PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Design and fabrication of multi-material structures for bioinspired robots

Mark R Cutkosky and Sangbae Kim

*Phil. Trans. R. Soc. A* 2009 **367**, 1799-1813
doi: 10.1098/rsta.2009.0013

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

*Phil. Trans. R. Soc. A* (2009) **367**, 1799–1813
doi:10.1098/rsta.2009.0013

# Design and fabrication of multi-material structures for bioinspired robots

By Mark R. Cutkosky[1,*] and Sangbae Kim[2]

[1] *Stanford University, Stanford, CA 94305, USA*
[2] *Harvard University, Cambridge, MA 02138, USA*

New multi-material rapid prototyping processes are making possible the design and fabrication of bioinspired 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 designed robots and more robust. Current challenges include extending this approach to the structures that involve microscopic as well as macroscopic features.

**Keywords: bioinspired design; materials; fabrication; biomimicry; robotics**

## 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, de-mining, 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' (Vogel 1995) 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 (Blickhan & Full 1993). 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, hair sensors, chemical sensors, etc. (Barth & Stagl 1976; Seyfarth *et al.* 1985; Barth 2004; Vincent *et al.* 2007). Parts of the exoskeleton are also covered with small spines that bend preferentially in one direction, providing superior traction during locomotion and manipulation (Spagna *et al.* 2007). In summary, the functions

* Author for correspondence (cutkosky@stanford.edu).

One contribution of 9 to a Theme Issue 'Biomimetics II: fabrication and applications'.

 

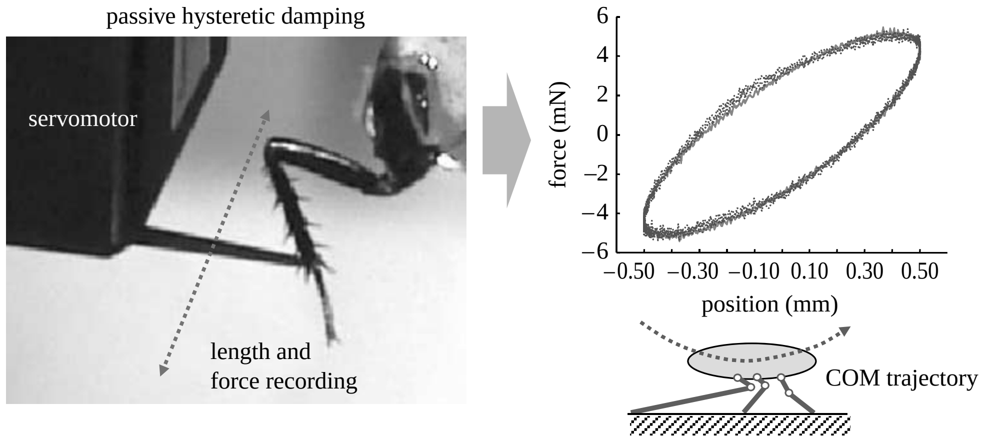


Figure 1. The passive properties of cockroach legs contribute to its stability, absorbing and dissipating energies as it runs with a bouncing alternating-tripod gait (dotted curve, data; solid curve, model; COM, centre of mass; Xu *et al.* 2000).

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 centre of mass accelerates and decelerates with each step (Biewener *et al.* 1981; Alexander 1984; Roberts *et al.* 1997). The ratio of leg stiffness to body mass is approximately $K \propto M^{2/3}$ over a wide range of species and dimensional scales (Full & Farley 2000). Forces are directed mainly parallel to the legs, with only small torques at the hips (Farley *et al.* 1993). This commonality of approach suggests that animals control 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 (Full & Koditschek 1999).

There is also ample evidence that the kinematics and passive mechanical properties of animal limbs contribute to their stability when running. The effects of these properties have been termed 'preflexes' in the biology literature (van Soest & Bobbert 1993; Brown & Loeb 2000). Preflexes provide an immediate response to perturbations without the delays of neural reflexes. For example, it has been shown empirically and in simulation (Kubow & Full 1999; Jindrich & Full 2002) 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 servomotor applies forces to the passive leg, resulting in a hysteresis loop that gives evidence of significant energy

