Climbing rough vertical surfaces with hierarchical directional adhesion

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***Abstract*— Prior research in biology and mechanics has shown the importance of hierarchy to the performance of dry adhesive systems on rough surfaces. The gecko utilizes several levels of hierarchy that operate on length scales from millimeters to 100s of nanometers in order to maneuver on smooth and rough vertical surfaces ranging from glass to rock. The gecko's hierarchical system serves two main purposes: it permits conformation to the surface for a large effective area of contact, and it distributes the load evenly among contacting elements. We present a new two-tiered directional adhesive system that provides these capabilities for a gecko-inspired climbing robot. The distal features consist of wedge-shaped structures with a base width of 50 μm and a height of approximately 180 μm. The wedges are mounted atop angled cylindrical features, 380 μm in diameter by approximately 1 mm long. Together, the proximal and distal features bend preferentially in the direction of inclination when loaded with a tangential force, achieving a combination of directional adhesion and conformation to rough surfaces. Using this system, a four legged robot that was previously restricted to climbing smooth surfaces is able to climb vertical surfaces such as a wood panels, painted metals, and plastics. On rougher surfaces, the two-tiered system improves adhesion by a factor of five compared to the wedge features alone. The hierarchical system also improved alignment and performance for large patch sizes.**

I. Introduction

As researchers have sought to extend the mobility of robots to vertical and inverted surfaces, much attention has been given to several biological species that accomplish such mobility through the use of hierarchical dry adhesive structures. Specifically, the gecko has served as inspiration due to its impressive performance on both smooth and rough surfaces. Tokay Geckos are known to utilize hierarchical adhesive structures on their toes to run at speeds greater than 1 m/s [1], hang their entire body weight from a single toe [2], and maneuver on rough vertical surfaces like sandstone without noticeable degradation of mobility [3]. While significant progress has been made on single level micro-fibrillar adhesive structures that perform well on smooth surfaces [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], gecko-mimetic adhesives that adhere repeatedly to rougher surfaces have yet to be realized. Additionally, scaling the results of these synthetic adhesives from small test patches to sizes useful for robotic applications has proved quite challenging because of the difficulties in aligning and loading large areas of the microstructures. This problem is exacerbated outside of the rigid and well-controlled tolerances of experimental test platforms. When comparatively imprecise and soft robot appendages attempt to engage and load the synthetic adhesives properly across large patch areas, the resulting performance is often much poorer.

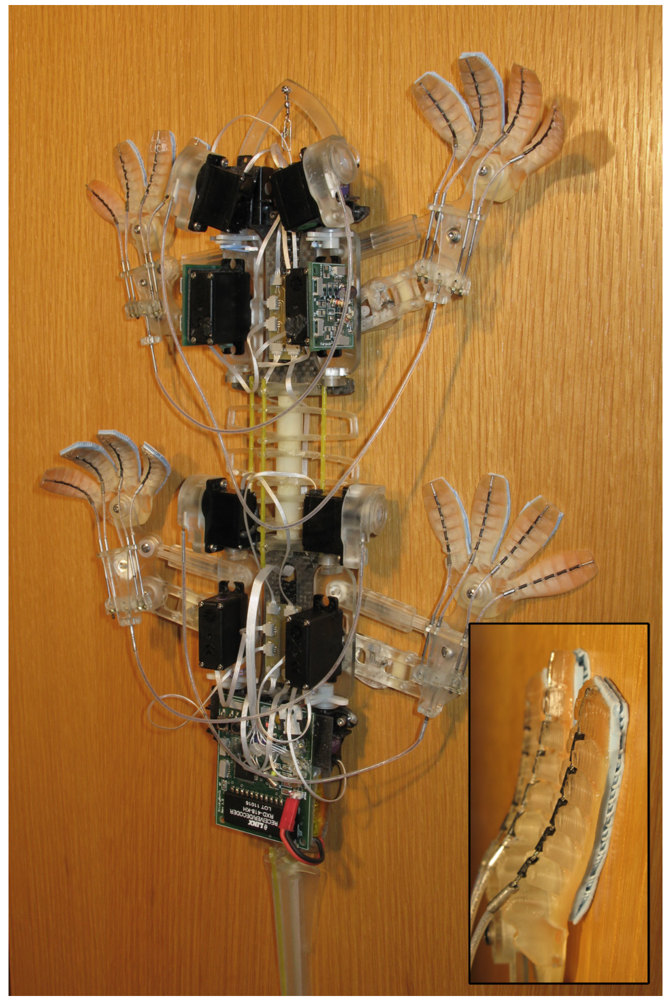

Fig. 1. The Stickybot robot platform mid-stride during a climb on an interior wooden door. The robot successfully climbed wooden doors, painted metal, and glass vertical surfaces using a hierarchical dry adhesive structure.

