Design and Fabrication of Multi-material Structures for Bio-inspired Robots]Design and Fabrication of Multi-material Structures for Bio-inspired Robots

Cutkosky-Kim]Mark R. Cutkosky[1] and Sangbae Kim[2]

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Abstract

Bio-inspired design, materials, fabrication, biomimicry, robotics New multi-material rapid prototyping processes are making possible the design and fabrication of bio-inspired robot structures that share some of the desirable properties of animal appendages. The structures combine stiff and compliant materials and incorporate sensors and other discrete components, resulting in robots that are less demanding to control than traditionally design robots and much more robust. Current challenges include extending this approach to structures that involve microscopic as well as macroscopic features.

1 Introduction

A new generation of small, legged robots is starting to make tracks out of the laboratory and into the world, for applications such as search and rescue, demining, planetary exploration and environmental monitoring. They owe their success to a heightened understanding of the design principles employed by their biological counterparts to locomote rapidly and robustly, and to advances in materials, sensors, actuators and control methods that allow those principles to be applied to robotic platforms. The resulting machines, while more sophisticated than their predecessors in terms of materials and dynamic tuning, are actually simpler to operate and more forgiving of variations in terrain.

As we examine materials and structures that contribute to the performance of running and climbing animals, we find that they are typically multi-functional and inhomogeneous. Hard materials are used sparingly (e.g., for teeth); compliant materials that absorb energy and "bend without breaking" [43] are the norm. Even when stiff materials are used, they are frequently not uniform. For example the calcified shells of crabs are mostly stiff but have regions that bend and bulge at the joints[10]. In addition, the exoskeleton is not just a structural element; it is a sensory organ. For example, the leg exoskeleton of a spider may have hundreds of strain sensors as well as hair sensors, chemical sensors, etc. [7, 6, 38]. Parts of the exoskeleton are also covered with small spines that bend preferentially in one direction, providing superior traction during locomotion

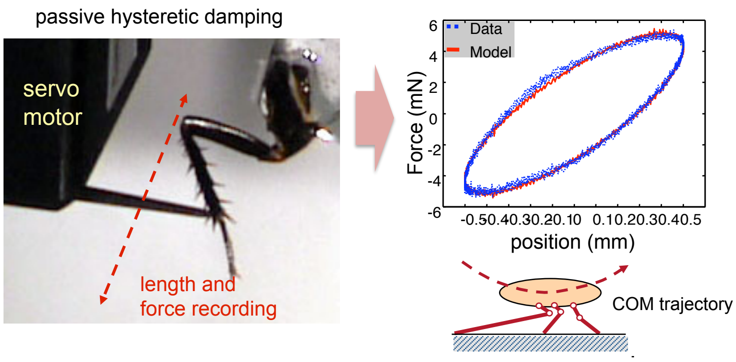

Figure 1: The passive properties of cockroach legs contribute to its stability, absorbing and dissipating energy as it runs with a bouncing alternating-tripod gait [45].

and manipulation [39]. In summary, the functions of providing structural support, sensing, and traction are not accomplished with separate systems but are coupled and achieved with complex, heterogeneous designs.

Functional coupling also extends to other areas of less interest to roboticists, such as feeding and procreation. Therefore, instead of attempting to copy the morphology of natural systems it is important to determine principles that are practical for robotic implementation with multi-material and multi-functional structures. A good example can be found in the combination of passive mechanical properties that contribute to fast, stable running in legged animals. Animals from insects to large mammals employ a similar bouncing, periodic motion when trotting, with energy stored and returned as the center of mass accelerates and decelerates with each step [3, 35, 8]. The ratio of leg stiffness to body mass is approximately $K \propto M^{2/3}$ over a wide range of species and dimensional scales [17]. Forces are directed mainly parallel to the legs, with only small torques at the hips [15]. This commonality of approach suggests that animals are controlling their very complex leg systems to behave as though they are following a template that can be described by a simpler model with many fewer degrees of freedom [18].

There is also ample evidence that the kinematics and passive mechanical properties of animal limbs contribute their stability when running. The effects of these properties have been termed "preflexes" in the biology literature [42, 11]. Preflexes provide an immediate response to perturbations without the delays of neural reflexes. For example, it has been shown empirically and in simulation [25, 29] that such mechanical feedback can simplify the control of dynamic locomotion in insects, acting to stabilize them as they run over rough terrain and respond to perturbations.