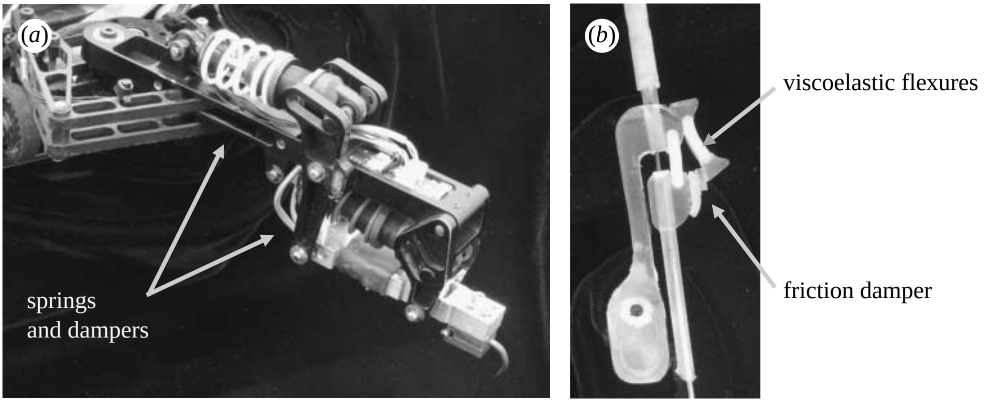


Figure 2. (*a*) The RiSE robot uses shock absorbers for compliance and damping. The elements help to distribute forces when climbing but increase complexity. (*b*) The iSprawl robot uses hard and soft viscoelastic materials to achieve similar functionality with many fewer parts. The legs are also robust: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

dissipation per cycle at the normal running speed (Xu *et al.* 2000). In fact, cockroach locomotion is not particularly efficient compared with larger animals, but is remarkably stable even with a predominantly fixed motor pattern. Consistent with this view, Full *et al.* (1998) 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 store and release energy, to simplify control and increase the robustness of locomotion over rough terrain (Pratt & Williamson 1995; Altendorfer *et al.* 2001; Iida & Pfeifer 2004; Poulakakis & Buehler 2005; Kim *et al.* 2006; Spenko *et al.* 2008; Scarfogliero *et al.* 2009). However, such elements significantly increase the complexity of the robot limbs. For example, the lower leg of the RiSE climbing robot (Spenko *et al.* 2008), shown in figure 2*a*, 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 (Altendorfer *et al.* 2001) and iSprawl (Kim *et al.* 2006) robots, has over 200 muscles (Full & Ahn 1995). 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 nanometres to centimetres (Autumn 2006; Russell *et al.* 2007). 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 bioinspired robots has been 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, figure 2*b* shows a leg from a small hexapedal robot, iSprawl (Kim *et al.* 2006), which 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 figure 2*a* 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 servomotor. The monolithic structure is robust because it can deform without failing in response to overloads.

In the following sections, we describe some of the fabrication advances that make such multi-material structures possible and illustrate them with examples of bioinspired 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 micrometres, we must 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 artefacts, 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 such as 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, which take advantage of the computer to replace a high part count and complex manufacturing sequences 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 (Jackson *et al.* 1999; Sun 2000; Dutta *et al.* 2001; Cheng & Lin 2005; Gouker *et al.* 2006; Gyger *et al.* 2006). One such process is three-dimensional printing (Jackson *et al.* 1999), in which various polymers are deposited in thin layers to create a three-dimensional part of almost arbitrary shape. Commercial versions are now available (Objet 2008) and the available tolerances and materials properties have steadily improved.

One limitation of 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 trade-off between

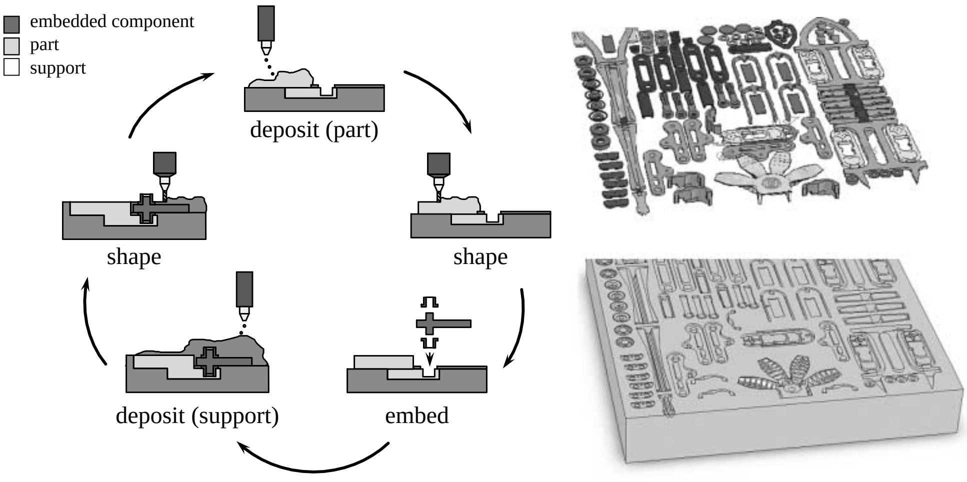


Figure 3. The SDM process consists of a cycle in which part materials (polymers) and sacrificial support materials are added and shaped. Discrete components are added after any shaping step. Multiple parts and materials for creating an entire robot can be fabricated on a common pallet.

