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Robotics in Scansorial Environments

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Abstract

We review a large multidisciplinary effort to develop a family of autonomous robots capable of rapid, agile maneuvers in and around natural and artificial vertical terrains such as walls, cliffs, caves, trees and rubble. Our robot designs are inspired by (but not direct copies of) biological climbers such as cockroaches, geckos, and squirrels. We are incorporating advanced materials (e.g., synthetic gecko hairs) into these designs and fabricating them using state of the art rapid prototyping techniques (e.g., shape deposition manufacturing) that permit multiple iterations of design and testing with an effective integration path for the novel materials and components. We are developing novel motion control techniques to support dexterous climbing behaviors that are inspired by neuroethological studies of animals and descended from earlier frameworks that have proven analytically tractable and empirically sound. Our near term behavioral targets call for vertical climbing on soft (e.g., bark) or rough surfaces and for ascents on smooth, hard steep inclines (e.g., 60 degree slopes on metal or glass sheets) at one body length per second.

Keywords

climbing robots, gecko adhesion, bioinspired design, power autonomous locomotion, scansorial agility

Disciplines

Electrical and Computer Engineering | Engineering | Systems Engineering

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ABSTRACT

We review a large multidisciplinary effort to develop a family of autonomous robots capable of rapid, agile maneuvers in and around natural and artificial vertical terrains such as walls, cliffs, caves, trees and rubble. Our robot designs are inspired by (but not direct copies of) biological climbers such as cockroaches, geckos, and squirrels. We are incorporating advanced materials (e.g., synthetic gecko hairs) into these designs and fabricating them using state of the art rapid prototyping techniques (e.g., shape deposition manufacturing) that permit multiple iterations of design and testing with an effective integration path for the novel materials and components. We are developing novel motion control techniques to support dexterous climbing behaviors that are inspired by neuroethological studies of animals and descended from earlier frameworks that have proven analytically tractable and empirically sound. Our near term behavioral targets call for vertical climbing on soft (e.g., bark) or rough surfaces and for ascents on smooth, hard steep inclines (e.g., 60 degree slopes on metal or glass sheets) at one body length per second.

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1. INTRODUCTION

No machine yet exists that can maneuver in the “scansorial” regime – that is, perform nimbly in general vertical terrain environments without loss of competence in level ground operation. We have built an autonomous robotic platform capable of quasi-static vertical climbing at fractions of a body length per second on a variety of substrates as well as quasi-static walking at speeds close to one body length per second. We are now trying to move the capabilities of this machine or a re-designed iteration into the dynamical behavioral regime that is presently the exclusive preserve of animals. In this paper, we introduce the RiSE platform as it presently exists and give a very brief preview of its near term evolution.

Two major research challenges face the development scansorial robotics. First, we seek to understand , characterize and implement the dynamics of climbing: wall reaction forces, limb trajectories, surface interactions, and so on. Second, we are designing, fabricating and deploying adhesive patch technologies that yield appropriate adhesion and friction properties to facilitate necessary surface interactions. Our approach to these challenges is inspired and informed by our study of gecko, arthropod, and some mammalian morphology and behaviors. The initial engineering effort has been focused on the design and implementation of passive, compliant, mechanically-tuned appendages, their integration into power- and computation- autonomous bodies, and the development of sensor-based control algorithms. Longer term emphasis will be on linking carefully designed mechanical structures with sensor-based strategies for adjusting stance

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and motion parameters, recovering from slips when traction is marginal, and thereby negotiating the terrain in a dynamical manner.

2. BIOINSPIRATION

Careful studies of animals climbing vertical force plates reveal a similar pattern of ground reaction forces in such dissimilar species as geckos in a "trotting" gait and cockroaches undertaking an alternating tripod gait [1], as depicted in Figure 1. Legs pull or push up only, with no decelerating forces in the vertical direction whatsoever. There are only negligible attachment and detachment forces associated with leg transition from stance to swing. In the normal direction, front legs pull in, rear legs push out to counter over-turning moments. Laterally, legs pull in toward the midline of the body to grip the substrate. Clearly, good adhesion is plays a key role in climbing.

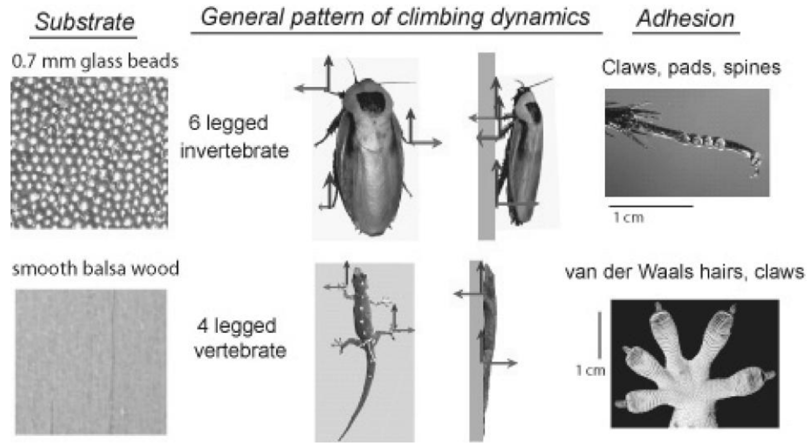

Figure 1. The wall-reaction forces (arrows not to scale) that cockroaches generate during rapid climbing of rough plates are similar to those of gecko lizards, animals with radically different morphology and adhesive mechanism. During foot touchdown, both species generate vertical forces from all limbs that pull up the wall, lateral forces on all limbs that pull toward the midline. The front limbs pull the head toward the wall, while the hind limbs push the abdomen away from the wall

