SpinybotII: Climbing Hard Walls With Compliant Microspines

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SpinybotII: Climbing Hard Walls with Compliant Microspines

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***Abstract*--A new climbing robot has been developed that can scale flat, hard vertical surfaces including concrete, brick, stucco and masonry without using suction or adhesives. The robot can carry a payload equal to its own weight and can cling without consuming power. It employs arrays of miniature spines that catch opportunistically on surface asperities. The approach is inspired by the mechanisms observed in some climbing insects and spiders. This paper covers the analysis and implementation of the approach, focusing on issues of spine/surface interaction and compliant suspension design.**

***Index Terms*—Robotics, Mechanisms.**

I. INTRODUCTION

IN recent years, there has been considerable progress in small, legged robots that can run rapidly and stably over rough terrain [1][2][3][4]. Climbing and maneuvering on vertical surfaces presents a more difficult challenge, which robots are just beginning to address. For applications such as surveillance or the inspection of hard-to-reach locations, we would like to have small robots that can climb a variety of hard and soft surfaces unobtrusively and cling for extended periods of time without high power consumption.

Previously developed climbing robots have generally employed suction cups [5][6][7], magnets [8][9] or sticky adhesives [10] to cling to smooth vertical surfaces such as windows and interior walls. None of these approaches is suitable for porous and typically dusty exterior surfaces such as brick, concrete, stucco or stone. A recent innovation employing a controlled vortex to create negative aerodynamic lift has been demonstrated on brick and concrete walls [11] with considerable success. However, this approach consumes significant power (whether the robot is moving or stationary), unavoidably generates noise, and is difficult to adapt to non-smooth surfaces such as window ledgesand corrugated surfaces. Still other robots employ hand and foot holds in the manner of a human climber [12][13].

When we look at animals that exhibit scansorial (vertical surface) agility, we find a variety of methods employed [14]. Larger animals such as cats and raccoons employ strong claws that penetrate wood and bark surfaces. Tree frogs and many insects employ sticky pads [15][16]. Geckos and some spiders employ large numbers of very fine hairs that achieve adhesion via van der Waals forces on almost any kind of surface [17][18][19]. Other insects, arthropods and reptiles employ small spines that catch on fine asperities [20]. All of these approaches are worthy of examination for bio-inspired climbing robots. However, dry adhesives and spines are particularly attractive for hard, dusty, exterior surfaces.

Several researchers are currently working on creating synthetic versions of the setae found in geckos or the scopulae seen on spiders [21][22][23]. The early results are intriguing but current synthetic adhesives are not able to sustain the kinds of tensile loads needed at the forelimbs of a climbing robot. Moreover, they are fragile and lack the self-cleaning property that allows geckos to climb dusty walls.

II. SPINE AND SURFACE SCALING

A. Spines in nature

Insects and arthropods that climb well on man-made and natural surfaces often use legs equipped with large numbers of small, sharp spines. Even geckos that frequent rock surfaces such as cliffs and caves have small claws on each toe in addition to their dry adhesive structures [24]. Unlike the claws of a cat, the small spines or claws do not need to penetrate the surface. Instead, they exploit small asperities (bumps or pits) on the surface. Several studies in the biology literature have considered the problem of spine/surface interaction. Dai *et al*. [20] present a planar model of spine/asperity contact and compute the maximum load per spine as a function of spine strength, relative size of the spine tip versus that of an asperity, and coefficient of friction. As expected, for rough surfaces the mechanical strengths of the spine and asperity become the limiting factors; for smoother surfaces friction is more important and the ability to pull in toward the surface is much reduced.

