

**Jorge G. Cham**  
**Sean A. Bailey**  
**Jonathan E. Clark**

Center for Design Research  
Stanford University  
Stanford, CA 94305-2232, USA

**Robert J. Full**

Dept. Integrative Biology  
University of California at Berkeley  
Berkeley CA 94720 USA

**Mark R. Cutkosky**

Center for Design Research  
Stanford University  
Stanford, CA 94305-2232, USA

## **Abstract**

*Robots to date lack the robustness and performance of even the simplest animals when operating in unstructured environments. This observation has prompted an interest in biomimetic robots that take design inspiration from biology. However, even biomimetic designs are compromised by the complexity and fragility that result from using traditional engineering materials and manufacturing methods. We argue that biomimetic design must be combined with structures that mimic the way biological structures are composed, with embedded actuators and sensors and spatially-varied materials. This proposition is made possible by a layered-manufacturing technology called Shape Deposition Manufacturing (SDM). We present a family of hexapedal robots whose functional biomimetic design is made possible by SDM's unique capabilities and whose fast (over 4 body-lengths per second) and robust (traversal over hip-height obstacles) performance begins to compare to that seen in nature. We describe the robots' design and fabrication and present the results of experiments that focus on their performance and locomotion dynamics.*

**KEYWORDS:** Biomimetic Robots, Locomotion, Shape Deposition Manufacturing

## **1. Introduction**

### ***Bending without Breaking***

Unlike animals, robots to date lack the robustness and versatility needed to operate in unstructured environments. This observation has prompted interest in biomimetic robots that take design inspiration from biology. Examples include running [Raibert, 1986], swimming [Anderson et al., 1998] and flying [Yan, et al. 2001] robot prototypes.

# **Fast and Robust: Hexapedal Robots via Shape Deposition Manufacturing**

Although biomimesis can take many forms, we believe the first step in making these efforts successful is to distill the fundamental principles of effective animal performance and then apply them to the robots' design. It is impractical to attempt a direct mapping between morphologies, actuators or control schemes since biological systems face many requirements such as reproduction and respiration which are not germane to the robot's design.

However, even biomimetic designs are compromised by the complexity and fragility imposed by traditional fabrication methods. These methods rely on assemblies of stiff metal structures, bearings and fasteners. The resulting devices are both fragile and difficult to build, especially at small scales. Fasteners and connectors work loose, limbs break, and motors and bearings fail as they become contaminated with grit. (Fundamentally, a machine designed to be assembled can also disassemble itself.)

In contrast, nature's mechanisms are robust. Sensors, actuators and structural materials are compactly integrated and enclosed, thereby protecting them against harsh external conditions while avoiding stress concentrations that cause failure. Moreover, nature uses soft materials frequently and stiff materials sparingly [Vogel, 1995]. Even nominally stiff structures such as cuticles, shells or bones, are rarely of uniform stiffness and are connected or surrounded by softer tissue. Part of the reason for the difference between human and natural approaches may be a difference in philosophy. Nature's guiding rule appears to be sufficient strength to avoid failure, not deformation.

Compliant materials in animals do more than provide sturdiness in uncertain environments. They improve performance and simplify control by providing mechanisms for energy storage and return and for passive stabilization

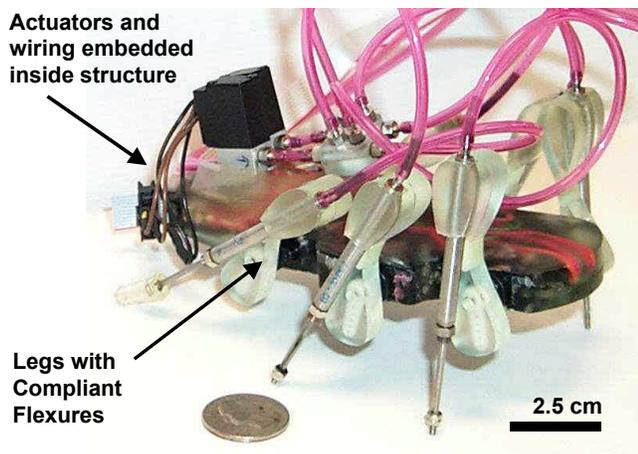


Figure 1. “Sprawlita,” a dynamically-stable running hexapod based on functional principles derived from biomechanical studies of the cockroach. The original prototype is capable of running at 3.5 body-lengths per second.

and disturbance rejection [van Soest and Bobbert, 1993; Brown and Loeb, 1997].

The advantages of compliance are also well established in robotics. Most commonly, some form of impedance control [Hogan, 1985] is applied to a robot with stiff limbs. In this case, unexpected link collisions will still produce high transient forces. Robots with compliant links have also been developed but even in these robots, most of the damping is achieved via control. In our experience, passive dampers are often considered at some point in designing a new robot or end-effector but ultimately abandoned due to the added cost, weight and complexity.

Our proposition is to make robots more like nature builds its mechanisms, with biomimetic structures that integrate compliance and functional components such as sensors and actuators [Bailey, et al., 1999]. This proposition is made possible by a layered-manufacturing technology called Shape Deposition Manufacturing (SDM) [Merz et al., 1994]. As described in detail later in the paper, SDM allows us to “grow” robust mechanisms through a repeated cycle of material deposition and shaping. The mechanisms can have almost arbitrary geometry with embedded actuators and sensors and heterogeneous structures with locally-varying compliance and damping. Although we can only begin to approximate the elegance of biological structures, the resulting robots are simpler to control and more tolerant of damaging loads than comparable assembled robots.

### ***Fast and Robust Legged Robots***

The limitations in performance imposed by traditional fabrication methods are particularly evident in legged robots

for rapid traversal of rough terrain. Studies of the biomechanics of running have shown that passive visco-elastic properties are at the heart of robust running [McMahon, 1984]. As described later in the paper, the basic mechanism for running in a variety of animals can be described by a Spring-Loaded Inverted Pendulum (SLIP) [Cavagna, et al., 1975]. Raibert’s pioneering work [Raibert, 1986] and contemporaries of our robots, such as RHex [Buehler, et al., 2000], are showing what is possible with simple mechanisms.