2.1. Gecko Adhesion

Geckos are extraordinary climbers because they generate effective wall reaction forces in milliseconds. They use a trotting gait to run up rough, smooth, solid or granulate vertical surfaces. Legs generate peak shear or vertical forces twice the body weight, while only the front leg produces an adhesive (or normal) force roughly 1/8 that of the shear force. The secret of effective force generation resides in the hybrid and hierarchical structure of the Gecko's toes. Flexible toes have both claws and toe pads densely packed with keratinous hairs or *setae*. A toe pad is comprised of flexible rug-like strips called lamellae that can hold nearly a 1/2 million setae. Each seta can have 100-1000 split-ends or branches ending in 200 nm tips termed *spatulae*. A single gecko can have 1 billion spatulae interact with a surface.

While the role of intermolecular forces as the basis for Gecko adhesion had been suspected for more than thirty years [2], the definitive role of van der Waals interactions has only recently been discovered [3]. Briefly, it is known [4] that van der Waals force is strong between polarizable surfaces (as measured by dielectric constant) and indifferent to polarity (as measured by water contact angle). It is known as well [2] that natural Gecko setae fail to adhere to poorly polarizable and hydrophobic materials such as Teflon. The recent work [3] establishes that a) natural setae on live Gecko toes adhere equally well to hydrophobic, polarizable (GaAs) and hydrophilic, polarizable (SiO2) materials; b) a single natural seta adheres equally well to hydrophobic, polarizable (Si) and hydrophilic, polarizable (Si02) MEMs cantilevers; c) van der Waals force models predict well the size of natural setae spatulae; and d) natural setae are highly hydrophobic.

Thus, observing that hydrophobic setae stick equally well to both hydrophobic and hydrophilic substrates, failing only when the dielectric constant goes low, and given the success of the model, one concludes that van der Waals represent the parsimonious explanation.

But it is clear that the materials properties alone are insufficient for adhesion. Autumn *et al.* [5] were unable to make single setae adhere or shear for several months until they integrated the knowledge of their hierarchical structure with their function. Using a newly developed MEMS force sensor [6], Autumn and collaborators [7] measured the adhesive and shear force of a single isolated gecko seta. Initial efforts to attach an isolated seta failed to generate forces above that predicted by Coulomb friction, but when they simulated the dynamics of gecko legs during climbing (based on force plate data; [8, 9] they discovered that a small normal preload force yielded a shear force of ~40µN, six times the force predicted by whole-animal measurements [10]. The small normal preload force, combined with a 5µm proximal shear displacement yielded a very large shear force of 200µN, 32times the force predicted by whole-animal measurements [10] and 100 times the frictional force measured with the seta oriented with spatulae facing away from the surface [7]. The preload and drag steps were also necessary to initiate significant adhesion (up to 40 µN) in isolated gecko setae. Animals uncurl their toes in 8 msec to preload their setae and peel their toes in 16 msec to change the setal angle for effective detachment. Only application of the correct preloading motions and strategies yielded anticipated results. In turn, the compliant properties of the adipose tissue that supports the setae appear to play an important role in ensuring that setae make contact at all.

Similarly, neither the spatular chemistry nor even its appropriate preloading can contribute to adhesion if the setae mat (stick together), or foul. Geckos are not known to groom their feet yet retain their stickiness for months between molts. How geckos manage to keep their feet clean while walking about with sticky feet has remained a puzzle until recently [11]. While self-cleaning by water droplets has been shown to occur in plant [12, 13] and animal [14] surfaces, no adhesive had been shown to self-clean. In a recent study Hansen and Autumn [11] demonstrate that gecko setae are the first known self-cleaning adhesive. Geckos with dirty feet recovered their ability to cling to vertical surfaces after only a few steps. Self-cleaning occurred in arrays of setae isolated from the gecko. Contact mechanical models suggest that self-cleaning occurs by an energetic disequilibrium between the adhesive forces attracting a dirt particle to the substrate and those attracting the same particle to one or more spatulae. Thus, the property of self-cleaning is intrinsic to the setal nanostructure, and therefore should be replicable in synthetic adhesive materials in the future

Finally, the self-cleaning, properly pre-loaded sticky materials cannot contribute to adhesion if they never get near the surface. No doubt, the complex morphology and musculature of the fingers, paws, and limbs play a critical role as well in bringing the compliant sticky pads to bear upon the substrate in the appropriate manner. It is clear from simulation studies of animal-like climbers that tuning the limb compliances correctly is much more important for climbing than for running. In particular, the ratios of linear and torsional compliances at the foot and ankle have an enormous effect on the climbing stability and efficacy. This effect is amplified by the relatively few actuated degrees of freedom of robot legs, as compared to animals.

2.2. More General Animal Climbing Strategies

But no animal relies on stickiness alone, for even the best adhesive must fail on badly enough broken or failure-prone surfaces. More qualitative observations of climbing animals reveal that when adhesion does fail, dynamics must take over.