B. Spine scaling for a climbing robot

Given the observed relationship between spine or claw size and animal size, we are led to ask: *For a climbing robot of a given size, how large should the spines be?* If we consider a robot that weighs approximately 0.5 Kg, we might expect spines or claws similar to those seen in squirrels or large climbing lizards. However, this argument ignores the point that spines made of hardened steel are much stronger and

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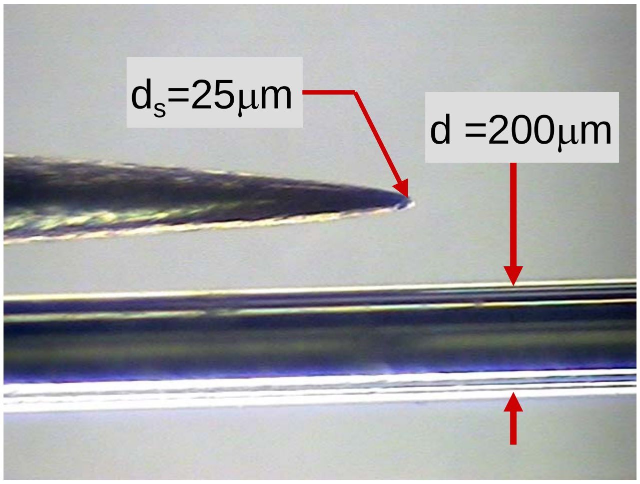

Fig.1 magnified view of typical shaft and tip for spines used in SpinybotII climbing robot.

stiffer than natural spines and can therefore be smaller while supporting a comparable load.

Indeed, if the strength of the spine/asperity contact were not a constraint, we should make the spines as small as possible. The reason behind this argument is that many natural surfaces, and some man-made surfaces such as concrete and stucco, have an approximately fractal surface topography [25][26][27] so that characteristic surface features (asperities) can be found over a wide range of length scales. Following the arguments of Dai *et al*. [20] for spines of a certain tip diameter, d_s, we are interested in asperities of average diameter $d_a \geq d_s$ to obtain effective interlocking. Given the self-similar nature of fractal surfaces, we can expect the density of such asperities to grow at least as $1/d_a^2$ per unit area of the wall.


Fig.2 View of upper section of SpinybotII on concrete wall and detailed view of several spines independently engaging asperities on the concrete surface.

In practice, there is a lower limit to the useful spine dimensions. We have found that when steel spines catch on asperities on concrete or stucco, the contact typically fails in one of three ways [30]:

- plastic failure of the base of the spine in bending,
- excessive elastic rotation of the spine tip causing it to slip off the asperity,
- brittle failure of the asperity itself.

In each of these cases, if we take a dimension such as the spine tip diameter, d_s, as a characteristic length and scale everything uniformly, then the maximum load of the spine/asperity contact increases as d_s^2 (see Appendix for details). For our first climbing robot, SpinybotI, we employed 4 spines per foot, each with a tip diameter of approximately 40 μm. This machine was able to climb stucco and rough concrete reliably. The spine/asperity contacts could sustain loads of several Newtons, usually limited by brittle failure of the asperity rather than of the spine. However, for surfaces such as smooth concrete and dressed stone, the probability of a spine encountering a useful asperity during a vertical stroke length of approximately 3 cm was too low for reliable climbing. SpinybotII employs two rows of spines on each foot, each spine having a tip diameter of approximately 25 μm. The maximum force per spine/asperity contact is 1-2 N, and the probability of finding useable asperities per square centimeter of wall is high.

To summarize the preceding arguments, as spines become smaller we can ascend smoother surfaces because the density of useable spine/asperity contacts increases rapidly. However, we need larger numbers of spines because each contact can sustain less force. In order to make use of large numbers of spines, the first two design principles behind climbing with microspines are therefore:

- ensure that as many spines as possible will independently find asperities to attach to,
- ensure that the total load is distributed among the spines as uniformly as possible.

The design of feet that embody these principles is described in Section III. In addition, as with any climbing robot, it is important to keep the center of gravity as close to the wall as possible and to avoid imposing any forces or moments at the feet that could lead to premature detachment. The features of SpinybotII that achieve these effects are described in Section IV.

III. TOE AND FOOT DESIGN: PROMOTING ATTACHMENT AND LOAD SHARING

The feet on SpinybotII represent the sixth generation of a compliant, spined design. A failing of earlier designs was that on close observation, only a few spines were carrying most of the load. Each foot of SpinybotII contains a set of 10 identical planar mechanisms, or "toes." The mechanisms are created using a rapid prototyping process, Shape Deposition Manufacturing [28] that permits hard and soft materials to be combined into a single structure. In the present case, the white and grey materials are hard and soft urethanes, of 75 Shore-D and 20 Shore-A hardness, respectively (Innovative Polymers Inc.). The resulting structure can be approximated as an elastic multi-link mechanism, as shown in Fig. 3. The soft urethane flexures provide both elasticity and visco-elastic damping. They permit greater extensions without failure than miniature steel springs (as were used on some of the earlier foot designs).