In the following sections, we present a family of small hexapedal robots whose fast (over 4 body-lengths per second) and robust (traversal over hip-height obstacles) performance exceeds that of most current legged robots and begins to compare with the performance seen in nature (see Figure 1 and multimedia Extensions 1, 2 and 3). We first describe their biomimetic design and fabrication and then present results of experiments that focus on their performance and locomotion dynamics. Finally, we discuss our conclusions and future work.

## **2. Functional Biomimetic Design**

Much recent interest in the field of walking and running robots has been placed on the adoption of principles found in animal locomotion [Ritzman et al., 2000]. The most common instance of this biomimicry is seen in the large number of walking robots that utilize six legs in a variety of gaits intended to maintain static stability [Bares et al., 1999; Waldron, 1986]. More recently, Case Western Reserve University has experimented with duplicating the complex cockroach morphology [Nelson et al., 1997]. Dynamic locomotion in animals has also received significant attention. For example, Raibert’s [1986] bouncing robots demonstrated the possibility of simple, dynamic running machines.

For the task of quick and robust traversal over uncertain terrain, we draw design inspiration from small arthropods. In particular, cockroaches are capable of remarkable speed and stability. For example, the American cockroach, *Periplaneta americana*, can achieve speeds of up to 50 body-lengths per second [Full and Tu, 1991]. The Death’s head cockroach, *Blaberus discoidalis*, is capable of traversing uneven terrain with obstacles up to three times the height of its center of mass without appreciably slowing down [Full et al., 1998]. Studies of these cockroaches suggest design principles for fast, stable, running hexapods:

1. self-stabilizing posture
2. thrusting and stabilizing leg function
3. passive visco-elastic structural elements
4. timed, open-loop/feedforward control

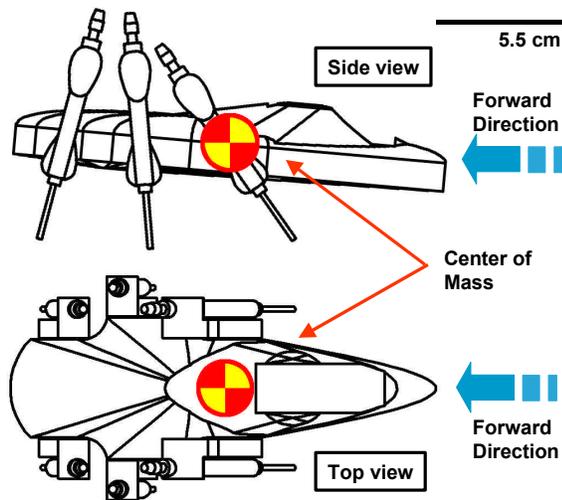


Figure 2. Self-stabilizing posture: a rear and low center of mass and a wide base of support contribute to the overall stability of locomotion.

5. integrated construction.

The following sections describe these principles and how they are implemented in the design and fabrication of our prototypes (see Extension 4 for a demonstration of these design principles).

### 2.1. Self-Stabilizing Posture

A sprawled hexapedal posture has several advantages. When walking, the center of mass can be maintained within a support polygon formed by at least three feet to ensure static stability. This approach, however, limits six-legged robots to walking slowly.

Observations of cockroaches running at high speeds, on the other hand, show that their centers of mass approach and even exceed the bounds of the triangle of support within a stride [Ting et al., 1994]. Cockroaches achieve a form of dynamic stability in rapid locomotion while maintaining a wide base of support on the ground.

Kubow and Full [1999] suggest a further advantage to an appropriately sprawled posture with large forces along the horizontal plane. Horizontal perturbations to a steady running cycle are rejected by the resulting changes in the body's position relative to the location of the feet. Generalizing these results to a horizontal plane spring-mass model revealed remarkable self-stabilizing properties (Schmitt, J. and Holmes, P., 2000a and 2000b).

Our first-generation prototype robot, approximately 16cm in length, was built for the simple task of fast straight-ahead running through rough terrain. Thus, it was designed with a similar, but not identical, sprawled morphology only in the

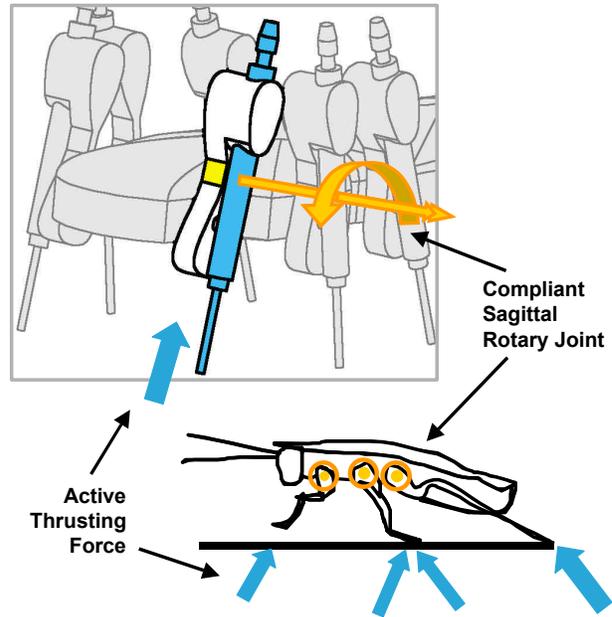


Figure 3. Studies of the cockroach's locomotion show that ground reaction forces are directed towards the hip joints, indicating that the legs essentially act as thrusters. In addition, each leg performs a different function: front legs act as decelerators while hind legs act as accelerators; middle legs act as both.

sagittal plane. The sprawl, or inclination, angle for each leg is limited by foot traction; for larger animals (or robots), it becomes progressively harder to sustain the necessary tangential forces. As shown in Figure 2, the center of mass was placed behind and slightly below the location of the hips, but still within the wide base of support provided by the sprawled posture.