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 with the average feature size, which is one reason why processes such as 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; Weiss *et al.* 1997) and was subsequently extended at Stanford for polymer and ceramic parts. We have focused on polymers, sometimes with fabric or fibre reinforcement, as these materials come the closest to the natural properties of materials such as 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 Weiss *et al.* (1997) and Binnard & Cutkosky (2000). Unlike the 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 tolerances of $\pm 0.01$ mm and avoids the stair-stepping effect of additive processes. The intermittent addition of sacrificial support material allows for the 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 bioinspired robots, we use hard machinist's wax as the sacrificial support material because it can easily be machined to a smooth finish.

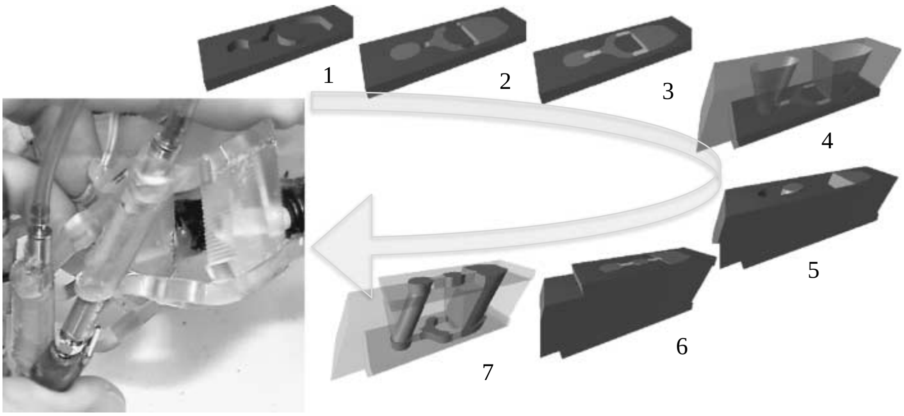


Figure 4. Spatial linkage of hard and soft viscoelastic polymers and corresponding SDM process plan. Hard polymer is added at steps 2, 5, 6, and soft material at steps 3, 7.

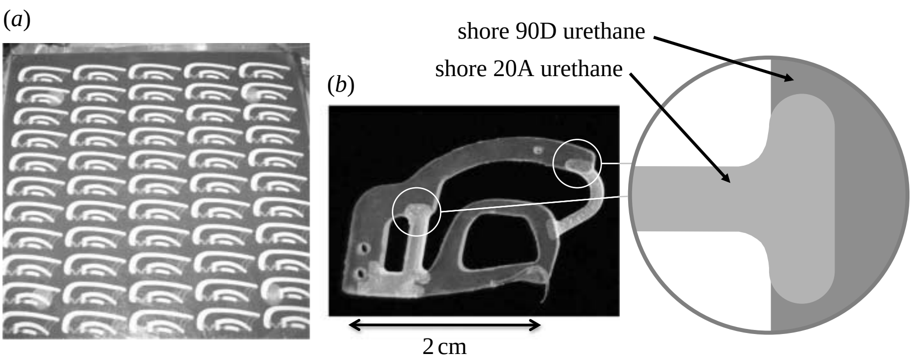


Figure 5. (*a*) Array of toes for a climbing robot in process on SDM pallet and (*b*) toe detail showing geometry at material junction to prevent tearing.

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 moulding 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 materials. 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.