Biological adhesives conform to rough surfaces and overcome variations in alignment through the use of a hierarchy. The gecko employs a cushioning layer between its skeletal frame and skin (ie. vascular and sinus networks)[3] as well as flap-like lamellae at the 1 mm scale, curved setal fibrils at the $\approx$100 μm scale, and a branched structure at the 1 μm scale to ensure that the $\approx$100 nanometer sized spatulae conform to the surface, making intimate contacts across the entire toe [17]. These meso-structures are also angled appropriately so that the downward loading of the gecko's body weight is distributed evenly to the nano-contacts and does not create peeling moments.

Previously, a hierarchical adhesive system consisting of silicon suspension elements coated in photoresist nanorods was fabricated [18] and displayed improved conformation to spherical probes. Hierarchical structures have also been fabricated using shape deposition manufacturing [19]. Theoretical work using hierarchical structured spring models showed enhanced adhesion on rough surfaces, especially when the effective stiffness of the system allowed displacements of the contacting elements well beyond the RMS roughness of the climbing surface [20]. Several wall climbing robots have been demonstrated using synthetic dry adhesives to climb smooth surfaces [21], [22], [23], [24] and even showed some success on a wooden surface [4]. However, a robot utilizing gecko-like adhesives has yet to demonstrate robust, rough surface climbing of vertical surfaces.

Other solutions to rough surface climbing have included using microspines to adhere to rough surfaces [25], [26], an impeller to pull the robot against walls of varying roughness [27], and electrostatic clamping forces [28]. However, hierarchical dry adhesion, as used by the gecko, has the advantages that it works on smooth and rough surfaces while requiring no power to maintain adhesion.

Our two-tiered approximation to the gecko's hierarchical system is described in the following sections. It has been used on the Stickybot [29] robot platform to successfully climb wooden doors and painted metal—in addition to smooth surfaces such as glass—continuously and without frequent cleanings.

II. Design and Fabrication

For synthetic dry adhesives to perform well on rough surfaces and to engage a high percentage of the microfeatures across large patch sizes, a hierarchical suspension structure is required. The hierarchy must, first, help the contacting features align and conform to the surface, and second, distribute the applied load to the contacting elements evenly. To meet these requirements, we fabricated a structure composed of a layer of directional polymer stalks [29] which supported a sheet covered with a wedge shaped microfibrillar adhesive [14],[30]. The result can be seen in Figure 2.

While the previously manufactured directional polymer stalks [29] are not the optimal geometry for a hierarchical suspension structure, they do possess the necessary characteristics when supporting an adhesive sheet. The directional polymer stalks are angled in their unloaded state, lowering their effective modulus during loading because they displace in bending rather than buckling. The unsupported regions between stalks permit the microwedge sheet to conform to small-radius bumps on the surface.

However, conformation is of no use if the structure cannot distribute applied loads evenly across the surface. In the loaded state, the directional polymer stalks are in tension and act semi-independently, distributing and decoupling forces across the adhesive sheet. The stalks do not transmit shear loads between them because they are disconnected. So, if the microwedge layer under a single stalk comes unattached, this has a minimal effect on the neighboring regions.

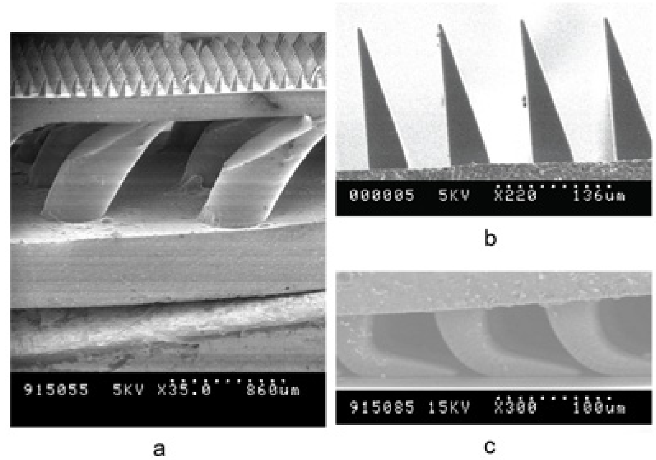

Fig. 2. a) SEM photo of the hierarchical adhesive system b) close up of terminal wedge shaped adhesive element in unloaded state c) wedge element in *loaded state*

