10, 58]. When animals wrap their limbs around tree trunks, distally located claws may engage by interlocking as they are pulled toward the mid-line and down.

Geckos pull their feet toward the mid-line of their body during climbing [12]. This action not only favors claw interlocking, but also setal attachment resulting in enhanced shear force [30, 51, 59]. Adhesion of individual gecko setae requires micron-scale displacements that pull the stalk toward the center of the foot [48].

3. Engineered Appendages

The RiSE family of hexapedal legged robots takes several cues from animal attachment mechanisms and foot design. For example, RiSE utilizes three unique mechanisms for attaching to walls: dactyls, spines, and adhesive patches. Dactyls are considered here to be sharp appendages that have no compliance between their tip and the robot body, which allows them to be driven into the climbing surface. Although dactyls have proven useful for climbing trees and other soft structures, this paper mainly focuses on the other two climbing mechanisms: spines and adhesive patches. Spines include a tuned compliance between them and the robot's legs, which differentiates them from dactyls. This compliance makes spines useful for climbing walls with small bumps and asperities such as stucco and brick. Adhesive patches are used for climbing smooth surfaces such as glass. The current versions of feet for RiSE are comprised of both spines and conventional adhesive patches composed of a variety of materials. Although no microstructured adhesive patch has been fully integrated into a foot for RiSE, the research of these adhesive patches is discussed here.

3.1. Sticky Pads: Synthetic Compliant Dry Adhesive Patches for Adhesion and Shear Force

Although gecko setae are composed of stiff material (keratin, ~ 3 GPa), their slenderness allows an array to have a low *effective* stiffness and thus satisfy the *Dahlquist criterion for tack* (< 300 kPa @ 1 Hz loading [60]). Similarly, the synthetic adhesive patches described here are made from a stiff polymer (1-10 GPa) that is molded into a compliant fiber array. Each element of the array is approximated as an elastic rod and is believed to deform either in a buckling [61, 62] or cantilever [63, 64] mode depending on the fiber orientation and direction of loading. Elastic rod theory suggests that array compliance is controlled by the fiber geometry and elastic modulus of the polymer.

Compliance is a necessary condition for pressure sensitive adhesion, as it enables intimate contact between two surfaces. When two surfaces come in close enough contact, weak atomic-level interactions occur between the surface molecules, generating an adhesive bond. Typically, this bond fails when the two surfaces are peeled apart. Depending on the surface geometry, the peeling resistance may be predicted by JKR theory [63] or a Kendall peel model [62, 65] and is related to the *work of adhesion* of the interface. Adhesion may also occur between fibers, but this can be avoided by selecting appropriate spacing and fiber geometry [63, 65, 66]

In addition to intimate contact, fiber compliance enables the array to form long bonds, which are essential for uniform load sharing [67]. Without compliance in both the tensile and compressive tensile directions, the interface is susceptible to high stress concentrations, which lead to crack propagation and bond failure. Bi-directional compliance is achieved by inclining the fibers so that they bend in a cantilever mode [68]. Such structures, however, require a spatular attachment at the tip that can bond with the surface (for various spatular designs, see [69]). A simpler design uses sufficiently slender vertical fibers such that they bend over and adhere to the substrate along their sides [62]. Bonds formed by side contact can be as long as the fiber themselves and have a peel resistance approximately equal to the work of adhesion per unit length of contact. It is believed that arrays of vertically aligned multi-walled carbon nanotubes [70] and cast polyimide fibers (see Figure 3) adhere in this way.

Rapid prototyping of various synthetic dry adhesives is accomplished with micro-casting [66, 68]. A coat of liquid polymer is deposited on a glass slide and then covered with a microporous filter (Isopore, Millipore Inc. or Anodisc, Whatman Inc.). After the polymer capillary fills the filter, it is allowed to cure. Next, the filter is etched away in solution and the molded polymer is rinsed and air dried. Several post-processing steps may be required to obtain the desired geometry, such as inclined fibers or spatular tips. Figure 3 shows an SEM of a polyimide structure cast from an alumina oxide Anodisc filter.