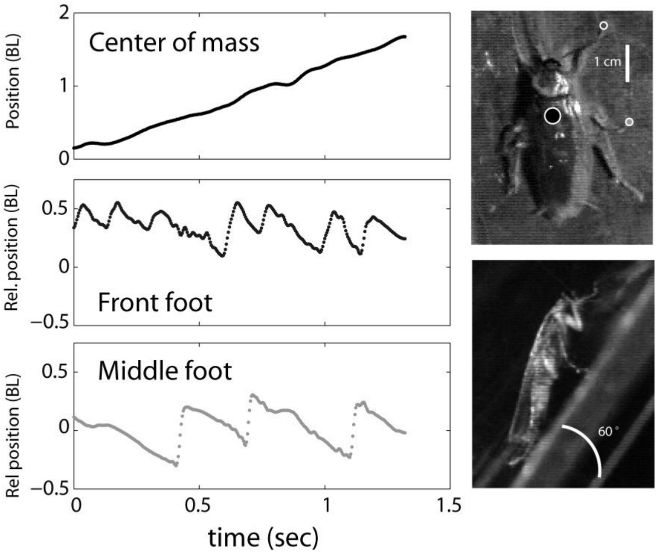

Figure 2. Cockroaches can climb smooth plates at speeds up to 3 BL/sec even without reliable adhesion at each contact. To achieve this performance they cycle the front (shown) and hind limbs more rapidly than the middle limb. The front limbs engage micro-asperities while the hind limbs and abdomen provide frictional force to prevent slipping and pitchback. The front and middle foot position are relative to the center of mass position. All units are in body lengths (approximately 3 cm).

To gain insight into a climbing strategy when foot adhesion is weak or unreliable, Full and colleagues [15] challenge cockroaches on a stainless steel plate at an angle of 60 degrees with respect to the level. The surface is not microscopically smooth; there are sparsely distributed micron-scale asperities on which the claws can engage. Although the feet cannot achieve reliable grip at each stride, we find that by using abdomen as a tail to aid frictional contact and prevent pitchback and by cycling the front and hind legs continuously the animals can ascend at up to 3 BL/sec. The front limbs and hind limbs cycle more rapidly than the middle limb; for example Figure 2 shows that front limb frequency is approximately double the middle limb frequency. To generate thrust, the front and middle limbs mainly engage the substrate through sporadic claw attachment while the hind limbs thrust and rely on frictional contact between the

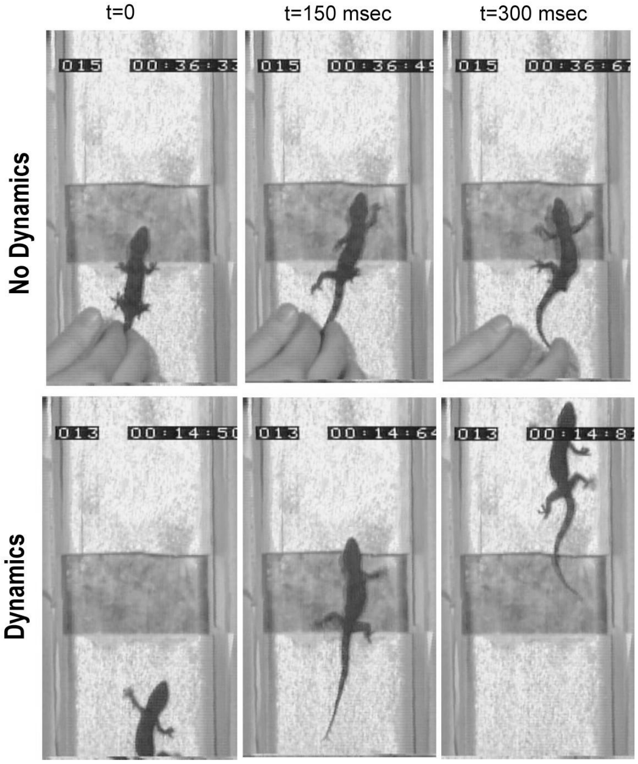

Figure 3. Geckos fail to cross gaps when begun from a standstill (upper panels). When the geckos ascend the track at 10 BL/sec, using the appropriate climbing dynamics, they negotiate the gaps.

legs/tarsal pads and the surface to generate force. The middle limbs act as anchors while the other limbs cycle. The animal also uses the abdomen to prevent pitchback and sliding down the plate. This complex gait is in contrast to the alternating tripod gait that the animals use when each foot achieves reliable adhesion at touchdown [15].

To test the crucial role of dynamics in rapid climbs, Full and colleagues [15] have performed experiments to challenge geckos to cross body length gaps in which they cannot generate adhesion with their setal pads. They create a vertical track at 90 degrees with respect to the level in which a stainless steel plate coated in graphite powder is interposed between two rough pieces of balsa word (Figure 3). The geckos easily grip the wood but cannot adhere to the metal plates. When the animals start from a standstill, they are unable to cross the gap, typically flailing until catastrophic pitch-back occurs. However, when allowed to run up the track at approximately 10 BL/sec (40 cm/sec), the animals cross the gap, often adhering to the upper portion of the track with only one limb even as the other limbs do not gain purchase in the gap. Numerical simulation of simplified mechanical models lends convincing evidence that it is not merely inertial forces that carry the body across the gap but properly tuned mechanical compliances are essential gap crossing [15].

3. PLATFORM DESIGN

Notwithstanding these indications and hints from nature, the RiSE robot, pictured in Figure 4 was designed in the face of constraints arising from the nature of contemporary commercial off the shelf technology. Our desire to use commercial off the shelf computational products places practical lower bounds on scale, that imply higher weight than might nominally be desirable.

3.1. Body and Limb Design

3.1.1. Morphology and Power Train

The current platform has twelve degrees of freedom (DOF), with six identical two DOF mechanisms spaced equally in pairs along the length of the body. Figure 5 depicts the layout of the platform. Two actuators on each hip drive a four bar mechanism, which is converted to foot motion along a prescribed trajectory, and positions the plane of the four bar mechanism angularly with respect to the platform.

