Climbing Walls with Microspines

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***Abstract*—A technology has been developed that enables robots to scale flat, hard vertical surfaces including concrete, brick, stucco and masonry without using suction or adhesives. It employs arrays of miniature spines that catch on surface asperities. The approach is inspired by the mechanisms observed in some climbing insects and spiders. The spiny foot technology has been utilized successfully on one robot, Spinybot, and is now being adapted to a larger, heavier robot, the RiSE platform. This short paper covers the implementation of the approach, focusing on the design principles and their extension to a range of platforms.**

***Index Terms*—legged robots, underactuated robots**

I. Introduction

In recent years, there has been considerable progress in small, legged robots that can run rapidly and stably over rough terrain [1]-[4]. Climbing and maneuvering on vertical surfaces presents a more difficult challenge, one which robots are just beginning to address. For applications such as surveillance or 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]-[7], magnets [8][9], or sticky adhesives to cling to smooth vertical surfaces such as windows and interior walls [5]-[10]. Still other robots employ hand and foot holds in the manner of a human climber [11][12]. None of these approaches is suitable for porous and typically dusty building 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 [10]. 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 ledges and corrugated surfaces. For these reasons, spines are particularly attractive for hard, dusty, exterior surfaces.

II. Principles of Climbing with Spines

Unlike the claws of a cat, small spines do not need to penetrate surfaces. 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.* [13] 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. Following the arguments of Dai *et al.* [13] for spines of a certain tip radius, r_s, we are interested in asperities of average radius $r_a \geq r_s$ to obtain spine engagement.

Since many natural surfaces, and some man-made surfaces such as concrete and stucco, have an approximately fractal surface topography [14], characteristic surface features can be found over a wide range of length scales. Given the self-similar nature of fractal surfaces, we can expect the density of such asperities to grow as $1/r_a^2$ per unit area of the wall. If we take a dimension such as the spine tip radius, r_s, as a characteristic length and scale everything uniformly, then the maximum load of each spine/asperity contact increases as r_s^2 [15].

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 sustains less force. Therefore, the key design principles behind climbing with microspines are:

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

A. Spinybot

The above principles have been demonstrated in a 400g climbing robot, Spinybot, that readily climbs hard surfaces such as concrete, brick, stucco and sandstone walls. The robot's six limbs are under-actuated mechanisms [16] in which a single actuator, in combination with passive compliances, is responsible for engaging and disengaging the spines. A seventh actuator produces a ratcheting motion that alternately advances the legs in each of two tripods up the wall (refer to accompanying video submission to view climbing motion).

Spinybot's feet each consist of ten planar toe mechanisms with two spines per toe. The mechanisms are created using a rapid prototyping process [17] that permits hard and soft materials to be combined into a single structure. As shown in Fig. 1, each toe consists of several hard members connected by soft links (75 Shore-D and 20 Shore-A hardnesses, respectively), with the spines embedded in the hard plastic. Each spine has a shaft diameter of 200µm and a tip radius of 12-25µm. 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. Each toe mechanism can deflect and stretch independently of its neighbors to maximize

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the probability that multiple spines on each foot will find asperities and share the load.

The robot also employs a tail that reduces the forces required at the front limbs to overcome body pitch-back from the wall. The legs pull inward slightly toward the centerline to reduce the upsetting moments (in the plane of the wall) should one of the legs momentarily lose its grip [16].

III. Adapting Spines to Larger Robots

The design principles summarized above can be applied to other robot platforms, with some adaptation required to accommodate larger loads.

A. The RiSE Platform

The RiSE platform, shown in Fig. 2a, is a 3.2 Kg, 6-legged, 2-DOF/leg robot [18]. The robot employs many of the same features as Spinybot, including a tail, pull-in motions, and a sprawled posture with the center of mass close to the wall. However, it is approximately 7.5 times heavier than Spinybot and much more powerful, while occupying similar dimensions (0.5m long, including tail). Therefore, additional measures are needed to prevent spine failures.