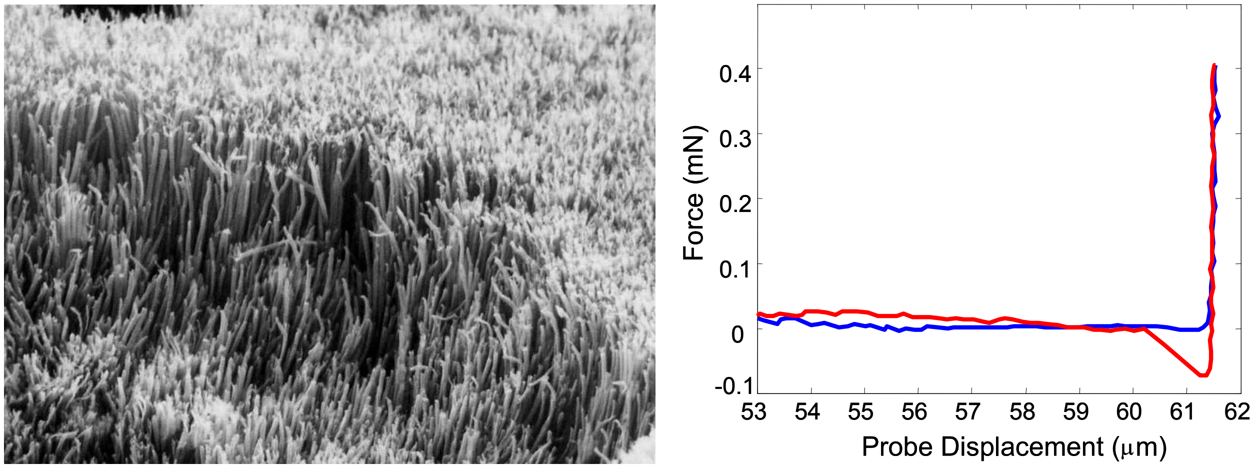

Figure 3 : (left) Polyimide fibers (60μm long, 0.2μm diameter) in a dense, vertically aligned array. Such fibers are predicted to adhere in side contact; (right) Force-displacement curve for this type of array (measured with spherical probe, 9.3mm radius). Adhesion is 0.54N/cm^2.

As the technology behind these synthetic adhesive patches matures, they will be further integrated into the feet of the RiSE platform.

3.2. Spines: Synthetic Multi-scale Probes and Hooks for Shear Force Generation

The feet on the current RiSE platform represent the ninth and tenth generations that incorporate spines, which allow the robot to attach onto small asperities on the wall. Lighter, more specialized platforms have demonstrated the ability to scale a wide range of vertical surfaces using these technologies [74]. Each foot is comprised of 20 to 30 "toes," and each toe is a multi-bar linkage that acts independent of its neighbors (see Figure 4). This allows each toe to catch its own asperity without affecting the other toes. The toes and feet are generated using the Shape Deposition Manufacturing Process (SDM) [71, 72], which permits materials of various stiffness to be integrating into a single piece. For example, the current generation of toes on RiSE consists of two polyurethanes, one with a hardness of 72 Shore-D, the other with a hardness of 50 Shore-A. By altering the shape or the material, different behaviors of the foot can be achieved.