Figure 4. The RiSE Platform ascending a tree

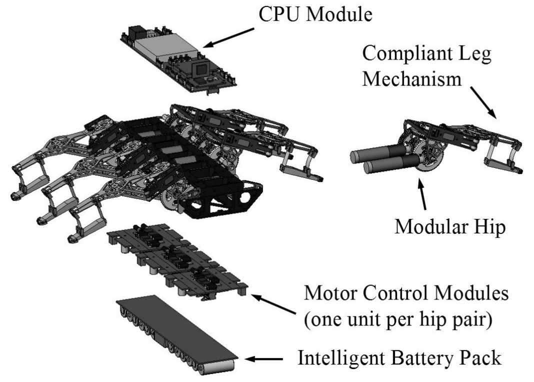

Figure 5. Overall layout of the RiSE platform.

The significant weight of the available COTS actuators and gears militated against a fully actuated, six-legged climbing system. Six under-actuated legs (each with two actuated DOFs) appeared preferable to four fully actuated legs, primarily for reasons of attachment redundancy. As the capability to build feet with more local attachment redundancy and actuation increases, the idea of a fully actuated climbing quadruped layout may be revisited.

Another distinguishing feature of the current platform is the fixed tail, which aids in artificially shifting the point of rotation away from the rear foot attachment points. This effectively decreases the pitch-back moment in case fore limb attachment fails. In the future this tail will be actuated, extending its effective contact range over surface perturbations and augmenting horizontal body pitch adjustments. Additionally, moving the tail out of the way will become more important as vertical to horizontal surface transitions progress.

One of the key features of the platform is its ability to change posture. Significant abduction/adduction motion (hereafter, the "*wing*" degree of freedom), enables the robot to conform to varied amounts of surface curvature, as shown in Figure 6. The sprawled climbing configuration, together with a flat body, minimizes gravity torque. A small decrease in CG offset can have significant impacts on the pitch back moment of the robot. In addition to reducing the required normal force for the fore legs, a reduction in pitch-back moment increases the time available for re-grasping. In addition to adjusting to convex scansorial terrains, the wing DOF enables to platform to stand upright, enabling significant horizontal mobility

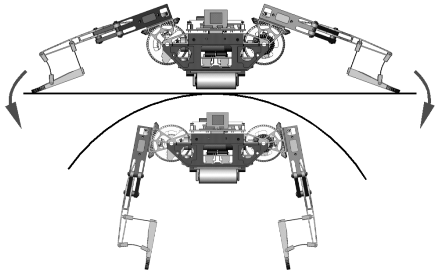

Figure 6. Abduction/adduction is achieved via the "wing" degree of freedom.

A unique hip mechanism leaves all actuators on the body, minimizing leg mass (to less than 1% body mass), and foot impact forces while actuating two DOF. Both DOF are actuated through a differential gear mechanism. Through the combined motions of two actuators each hip can actuate the wing DOF and four-bar mechanism, either independently or simultaneously.

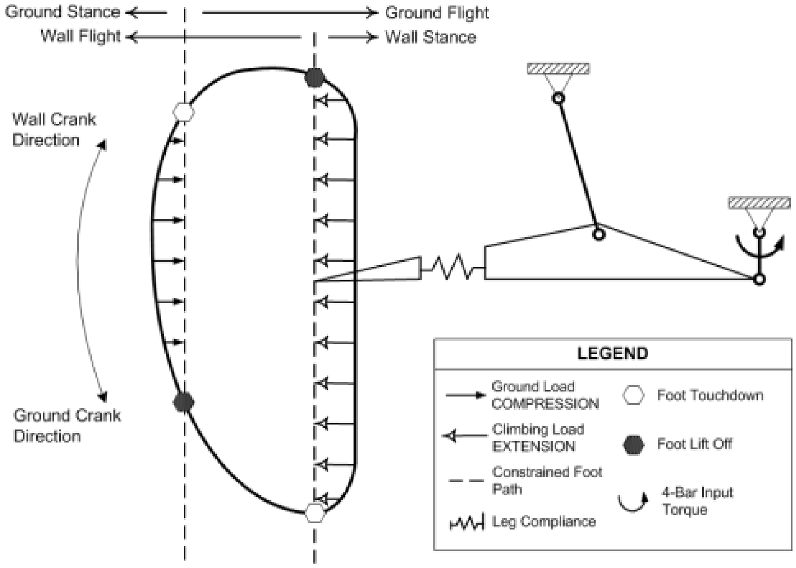

Figure 7. The RiSE leg – a four-bar linkage design whose careful design affords foot trajectories for both climbing and running.

3.1.2. Legs

The upper leg is comprised of a four bar mechanism which achieves broad functionality under a tightly constrained design space.

Figure 7 depicts the four bar and resultant foot trajectory with its ability to generate important force vectors towards the body midline during climbing. Through the selection of appropriate touchdown points along the foot curve the remaining lateral travel of the leg loads the lateral compliance of the leg mechanism prior to entering the straight wall stroke. Any difference between the constrained foot path and the travel of the upper leg applies loading to the compliance at the output of the four bar. Due to the constrained motion of the four bar mechanism, the same trajectory has to be used to achieve foot paths for horizontal mobility. To achieve this, the opposite portion of the foot path is used during terrestrial locomotion. In a similar way, the leg axis compliance is loaded during stance; however during ground stance the compliance loading is compressive. Finally, by combining the wing motion with the four bar crank motion, a large array of options for attachment and detachment is possible from a very under actuated system.