Figure 1 shows an example corresponding to a single leg of a cockroach, which has been isolated for mechanical testing. A servo motor applies forces to

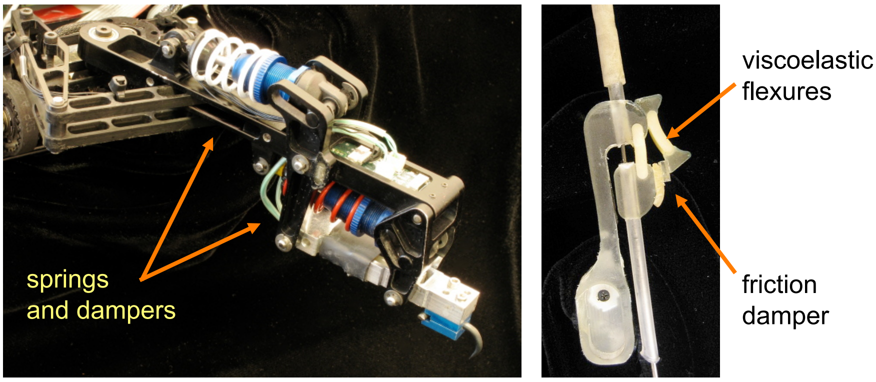

Figure 2: The RiSE robot (left) uses shock absorbers for compliance and damping. The elements help to distribute forces when climbing but increase complexity. The iSprawl robot uses hard and soft, viscoelastic materials to achieve similar functionality with many fewer parts. The legs are also robust: overloads are accommodated by bending without breaking.

the passive leg, resulting in a hysteresis loop that gives evidence of significant energy dissipation per cycle at the normal running speed [45]. In fact, cockroach locomotion is not particularly efficient compared to larger animals, but is remarkably stable even with a predominantly fixed motor pattern. Consistent with this view, Full *et al.* [19] observed only minor changes in a cockroach's muscle activation pattern as it rapidly transitions from smooth to uneven terrain.

The advantages of tuned, passive compliance and damping have not gone unremarked in robotics and several multi-legged robots have used elastic elements to simplify control and increase the robustness of locomotion over rough terrain [4, 23, 33, 28, 40, 34]. However, such elements significantly increase the complexity of the robot limbs. For example, the lower leg of the RiSE climbing robot [40], shown in Figure 2, contains over 70 parts not including sensors and electronics. Indeed, when we attempt anything close to biological models we are faced with daunting complexity at every dimensional scale. For example, the cockroach, which is the approximate model for the RHex [4] and iSprawl [28] robots, has over 200 muscles [16]. Another example that has recently been the focus of attention is the adhesive apparatus of the gecko, which consists of a remarkable hierarchy of primarily passive compliant elements with features at length scales ranging from hundreds of nanometers to centimeters [5, 36]. In contrast to natural systems, growing and differentiating cell by cell, engineers traditionally take a top-down approach. Each increment of complexity in terms of components, geometry, kinematics, sensing and control is expensive and difficult.

In recent years, however, the difficulty of creating bio-inspired robots is diminishing, in part due to new manufacturing processes that allow complex multi-material structures to be fabricated in small quantities and at modest cost. With some of these processes it is also possible to embed sensors, actuators and other discrete components to emulate some of the multi-functional characteristics of biological appendages. For example, the right image in Figure 2 shows a leg from a small hexapedal robot that uses flexures to replace conventional pin joints. The main portion of the leg consists of a hard polyurethane for strength and stiffness, but the material switches to a viscoelastic polyurethane in the flexures to provide a combination of compliance and damping similar to that provided by the shock absorbers in the RiSE robot at left and the insect leg in Figure 1. The leg structure also contains an embedded sleeve for an actuating cable and an insert for attachment to a servo motor. The monolithic structure is robust because it can deform without failing in response to overloads.

In following sections we describe some of the fabrication advances that make such muti-material structures possible and illustrate them with examples of bio-inspired robotic mechanisms that they have enabled. However, as we extend this approach to a wider range of dimensional scales we encounter new difficulties. For creating structures at the scale of micrometers we must to turn to different manufacturing processes (e.g. lithography) for which the range of available materials and geometries is more restricted.