For small deflections, the linear and rotational stiffness of each spine in the *(x,y)* plane can be modeled using a 3x3 stiffness matrix, K, taken with respect to a coordinate system embedded in the spine:

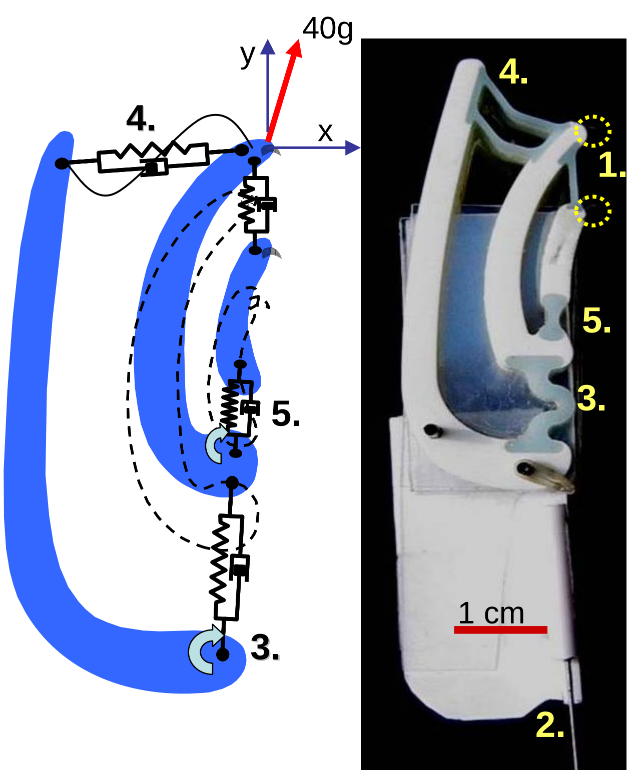

Fig. 3. Photograph and equivalent elastic linkages for one toe of the climbing robot. Linkage at left shows the deflected position for a 40g load, superimposed on the undeflected position (shown in dotted lines). Key to labels: **1**. 200 µm diameter spines (inside dotted circles), **2**. tendon for applying loads, **3.** soft urethane flexure permitting travel in *y* direction, **4**. buckling flexures with low stiffness in the *-x* direction under compression, higher stiffness under tension, **5**. primarily rotational flexure for the proximal spine.

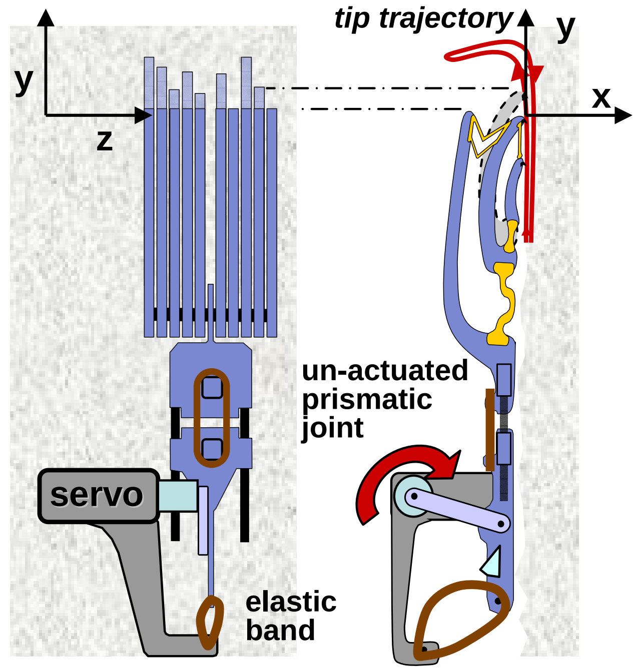

Fig. 4. Side and plan view of one foot containing 10 toes, each like the toe shown in Fig. 3. The toes can deflect independently of each other. In addition, the entire foot can displace in the distal (*y*) direction due to an un-actuated prismatic joint. The attachment trajectory of the foot consists of an upward (+*y*) motion, followed by lift-off motion (-*x*), touchdown (+*x*), and a downward pull (-*y*). The sequence of motions is accomplished using an under-actuated mechanism consisting of a single rotary RC servo motor and an elastic band that is initially loose and becomes taut as the leg moves upward. At the end of stroke, a hard stop causes the leg to remain pressed against the wall.