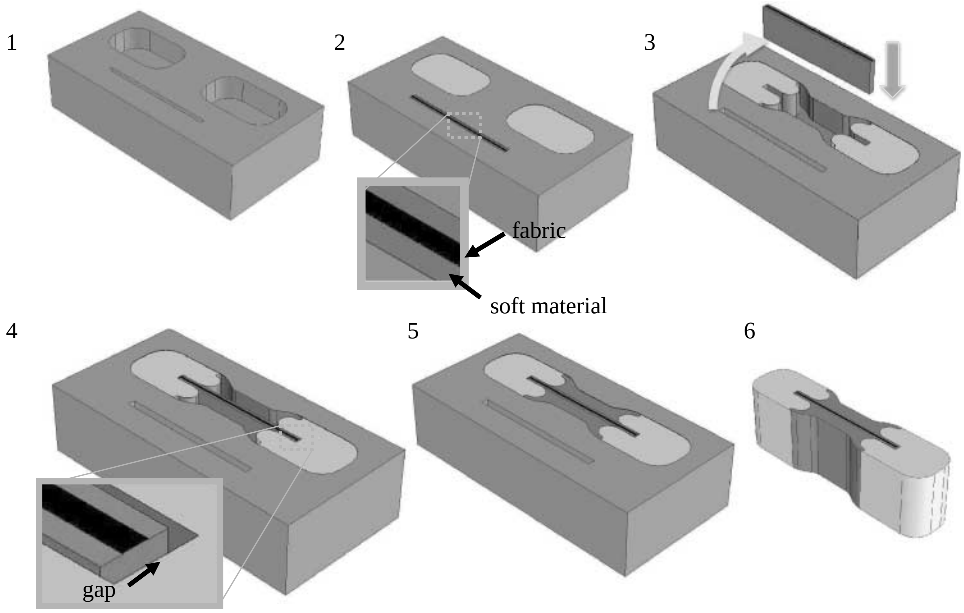


Figure 6. Schematic process plan for creating multi-material parts with fibres that traverse material boundaries.

With attention to such details, the flexible elements can accommodate large strains with long fatigue life. (Flexures from the 2002 Sprawlita robot (Cham *et al.* 2002) have survived over a million cycles.)

Some of the most challenging components are those that involve flexible elements such as fibres, wires or fabrics that must traverse 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 fibres without damaging them or being obstructed by them. Several solutions are presented in Hatanaka & Cutkosky (2003). One of the simplest is shown in figure 6. Referring to the numbers in the figure, the first step is to create a mould in some sacrificial material (1). The fibres are placed in a thin cavity, applying tension as needed. (Sacrificial material can also be used to create a consumable fixture for aligning the fibres.) The next step (2) is to cast a thin layer of soft material (e.g. a soft urethane) into the mould, encapsulating the fibres. After the material cures, it is released from the mould. At this point, the item has just enough stiffness that it can be handled without special fixturing and tensioning provisions (3). Meanwhile, hard material is cast into a second cavity and machined to shape. Machining the hard material provides a fresh surface that promotes adhesion when soft material is subsequently added. The flexible part is inserted into the second cavity (4) and soft material is cast around it (5). The soft material flows around the flexible element and bonds with the shaped hard material. After the soft material has cured, the part is released (6). The result in this case is a fibre-reinforced flexural element. Although now there is a thin layer of soft material in between the fibres and the hard material, the behaviour of the part is not affected because the soft material is incompressible and is constrained on all sides by the surrounding hard material.

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 such as lithography, as used in creating MEMs parts. Unfortunately, these processes typically are limited to '2.5-dimensional' shapes with stair stepping in the vertical direction. This limitation can be addressed in part with techniques such as multiple-angled exposures, as used in creating arrays of sharp vertical wedge-shaped structures for adhesion (Santos *et al.* 2007). Other promising techniques include chemical vapour deposition induced by focused ion beams (FIB-CVD), which can create almost arbitrary three-dimensional geometries out of many different materials with feature sizes of the order of 80 nm (Morita *et al.* 2003). This technology permits both material addition and removal. Another sub-micrometre three-dimensional manufacturing method is the two-photon polymerization process, which allows features with a resolution of approximately 120 nm (Kawata *et al.* 2001). 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. However, the machining of each item is done individually. A related commercial process (Eoplex 2008) 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 such as 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 Lanzetta & Cutkosky (2008) 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 §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, a growing community of researchers, starting with efforts such as Beer *et al.* (1997), has adopted the following approach. (i) Identify exemplars from Nature that excel at a particular task. Examples include cockroaches that run over rough terrain, and geckos that manoeuvre with agility on vertical surfaces. (ii) Collaborate with biologists and research the literature to understand the mechanisms that appear to contribute to the animal's success. (iii) Develop hypotheses about simplified design principles that can be adapted to robotic implementation. These design principles represent an abstraction of the complex structures and behaviours observed in animal models. (iv) 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 behaviour. (v) 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.

### (*a*) *Hexapedal running robots*

The iSprawl robot (Kim *et al.* 2006) 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 (although 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 forwards 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 five body lengths per second, or about as fast as other bioinspired 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 misplaced steps. We hypothesized that the ideal trajectory for the centre of mass would 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.

Figure 7*a* shows a schematic 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*b*. 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 labelled (3). At the same time, the robot centre 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 centre of mass would follow the trajectory (2).)