The lower leg takes the form of a compliant mechanism and connecting the rigid upper leg and the ankle. Two compliant mechanisms were explored through the initial phase of experimentation we report on here. The initial design, depicted in Figure 8(a), enabled a partial decoupled adjustment of lateral and normal leg compliance. Experimental results suggested drastically increased normal compliance to handle a very wide array of materials, each with their own respective compliance. The second mechanism, shown in Figure 8(b), addressed the need to provide different leg axis compliance for compressive running loads and tension climbing loads.

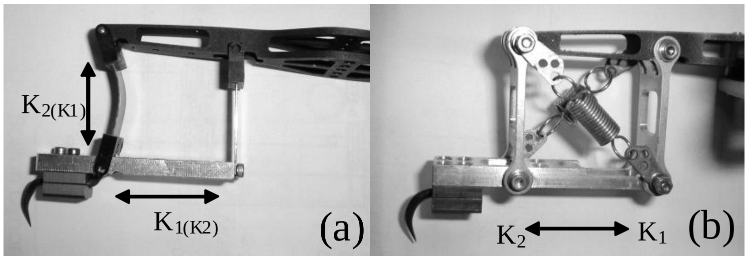

Figure 8. A compliant mechanism connects the ankle to the rigid upper leg. The first design (a) was replaced by a mechanism (b) that better decouples lateral and normal compliance to address differences in loads characteristic of running and of climbing.

3.2. Foot Appendage Design and Fabrication

3.2.1. Bioinspired Design

Looking to nature, one finds that most animals that exhibit scansorial agility employ multiple forms of adhesion. For example, as discussed above, geckos easily climb glass by use of the hierarchical hair structures on their toes; however, they also utilize claws to climb hard rough surfaces, since it can be difficult to generate the necessary contact area to adhere to these surfaces with dry adhesion alone. For the RiSE robot to succeed in climbing in both natural and man-made environments it has proven necessary to use multiple adhesion mechanisms. The RiSE robot will use dry adhesion (see Section 3.3) in combination with spines. In addition to multiple strategies, one also finds considerable redundancy in nature's climbers. For example, a tokay gecko can easily hang using the adhesive capabilities of just one toe. Initial studies of climbing with spined feet have also revealed other important design principles.

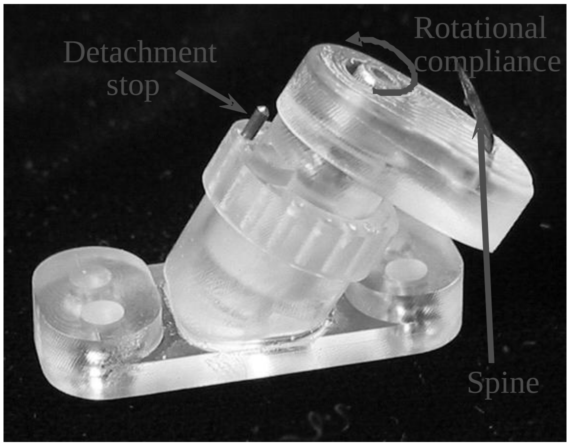

Figure 9. RiSE robot modular spined foot and compliant ankle produced via shape deposition manufacturing. Rotational compliance prevents large internal forces from being generated at the foot and leg during each stride.

An investigation of foot designs that utilize arrays of spines has been undertaken on an independent foot and toe development platform, dubbed SpinyBot [16]. A dedicated platform avoids the need to contend with the complex spatial motion of the RiSE robot limbs, while trying to understand fundamental design principles for compliant under-actuated feet with arrays of spines. SpinyBot is a simple open loop, RC servo driven platform meant for investigating passive spined foot designs. It utilizes arrays of micro-spines with an average tip radius of 10-12μm, supported on a compliant suspension that embodies several fundamental design principles. The smaller the spine tips, the smoother the surface that the robot can climb – and the weaker each individual spine/asperity contact. Therefore, it is essential to distribute the load uniformly among as many spines as possible. Initial foot prototypes with spines all attached to a single rigid substrate showed that only a few spines carried a majority of the load. To share attachment forces across a multitude of spines each spine must be independently supported with compliance along the direction of foot stroke as well as the direction normal to the wall surface. Furthermore, it is desirable for cross-coupling between the extension and rotation of the spine suspension to cause the spine to pitch forward in a way that further engages the wall surface as shown in Figure 10. Currently SpinyBot is capable of climbing hard vertical surfaces such as concrete, stucco, brick, and dressed sandstone with average asperity diameters of greater than 25mm [16]. The design principles from SpinyBot are currently being integrated into the design of feet for the RiSEbot.

3.2.2. Shape Deposition Manufacturing for Rapid Prototyping

Shape Deposition Manufacturing [17] has been utilized with great success to make tough integrated multi-material assemblies with embedded components for biologically inspired running robots [18]. The flexibility of this process is also ideal to produce the feet of SpinyBot, which contain a set of 10 identical planar mechanisms, or “toes.” These feet incorporate hard and soft urethanes, of 75 Shore-D (white) and 20 Shore-A (blue/grey) hardness, respectively (Innovative Polymers Inc.). The resulting structure can be approximated as an elastic multi-link mechanism, as shown in Figure 10. 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 early foot designs).