B. Using Spines with Heavy Robots

As discussed in the previous section, the desired spine tip dimensions are primarily a function of the surfaces to be climbed, and not of robot size. Consequently, for a given surface a heavier robot requires more spines per foot and the risk of spine failure (or surface failure) is greater. In the worst case, Spinybot can hang on one or two spines without

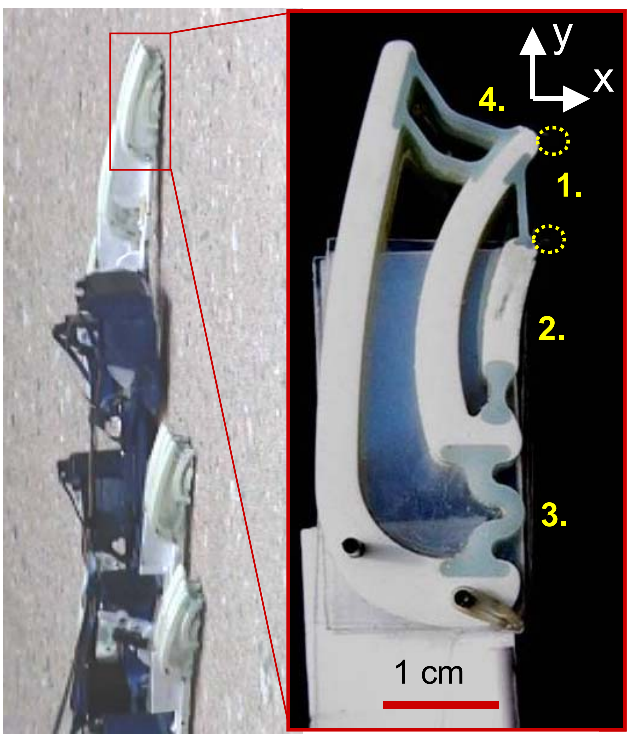

Fig. 1. View of upper section of Spinybot on concrete wall and detailed view of a toe on the foot. Each toe consists of two spines (1) embedded in hard polyurethane members (2). Soft polyurethane linkage (3) permits the hard members and spines to extend in the axial direction (upwards in the plane of the wall), and linkage (4) buckles to allow the spines to comply to the surface, but resists extension to disengage the spines.

TABLE I

Effect of Scaling Parameters on Toe Compliances

Compliance (1/k)	x-direction	y-direction
Number of toes N	$\sim 1/N$	$\sim 1/N$
Robot mass M	constant	$\sim 1/M$
Spine tip radius r_s	constant	$\sim r_s$

Table I. Desired suspension compliances in the x- and y-directions vary as a function of robot weight, spine size and number of spines. In Fig. 1, these are the compliances for (4) to compress and (3) to extend, respectively. The x-compliance is varied to keep the compliance of the entire foot constant. The y-compliance is varied to achieve appropriate y-displacements, such that most of the spines are engaged but not over-extended. In most cases the number of toes N should be chosen as $N \sim 1/r_s$ for a constant robot mass, assuming the spine dimensions are proportional to the tip radius r_s.

inducing failures. For the RiSE platform it is necessary to ensure that the weight of the robot is never loaded on just a few spines.

The loading problem is complicated by the need to tune the compliances of the toes based on total robot weight and total number of spines. The toes also need to stretch independently of their neighbors to ensure that each spine has a high probability of engaging asperities and to ensure load sharing. Consequently, it does not suffice simply to make the toes robust and stiff.