A. Wedge Fabrication

The wedge shaped adhesive structure was fabricated using a molding process. Initially, SU-8 [31], a thick epoxy-based photoresist, was used to fabricate molds in a dual angle dual exposure lithography process. First, an angled backside exposure was performed followed by an aligned, vertical, topside exposure. The photoresist was then developed and Polydimethylsiloxane (PDMS) was cast into the mold and spun at moderate RPM to control the backing layer thickness. Once cured, the resulting elastomeric structures were released by hand. The molds were reusable for greater than 10 cast/peel cycles. Daughter molds made of polyurethane were also fabricated from master PDMS patches, increasing mold longevity and expanding the available materials for the cast wedge structures. (The original SU-8 photoresist molds were fragile, difficult to make, and inhibited the curing of some polymers.) Details of the microfabrication process can be found in [14][30]. Figure 3a shows the wedge shaped adhesive fabrication procedure.

B. Directional Polymer Stalk Fabrication

The directional polymer stalks were manufactured using a 3 part mold created on a CNC mill. The mold consists of a wax base, Delrin mold, and a urethane top cap. The Delrin mold consists of 45 degree grooves cut by a custom ground slitting saw with through holes drilled into the faces of the grooves at a 20 degree angle. The wax base is simply a support structure that also determines the backing thickness of the directional polymer stalks. The urethane top cap is molded from the Delrin piece before the through holes are drilled. This cap provides a tight seal and allows capillary

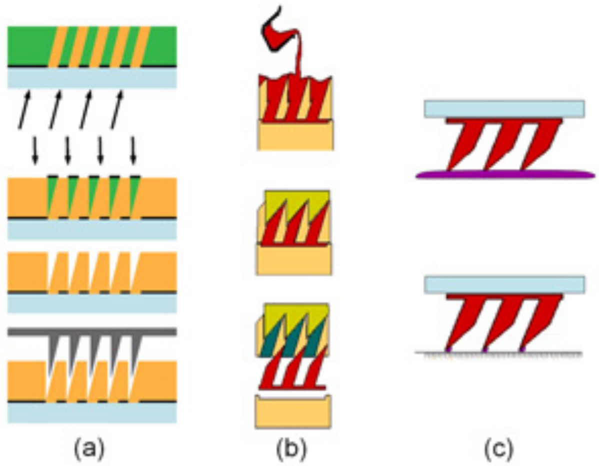

Fig. 3. a) Lithography fabrication sequence of the wedge structures b) Molding fabrication sequence of the directional polymer stalks c) Hierarchical system assembly

action of the liquid polymer to fill the mold completely and create sharp corners at the tips of the stalks. Further information on this procedure can be found in [32]. Figure 3b shows the directional polymer stalk fabrication procedure.

C. System Fabrication

To make the system of wedge shaped adhesives atop directional polymer stalks, a glass slide was placed against the back of a patch of the large stalks to keep the patch flat. The large stalks were then placed in a pool of TAP Blue silicone 0.3±0.05mm deep, causing the very tips of the stalks to become wetted with a ball of silicone (see Figure 3c, top), similar to results shown in [10]. The two parts of the adhesive system then bonded together when the large stalks were placed against the backing of a patch of microwedge structures and allowed to cure. The system was weighted only by the glass slide backing during the cure process (Figure 3c, bottom); this light weight did not cause the stalks to deflect significantly, so they bonded only at their very tips.

III. Analysis

A. Angular conformation requirements for rigid backing layers

One of the major obstacles to utilizing synthetic dry adhesives in climbing robots is alignment. For micro and nanostructured fibrillar adhesives, variation in angular alignment across a moderately sized patch can cause one edge of the adhesive to be overloaded while the opposite side is not even making contact. If we assume that a single fibril can tolerate a misalignment of 10% of its height, h, then the angular tolerance of a foot placement must be less than the following:

$$\theta < \arctan \frac{0.2h}{w} \tag{1}$$

where w is the width of the adhesive patch. Using this to calculate the requirements on our single level wedge shaped adhesive in a patch large enough to be used on a robot platform, we see that with h = 180 μm and w = 2cm, an angular alignment better than 0.103° is required.

This is far beyond the capability of most climbing robots demonstrating the clear need for a hierarchical system, not only for conformation to rough surfaces, but for the ability to self align large patches to glass and other smooth surfaces.