### 2.2 Thrusting and Stabilizing Leg Function

Using the stability provided by a tripod of support formed by at least three legs, many robotic walkers actuate the legs to move the robot's center of mass forward while minimizing internal forces in order to increase efficiencies [Kumar and Waldron 1990]. A common leg design places a vertically-oriented joint at the hip to avoid costly torques for gravity compensation. The resulting "rowing" action minimizes internal forces, but contradicts what is observed in the cockroach and other running animals.

Studies of the cockroach's ground-reaction forces during running indicate that legs act mainly as thrusters. The ground reaction forces for each leg point roughly in the direction of the leg's hip [Full et al., 1991]. In the cockroach's sprawled posture, the front legs apply this thrusting mainly for deceleration, while the hind legs act as powerful accelerators. Middle legs both accelerate and

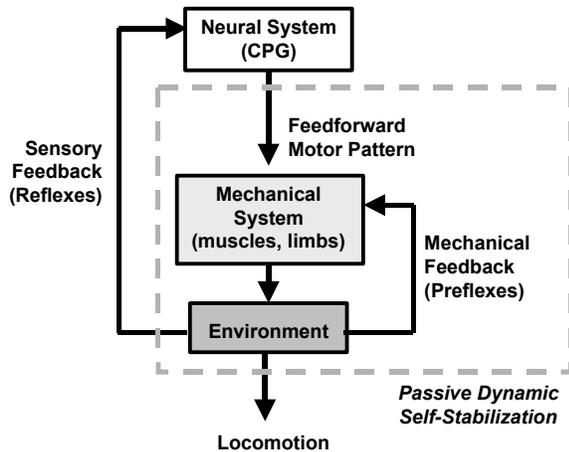


Figure 4. Suggested roles of a feedforward motor pattern, reflexes and sensory feedback. Here, disturbance rejection is the result of the mechanical system and not an active neural control loop. Adapted from [Full and Koditschek, 1999].

decelerate during the stride. The creation of large internal forces may be inefficient for smooth, steady-state running, but there is evidence it contributes to disturbance rejection in heading and speed [Kubow and Full, 1999] and permits rapid turning [Jindrich and Full, 1999].

A similar leg function has been designed in our robot as shown in Figure 3. The primary thrusting action is performed by a prismatic actuator, here implemented as a pneumatic piston. The piston is attached to the body through a compliant rotary joint at the hip. This unactuated rotary joint is based on studies of the cockroach’s compliant trochanter-femur joint, which is believed to be largely passive in the sagittal plane. In the prototype, the compliant hip joint is constructed as a flexure of visco-elastic material that allows rotation mainly in the sagittal plane, as shown in Figure 3.

These active-prismatic, passive-rotary legs are sprawled in the sagittal plane to provide specialized leg function similar to that in the cockroach. Servo motors orient the hips with respect to the body, thus setting the nominal, or equilibrium, angle about which the leg will rotate. By changing this angle, we can affect the function that the leg performs by aiming the thrusting action towards the back (to accelerate) or towards the front (to decelerate).

### 2.3 Passive Visco-elastic Structure

As mentioned, animals are commonly anything but rigid. In particular, studies of the cockroach *Blaberus discoidalis* are revealing the role of the viscoelastic properties of its limbs in locomotion [Garcia et al., 2000; Meijer and Full, 2000; Meijer and Full, 1999]. This visco-elasticity resides

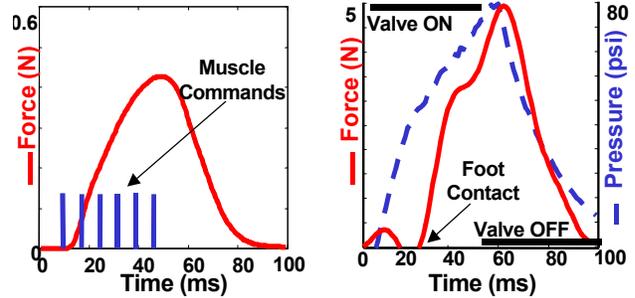


Figure 5. A comparison of isometric muscle force output [Full and Meijer, 2000] in response to motor commands and pneumatic piston force output in response to solenoid valve input on Sprawlita.

not only in the limbs’ joints, but also in their muscles and exoskeleton.

Our prototype’s legs contain a passive rotary hip joint fabricated as a flexure of viscoelastic urethane embedded in a leg structure of stiffer plastic. The flexures, like the cockroach’s limbs, dissipate significant energy through hysteresis, as evidenced by force-displacement plots of the material under sinusoidal loading [Xu et al., 2000]. The legs exhibit slightly underdamped behavior when not in contact with the ground. These leg flexures are an initial attempt at integrating desired impedance properties into the structure of the robot itself. Although it primarily allows rotation in the sagittal plane, the joint provides some compliance in the other directions as well.

### 2.4 Open-Loop/Feedforward Control

The self-stabilizing properties of the visco-elastic mechanical system and functional morphology mentioned above have been termed “preflexes” [Brown and Loeb, 1999]. These preflexes provide an immediate, or “zero-order” response to perturbations without the delays of neural reflexes. Studies of the cockroach running over uneven terrain suggest that these preflexes play a dominant role in the task of locomotion. For example, there are only minor changes in the cockroach’s muscle activation pattern as it rapidly transitions from smooth to uneven terrain [Full et al., 1998]. There is no carefully controlled foot placement or noticeable changes in gait pattern. These findings suggest a control hierarchy, as shown in Figure 4 [Full and Koditschek, 1999].