The basic scaling relationships among the desired compliances, spine size, robot mass, and number of spines are summarized in Table I. To conform to surfaces appropriately, the compliance of the toes in the $-x$ direction (see Fig. 1) should vary as $1/N$, where N is the number of toes, in order to maintain constant x-compliance for the entire foot. The x-compliance should not depend on the mass of the robot M or the spine tip radius r_s. To maintain appropriate load-sharing between spines, the compliance of the toes in the $+y$ direction should vary as $1/N$ for a given stroke distance down the wall. Also, the y-compliance should vary as $1/M$ since heavier loads will extend the toes more. The stroke distance and thus y-compliance should be proportional to the spine tip radius r_s, because the distance required to find an asperity will usually vary as r_s.

In addition to changing the toe compliances for the RiSE platform, solutions were developed to prevent toe damage from overloading. Overload stops were developed (see Fig. 2) with a passive end-of-travel mechanism such that the spine automatically disengages from the surface in many cases if the overload condition is reached, or is prevented from extending further if it does not disengage.

To climb the widest possible variety of walls for a given minimum spine size, it may be desirable to have a combination of large spines as well as smaller spines. Man-made surfaces such as concrete aggregate are composed of comparatively large smooth patches surrounded by a matrix with larger asperities. Since small spines may not have the clearance to reach the large asperities, but may still be too large to engage micro-asperities on the smooth patches, a few large spines can be used in addition to many small spines to best take advantage of the surface. The feet for RiSE use several large (r_s = 40µm) spines in the middle of the foot and

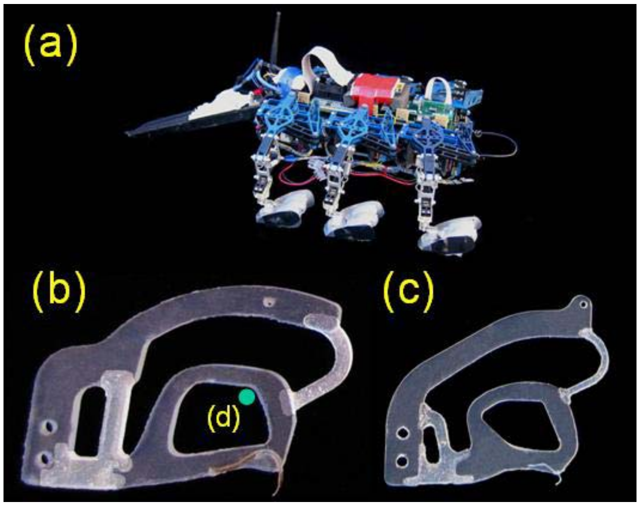

Fig. 2. Photographs of the RiSE robot (a), toe with large spine (b), and toe with small spine (c). The hole in the center of each toe provides overload protection in conjunction with a pin (d) on the foot. This causes the toe to disengage or not extend further upon excessive extension.

have 40 smaller (r_s = 12-25µm) spines on the sides, as shown in Figs. 2b and 2c.

IV. Conclusions and future work

Spinybot climbs reliably on concrete, stucco, brick, and dressed sandstone surfaces with average asperity radii of greater than 12µm. The essential principles behind its operation include using many miniature spines with a compliant suspension that ensures that the load is shared uniformly among them. The same principles can also be applied to larger robot platforms. Desired spine tip radius is a function of average asperity size for the surfaces to be climbed and not of robot size. Therefore, large robots require more spines and correspondingly a more careful design to ensure loads are shared evenly among them.

It is a challenge to make the heavier RiSE platform climb as wide a range of outdoor surfaces as Spinybot does. However, with a suitably adapted combination of miniature spines and suspensions it is already able to climb rough concrete and stucco surfaces. Further improvements in climbing ability are likely with refinements in toe design and the incorporation of active contact force control using feedback from force sensors at the ankles.

A second challenge is to climb surfaces such as 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 radius may be on the order of a few micrometers, requiring spine tip radii of perhaps 1 µm. These extremely small spines will be over 100 times weaker than the spines on Spinybot and a large number will be required, unless the overall mass of the robot can be reduced correspondingly. Going still smaller, we approach the dimensions of the hairs being investigated for synthetic dry adhesives [19][20]. 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.

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