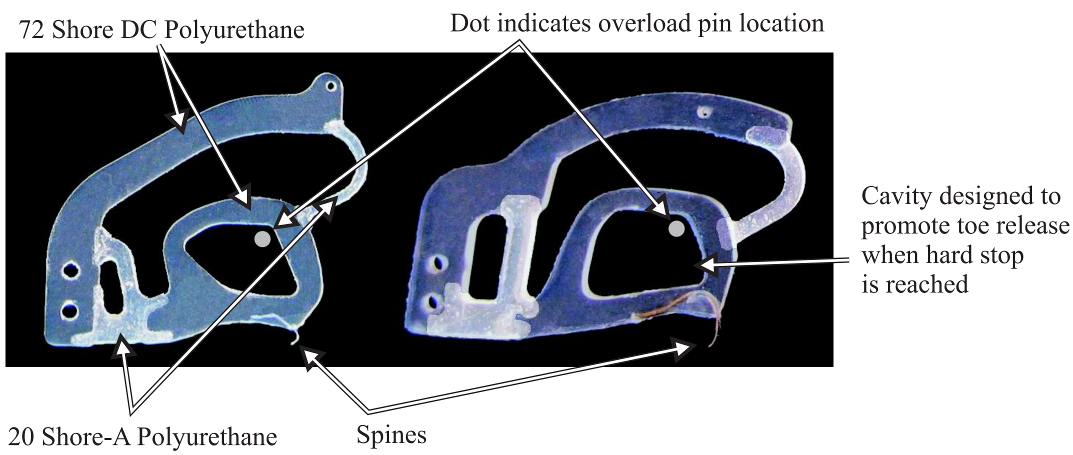

Figure 4: Diagram of Generation 3 Feet for RiSE Platform.

3.3. Ankles

In addition to the toes, the RiSE feet have SDM manufactured ankles that exhibit anisotropic stiffness (see Figure 5). The stiffness permits the foot to rotate freely in yaw. This allows the foot to maintain its orientation on the climbing surface while the leg sweeps through its stroke. The ankle's pitch degree of freedom is stiff which helps keep the toes in contact with the climbing surface. The yaw degree of freedom is compliant which facilitates proper foot orientation to the wall.

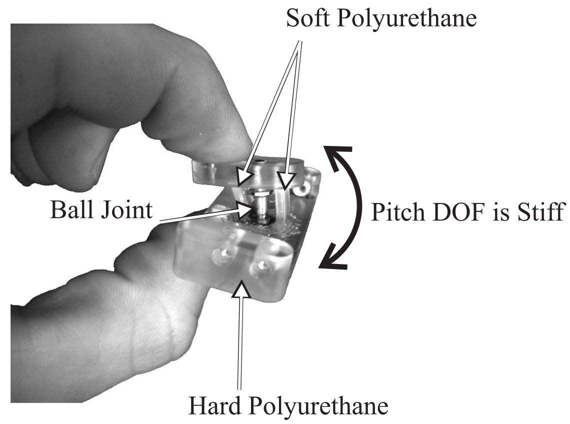

Figure 5: RiSE ankle demonstrating anisotropic stiffness.

3.4. Integrated Foot

Figure 6 shows the latest generation of the integrated foot. As a placeholder for the synthetic compliant dry adhesive patches described in Section 3.1, conventional adhesives patches comprised of polyurethane with a Shore-A hardness of 20 are used. Additionally, an integrated 3-axis force sensor is attached between the ankle and the lower leg of the robot.