In this scheme, the basic task of locomotion is accomplished by a properly tuned mechanical system activated by a feedforward, or open-loop, control input. This combination effectively provides a mechanical “closed-loop” that is sufficient to maintain stability in the face of perturbations or terrain changes [Cham et al., 2000; Ringrose, 1997]. Sensory information is then used to modify

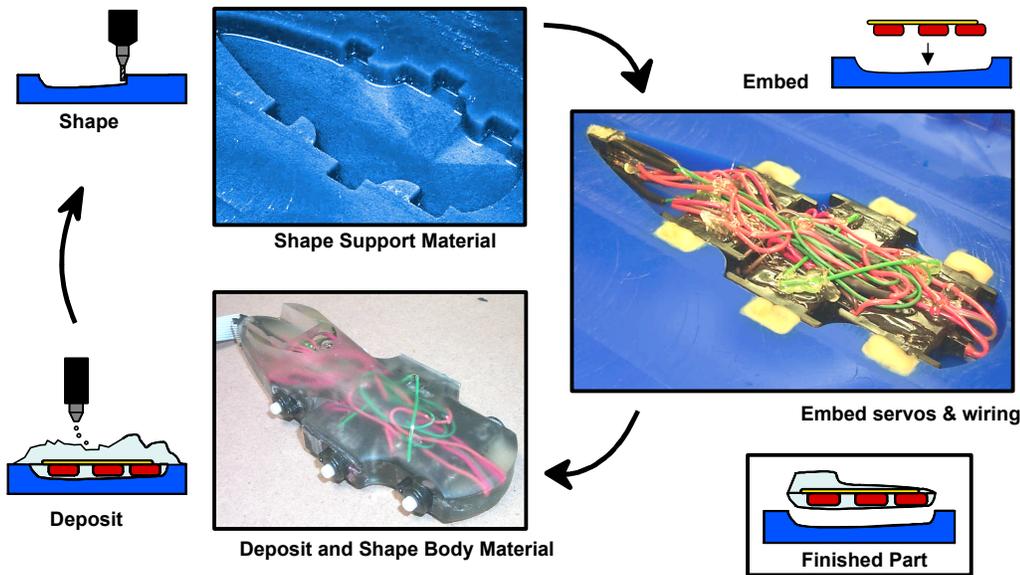


Figure 6. Shape Deposition Manufacturing (SDM) consists of alternating cycles of material deposition and shaping. The hexapod’s servos and wiring were embedded inside the structure of the body. As shown in the figure, they were first placed in a shaped geometry of support material and then encased by depositing material in the following step.

the feedforward pattern to change the animal’s behavior in order to adapt to changing conditions. For example, rapid turning may be effected simply by changing the amount of force production in the legs [Jindrich and Full, 1999].

Our robot is controlled by alternately activating tripods, composed of a front and rear leg on the same side and a middle leg on the opposing side. Each of these tripods is pressurized by a separate 3-way solenoid valve, which connects the pistons to either a pressurized reservoir or the atmosphere. The valves are operated at a frequency and duration determined respectively by the stride period and duty cycle of a binary on/off activation pattern. For initial experiments this simple stride pattern was provided through a tether by an off-board computer. In subsequent experiments, a small, on-board computer provides this pattern. Current work focuses on adaptation, or self-tuning, of this pattern to changing terrain conditions using only binary ground-contact information from the robot’s feet [Cham et al., 2001].

Despite the binary activation of the valves, the force output is surprisingly muscle-like in profile as shown in Figure 5. The compressibility of air, the tubing lengths, valve porting, and small piston orifices conspire to transform the square wave valve input into a gradual build-up of force and stiffness that reduces the impact when feet strike the ground.

The feedforward controller also commands the nominal angle for each hip, which determines foot placement and thrust direction. However, these angles are not changed within each stride, but are instead servoed in response to changes in the desired task. For example, forward and backward velocity as well as turning radius are a function of the nominal angles of each hip. In a later section, we will see

the performance of this simple control scheme, and the effects of changing the feedforward pattern.

### 3. Fabrication of Biomimetic Structures

The reflexes, or passive mechanical properties, mentioned above, could theoretically be constructed or approximated using traditional manufacturing methods. At small scales, however, this becomes impractical for several reasons. First, design and assembly become difficult as the structure’s volume is increasingly dominated by fasteners and connectors at small scales. Second, these connectors often fail under the collisions and falls that are unavoidable in running over rough terrain. Finally, assembled off-the-shelf compliant elements are nearly impossible to “tune,” that is, to create with desired spatial compliance and damping properties. This section describes a manufacturing process that circumvents these problems and makes practical the application of nature’s design lessons in our prototype robots.

Shape Deposition Manufacturing (SDM) is a layered prototyping method in which parts or assemblies are built up through a cycle of alternating layers of structural and support material. Unlike other rapid-prototyping processes, SDM shapes each layer of material on a computer-controlled milling machine after it is deposited. This allows for high precision features and avoids the common stair-stepping effect. The intermittent addition of sacrificial support material allows for the construction of nearly arbitrary geometries and facilitates the inclusion of embedded components (see Extension 5). The process is described in greater detail in [Merz et al., 1994; Binnard and Cutkosky, 2000].

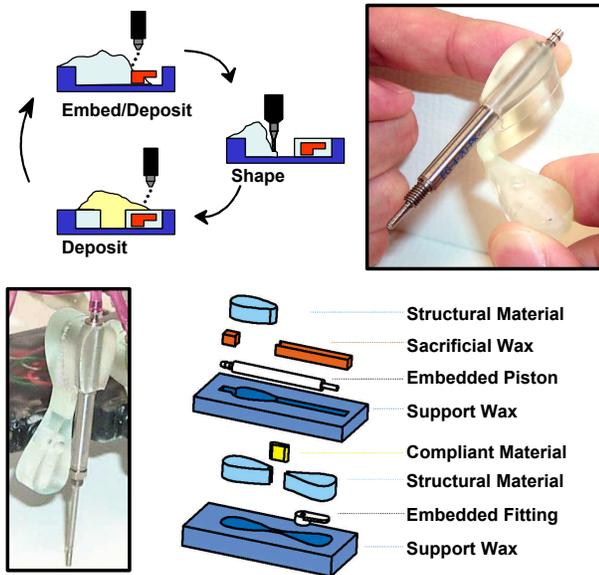


Figure 7. Process plan for the robot legs. The figure shows the alternating layers of hard and soft material and embedded components used to make the compliant legs.