Shape Deposition Manufacturing will also be used to meet the challenge of integrating dry adhesives (see Section 3.3) and arrays of spines into a single coherent foot assembly. Particular care will be needed in this integration in order to: 1) preserve the hierarchical compliance necessary to conform to surfaces at multiple length scales; and 2) ensure durability of the adhesives (preventing local stress concentrations, for example). The compliant load-sharing solutions used for microspines will be extended for this purpose. Recently developed methods for cross-material-boundary component embedding will be also applied to embed tactile sensors for measuring foot forces and assessing quality of foot attachment.

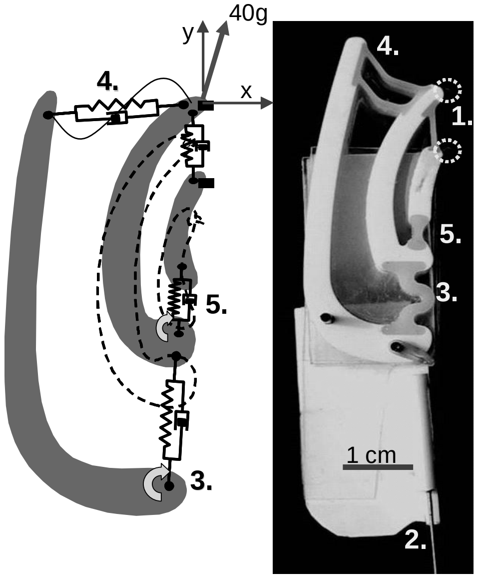

Figure 10. Photograph and equivalent elastic linkage for one toe. Linkage at left shows the deflected position for a 40g load, superimposed on the undeflected position (shown in dotted lines). Key to labels: **1**. 200 µm diameter spines (inside dotted circles), **2**. tendon for applying loads, **3.** soft urethane flexure permitting travel in *y* direction.

3.3. Progress in Design and Fabrication of Synthetic Dry Adhesives

Traditional pressure sensitive adhesives (PSAs) are made of soft viscoelastic materials. PSAs display tack, the property of instantaneously “wetting” an opposing substrate under little or no applied pressure [19]. To do so, PSAs are found to satisfy the “Dahlquist criterion for tack,” which states that the modulus should be less than 300kPa when measured at 1Hz [19]. Gecko setae are made from keratin, a material orders of magnitude stiffer (~3GPa) than required by the Dahlquist criterion for tack. Rather than being formed from a soft bulk material, gecko adhesives, and the fiber array adhesives they inspire, achieve a low effective modulus due to the geometry of their micro- and nano-structures. Viewing the individual fibers as cantilever beams, the stiffness may be lowered by decreasing the material modulus, but also by increasing fiber length or decreasing fiber radius [20]. With an appropriate single-fiber model, such as the cantilever model, an effect modulus for the array can be computed [21, 22]. Using a JKR model for the adhesive interaction of the fiber tip with a substrate, the pull-off force of a fiber array on a rough surface can be computed [21, 23]. One problem that has arisen in many of the synthetic fiber array adhesives is clumping, where neighboring fibers stick together in bundles. Anti-clumping conditions were provided in [20, 22]. For a given fiber geometry, the anti-clumping condition reduces to spacing the fibers at least some minimum distance apart. This decreases the fiber density, which in turn decreases the theoretical maximum adhesive force provided by the array (if all the fibers could independently contact the surface). In [24], clump size is predicted for fibers packed close enough to clump. Small amounts of clumping are tolerable so long as interaction with an opposing surface during preload is enough to break apart the clumps. Much of the clumping in synthetic arrays appears to be driven by capillary adhesion. (Clump formation is observed as samples dry.) Interestingly, gecko setae are never observed to clump (though anoles show occasional mild clumping). This may be due to the hydrophobicity of keratin, which allows the setae to avoid the effects of capillary adhesion.

It is interesting to note that the Dahlquist criterion, the pressure sensitive adhesive community's predominant heuristic for tack, is in terms of material stiffness rather than surface energy. Roughly, this is because the surface energies of polymers are typically within an order of magnitude of 50mJ/m2, while Young's modulus varies over many orders of magnitude, e.g. less than 100kPa for many PSAs to 10GPa for a stiff polyimide or polyurethane. However, this does not mean that control of geometry makes material choice irrelevant. For example, a material with a high elastic limit is desired so that plastic deformation and fracture do not occur under typical operating conditions. Similarly, a hydrophobic material is desired in order to avoid clumping due to capillary adhesion, allowing fibers to be packed more densely. While geometry plays a role here as well (fibers can be made more slender to avoid fracture, and can be made less slender or spaced farther apart to avoid clumping), material choice is an important dimension in the design space.

In order to prototype a wide variety of synthetic fiber structures rapidly, we have developed a process using commercially available filters, e.g. Millipore Isopores [24]. The steps of the process are 1) spin-coat a thin layer of polymer (polyimide) 2) Apply a filter and allow it to capillary fill 3) Cure polymer 4) Etch away filter (using methylene chloride for polycarbonate filters). Postprocessing steps may be performed to further modify fiber geometry. This process is simple, but capable of producing a wide variety of structures, some of which are strikingly similar to their biological analogs. For example, see Figure 11.

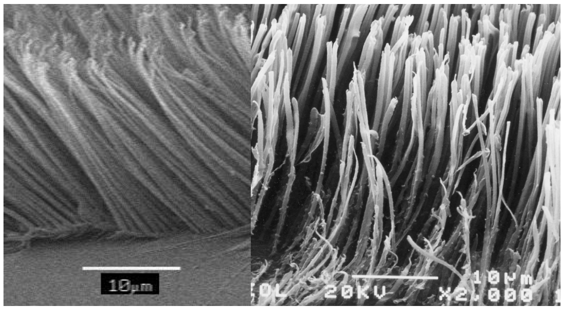

Figure 11. (*left*) Setae of the Anolis Equestris, length 23um, diameter 0.5um. Anoles such as this have unbranched setae with a spatula tip. (*right*) Polyimide fiber array synthesized using Millipore Isopore filters, length 22um, diameter 0.6um. A. Equestris image courtesy Anne Peattie.