B. Conformation

The importance of a low elastic modulus in rough surface conformation can be evaluated using the mechanics of contact between a flat surface and a sinusoidal surface. It has been shown that for a given mean pressure, the contact area increases with a non-dimensional parameter α^2, representing“the ratio of the surface energy in one wavelength to the elastic strain energy when the wave is flattened” [33] where

$$\alpha = \sqrt{\frac{2\lambda w}{\pi^2 \Delta^2 E^*}} \tag{2}$$

and λ is the wavelength of the sinusoidal surface, w is the work of adhesion (a measure of adhesive strength), Δ is the amplitude of the sinusoidal surface, and E^* is the effective Young's modulus of the interface. Therefore, for a given surface and adhesive strength, the contact area is inversely proportional to $\sqrt{E^*}$.

The angled of a gecko's setal array has been shown to lower the effective modulus during attachment of the array when compared to the bulk material [34]. Modeling the DPS stalks as Hookean elastic cantilevered beams, the effective elastic modulus is given by

$$E_{eff} = \frac{3EIDsin(\phi)}{L^2 cos^2(\phi)[1 + \mu tan(\phi)]} \tag{3}$$

where E is the bulk elastic modulus, I is the moment of inertia of the beam, D is the number of beams over a given area, ϕ is the angle of the beam to the horizontal, L is the length of the beam, and μ is the ratio of shear to normal force. The DPS stalks have an array density of 100/mm^2 and are made of silicone rubber of approximately E=660 kPa, giving an effective modulus that drops to the order of 10^4-10^5 Pa. This analysis was confirmed experimentally on the hierarchical structure with measured effective moduli of 15-25 kPa.

C. Backing Layer Deflections

One important design consideration in making these hierarchical systems is the thickness of the wedge backing layer. A thinner backing layer permits conformation to smaller surface radii, potentially increasing the maximum possible adhesion or range of surfaces to which adhesion is possible. However, a thin backing layer does not distribute forces well, so the loads from the directional polymer stalks will be more concentrated within a small radius of where each stalk contacts the backing layer.

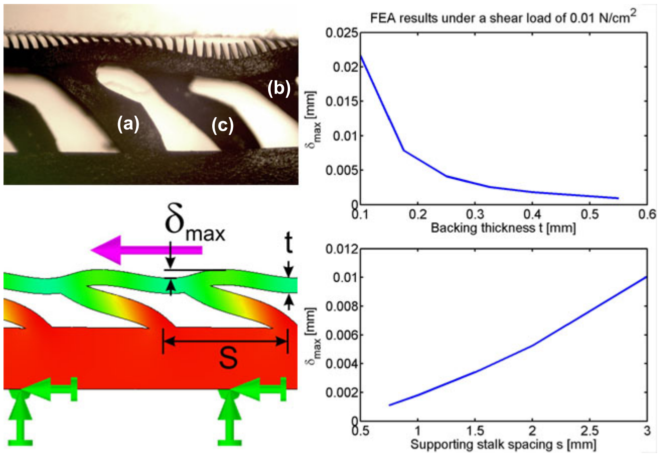

Fig. 4. Top left, picture of DPS-microwedge system exhibiting ripples in the microwedge backing layer under shear loading. Bottom left, screen capture of finite element analysis of the rippling behavior. t is the backing layer thickness, s is the spacing between stalks, and δ_{max} is the ripple amplitude. The pink arrow shows an applied shear load. Right, plots of FEA results under a very small (0.01N/cm^2) shear load showing general trends in ripple amplitude versus backing layer thickness and stalk spacing.

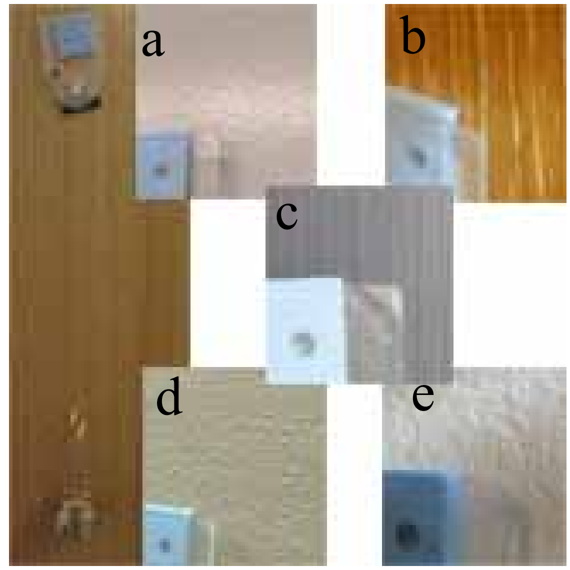

Fig. 5. Patches adhered to a variety of semi-rough surfaces a)smooth metal b)wood c)moderate metal d)rough metal e)painted wall