Figure 6 shows the basic cycle of the process, illustrated by in-process pictures of the fabrication of the robot’s body. SDM’s capability of embedding components inside the part in a precise and repeatable fashion [Cham et al., 1999] was used to create the robot’s body with embedded servos and wiring. This was done by first shaping the support substrate (high melting-temperature wax) as a mold for the bottom of the body. The embedded components were then placed, with their moving parts encased in sacrificial material (low melting-temperature wax), to prevent later intrusion of plastic. A layer of structural material (pourable polyurethane) was then deposited and shaped, thereby encasing the embedded components. Finally, the sacrificial material was removed from the finished part to access the servos.

The construction of the multi-material compliant legs, as shown in Figure 7, takes advantage of SDM’s capability to vary the material properties during construction (see Extension 6). Each layer was built up of a different material, each with its own characteristics. The deposition of a layer of soft viscoelastic polyurethane creates the compliant, damped hip flexure. A stiffer grade of polyurethane was used for the structural members, which encase the piston and servo mounting. These leg structures have proven to be robust and have undergone over a million cycles without failure.

Modeling has been done to compare the properties of these polyurethanes with the material characteristics found

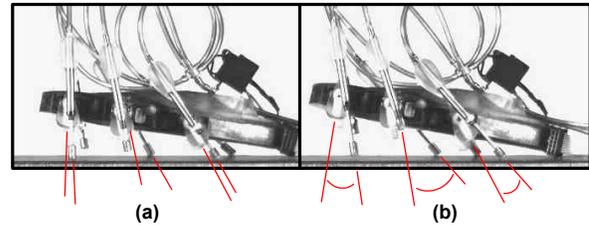


Figure 8. High-speed footage of the running robot in a) mid-stance and b) full extension. As shown, the compliance in the legs plays an important role in the locomotion, as evidenced by the large deflections during the stride.

in the exoskeleton of cockroaches. It was found that, for normal running frequencies, a simple viscoelastic material model can be fit to both the biological materials and the polyurethanes [Xu et al., 2000].

#### 4. Results: Performance Testing.

This section presents results of velocity tests and discusses initial attempts to understand the role of the robot’s “preflexes” on this performance metric. The results presented here are for our first-generation prototype, “Sprawlita,” whose maximum speed is 55 cm/s, or 3.5 body-lengths per second. More recent prototypes, not reported here, are designed to minimize pneumatic delays by using one solenoid valve per leg. These prototypes can run at 70 cm/s, or approximately 4.5 body-lengths/s (see Extension 3 and 7).

The basic mechanism for locomotion in the robot is shown in Figure 8 (see also Extension 8). As shown, the rotational compliance in the legs is essential in generating motion. At the beginning of the half-stride (a), the tripod has just made contact with the ground and the hip deflections are small. Near the end of the half-stride (b), the pistons are at full stroke and the compliant hips are significantly deflected. Once the tripod is retracted, the legs passively return to their equilibrium positions.

Variations in stride period, tripod duty cycle and nominal leg angles have a significant effect on the speed of locomotion. Moreover, the optimal parameter settings vary as a function of the slope and hardness of the terrain. For example, Figure 9 shows how the velocity varies as a function of the slope for two different stride periods. As seen, the shorter period results in faster performance on level ground. But for slopes of greater than 12 degrees the longer period is preferable.

To better understand the most important factors influencing the speed of locomotion we performed a partial factorial set of experiments [Box and Bisgaard, 1988] for

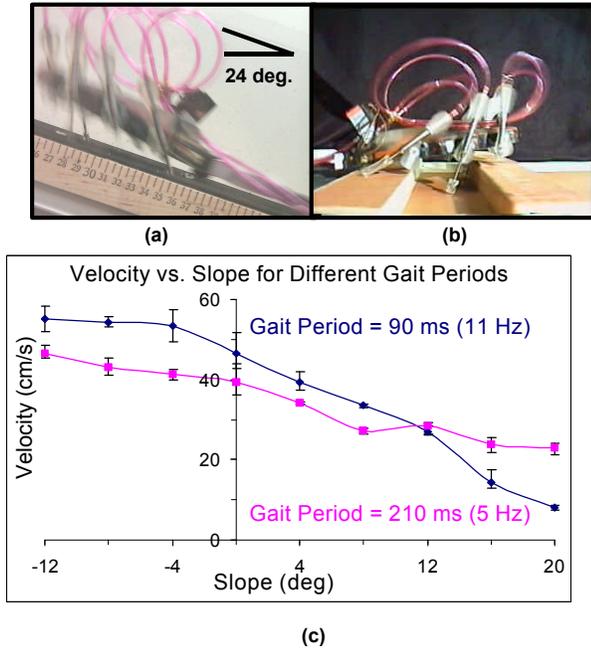


Figure 9. Performance test results. The prototype is capable of surmounting a) uphill slopes of up to 24 degrees and b) hip-height obstacles. c) Tests over different slopes indicate the need to adapt the variables of locomotion to environmental conditions.

the following parameters: stride period, duty cycle, front hip angle, middle hip angle, rear hip angle, and flexure compliance.

The parameter variation experiments were conducted on level ground and at a moderate slope of 8 degrees. High and low values were chosen empirically based on reasonable values for level ground and hill climbing. Under the experiment's conditions, the maximum speed on smooth level ground was 42cm/s or approximately 2.5 body lengths per second. The most significant factors affecting the speed of locomotion were, in decreasing order of significance: hip compliance, rear leg angles, front leg angles, and stride period. These results emphasize the importance of properly tuning the impedance properties of the system. For running uphill the most significant parameters to vary, again in decreasing order of significance, were stride period, rear leg angles, and front leg angles. This agrees with the tests shown in Figure 9 and suggests the importance of adaptation of the basic feed-forward pattern to match changes in the environment.

On flat, even terrain, the robot is able to clear obstacles 3.5cm high corresponding to its ground clearance, or one "belly-height" (see Extension 9). As slope increases, the height of the maximum obstacles decreases. The ability to move across various ground conditions was also tested.