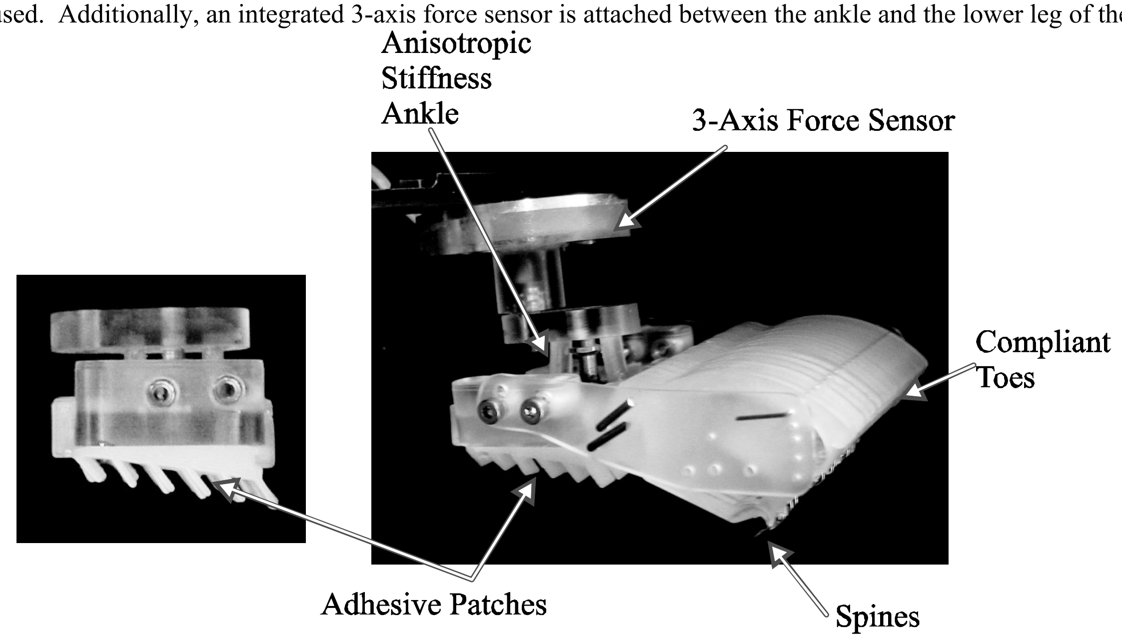

Figure 6: Generation three foot with integrated adhesive patches and three axis force sensor.

3.5. Performance: climbing experience with engineered feet

The first generation of feet utilized on the RiSE robot consisted of simple dactyls, which allowed the platform to successfully climb trees, carpeted walls at 90°, and wood planks at 45° (see Figure 1). The latest generation (Figure 7) allows RiSE to climb stucco at 90° (see Figure 6). RiSE has also climbed sheetrock at 70° and plexiglass at 45° using this generation of feet.

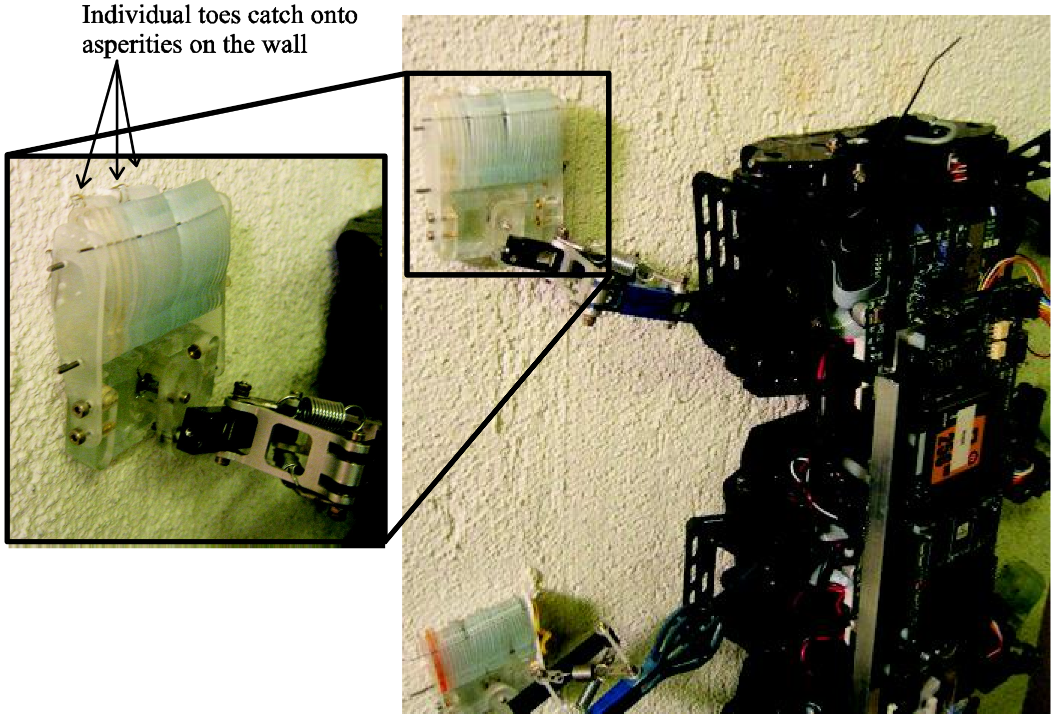

Figure 7: RiSE, climbing a stucco wall with a detailed view of the shape deposition manufactured toes engaging surface asperities.

4. Toward a "public interface" for integration of specialized synthetic appendages onto general purpose feet

It is recognized that no current self-cleaning adhesive has shown to be feasible for a climbing robot. In addition to the work of using filters described in Section 3.1, other researchers are investigating the use of Multi-walled Carbon NanoTubes (MCNT) as a potential dry adhesive. It has been shown that significant adhesion force can be obtained between one to five MCNTs and the tip of an atomic force microscope [73]. However, this is not sufficient for the purpose of a climbing robot. To successfully integrate a dry adhesive into a climbing robot, significant adhesion force must be shown for a patch of hairs with an area of at least 2 mm^2.