Furthermore, one effect we observed with backing thicknesses of $\leq$250μm was the tendency for the wedge layer to form ripples when loaded in shear. Because the directional polymer stalks are connected to the wedge backing layer with a finite radius, loading the stalks causes moments in the wedge backing layer where they attach. These moments cause ripples to form in the wedge layer, at times pulling the wedges off the surface. Figure 4, top left, shows an example of this: stalks (a) and (b) cause the microwedge layer to ripple and detach. Stalk (c) is offset from these two stalks in the into-the-page direction, so it does not influence the ripple.

Finite element analysis simulations using CosmosWorks were run on 2-D structures with dimensions close to the structures we made, showing the general effects of the backing layer thickness and stalk spacing when the backing layer was loaded in shear (figure 4). The induced ripple increases as thickness decreases or stalk spacing increases. Making the stalks thinner where they attach to the wedge layer would reduce the induced moments, although care must be taken to ensure the structure is strong enough to withstand the necessary tensile loads. Empirically, with a backing thickness of 250μm we observed ripples with shear loads on glass while with a backing thickness of 400μm no ripples were observable under any load.

IV. Results

The hierarchical adhesive successfully supported loads while attached to a variety of surfaces. 9 cm^2 patches of adhesive were tested on the surfaces shown in Figure 5. The first sample had a thin backing layer for the microwedges (~250μm) while the second had a thick backing layer (~400μm). The strength of the attachment was quantified by hanging weights from the foot. As seen in Table I the patch with a thick backing layer generally performed better than the sample with a thin backing layer.

To compare the adhesive performance of the hierarchical system against the wedge shaped adhesive and the directional polymer stalks, three materials were selected and tested on a custom built experimental stage. The stage consists of a 6-axis load cell and 3 linear stages that allow closed loop control of position. Details on this apparatus can be found in [35]. Maximum adhesion numbers were recorded for the adhesive samples on glass, RMS roughness ~3nm [3], smooth granite, RMS roughness 21 μm [25] , and roughly sanded pine. The results of these experiments are plotted in Figure 6. While all three adhesive systems perform well on glass, only the hierarchical system retains significant performance on the rougher surfaces. Adhesion increased with preload pressure up to pressures of approximately 2 kPa for all three surfaces. Using preload pressures greater than 2 kPa did not increase or decrease adhesive performance. Patches underwent a battery of 240 cycles on the experimental stage and showed no decrease in performance on clean glass surfaces. In real-world testing, patches were cleaned periodically (~200 cycles) to remove dirt picked up from climbing surfaces.

Data were also collected for the hierarchical system and for standalone patches of the wedge shaped adhesive at different patch areas to determine if the hierarchy also helped align large patches to a surface. Patch sizes ranging from less than 0.25 cm^2 to greater than 12 cm^2 were tested. Adhesion data are plotted in Figure 7. While standalone wedge shaped adhesive patches produced good adhesive pressures at small patch sizes, they were unable to align all of the contacts across large patch areas and suffered from limited returns as patch area grew. The hierarchical adhesive system maintained similar adhesive pressures across all patch sizes indicating an ability to self align the terminal features to the surface.

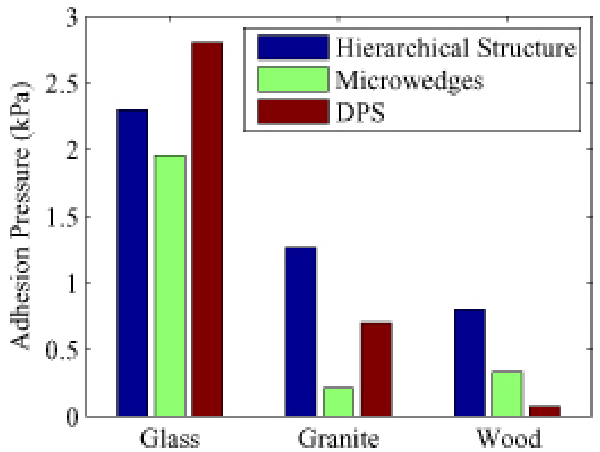

Fig. 6. The hierarchical system retained significant adhesion on both granite and wood, surfaces which were non-sticky for the standalone adhesives