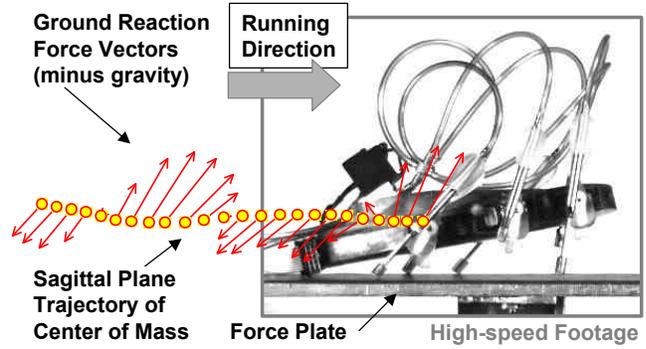


Figure 10. Apparatus for experiments: High-speed video and markers were used to track the robot's trajectory; a force plate measured ground reaction forces for both the whole body and for individual feet.

While the robot is capable of moving across different soils such as sand, foot design is important to prevent miring (see Extension 10).

## 5. Results: Locomotion Dynamics

As our prototype "Sprawlita" scurries across the floor and over obstacles, the combination of the "preflexes" and open-loop control scheme result in insect-like locomotion. However, a closer examination of the ground reaction forces and center-of-mass trajectories reveals some differences to the cockroach's locomotion. This section details experiments to compare the locomotion dynamics of Sprawlita to that of its exemplar, *Blaberus discoidalis*, in terms of two metrics commonly used in biomechanical studies: pendulum-like energy recovery and ground-reaction force patterns.

### 5.1 Basis for Comparison: Walking and Running Models of Animals

In animals there are very distinct patterns of force and motion when walking or running [Cavagna, 1975; Blickhan and Full, 1987]. During walking, the kinetic and potential energies of the center of mass fluctuate out of phase in a sinusoidal manner. Theoretically, the potential and kinetic energies can be exchanged via a pendulum-like energy recovery mechanism.

In contrast, running in animals is characterized by the kinetic energy and potential energy fluctuating in-phase, eliminating the possibility of pendulum-like energy exchanges. This type of motion can be characterized by what is called the spring loaded inverted pendulum (SLIP) model. This model also produces a characteristic set of ground reaction patterns, with the vertical force leading the horizontal force by a phase difference of 90 degrees [Cavagna, 1975].

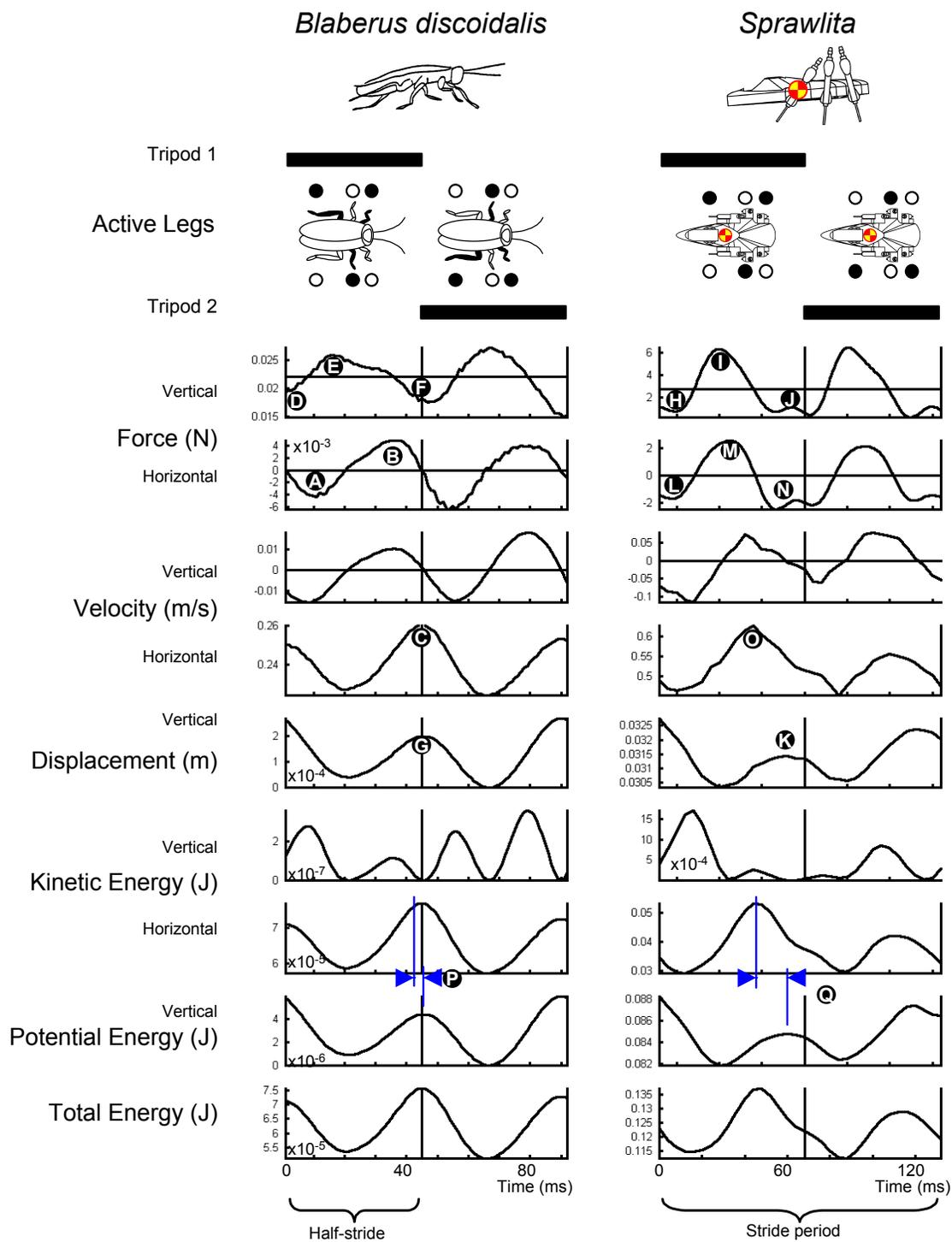


Figure 11. The results of force plate and high-speed video experiments described in Section 3 show certain differences in the locomotion of *Blaberus discoidalis* [Full and Tu, 1990] and *Sprawlita*. The respective amounts of pendulum-like energy recovery, calculated from the center-of-mass energetics, indicate that neither hexapod is “walking.” The respective ground reaction force plots show that the standard model of animal running, the spring-loaded inverted pendulum (SLIP) model, fits the cockroach and the robot well, with some differences due to foot dragging. Labels (A) - (Q) correspond to features discussed in Sections 5 and 6.