2 Multi-material fabrication methods, challenges and opportunities

For as long as people have been creating artifacts, the predominant approach has been one in which parts are shaped (by chipping, carving, machining, grinding, chemical erosion, laser ablation, etc.) and then assembled or joined. The complexity of the final structure is a direct function of the constituent shapes and of the number of parts, materials and shaping processes. For simplicity, and to reduce costs, most human-made products use a small number of materials, most of which are relatively uniform. Using this approach it is difficult to create structures like those found in nature, with spatially varying mechanical properties and integrated combinations of structural support, energy storage and sensing. The traditional approach to shaping and assembling parts also incurs practical difficulties when creating small robots that operate outside the laboratory. Assemblies of small parts are fragile: screws and connectors work loose, metal limbs bend, motors and bearings fail as they become contaminated with grit.

In recent years, rapid prototyping processes have been developed that take advantage of the computer to replace complexity on the shop floor with complexity in a three-dimensional computer representation. In particular, several groups have developed multi-material prototyping methods that allow structures to have similar variations in stiffness, damping, etc. as seen in nature [14, 24, 20, 21, 41, 13]. One such process is 3D printing [24] in which various polymers are deposited in thin layers to create a three-dimensional part

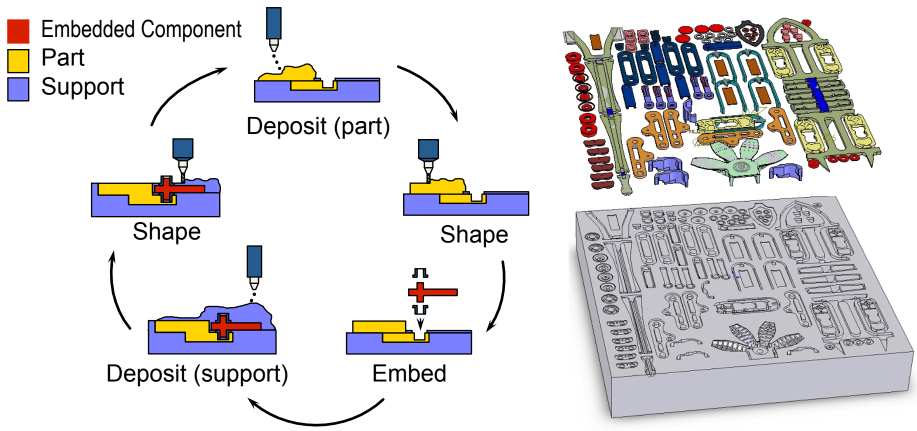

Figure 3: The SDM process consists of a cycle in which part materials (polymers) and sacrificial support materials are added and shaped. Discrete components are added after any shaping step. Multiple parts and materials for creating an entire robot (here, Stickybot [27]) can be fabricated on a common pallet.

of almost arbitrary shape. Commercial versions are now available [2] and the available tolerances and materials properties have steadily improved.

One limitation most layered rapid prototyping processes is that they are primarily additive: material is deposited and typically undergoes a curing or phase change process to obtain final properties. There is a tradeoff between resolution and speed, both of which depend on layer thickness. There is also a limitation on the achievable surface finish when making three dimensional, contoured parts due to "stair stepping" from the finite thickness of the layers. (A similar limitation applies to lithographic processes used for creating micromechanical structures.) In comparison, material removal processes can produce close tolerances and smooth surface finishes in comparison to the average feature size, which is one reason why processes like machining and grinding are used for optics, flexures, ball bearings and similar products.

In our own work we have used a process called Shape Deposition Manufacturing (SDM). SDM began at Carnegie Mellon University for creating multi-material metal parts (e.g. copper and stainless steel) [31] and was subsequently extended at Stanford for polymer and ceramic parts. We have focused on polymers, sometimes with fabric or fiber reinforcement, as these materials come closest to the natural properties of materials like skin, chitin (insect exoskeleton) and β keratin as found in reptile scales and gecko setae.