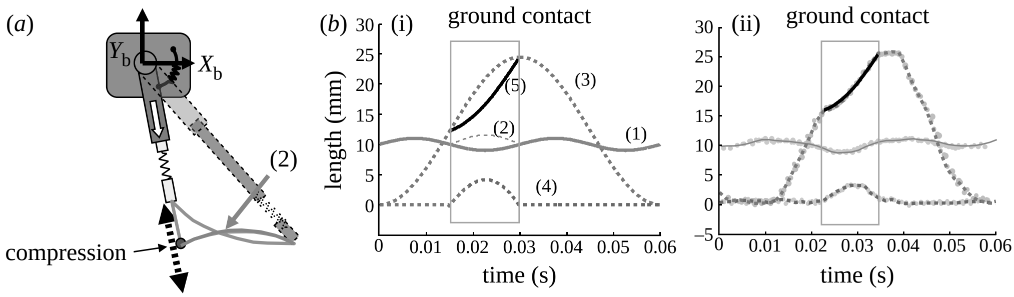


Figure 7. (*a*) Schematic of iSprawl robot leg (figure 2*b*), (*b*)(i) desired (hypothesized) and (ii) actual (over three steps) motions of the body, leg and foot, with curves labelled for discussion in the text.

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 $1.7\ \mathrm{N\ mm^{-1}}$ per leg, accounting for differences in leg angles between the rear, middle and front legs (Kim *et al.* 2006). The experimental results for iSprawl are shown in figure 7*b*(ii). Data points are shown, corresponding to the positions of reflective markers on the body and the middle leg, recorded at $500\ \mathrm{frames\ s^{-1}}$ 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 $\mathrm{s^{-1}}$, or $2.3\ \mathrm{m\ s^{-1}}$, versus 5 body lengths $\mathrm{s^{-1}}$).

### (*b*) *Climbing with directional adhesives*

As a second example of the bioinspired design process, we consider a robot for climbing vertical surfaces, inspired by the gecko. Stickybot (Kim *et al.* 2008) is an embodiment of our hypotheses about the requirements for mobility on vertical surfaces using dry adhesion. The key point is that the robot does not need high levels of adhesion; it needs *controllable* adhesion. The essential ingredients are the following:

- hierarchical compliance for conforming at centimetre, millimetre and micrometre 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.

The adhesive system of the gecko involves a remarkable hierarchy of structures, which ranges from feet and toes at the centimetre scale, to lamellae, setae and finally spatulae with dimensions of a few hundred nanometres on a side

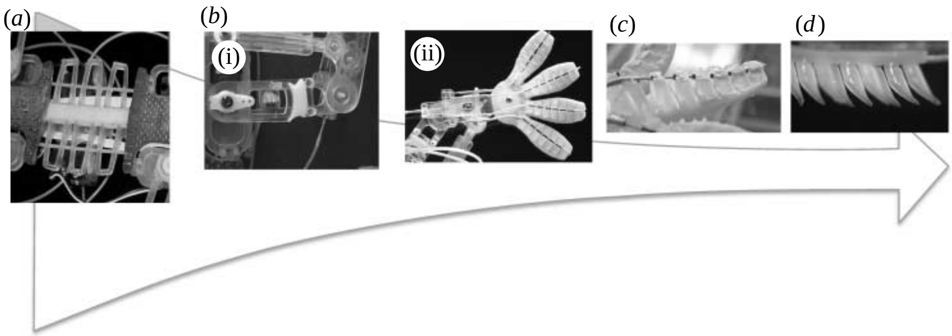


Figure 8. Hierarchical compliance structure of Stickybot includes (*a*) body compliance (flexible body articulation; $10^{-1}$ m), (*b*) serial compliances with (i) force sensor at the limbs, (ii) differential cable system ($10^{-2}$ m), (*c*) under-actuated cable-driven toes ($10^{-3}$ m) and (*d*) a segmented toe structure (directional polymeric stalks; less than $10^{-4}$ m). Each compliant element is composed of soft and hard polymers.

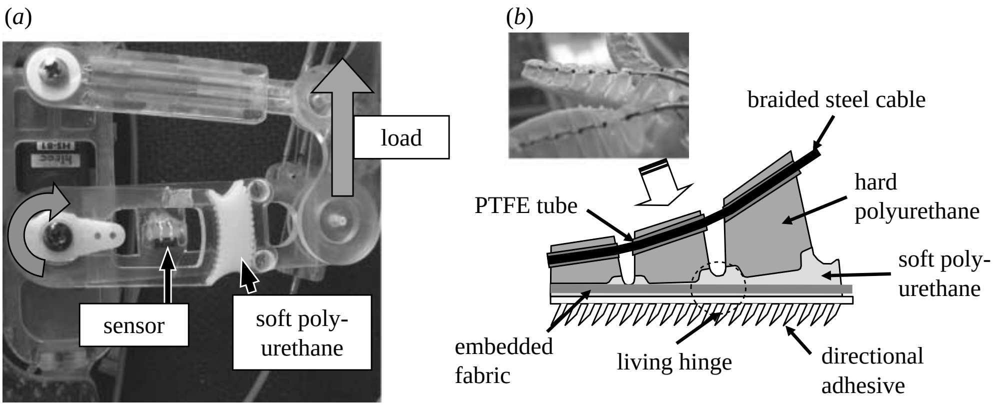


Figure 9. (*a*) Viscoelastic material provides a compliant, damped element in series with an actuated degree of freedom; a sensor measures deflections to estimate force. (*b*) Toe consists of hard and soft polymers with embedded fabric to ensure approximately uniform normal and shear stress over the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