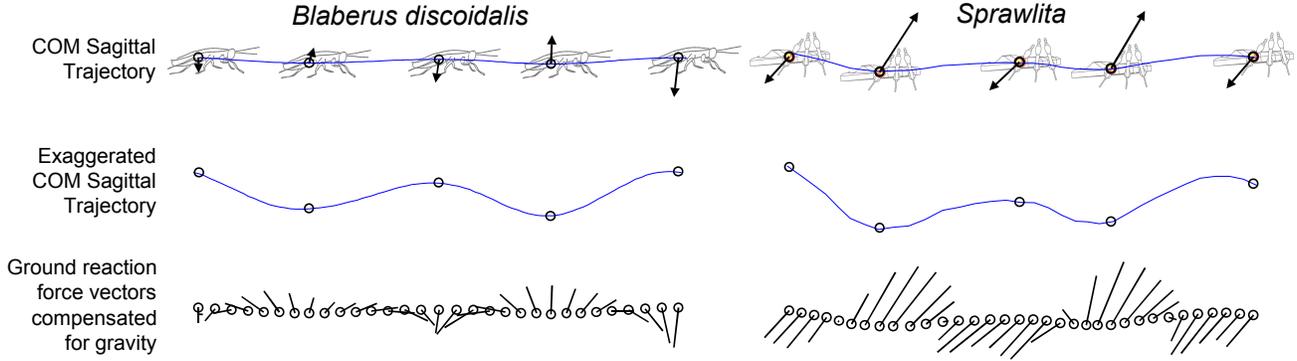


Figure 12. Ground reaction force vectors superimposed onto position data for an entire stride period. The vertical axis of the middle plot is exaggerated for detail. The ground reaction force vectors shown have been compensated for gravity by subtracting the weight of the robot from the vertical force measurement.

Ground reaction force patterns and pendulum-like energy recovery measures help qualitatively determine how much each basic mechanism of locomotion is utilized.

### 5.2 Equipment and Methods: Cockroach Measurements

Position, velocity and ground reaction force measurements for the *Blaberus discoidalis* cockroach (mean mass 0.0026kg) were obtained in [Full and Tu, 1991]. In summary, the cockroaches were run along a track with a force platform while a high-speed video system captured the locomotion at 60 frames/second. Kinetic and potential energy data were calculated by integrating the force signals. Stride beginnings and endings were determined by vertical ground reaction force patterns and verified using video information.

### 5.3 Equipment and Methods: Robot measurements

Sprawlita (mass 0.275kg) was run along a plywood surface, with reflective markers attached to nose, back, each leg, and each foot. A high-speed video system captured the locomotion at 250 frames per second. The force platform was a modified 6-axis force-sensitive robotic wrist. An aluminum plate covered with a thin rubber layer to prevent slippage, as shown in Figure 10, was attached to the force wrist and placed flush with the plywood surface. The natural frequency of the force plate was 143Hz. Forces were filtered by an analog 4th order Butterworth filter at 100Hz, and then sampled at 1000Hz and converted to a digital signal. Forces were then digitally filtered at 50Hz by a Butterworth filter with zero phase shift. The minimum resolution of the force plate is approximately 0.1N in the vertical and fore-aft directions.

Center of mass position data were calculated by tracking the reflective markers attached to the body. Velocity was calculated by taking the derivative of the position data. As

with the cockroach, stride beginnings and endings were determined by vertical ground reaction force patterns, and verified using video information.

### 5.4 Biomimetic Comparison: Pendulum-like Energy Recovery

As discussed previously, a significant amount of energy may be available for recovery during walking via a pendulum-like energy recovery mechanism. In animals, this mechanism is used extensively, as energy recovery values approach 70% in walking humans [Cavagna, 1975] and 50% in crabs [Blickhan and Full, 1987]. This measure can be calculated by:

$$\frac{(\Sigma HKE + \Sigma GPE) - \Sigma TE}{\Sigma HKE + \Sigma GPE} \times 100\%$$

Here,  $\Sigma HKE$  is the sum of the positive changes in horizontal kinetic energy during one stride,  $\Sigma GPE$  is the sum of the positive changes in gravitational potential energy during one stride, and  $\Sigma TE$  is the sum of the positive changes in the total mechanical energy of the center of mass during one stride. If there is only one peak in the given energy measure per stride, then the sum of the positive changes is simply the amplitude. In addition, vertical kinetic energy is typically excluded from these calculations as it is generally negligible in comparison to the other energies. Typical pendulum-like energy recovery is about 2% in running animals [Cavagna, 1975]. Thus, this metric is a quantitative indication of whether the observed locomotion is well represented by an inverted pendulum model, indicating walking dynamics.