Recent research has shown adhesion force for a single 2x3 cm^2 patch that is capable of 10 N/cm^2 in normal and 8 N/cm^2 in shear [70]. This is accomplished by using an oxygen plasma etch to remove the tips of the MCNTs, which provides a more uniform patch to be presented to the surface. However, a large (~8 N) preload was necessary and the adhesion force quickly dropped to 2-3 N/cm^2 in normal and 3-4 N/cm^2 in shear after the sample was removed from the wall and then reapplied. This was presumably due to a large number of the MCNT being damaged from the preload.

Due to the fact that there are multiple solutions to this problem, a "public interface" is presented here in hopes that the community of MEMS, and nanomaterial designers will submit adhesive or friction enhancing materials for operational tests using the robot.

4.1. Physical and behavioral requirements

There are a number of physical and behavioral requirements that must be met. These as well as some suggestions are given below:

- The specimen patches need to be at least 2mm x 2mm to facilitate assembly onto the foot suspension systems. Smaller specimens are possible if alternate fabrication methods are used, such as bonding a row of specimens onto a row of suspension elements and dicing them afterward.

- The specimens must be composed of micro- or nanofibers and a substrate. Preferably the substrate is flexible to order to promote proper alignment of the tips of the fibers with the climbing surface. The substrate would be no more than 100μm thick and should be thin enough to be attached to curved surfaces with a radius of curvature of r = 5mm or less.
- The fibers should be approximately cylindrical in shape with maximum diameters of 2μm and lengths of at least 20μm. The nanofibers do not require a round cross section.
- The fibers cannot be too flexible in any direction nor can the fibers have a surface energy such that they clump together.
- The fibers can be tapered from base to tip, and there may be some advantages for the fibers to have distal features such as the spatulae seen on gecko hairs.
- The density of nanofibers should be at least 10,000/mm^2 in order to achieve adequate functional levels of adhesion.
- The dry adhesive should demonstrate directional frictional/adhesive loading properties similar to that found in geckos.

Approximately 75% or better of the nanofibers must meet the physical requirements listed above. It should be possible to cut or dice the specimens into smaller patches as part of the manufacturing process for integrating them with feet. During this process it may be possible to encapsulate the substrate and nanofibers in a sacrificial material to prevent damage. The final specimen should be bondable to suspension elements being designed at Stanford.

4.2. Functional Requirements

The physical and behavioral requirements given above detail the requirements and give recommendations for a sample to be considered microstructured. This section outlines the functional requirements for the sample to be of practical use for a climbing robot.

First, when specimens are pressed against a moderately smooth surface, they must provide adequate levels of adhesion and shear traction. For purposes of testing, a good example of a "moderately smooth" surface is machined granite tile, for which a surface profile is given in Figure 8.

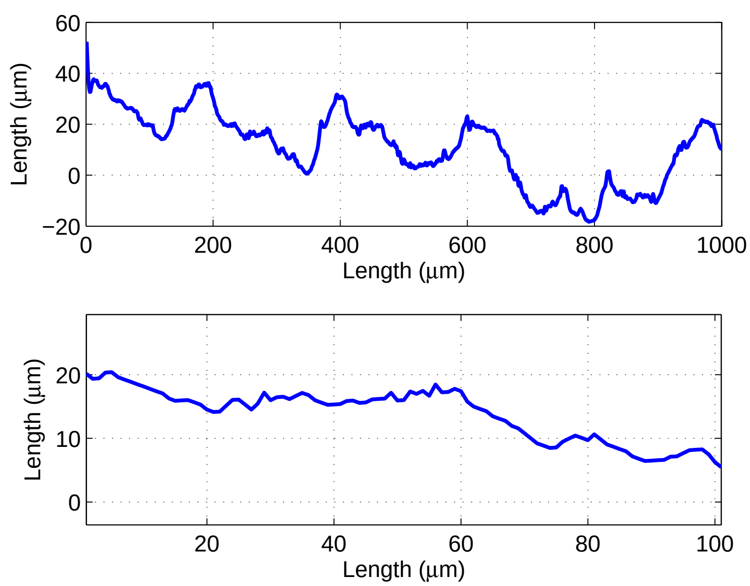

Figure 8: Surface profile for a machined granite tile (top) and same surface magnified such that the axis length scales match (bottom). The surface is qualitatively smooth to the touch, but not polished.