4. SOFTWARE AND CONTROL

4.1. RHexlib and Beyond

RHexLib is a real-time software architecture for the control of robot platforms that require high-bandwidth sensor processing and motion control. It was originally designed for the RHex hexapod robot [25] but later adapted to several other robotic platforms such as the Carnegie Mellon Deminer robot [26], the CalTech Multi-Vehicle Wireless Testbed [27] and finally the RiSE climbing robot. Among others, important features of RHexLib include a static scheduler for modular definition and execution of periodic tasks, mechanisms for transparent access to different platform instances (including physical and simulated) and flexible real-time network communication tools. In contrast to comparable systems with a similarly wide range of available tools, RHexLib does not impose any particular control or planning framework, leaving it up to the developers to choose the most appropriate formalism for a particular task.

The current RiSE platform incorporates only the most basic sensing of motor positions through incremental encoders. In consequence, our current behavioral suite consists of families of open-loop trajectories for the wing and crank degrees of freedom for each leg, enforced through local Proportional-Derivative (PD) feedback at 300 Hz. Under these constraints, our experiments involve exploration within a finitely parameterized gait design space. We use families of periodic, piecewise cubic trajectories assigned to individual legs in conjunction with constant phase offsets for all six legs, admitting a variety of patterns ranging from a typical alternating tripod gait (see Figure 12) to alternatives such as tetrapedal, metachronal or pentapedal (see Figure 13) gaits. Through the use of modular RHexLib features, the current RiSE software provides convenient tools for the definition, generation and execution of such gait families.

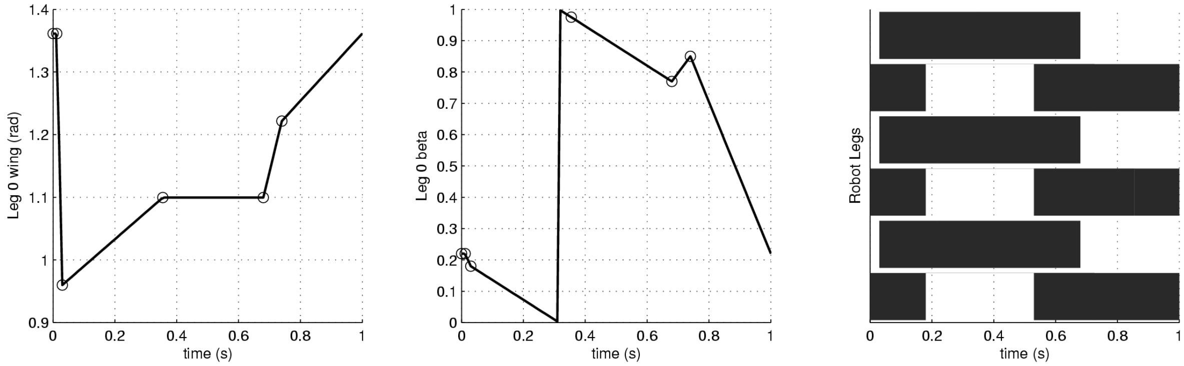

Figure 12. Alternating Tripod Gait Characteristics showing wing (leftmost plot) and crank (middle plot) reference trajectories as well as leg touchdown pattern (darkened portions of rightmost plot). Circles mark the meeting points of different phases (cubic spline pieces).

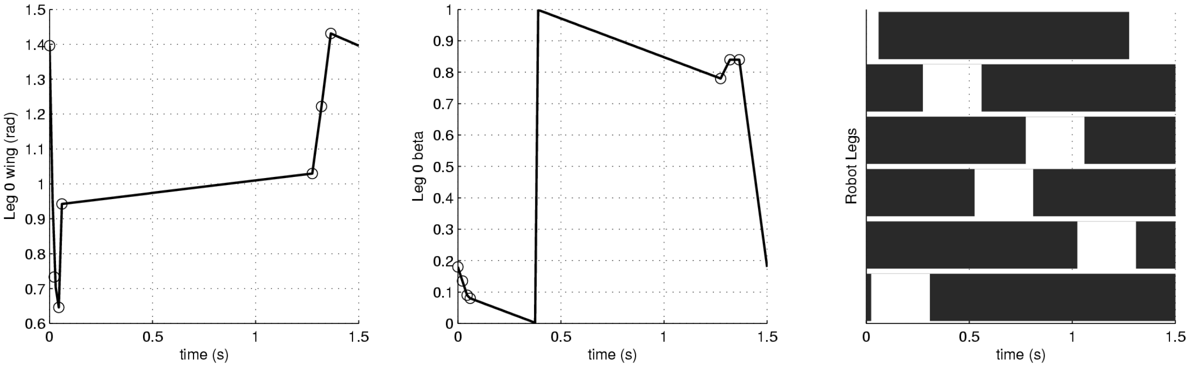

Figure 13. Pentapod Gait Characteristics showing wing (leftmost plot) and crank (middle plot) reference trajectories as well as leg touchdown pattern (darkened portions of rightmost plot). Circles mark the meeting points of different phases (cubic spline pieces).