In SDM, parts or assemblies are built up through a cycle of alternating layers of structural and support material, as shown in Figure 3. The process is described briefly here and in greater detail in [44, 9]. Unlike most other rapid-prototyping processes, SDM shapes each layer of material on a computer-controlled milling machine after it is deposited. This approach allows for toler-

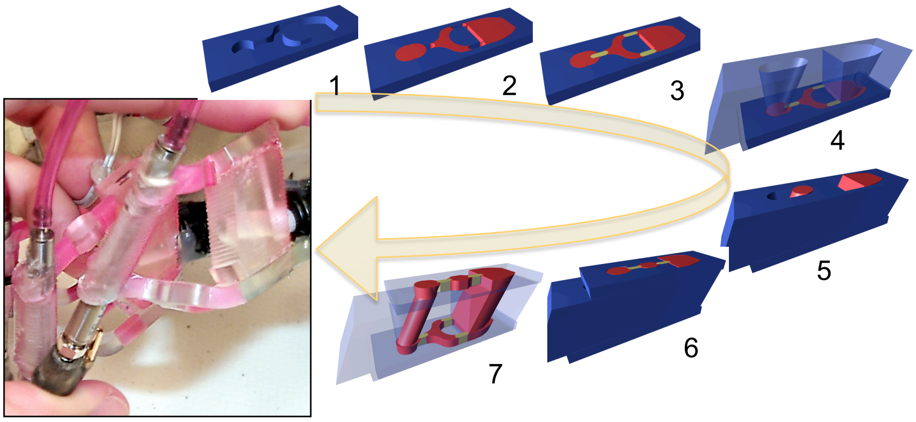

Figure 4: Spatial linkage of hard (clear) and viscoelastic (pink) polymers and corresponding SDM process plan. Hard polymer is added at steps 2, 5, 6, and soft material at steps 3, 7.

ances of $\pm$ 0.01 mm and avoids the stair-stepping effect of additive processes. The intermittent addition of sacrificial support material allows for construction of nearly arbitrary geometries and facilitates the inclusion of embedded components. Depending on the equipment used, tool diameters and feature sizes of 200 μm or less are possible. For creating bio-inspired robots, we use hard machinist's wax as the sacrificial support material because it can easily be machined to a smooth finish.

The use of a sacrificial support material is particularly helpful when embedding discrete components and when working with soft elastomers that are not machinable. For embedding components such as sensors, microprocessors, bearings, etc., the approach is first to machine a temporary fixture to hold and align the component. The component then becomes attached to, or encapsulated within, the structure as additional part material is added in the next SDM cycle. The creation of cavities (e.g. for pneumatics) requires a similar approach. In this case, a sacrificial material, such as a wax with a low melting point, defines the geometry of the cavity. Part material surrounds the sacrificial material, which is later melted or dissolved. When working with soft elastomers, the solution is to machine a molding cavity in part and/or sacrificial material and to cast the soft elastomer in place, as shown in Figure 4. For the flexures, it is important that the cavity have a smooth surface for high fatigue life with large strains. In addition, it is important to consider the geometry at the junction between hard and soft material. A simple butt-joint will result in large stress concentrations in the soft material near the corners. To overcome this tendency, the soft material should be given a "root" with rounded corners that extends into the adjacent hard material, as shown in Figure 5. With attention to such details, the flexible elements can accommodate large strains with long fatigue

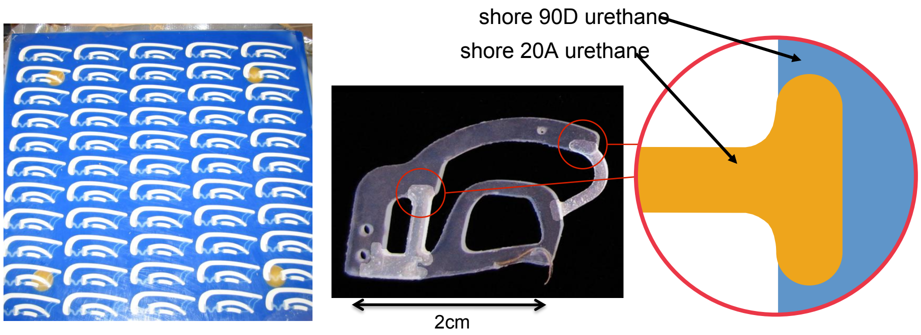

Figure 5: Array of toes for a climbing robot in process on SDM pallet and toe detail showing geometry at material junction to prevent tearing.

life. (Flexures from the 2002 Sprawlita robot [12] have survived over a million cycles.)