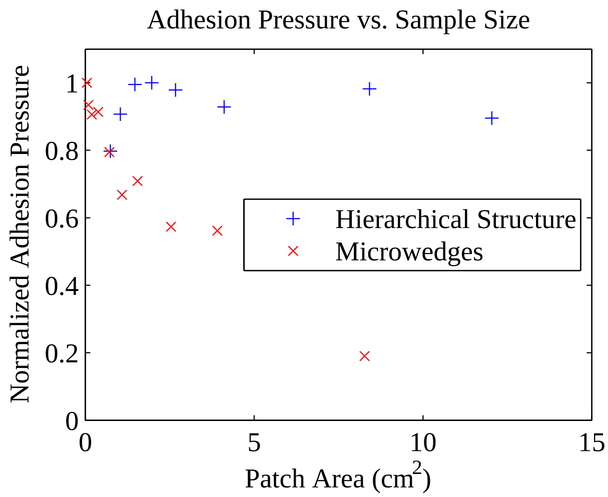

Fig. 7. The hierarchical system self aligned across large patches to maintain adhesive pressure regardless of patch size. The wedge shaped adhesive was unable to align across large patch sizes and adhesive pressure dropped with increasing patch area.

V. Discussion

In earlier work [29], [29] we have argued for the importance of directional dry adhesion for efficient climbing. In this paper we focus on two considerations of importance for climbing rough surfaces:

- conformation to the surface, maximizing the real contact area, and
- even load distribution across a patch, minimizing stress concentrations that lead to peeling and detachment.

The hierarchical system exhibits both of these properties. The 1 mm tall directional polymer stalks enable conformation to moderate-scale roughness on the surface and the 200 μm tall wedge structures conform to roughness on a finer scale. The suspension structure is very soft during conformation because the stalks are in a bending mode and have a significant aspect ratio. During loading, the structure remains in a bent state, but also goes into a much stiffer tensile mode, pulling fairly uniformly on the many wedges. The ability

TABLE I
COMPARISON OF ADHESION ON VARIOUS SURFACES

Sample	Thin (250μm) Backing Layer	Thick (400μm) Backing Layer
Glass	200g	240g
Lightly Textured Metal	170g	220g
Wood	140g	200g
Medium Texture Metal	130g	190g
Heavily Textured Metal	120g	130g
Painted Wall	110g	145g

to maintain the contact established during conformation is not compromised because the forces due to loading (mainly tensile) are nearly perpendicular to the forces created during conformation (mainly bending).

When loaded, the stalks bend and cause the structure to become thinner than its original state. Due to this, if the wedge layer under one suspension stalk detaches, the stalk will try to straighten, pushing the wedge layer back against the surface and reestablishing contact. In practice, we see that as loads on a hierarchical system are varied, the regions of the wedge layer in contact with the surface change, indicating that contacts that detach from the surface can reattach while the overall patch remains loaded. This makes climbing more robust, because variations in the load's magnitude and direction can be compensated for by localized slipping and reattachment of the adhesive structure.

However, this system is still far from the optimal hierarchy, and while it has enabled Stickybot to climb several semi-rough surfaces, the ability to climb grossly rough surfaces could be achieved with a more optimized adhesive system. One limitation is that the contacting elements are still connected by a continuous backing layer, making conformation to highly rough surfaces impossible due to its finite bending radius. The terminal elements in our system, being 10s of μm in size, are also too large to conform to surfaces on a nanometer scale, in comparison to the geckos' spatulae which are around 200nm [17]. Smaller terminal elements would likely enhance adhesion on all surfaces, as long as they were able to align and conform to the surfaces adequately.

To create more complex hierarchical systems, one could imagine multiple anisotropic backing layers, as shown in figure 8. To enable better conformation, the layers could be cut into smaller patches at lower levels of the hierarchy, as indicated by the black bar in the figure. However, there is a minimum patch size: because the patches have non-zero height, pulling in shear from the backing layer will cause moments at the surface which would tend to peel the patches. A patch's length-to-height ratio must be large enough that these moments do not cause peeling at the patch edges. Ultimately, at the smallest length scales it may be necessary to have a different load-sharing scheme which eliminates this backing layer entirely, although at larger length scales this strategy is very effective.