4.2. Evolution of Climbing Gait

As outlined in Section 3, the RiSE robot incorporates many of the biological inspirations of Section 2 in the passive morphology of its mechanical design. Consequently, the complexity of the platform and the size of the gait design space are significantly reduced. While this results in significant advantages such as much smaller mass, slimmer profile and increased reliability for the robot, it also imposes nontrivial constraints on the space of control strategies. The challenge is to understand the interplay between the passive robot mechanics under the effect of complex adhesive and frictional surface interactions, with the choice of possible gait trajectories. To this end, our starting point has been extensive empirical studies to explore the available gait trajectory space in conjunction with revisions and improvements on design choices for compliant ankle structures and foot morphologies.

Not surprisingly, each possible combination of foot design and climbing surface imposes unique constraints on the forces that can be supported and maintained by the resulting contact. Similarly, for each of these combinations, there are significant variations in proper strategies for correct attachment and detachment of each foot. Our approach has been to decompose the trajectories of each leg into multiple phases for attachment, stance and detachment, and empirically tune their durations, shapes and relative timings on individual surfaces to respect the associated contact constraints (see Figures 12 and 13). In doing so, we were also able to revise the compliant ankle elements, restricting their freedom of motion to radial extension and radial compression with different stiffnesses for climbing walking, respectively.

In addition to local constraints on admissible gaits, there are also global considerations that arise from the distribution of forces among legs in contact and the overall forward progress of the robot body. In this context, one of the most important gait design parameters was found to be the relative phases of all six legs, allowing control over the distribution of the robot weight onto a chosen number of legs. While weak (i.e. cork) and slippery (i.e. lucite) surfaces require maximal support with pentapod gaits (see Figure 13), stronger structures such as carpet are easily able to accomodate much faster tripod gaits with fewer supporting contacts (see Figure 12).

Another important global property of admissible gaits is the consistency of stance profiles among all contact legs. Differences in speed or inconsistent wing movements for concurrent contacts invariably build up large internal forces on the robot, usually resulting in either premature disengagement of one or more contacts or structural failure of internal gear mechanisms. Given the finite but very large dimension of the gait design space, significant care and tuning is required to identify and avoid such trajectory and phase combinations.

5. CONCLUSION

5.1. Summary of Present Performance

We have recently completed an extensive set of experiments with RiSE on a variety of surface materials and slopes, performed in the facilities provided by the Southwest Research Institute (SwRI) Small Robotic Vehicle Testbed. Dactyl feet were successfully used on carpet, cedar planks, outdoor tree trunks, chainlink fence and a brick wall. Best climbing performance was achieved on carpet using the dactyl feet with no significant failures and reasonable maneuverability on a vertical surface through the use of multiple gaits for forward and backward locomotion as well as turning. Nevertheless, the single large dactyl on each foot is susceptible to detachment problems, resulting in decreased climbing performance and occasional damage to the robot's gear mechanisms. These observations motivate our the integrated foot designs discussed in Section 3.2, which will incorporate multiple compliant small spines with adhesive pads for friction and support.

Cork was one of the most challenging non-smooth surfaces due to its structural weakness and its consequent inability to support the robot's weight in case of even a single failed attachment. A pentapedal gait (Figure 13) with the single spine feet was used for this surface and the robot was able to climb a vertical stretch of roughly 4 m without interruption. Lucite and other smooth surfaces clearly pose one of the most difficult challenges for RiSE's climbing behaviors. In the absence of asperities on the surface to provide support for spinal structures, the RiSE robot's feet must rely on friction and – as the synthetic self-cleaning dry adhesive materials discussed in Section 3.3 become available – adhesion mechanisms to establish proper contact with the surface. Using a specialized prototype foot design that makes use of pressure sensitive adhesive materials, the RiSE robot was able to climb a 55 degree slope on lucite using a pentapedal gait.

Finally, we were also able to design very specialized open loop gaits for climbing vertical chainlink fences, brick walls and tree trunks. In the absence of feedback, extensive tuning and multiple design iterations were necessary to achieve successful climbing on these surfaces. Furthermore, the resulting gaits were highly specialized and consistently failed in the presence of even small structural changes in the surface morphology, such as the size of the bricks or the scale of the chainlink. Not surprisingly, our current direction in the RiSE project is to incorporate proprio- and exteroceptive sensing and feedback modulation of gaits which has the potential to eliminate most of these problems.

5.2. Near Term Future Development

Beyond these immediate improvements, we seek to advance beyond this initial success and realize the underlying motivation for this work – the premise that animals use their tuned and adapted body mechanics in a dynamically intelligent manner to maneuver at will in the physical world.

To achieve this goal we will model, simulate, experiment with and tune our present robot's body, sensorium, and behavioral suite to achieve in the final year a truly dynamical scansorial robot that uses bioinspired materials and algorithms to climb a wide range of vertical surfaces while retaining the ability to function equally nimbly on level ground. The robot will incorporate proprioceptive (leg strain, foot contact, inertial motion) and exteroceptive (camera and proximity) sensors to recover from otherwise catastrophic slipping or from locally failed ground material. It will incorporate novel appendages with synthetic self-cleaning dry adhesive patches inspired by analogous Gecko hairs and use these novel materials to assist climbing on a wide range of natural and human-made surfaces. Success will derive from 1) the design and implementation of passive, compliant, mechanically-tuned appendages, incorporating a hierarchy of materials and structures, 2) their integration into power- and computation- autonomous bodies, and 3) the development of dynamically sound sensor-based control algorithms, leading to autonomous robot behaviors that exhibit general scansorial abilities inspired and informed by appropriate animal models.

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