Some of the most challenging components are those that involve flexible elements such as fibers, wires or fabrics that must transcend the boundary between two different part materials. The difficulties include holding the flexible material in place during processing, and selectively adding or removing material around the fibers without damaging them or being obstructed by them. Several solutions are presented in [22]. One of the simplest is shown in Figure 6. Referring to the numbers in the figure, the first step is to create a mold in some sacrificial material (1). The fibers are aligned in the mold (2), applying tension as needed. (Sacrificial material can also be used to create a consumable fixture for aligning the fibers.) The next step is to cast a thin layer of soft material (e.g. a soft urethane) into the mold (3). After the material cures, it is released from the mold (4). At this point, the item has just enough stiffness that it can be handled without special fixturing and tensioning provisions. The flexible item is placed (6) in another mold (5) that will define the ultimate part shape. Generally, the hard part material is added first (7) so that it can be shaped (8) to create mold for the second material. Machining the hard material provides a fresh surface that promotes adhesion when the soft material (9) is added.

The SDM process is effective for fabricating multi-material components with feature sizes ranging from 0.1 mm to 10 cm. For smaller features, it becomes necessary to use other technologies including such as lithography, as used in creating MEMs parts. Unfortunately, these processes typically are limited to "$2\frac{1}{2}$ dimensional" shapes with stair-stepping in the vertical direction. This limitation can be addressed in part with techniques like multiple angled exposures, as used in creating arrays of sharp vertical wedge-shaped structures for adhesion [37]. Other promising techniques include chemical vapor deposition induced by focused ion beams (FIB-CVD), which can create almost arbitrary 3D geometries out of many different materials with feature sizes on the order of 80nm [32]. This technology permits both material addition and removal. Another

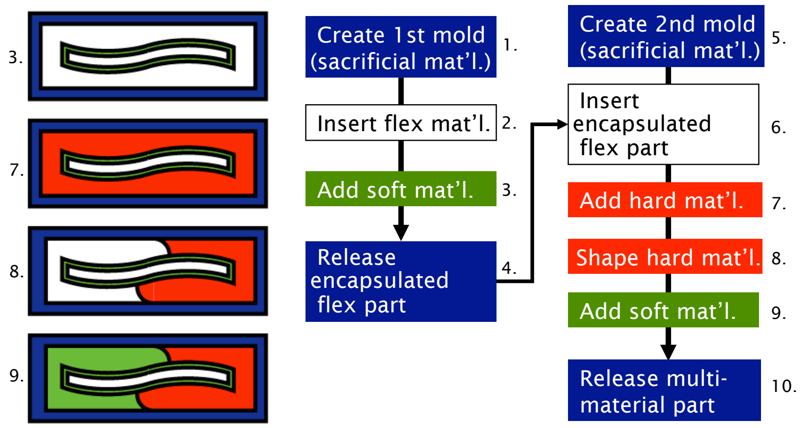

Figure 6: Schematic process plan for creating multi-material parts with fibers that transcend material boundaries.

sub-micron three dimensional manufacturing method is the two-photon polymerization process, which allows features with a resolution of approximately 120nm [26]. The quality of geometry can be improved by multi-path scanning methods. However, to adapt these techniques for producing arrays of features for robots will require improvements in processing speed and batch size.

More generally, an issue with most rapid prototyping processes is that they are essentially serial, creating features one at a time. This is a problem when large arrays of parts or features are required. In some cases, multiple parts can be fabricated on a common pallet as in Figures 3 and 5, which reduces the build time in the vertical direction. However the machining of each item is done individually. A related commercial process [1] uses a series of masks or stencils for depositing and shaping each layer. Time and money are invested in creating the stencils, but then all parts on a pallet are created simultaneously for each layer.

A final noteworthy limitation of all layered prototyping processes, whether at microscopic or macroscopic scale, is that they have a growth direction, which is typically vertical (perpendicular to the pallet in Figure 3). Building in the growth direction is typically slow and it is much harder to achieve high geometric complexity in this direction. For creating hierarchical structures like those employed by the gecko for climbing, this presents a problem, as such structures have high complexity in different directions at different length scales. One solution proposed in [30] is to switch growth directions when progressing from one stage to the next in the hierarchy, however this adds considerably to the processing complexity.