$$\begin{bmatrix} k_{xx} & k_{xy} & k_{x\theta} \\ k_{xy} & k_{yy} & k_{y\theta} \\ k_{x\theta} & k_{y\theta} & k_{\theta\theta} \end{bmatrix}$$

At initial contact, we require that k_{xx} be very small for displacements in the *-x* direction, so that a large number of toes can conform to uneven surfaces without requiring a significant engaging normal force. This is accomplished through the flexures at the end of the toe (labeled **4**. in Fig. 3), which are designed to buckle so that they have a very low stiffness for *-x* deflections. For small tensile loads on the foot (in the +*x* direction), some toes will still be compressed from the foot's engaging motions. k_{xx} should still be small in this case so these compressed toes do not push the foot away from the wall. Finally, for large tensile loads, k_{xx} should be large so the toes can disengage from the wall. This is also accomplished with the flexures at the end of the toe.

At the same time, k_{yy} should be moderate, as it represents a trade-off. A softer k_{yy} allows each toe to stretch more in the longitudinal direction to increase the probability that each one will catch an asperity during the downward stroke of the foot; but if k_{yy} is too soft, the mechanism will require an excessive stroke length to support a given load. In essence, these factors determine the "asperity search length" for the downward

TABLE I
STIFFNESS AND DAMPING PARAMETERS FOR TOE LINKAGE

Location (numbered label, Fig. 3)	Parameter in kinematic model k = linear stiffness element c = linear damping element k_t = rotational stiffness element
1.	k = 60 N/m c = 0.1 Ns/m
3.	k = 60 N/m c = 0.1 Ns/m k_t =0.005 Nm
4.	k = 90N/m in tension k = 0.005N/m in compression c = 0.02 Ns/m
5.	k =100 N/m c = 0.001 Ns/m k_t = 0.001 Nm

stroke of the toe. At the same time, k_{xy} should be small so that stretching in the y direction does not cause the spines to retract. The $k_{x\theta}$ and $k_{y\theta}$ terms should also be small and, preferably, slightly negative so that displacements in the x or y direction are not accompanied by anticlockwise rotations in the (x, y) plane that would lead to premature disengagement.

The mechanism shown in Fig. 3 was modeled in the Working Model™ software (MSC Inc.) and the various linear and rotational stiffness elements were adjusted until the model matched deflections obtained when applying small loads and measuring the corresponding displacements in bench-top tests. The results are summarized in Table I. The mechanism is designed so that initial contact at the inner, or proximal, spine actually forces the distal spine slightly outward (+x direction) to increase the probability that it will also contact an asperity.

Once one or both spines have contacted the wall, the toe can apply a force that is mainly vertical, with a small inward (+x) component to help the robot climb. Fig. 3 shows the effect of a typical 40 gram load sustained by one toe in climbing. Each toe mechanism can deflect independently of its neighbors (as seen in the detailed inset in Fig. 2) to maximize the probability that many spines on each foot will find asperities and share the total load.