VI. Conclusion

For dry adhesives to be practically useful, large patch areas will need to be able to conform to rough surfaces

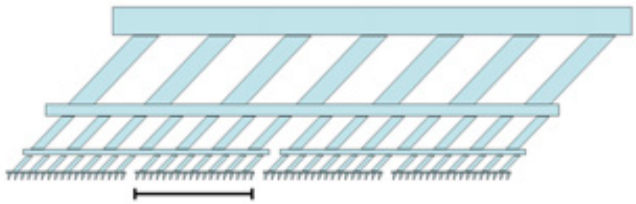

Fig. 8. Concept drawing of a possible hierarchical system using multiple layers of anisotropic material.

and perform effective load-sharing. Careful alignment of the patches to surfaces is not always possible, and even when dry adhesive patches are mounted on rigid experimental setups a significant decrease in adhesive pressure with patch area is observed[14]. A clear need for hierarchical systems exists, and as the design and manufacturing of these systems improves, robots will be further enabled to climb smooth and rough vertical surfaces with the extensive range of synthetic dry adhesives that have been developed.

VII. Acknowledgments

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References

[1] K. Autumn and N. Gravish, "Gecko adhesion: evolutionary nanotechnology," *Philosophical transactions Series A, Mathematical, physical, and engineering sciences*, vol. 366, no. 1870, pp. 1575–90, 2008.

[2] K. Autumn, A. Dittmore, D. Santos, M. Spenko, and M. Cutkosky, "Frictional adhesion: a new angle on gecko attachment," *Journal of Experimental Biology*, vol. 209, no. 18, pp. 3569–3579, 2006.

[3] A. Russell, M. Johnson, and S. Delannoy, "Insights from studies of gecko-inspired adhesion and their impact on our understanding of the gekkotan adhesive system," *Journal of Adhesion Science and Technology*, 2007.

[4] B. Aksak, M. Murphy, and M. Sitti, "Gecko inspired micro-fibrillar adhesives for wall climbing robots on micro/nanoscale rough surfaces," *IEEE ICRA*, 2008.

[5] J. Lee, C. Majidi, B. Schubert, and R. S. Fearing, "Sliding-induced adhesion of stiff polymer microfibre arrays. i. macroscale behaviour," *Journal of The Royal Society Interface*, vol. 5, no. 25, pp. 835–844, 2008.

[6] A. K. Geim, S. V. Dubonos, I. V. Grigorieva, K. S. Novoselov, A. A. Zhukov, and S. Y. Shapoval, "Microfabricated adhesive mimicking gecko foot-hair," *Nat Mater*, vol. 2, no. 7, pp. 461–463, 2003.

[7] Y. Tsai, W. Shih, Y. Wang, L. Huang, and P. Shih, "E-beam photoresist and carbon nanotubes as biomimetic dry adhesives," *Micro Electro Mechanical Systems*, 2006.

[8] S. Gorb, M. Varenberg, A. Peressadko, and J. Tuma, "Biomimetic mushroom-shaped fibrillar adhesive microstructure," *Journal of The Royal Society Interface*, vol. 4, no. 13, pp. 271–275, 2006.

[9] L. Ge, S. Sethi, L. Ci, P. M. Ajayan, and A. Dhinojwala, "Carbon nanotube-based synthetic gecko tapes," *Proc Natl Acad Sci USA*, vol. 104, no. 26, pp. 10 792–5, 2007.

[10] M. Murphy, B. Aksak, and M. Sitti, "Adhesion and anisotropic friction enhancements of angled heterogeneous micro-fiber arrays with spherical and spatula tips," *Journal of Adhesion Science and Technology*, 2007.

[11] Y. Zhao, T. Tong, L. Delzeit, A. Kashani, and M. Meyyappan, "Interfacial energy and strength of multiwalled-carbon-nanotube-based dry adhesive," *Journal of Vacuum Science & Technology B: Microelectronics*, 2006.

[12] A. Mahdavi, L. Ferreira, C. Sundback, and J. Nichol, "A biodegradable and biocompatible gecko-inspired tissue adhesive," *Proceedings of the National Academy of Sciences*, 2008.

[13] B. Yurdumakan, N. R. Raravikar, P. M. Ajayan, and A. Dhinojwala, "Synthetic gecko foot-hairs from multiwalled carbon nanotubes," *Chem. Commun.*, no. 30, p. 3799, 2005.

[14] A. Parness, D. Soto, N. Esparza, N. Gravish, M. Wilkinson, K. Autumn, and M. Cutkosky, "A microfabricated wedge-shaped adhesive array displaying geckolike dynamic adhesion, directionality, and long life," *Journal of the Royal Society Interface*, 2009.