3 Analysis and synthesis of multi-material structures

As mentioned in Section 1, the challenge facing robot designers is not to try to duplicate biological systems, which are beyond current fabrication capabilities and serve many objectives (e.g. procreation) beyond those of interest in robotics. Instead, after designing and building several small, mobile bio-inspired robots, we argue for the following approach: (1) Identify exemplars from nature that excel at a particular task. Examples include cockroaches that run over rough terrain, and geckos that maneuver with agility on vertical surfaces. (2) Collaborate with biologists and research the literature to understand the mechanisms that appear to contribute to the animal's success. (3) Develop hypotheses about simplified design principles that can be adapted to robotic implementation. These design principles represent an abstraction of the complex structures and behaviors observed in animal models. (4) Apply the principles to the development of small robots, which take advantage of rapid prototyping technology to create multi-material structures that exhibit a desired behavior. (5) Test and evaluate the robots to reveal where the design principles should be refined or augmented. The resulting insights are valuable to both roboticists and biologists to deepen their understanding about what is important, and why.

3.1 Hexapedal running robots

The iSprawl robot [28] is the latest in a series of hexapods that adapts several design principles from running insects, and the cockroach, in particular:

- Use a wide stance, with legs sprawled in the fore-aft direction for stability (allthough a 0.1 m robot cannot be as sprawled as an insect, because mass grows as L^3).
- Direct propulsive and braking forces primarily along rear and front legs, respectively.
- Use passive elements to apply small torques at the hips that swing the legs forward at the end of each step.
- Keep the legs light and slender with low polar moment of inertia to maximize the stride frequency.
- Run with a predefined motor pattern that actuates the legs in an alternating-tripod gait. (This approach takes advantage of a self-stabilizing phenomenon in which overly long strides tend to result in shorter strides during the next step and vice versa.)
- Change the equilibrium configurations of the legs to achieve changes in speed and to steer.

Following these principles, iSprawl could immediately run at approximately 5 body-lengths/second, or about as fast as other bio-inspired robots of its size. However, from watching high-speed video footage it was clear that the locomotion was inefficient, with excessive rolling and pitching and occasional mis-placed steps. We hypothesized that the ideal trajectory for the center of mass would

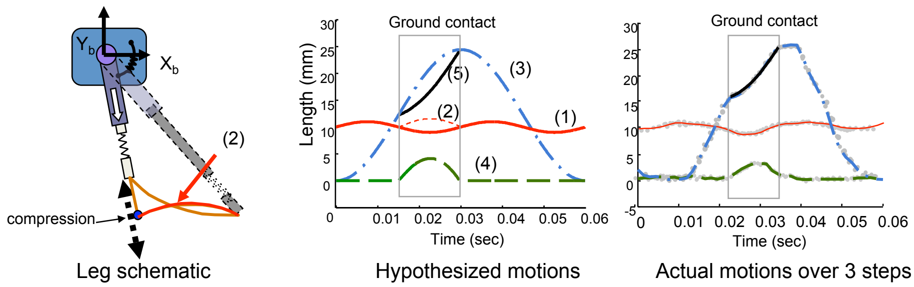

Figure 7: Schematic of iSprawl robot leg (photo in Fig. 2) and desired motions (middle) and actual motions (right) of the body, leg and foot, with curves labeled for discussion in the text.

be low amplitude sinusoid, with minimal pitching and rolling and with a nearly constant horizontal velocity. To achieve such a trajectory, it is necessary for the legs to have added axial compliance, as illustrated in Figure 7.

The left image in Figure 7 shows a schematic view of a leg. There is a passive torsional spring and damper at the hip, achieved by the viscoelastic flexures seen in the photograph of the same leg in Figure 2. The leg is actuated by a push-pull cable system that is driven by a motor through a slider-crank mechanism. Accordingly, the foot velocity with respect to the leg is approximately sinusoidal, as indicated by the dashed curve labeled (3). At the same time, the robot center of mass traces a sinusoid with respect to the ground with an amplitude of approximately 1 mm, as indicated by curve (1). While the foot is in contact with the ground, it is necessary for the leg to compress in the axial direction. The spring compression is indicated by the dashed curve (4). (If the leg did not compress, the leg would act as an inverted pendulum and the center of mass would follow the trajectory (2).) The consequence of leg compression is that the actual trajectory of the foot with respect to the leg is given by curve (5) during ground contact, instead of the nominal trajectory (3). Inserting the appropriate numerical values for the masses, stiffnesses and amplitudes results in an estimated leg compression of approximately 4 mm. The robot runs with a 14 Hz stride frequency, corresponding to a vertical oscillation frequency of 28 Hz. The optimal leg stiffness was found to be approximately 1.7N/mm per leg, accounting for differences in leg angles between the rear, middle and front legs [28]. The experimental results for iSprawl are shown in the right-hand plot. Data points are shown, corresponding to the positions of reflective markers on the body and the middle leg, recorded at 500 frames/second as the robot ran on a treadmill. Data for three successive strides are shown to illustrate the repeatability of the motion.