An important observation of agile scansorial animals like geckos is that they employ *multi-level conformability* (e.g. lamellae, toes, and limbs) and *redundancy* (multiple pads per toe, multiple toes per foot, and multiple feet in contact) for reliable climbing. The same principles have been found necessary for SpinybotII. Accordingly, the entire foot mechanism is mounted on a prismatic joint with an elastic suspension that allows it to move up to 1 cm in the distal (+y) direction (see Fig. 4). In addition, the entire foot assembly is spring loaded by a second elastic element behind the pivot, where it is connected to a rotary RC servo motor. The result is an under-actuated R-R-P serial kinematic chain that traces a

TABLE II
SPINYBOTII SPECIFICATIONS

Mass	0.4 Kg
Max payload	0.4 Kg
Climbing speed	2.3 cm/s
Distance: COM to wall surface	2.0 cm
Batteries	lithium polymer total 340 mAh, 7.4 volts
Processor	40 MHz PIC
Servo motors (7 total)	0.37 Nm torque
Camera	0.02 Kg

loop trajectory, as shown in Fig. 4, when the servo motor rotates back and forth. After some experimentation, the best elastic elements were found to be 6.4mm diameter elastic bands commonly used for dental braces.

IV. BODY DESIGN: PROMOTING LOAD SHARING AND STABILITY

Moving from the foot to the body as a whole, we see in Fig. 5 that the robot utilizes an alternating tripod gait, as found in climbing insects. At any time, the robot is ideally clinging by three feet. Like many climbing animals, the robot also has a tail which reduces the forces required at the front limbs to overcome body pitch-back from the wall. This pitch-back moment is produced by gravity acting at the center of mass, which is located approximately 2 cm outward from the wall. The weight of the robot, including lithium polymer batteries,

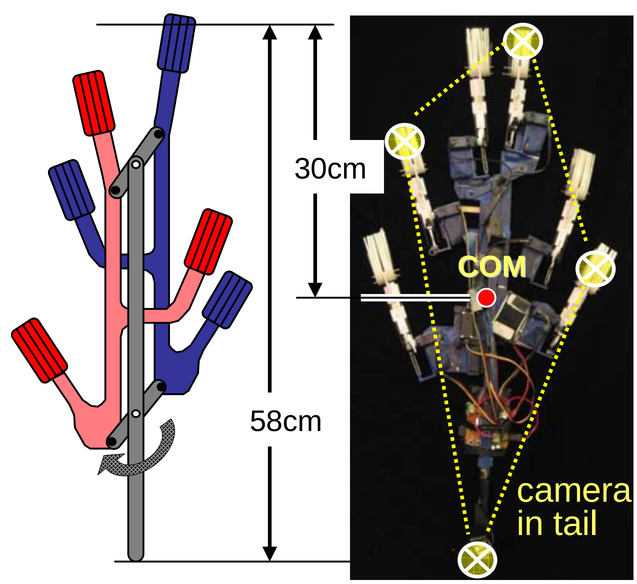

Fig. 5. Photograph of SpinybotII wall and diagram of climbing mechanism. Each set of three legs is attached to a mechanism that allows the robot to "ratchet" its way up the wall with an alternating tripod gait. A long tail helps to reduce the pitching moment. The center of mass (COM) is always within the polygon of contacts, to minimize yawing rotations in the plane of the wall.

wireless camera, and PIC microprocessor is 0.4 Kg. It can carry an additional payload of 0.4 Kg while climbing. The climbing speed is currently quite slow (2.3cm/s) but can easily be improved upon with the addition of structural damping in the limbs and toe suspension.

On initial contact of each spine with the wall, the spine and toe suspension oscillate as an underdamped structure. Such oscillations reduce the probability of engaging useful asperities encountered as the spines are stroked along the wall. The addition of structural damping will greatly improve climbing performance (attachment) and permit climbing at greater speeds. Higher performance motors may also be desirable.

While the main concern for vertical climbing is to avoid pitching back from the plane of the wall, it is also important to maintain rotational stability in the plane of the wall so that momentary slips to not become catastrophic. As seen in Fig. 5 the center of mass of SpinybotII lies within a polygon of contacts at all times. Also, as observed in climbing insects and reptiles, the legs have a slight inward pull, toward the centerline of the robot. This arrangement reduces the upsetting moments (in the plane of the wall) about the center of mass, should one of the legs momentarily lose its grip.

V. CONCLUSIONS AND FUTURE WORK

SpinybotII climbs reliably on a wide variety of hard, outdoor surfaces including concrete, stucco, brick, and dressed sandstone with average asperity diameters of greater than 25µm. The main principles behind its success have been explained in Sections II-IV. A video of SpinybotII climbing various buildings around the Stanford campus and some close shots of its feet and toes engaging asperities can be found at http://bdml.stanford.edu/RiSE/Downloads/ .