[15] M. Murphy, B. Aksak, and M. Sitti, "Gecko-inspired directional and controllable adhesion," *Small*, 2008.

[16] L. Qu, L. Dai, M. Stone, Z. Xia, and Z. Wang, "Carbon nanotube arrays with strong shear binding-on and easy normal lifting off," *Science*, no. 322, pp. 238–242, 2008.

[17] K. Autumn, "Properties, principles, and parameters of the gecko adhesive system," 2006, pp. 225–256.

[18] M. Northen and K. Turner, "Meso-scale adhesion testing of integrated micro- and nano-scale structures," *Sensors and Actuators A: Physical*, vol. 130-131, pp. 583–587, 2006.

[19] M. Lanzetta and M. Cutkosky, "Shape deposition manufacturing of biologically inspired hierarchical microstructures," *CIRP Annals-Manufacturing Technology*, 2008.

[20] T. Kim and B. Bhushan, "Adhesion analysis of multi-level hierarchical attachment system contacting with a rough surface," *Journal of Adhesion Science and Technology*, 2007.

[21] K. Daltorio, T. Witushynsky, G. Wile, L. Palmer, A. Malek, M. Ahmad, L. Southard, S. Gorb, R. Ritzmann, and R. Quinn, "A body joint improves vertical to horizontal transitions of a wall-climbing robot," *IEEE ICRA*, pp. 3046 – 3051, 2008.

[22] K. Daltorio, A. Horchler, S. Gorb, R. Ritzmann, and R. Quinn, "A small wall-walking robot with compliant, adhesive feet," *IEEE RSJ*, 2005.

[23] M. Murphy and M. Sitti, "Waalbot: An agile small-scale wall-climbing robot utilizing dry elastomer adhesives," *Mechatronics*, 2007.

[24] O. Unver, A. Uneri, A. Aydemir, and M. Sitti, "Geckobot: a gecko inspired climbing robot using elastomer adhesives," *IEEE ICRA*, pp. 2329– 2335, 2006.

[25] A. T. Asbeck, S. Kim, M. R. Cutkosky, W. R. Provancher, and M. Lanzetta, "Scaling hard vertical surfaces with compliant microspine arrays," *Int J Robot Res*, vol. 25, no. 12, pp. 1165–1179, 2006.

[26] M. J. Spenko, G. C. Haynes, J. A. Saunders, M. R. Cutkosky, A. A. Rizzi, R. J. Full, and D. E. Koditschek, "Biologically inspired climbing with a hexapedal robot," *J. Field Robot.*, vol. 25, no. 4-5, pp. 223–242, 2008.

[27] vortex, "www.vortexhc.com," 2006.

[28] H. Prahlad, R. Pelrine, S. Stanford, and J. Marlow, "Electroadhesive robots—wall climbing robots enabled by a novel, robust, and electrically ...," *IEEE ICRA*, Jan 2008.

[29] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, D. Santos, and M. Cutkosky, "Smooth vertical surface climbing with directional adhesion," *IEEE Transactions on Robotics*, vol. 24, no. 1, pp. 65 – 74, 2008.

[30] D. Soto, A. Parness, N. Esparza, T. Kenny, K. Autumn, and M. Cutkosky, "Microfabricated dry adhesive displaying frictional adhesion," *Hilton Head 2008 solid state sensors, actuators, and microsystems*, June 2008.

[31] Microchem, "Microchem.com," 2008.

[32] D. Santos, M. Spenko, A. Parness, S. Kim, and M. Cutkosky, "Directional adhesion for climbing: theoretical and practical considerations," *Journal of Adhesion Science and Technology*, vol. 21, no. 12-13, pp. 1317–1341, 2007.

[33] K. Johnson, "The adhesion of two elastic bodies with slightly wavy surfaces," *International Journal of Solids and Structures*, vol. 32, no. 3/4, pp. 423 – 430, 1995.

[34] K. Autumn, C. Majidi, R. Groff, A. Dittmore, and R. Fearing, "Effective elastic modulus of isolated gecko setal arrays," *Journal of Experimental Biology*, pp. 3558–3568, Jan 2006.

[35] D. Santos, S. Kim, M. Spenko, A. Parness, and M. Cutkosky, "Directional adhesive structures for controlled climbing on smooth vertical surfaces," *IEEE ICRA*, 2007.