In summary, when the iSprawl robot was tuned to match a particular hypothesis about the desired body motion, it ran more smoothly and much faster (up to 15 body-lengths/second, or 2.3 m/s, versus 5 body-lengths/second).

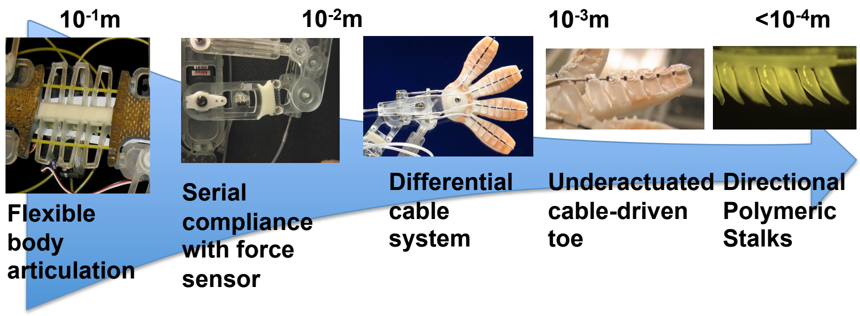

Figure 8: Hierarchical compliance structure of Stickybot includes body compliance, serial compliances at the limbs, under-actuated toes and a segmented toe structure. Each compliant element is composed of soft and hard polymers.

3.2 Climbing with directional adhesives

As a second example of the bio-inspired design process, we consider a robot for climbing vertical surfaces, inspired by the gecko. Stickybot [27] is an embodiment of our hypotheses about the requirements for mobility on vertical surfaces using dry adhesion. The key point is that the robot doesn't need high levels adhesion; it needs *controllable* adhesion. The essential ingredients are:

- hierarchical compliance for conforming at centimeter, millimeter and micrometer scales,
- anisotropic dry adhesive structures so that we can control adhesion by controlling shear tractions, and
- distributed force control that works with compliance and anisotropy to achieve stability.

A hierarchy of conformable elements

The adhesive system of the gecko involves a remarkable hierarchy of structures that ranges from feet and toes at the centimeter scale, to lamellae, setae and finally spatulae with dimensions of a few hundred nanometers on a side [5]. Interestingly, from the level of lamellae downward, the structures are passive elements, made of a stiff, hydrophic material (β keratin) that, by virtue of the shapes that it is incorporated into, conforms like a very soft material when placed into contact with surfaces and loaded in shear. Intimate conformation is essential because the adhesion arises from van der Waals forces, which are relatively weak and decrease with separation as $1/d^3$.

In Stickybot a similar, albeit much less sophisticated, hierarchy of compliances is responsible for conformation over a range of length scales from 10^{-1} m to $< 10^{-4}$ m, as shown in Figure 8. At the level of legs and feet, passive compliant elements are used in series with each actuated degree of freedom, to help distribute loads and ensure that small positioning errors do not produce large force errors (Figure 9). Hall effect sensors measure the compliant deflec-

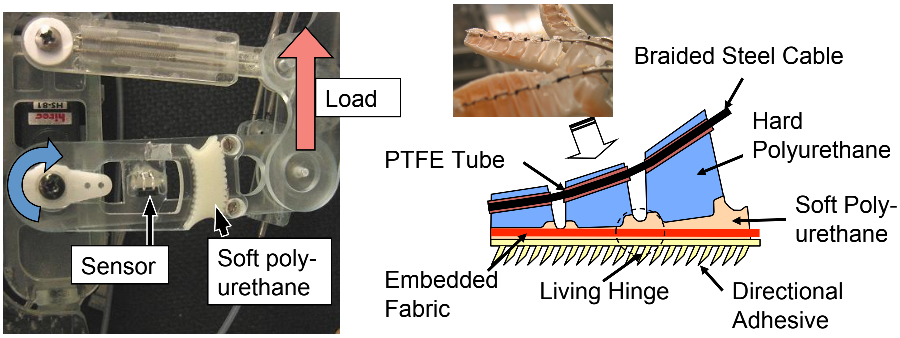

Figure 9: Left: Viscoelastic material provides a compliant, damped element in series with an actuated degree of freedom; a sensor measures deflections to estimate force. Right: Toe consists of hard and soft polymers with embedded fabric to ensure approximately uniform normal and shear stress over the contact area. Small angled stalks conform to the surface when loaded in shear.