Watching the video closely will also reveal several instances in which one foot briefly loses its grip. However, there is enough redundancy and compliance that the robot does not fall. Of course, if the robot encounters a very smooth patch, it either fails to proceed or falls. For greater reliability, we are investigating miniature accelerometers at the toes that will indicate when contact has occurred and whether the foot is stationary or slipping.

Although the autonomous version of Spinybot described in this paper also lacks the ability to move sideways on vertical walls, we have tested variants capable of (very slow) lateral locomotion under radio control. The inward lateral pull of the legs is essential for this capability.

The main practical limitation of SpinyBotII is that it lacks sufficient degrees of freedom to negotiate corners and transitions from vertical to horizontal surfaces (as when climbing over a window ledge. Adding degrees of freedom should be straightforward, except that the center of mass must remain close to the wall and the additional degrees of freedom must not interfere with the compliant design principles of the toes, feet and legs as described in this paper. Scaling SpinyBotII to larger payloads should also be straightforward; one simply needs more spines.

A more challenging problem is to tackle rough or corrugated surfaces. Either the feet and toes must have enough "suspension travel" to accommodate the contours of the surface or they must have an additional active degree of freedom, like the toes of geckos or the tendon-actuated tarsus of insect legs. On such surfaces it should be possible to exploit internal "grasp" forces, in a manner similar to that used by robots that climb with hand-holds and foot-holds [13] [12] , for additional security.

The spines and toes on SpinybotII are also optimized for contact with hard surfaces. For soft materials, larger claws that penetrate the surface are more effective [29]. Adding larger, penetrating, claws to the feet of a robot like SpinybotII is certainly possible. We suspect that it will be necessary to make them retractable (like the claws of a cat) so that they will not interfere with the function of the microspines on hard surfaces.

Another challenging problem is to climb surfaces, such as polished stone or interior wall panels, with much lower roughness than concrete or sandstone. The scaling arguments in Section II should still apply. However, for smooth panels the average asperity diameter may be on the order of a few micrometers, requiring spine tip diameters of perhaps 4 µm. These extremely small spines will be over 100 times weaker than the spines on SpinybotII and a large number of them will be required, unless the overall mass of the robot can be reduced correspondingly. Going still smaller, we approach the dimensions of the hairs that are being investigated for synthetic dry adhesives [19][21][22][23]. An interesting question is whether some combination of spines and adhesive hairs will ultimately prove most effective for scaling a wide variety of hard vertical surfaces.

APPENDIX SPINE FAILURE MODES

The spine/asperity contacts have three primary failure modes.

- The first mode of failure is due to the tensile stress at the base of the spine [31].

Maximum stress on cylindrical cantilever beam:

$$\sigma_{\max} = \frac{Mc}{I} = \frac{32 f\ l\ d_s}{\pi\ d_s^{\,4}} \quad \propto \frac{1}{d_s^{\,2}} \quad (if \quad \frac{l}{d_s} = const)$$

$$M = f\ l,\ \ c = \frac{d_s}{2},\ \ I = \frac{\pi\ d_s^{\,4}}{64}$$

f = force exerted on tip of the spine
d_s = diameter of cross section of spine
l = spine length

- The second mode of failure is excessive tip rotation.

Deflection angle at the tip of cantilever beam:

$$\theta = \frac{f\ l^2}{2EI} = \frac{32 f\ l^2}{E\ \pi\ d_s^{\,4}} \quad \propto \frac{1}{d_s^{\,2}} \quad (if \quad \frac{l}{d_s} = const)$$

• The third mode of failure is that the asperity itself may break off or fail in shear.

Shear stress failure:

$$\sigma_{\max} = \frac{f}{A} = \frac{4f}{\pi\ d_a^{\ 2}} \quad \propto \frac{1}{d_s^{\ 2}} \quad (if \quad d_a = d_s)$$

The details of the asperity failure will depend on whether the material is brittle and whether cracks or defects are present [30]. However, the strength of the asperity is generally expected to increase as the square of asperity diameter.

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