(Autumn 2006). Interestingly, from the level of lamellae downwards, the structures are passive elements, made of a stiff, hydrophobic material (β-keratin) that, by virtue of the shapes that it is incorporated into, conforms as 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 are responsible for conformation over a range of length scales from $10^{-1}$ m to less than $10^{-4}$ 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 deflections 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

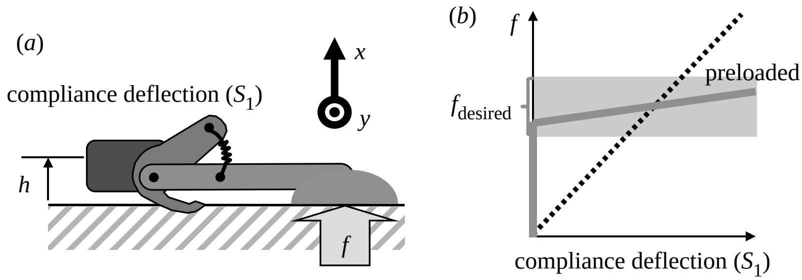


Figure 10. (*a*) Schematic of the wing compliance in transverse plane (top view). (*b*) The force–deflection relationship for a linear spring (dotted line) when compared with the preloaded case (solid line).

continuous attention to the ratios of forces in the normal and fore–aft directions. In operation, one Stickybot foot can create approximately 0.2 N of normal force without disturbing the balance of the body, whereas the typical vertical force per foot is approximately 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 by 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 compression or tension produces an approximately uniform normal stress over the contact patch. A flexible but relatively inextensible fabric is embedded in the foot (labelled 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 (Kim *et al.* 2008).

One general difficulty with using under-actuated mechanisms is that there may be trade-offs 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 nonlinear stiffness or a stiffness with preload can resolve this problem. Thus, in figure 10, there is a preload such that compliant deflections occur only when the normal force exceeds a threshold. Subsequently, the force stays within a 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, bioinspired 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 fibres, 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 micrometre 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 with 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 prototyping facility. In this way, for example, one might pattern dense arrays of sensors over the curved surface of a robot limb.

This work has been supported by the DARPA BioDynotics programme and in part by an NSF NIRT (0708367). We gratefully acknowledge the help of the research team at the Stanford BDML and many rewarding discussions with biologists R. J. Full and K. Autumn. Thanks are due to A. Asbeck for his comments on the manuscript.

## References

Alexander, R. M. 1984 Elastic energy stores in running vertebrates. *Am. Zool.* **24**, 85–94. (doi:10.1093/icb/24.1.85)

Altendorfer, R., Moore, N., Komsuoglu, H., Buehler, M., Brown Jr, H. B., McMordie, D., Saranli, U., Full, R. & Koditschek, D. E. 2001 RHex: a biologically inspired hexapod runner. *Auton. Robots* **11**, 207–213. (doi:10.1023/A:1012426720699)

Autumn, K. 2006 Properties, principles, and parameters of the gecko adhesive system. In *Biological adhesives*, pp. 225–256. Berlin, Germany: Springer Verlag.

Barth, F. G. 2004 Spider mechanoreceptors. *Curr. Opin. Neurobiol.* **14**, 415–422. (doi:10.1016/j.conb.2004.07.005)

Barth, F. G. & Stagl, J. 1976 The slit sense organs of arachnids. *Zoomorphologie* **86**, 1–23. (doi:10.1007/BF01006710)

Beer, R., Quinn, R., Chiel, H. & Ritzmann, R. 1997 Biologically inspired approaches to robotics. *Comm. ACM* **40**, 31–38. (doi:10.1145/245108.245118)

Biewener, A. A., Alexander, R. M. & Heglund, N. C. 1981 Elastic energy storage in the hopping of kangaroo rats. *J. Zool.* **195**, 369–383.