tions to provide the controller with an estimate of traction forces in the fore-aft direction. Unlike the case of motion over level ground, vertical climbing requires continuous attention to the ratios of forces in the normal and fore-aft directions. In operation, one Stickybot foot can create about 0.2 N of normal force without disturbing the balance of the body, whereas the typical vertical force per foot is around 2 N, which is a just over half the body weight.

Like the toes of the gecko, the toes of Stickybot can curl over rounded surfaces. For simplicity, the four toes on each foot are actuated a single “tendon” (a braided steel cable) through a double rocker-bogie linkage. The path of the cable in each toe is a section of a circular arc, to ensure that cable tension produces an approximately uniform normal stress over the contact patch. A flexible but relatively inextensible fabric is embedded in the foot (labeled in Figure 9) to prevent stretching from producing a shear stress concentration at the leading edge of the contact patch. Together, these features ensure that the angled polymer stalks experience an approximately uniform loading [27].

One general difficulty with using under-actuated mechanisms is that there may be tradeoffs in tuning the compliance values. For example, in the direction normal to the surface, the stiffness should be quite low so that variations in the surface height and positioning errors do not produce significant variations in the normal force. However, if the series elastic element is too soft, there will be a large “wind up” in the actuated degree of freedom, with significant stored elastic energy and a large required range of motion for the corresponding actuator. A non-linear stiffness or a stiffness with preload can resolve this problem. Thus in Figure 10 there is a preload such that compliant deflections only occur when the normal force exceeds a threshold. Subsequently, the force stays within a

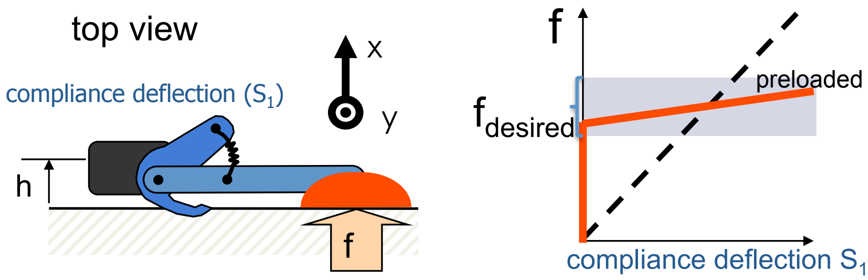

Figure 10: Left: Schematic representation of the wing compliance in traverse plane. Right: the force-deflection relationship for a linear spring (dotted line) as compared to the preloaded case (red solid line).

narrow band despite variations in positioning.

4 Conclusions

The foregoing examples illustrate ways in which multi-material structures, with intentional compliance and damping, can enable small, bio-inspired robots to emulate some of the characteristics that are found in animals, which contribute to the animals' performance in locomotion over uncertain terrain. The structures are made possible by new rapid prototyping processes that allow hard and soft materials, as well as sensors, actuators, fabrics and fibers, to be integrated in a structure. The resulting parts are simpler and much more robust than comparable assemblies created using traditional methods.

Looking ahead, one of the major challenges will be to adapt this approach to systems that involve features spanning a wide range of dimensions, with particular attention to features at the micrometer scale. At present, the processes used for micro-scale fabrication are quite different from those used in making macroscopic parts. They work with a limited range of materials and they offer a limited range of detailed geometries in three dimensions. The facilities for these processes have strict requirements on contamination and, in consequence, it is generally not possible to bring large multi-material structures into them for processing. Ultimately, technologies such as self-assembling polymers may allow complexity comparable to that seen in nature. In the interim, a promising technique may be to adapt laser micromachining and lithographic methods so that they can be applied, in-situ, to non-flat surfaces in a macro-scale rapid prototoyping facility. In this way, for example, one might pattern dense arrays of sensors over the curved surface of a robot limb.

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