The profile in Figure 8 can be approximated with a two-term Fourier series (see Figure 9):

$$Height(x, y) = 2\cos\left(\frac{2\pi}{60x}\right)\cos\left(\frac{2\pi}{60y}\right) + \frac{3}{2}\cos\left(\frac{2\pi}{6x}\right)\cos\left(\frac{2\pi}{6y}\right) \tag{1}$$

where x and y are linear dimensions parallel to the surface, measured in μm. This surface lacks features at the finest length scales but presents a challenge for conformability at the scale of 1-2μm, which is believed to be the greatest unmet requirement for prototype nanofibers samples produced to date.

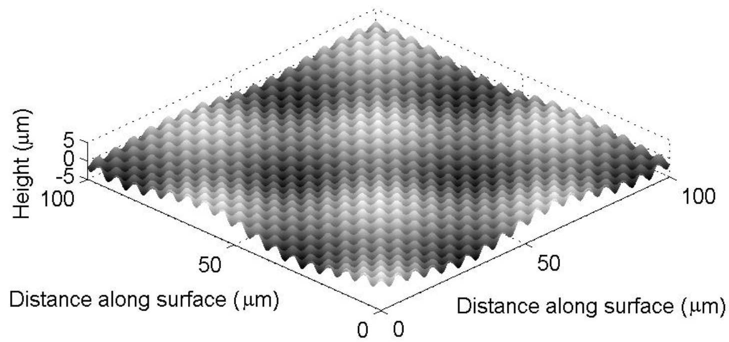

Figure 9: Reference surface.

Other materials with similar surface properties include interior wall panels and ceramic tile. Glass is considerably smoother and is less useful as a surface for testing.

Second, a sufficient number of fibers must make contact with the reference surface to obtain useful levels of adhesion and shear force. For the purposes of this specification, minimum "useful" levels are:

- Adhesion ≥ 0.06N/cm^2 – For smaller patches, somewhat higher adhesive levels will be required, assuming that not all patches mate perfectly with the surface. For example, it is anticipated that 4x10^{-3}N per 2mm x 2mm square sample, as measured in a pure normal force pull-off test, is needed.
- Shear ≥ 0.5N/cm^2 (i.e., at least 0.03N per 2mm x 2mm square sample, as measured in a pure shear force pull-off test, again assuming that not all patches mate perfectly).

These values are obtained assuming a small robot of 0.15 Kg mass with modest dynamic loading. For larger robot platforms, higher values of adhesion and shear stress will be needed for practical climbing without enormous feet. For rougher surfaces, it is assumed that the meso-scale suspension structures being designed at Stanford will provide the necessary conformability.

The above functional requirements for the specimens impose corresponding functional requirements for the nanofibers and the substrate. The fibers should not not detach from the substrate under imposed shear and tensile loads. The fibers and substrate should also not sustain permanent damage when larger shear forces (up to 10x the minimum values listed above) are applied in combination with positive normal forces of up to 1.0N/ cm^2.

Last, the specimens should also be able to undergo 1000 or more attach/detach cycles without significant reduction in their adhesive functionality.

5. Conclusion: Future Platform Evolution

The design of the feet for the biologically inspired RiSE family of robots is ongoing. Further improvements include an activated pitch degree of freedom that will allow the dactyls to be incorporated into the lower leg alongside the spiny-toes and adhesive patches. The activated pitch degree of freedom will also allow the robot to more carefully present the foot to the climbing surface, which should improve climbing performance. As the synthetic dry adhesives improve in performance and reliability, they will be further integrated into the foot, permitting the robot to climb more difficult surfaces including painted interior walls and frosted glass. In addition, the continuing study of animal climbing techniques will hopefully lead to more design improvements.

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