Binnard, M. & Cutkosky, M. R. 2000 Design by composition for layered manufacturing. *J. Mech. Des.* **122**, 91–101. (doi:10.1115/1.533549)

Blickhan, R. & Full, R. 1993 Similarity in multilegged locomotion: bounding like a monopode. *J. Comp. Physiol. A Sens. Neural Behav. Physiol.* **173**, 509–517. (doi:10.1007/BF00197760)

Brown, I. & Loeb, G. 2000 A reductionist approach to creating and using neuromusculoskeletal models. In *Biomechanics and neural control of posture and movement* (eds J. Winters & P. Crago), pp. 148–163. New York, NY: Springer.

Cham, J. G., Bailey, S. A., Clark, J. E., Full, R. J. & Cutkosky, M. R. 2002 Fast and robust: hexapedal robots via shape deposition manufacturing. *Int. J. Robot. Res.* **21**, 869–882. (doi:10.1177/0278364902021010837)

Cheng, J. & Lin, F. 2005 Approach of heterogeneous bio-modeling based on material features. *Comput. Aided Des.* **37**, 1115–1126. (doi:10.1016/j.cad.2005.02.003)

Dutta, D., Prinz, F. B., Rosen, D. & Weiss, L. 2001 Layered manufacturing: current status and future trends. *J. Comput. Inf. Sci. Eng.* **1**, 60–71. (doi:10.1115/1.1355029)

Eoplex 2008 High volume print forming process. See http://eoplex.com.

Farley, C., Glasheen, J. & McMahon, T. 1993 Running springs: speed and animal size. *J. Exp. Biol.* **185**, 71–86.

Full, R. & Ahn, A. 1995 Static forces and moments generated in the insect leg: comparison of a three-dimensional musculo-skeletal computer model with experimental measurements. *J. Exp. Biol.* **198**, 1285–1298.

Full, R. J. & Farley, C. T. 2000 Musculoskeletal dynamics in rhythmic systems—a comparative approach to legged locomotion. In *Biomechanics and neural control of movement*, pp. 192–205. New York, NY: Springer-Verlag.

Full, R. J. & Koditschek, D. E. 1999 Templates and anchors: neuromechanical hypotheses of legged locomotion on land. *J. Exp. Biol.* **202**, 3325–3332.

Full, R., Stokes, D. R., Ahn, A. N. & Josephson, R. K. 1998 Energy absorption during running by leg muscles in a cockroach. *J. Exp. Biol.* **201**, 997–1012.

Gouker, R. M., Gupta, S. K., Bruck, H. A. & Holzschuh, T. 2006 Manufacturing of multi-material compliant mechanisms using multi-material molding. *Int. J. Adv. Manuf. Technol.* **30**, 1049–1075. (doi:10.1007/s00170-005-0152-4)

Gyger Jr, L. S., Spranklin, B., Gupta, S. & Bruck, H. 2006 Bio-inspired, modular, and multifunctional thermal and impact protected embedded sensing controls actuation power element structures. In *Proc. 2006 SEM Annual Conf. and Exposition*, vol. 3, pp. 1–12.

Hatanaka, M. & Cutkosky, M. 2003 Process planning for embedded flexible materials in multi-material prototypes. In *ASME DETC2003/DFM-48166, Chicago, IL.*

Iida, F. & Pfeifer, R. 2004 Self-stabilization and behavioral diversity of embodied adaptive locomotion. In *Embodied artificial intelligence*, vol. LNAI 3139 (eds F. Iida, R. Pfeifer, L. Steels & Y. Kuniyoshi). Lecture Notes in Artificial Intelligence, pp. 119–129. Berlin, Germany; Heidelberg, Germany: Springer-Verlag.

Jackson, T. R., Liu, H., Patrikalakis, N. M., Sachs, E. M. & Cima, M. J. 1999 Modeling and designing functionally graded material components for fabrication with local composition control. *Mater. Des.* **20**, 63–75. (doi:10.1016/S0261-3069(99)00011-4)

Jindrich, D. L. & Full, R. J. 2002 Dynamic stabilization of rapid hexapedal locomotion. *J. Exp. Biol.* **205**, 2803–2823.

Kawata, S., Sun, H.-B., Tanaka, T., Takada, K., Padmanabhan, P., Schultz, L. & Ramaswami, K. 2001 Finer features for functional microdevices. *Nature* **412**, 697–698. (doi:10.1038/35089130)

Kim, S., Clark, J. E. & Cutkosky, M. R. 2006 iSprawl: design and tuning for high-speed autonomous open-loop running. *Int. J. Robot. Res.* **25**, 903–912. (doi:10.1177/0278364906069150)

Kim, S., Spenko, M., Trujillo, S., Heyneman, B., Santos, D. & Cutkosky, M. 2008 Smooth vertical surface climbing with directional adhesion. *IEEE Trans. Robot.* **24**, 1552–3098.

Kubow, T. M. & Full, R. J. 1999 The role of the mechanical system in control: a hypothesis of self-stabilization in hexapedal runners. *Phil. Trans. R. Soc. Lond. B* **354**, 849–861. (doi:10.1098/rstb.1999.0437)

Lanzetta, M. & Cutkosky, M. 2008 Shape deposition manufacturing of biologically inspired hierarchical microstructures. *CIRP Ann.* **57**, 231–234. (doi:10.1016/j.cirp.2008.03.102)

Morita, T. *et al.* 2003 Free-space-wiring fabrication in nano-space by focused-ion-beam chemical vapor deposition. *J. Vac. Sci. Technol. B Microelectron. Nanometer Struct.* **21**, 2737–2741. (doi:10.1116/1.1630329)

Objet 2008 Polyjet 3d printing system. See http://object.com.

Poulakakis, I. & Buehler, M. 2005 Modeling and experiments of untethered quadrupedal running with a bounding gait: the scout ii robot. *Int. J. Robot. Res.* **24**, 239–256. (doi:10.1177/0278364904050917)

Pratt, G. & Williamson, M. 1995 Series elastic actuators. In *Intelligent robots and systems*, vol. 1, pp. 399–406. Pittsburgh, PA: Institute of Electrical and Electronics Engineers.

Roberts, T. J., Marsh, R. L., Weyand, P. G. & Taylor, C. R. 1997 Muscular force in running turkeys: the economy of minimizing work. *Science* **275**, 1113–1115. (doi:10.1126/science.275.5303.1113)

Russell, A., Johnson, M. & Delannoy, S. 2007 Insights from studies of gecko-inspired adhesion and their impact on our understanding of the gekkotan adhesive system. *J. Adhes. Sci. Technol.* **21**, 1119–1143. (doi:10.1163/156856107782328371)

Santos, D., Spenko, M., Parness, A., Kim, S. & Cutkosky, M. 2007 Directional adhesion for climbing: theoretical and practical considerations. *J. Adhes. Sci. Technol.* **21**, 1317–1341. (doi:10.1163/156856107782328399)

Scarfogliero, U., Stefanini, C. & Dario, P. 2009 The use of compliant joints and elastic energy storage in bio-inspired legged robots. *Mech. Mach. Theory* **44**, 580–590. (doi:10.1016/j.mechmachtheory.2008.08.010)

Seyfarth, E.-A., Eckweiler, W. & Hammer, K. 1985 Proprioceptors and sensory nerves in the legs of a spider, *Cupiennius salei* (Arachnida, Araneida). *Zoomorphologie* **105**, 190–196. (doi:10.1007/BF00312156)

Spagna, J. C., Goldman, D. I., Lin, P.-C., Koditschek, D. E. & Full, R. J. 2007 Distributed mechanical feedback in arthropods and robots simplifies control of rapid running on challenging terrain. *Bioinspir. Biomim.* **2**, 9–18. (doi:10.1088/1748-3182/2/1/002)

Spenko, M. J., Haynes, G. C., Saunders, J. A., Cutkosky, M. R., Rizzi, A. A., Full, R. J. & Koditschek, D. E. 2008 Biologically inspired climbing with a hexapedal robot. *J. Field Robot.* **25**, 223–242. (doi:10.1002/rob.20238)

Sun, W. 2000 Multi-volume cad modeling for heterogeneous object design and fabrication. *J. Comput. Sci. Technol.* **15**, 27–36. (doi:10.1007/BF02951924)

van Soest, A. J. & Bobbert, M. 1993 The contribution of muscle properties in the control of explosive movements. *Biol. Cybern.* **69**, 195–204. (doi:10.1007/BF00198959)

Vincent, J., Clift, S. & Menon, C. 2007 Biomechanics of campaniform sensilla: measuring strain from the deformation of holes. *J. Bionic Eng.* **4**, 63–76. (doi:10.1016/S1672-6529(07)60015-8)

Vogel, S. 1995 Better bent than broken. *Discover*, May 1995, pp. 62–67.

Weiss, L. E., Merz, R., Prinz, F. B., Neplotnik, G., Padmanabhan, P., Schultz, L. & Ramaswami, K. 1997 Shape deposition manufacturing of heterogenous structures. *J. Manuf. Syst.* **16**, 239–248. (doi:10.1016/S0278-6125(97)89095-4)

Xu, X., Cheng, W., Dudek, D., Hatanaka, M., Cutkosky, M. R. & Full, R. J. 2000 Material modeling for shape deposition manufacturing of biomimetic components. In *DETC/DFM 2000*, pp. 10–14. Baltimore, MD: ASME.