The pendulum-like energy recovery values for a running cockroach are quite low, with a mean of 15.7%. This is a result of the kinetic energy leading the potential energy by only 7.6 degrees as shown in Figure 11 (P). While this is not

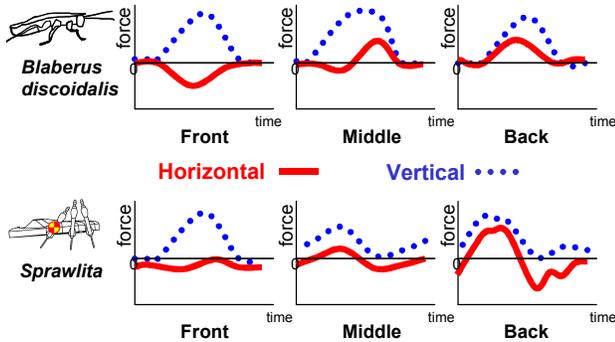


Figure 13. Plots of the individual leg ground reaction forces for *Blaberus discoidalis* [Full et al., 1991] and *Sprawlita*. As indicated, dragging occurs in the middle and rear legs of *Sprawlita* during locomotion. This and the relative lack of deceleration provided by the front legs account for differences in locomotion dynamics.

surprising for the animal during fast locomotion, it is interesting that even at one-quarter the maximum stride frequency (3Hz), the amount of pendulum-like energy recovery is low. At very low speeds, locomotion becomes intermittent, taking only a few quick strides at a time. Thus it seems that this animal actually prefers a running gait.

As shown in Figure 11 (Q), the phase difference between the kinetic and potential energies in our robot would seem to place its locomotion closer to the inverted pendulum model observed in walking animals than to the running model observed in the cockroach. Here, the kinetic energy leads the potential energy by approximately 60 degrees. However, the actual calculated value of pendulum-like energy recovery for *Sprawlita* is relatively low at 10.2%. This low value is due to the non-sinusoidal shapes of the energetics and the large difference between the magnitudes. Thus, like the cockroach, the robot does not exhibit the pendulum-like energy recovery associated with walking. However, there are still some dynamic differences which are evident in a comparison of ground reaction forces.

### 5.5 Biomimetic Comparison: Ground Reaction Forces

The ground reaction forces produced by *Blaberus discoidalis* are what one would expect for a running animal with bouncing dynamics. During the first part of a half-stride, the fore-aft horizontal force applies a braking force, slowing the body down as shown in (A) of Figure 11. As the half-stride progresses, the fore-aft force changes direction and an accelerating force is produced (B), causing the body to increase speed, with maximum horizontal velocity attained at the end of half-stride (C). In short, there is a clear brake-propel pattern over the course of each half-stride.

As shown in Figure 11, the vertical force pattern is just as distinctive. The vertical force is a minimum at the beginning of a half-stride (D) and increases to a maximum that occurs during in the middle of the half-stride (E). The vertical force then returns to the minimum by the end of the half-stride (F), resulting in a maximum vertical displacement as the cockroach switches from one tripod of legs to another (G). In short, the vertical force oscillates about the weight of the body in a minimum-maximum-minimum pattern over the course of the half-stride.

The aggregate of these fore-aft and vertical force patterns as shown in Figure 12 verify that the overall body motion of the cockroach is well characterized by the spring-loaded inverted pendulum model and is dynamically similar to other animals during running [Cavagna, 1975; Full and Farley, 2000].

As shown in Figure 11, the vertical force patterns generated by the robot are quite similar to the cockroach. At the beginning of the half-stride, the vertical force is a minimum (H), very close to zero. Midway through the half-stride, the vertical force peaks (I) and then decreases back towards the minimum by the end of the half-stride (J), resulting in a maximum displacement near the tripod switch (K). As with the cockroach, there is a clear minimum-maximum-minimum pattern over the half-stride.

The fore-aft horizontal forces, on the other hand, begin to show some dissimilarities. As in the cockroach, the fore-aft forces begin the half-stride at a minimum (L), decelerating the body, and increase to a maximum (M), accelerating the body. Considering only this portion of the half-stride, there is a brake-propel cycle in both the animal and the robot. However, the latter part of the half-stride shows a pattern of light vertical forces (J) and decelerating fore-aft forces (N), resulting in an early horizontal velocity peak (O). This difference in the horizontal forces explains the large phase difference between the kinetic and potential energies as discussed earlier.

Examination of the video data reveals that the robot assumes a “pseudo-flight” phase in which the middle and rear feet never quite leave the ground. Instead, they drag along in light contact, which accounts for the differing force patterns. The phenomenon is a result of the thrusting pistons reaching the end of their stroke before the stride is complete. At the same time, the torsional elements in the hips apply torques to the legs which keep the feet in contact with the ground.

### 5.6 Biomimetic Comparison: Individual Leg Ground Reaction Forces

There are many ways in which the SLIP model ground reaction force patterns can be produced by a system with multiple legs. In contrast to the Raibert approach of running

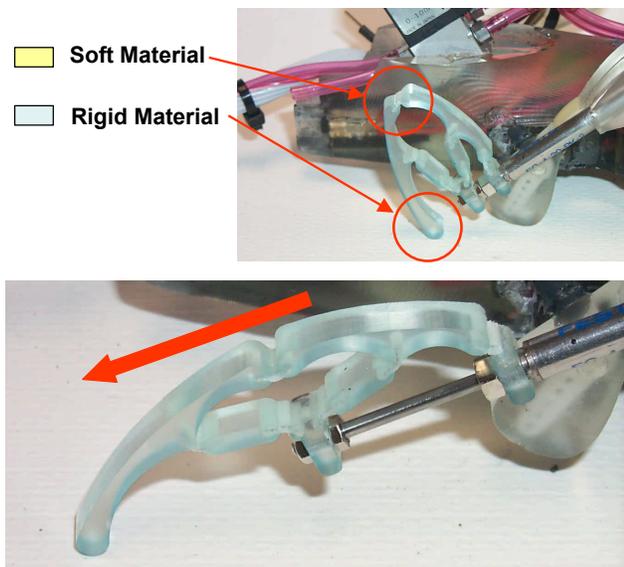


Figure 14. Multi-material prototype leg extension mechanism made from two materials: a rigid material for the links and a soft material (reinforced with polyester fibers) for the flexures. A comparable mechanism assembled from off-the-shelf components would be more cumbersome, fragile and difficult to fabricate (see Extension 11).

with symmetry [Raibert, 1986], each of the cockroach’s legs carries out very different functions in producing the SLIP-like behavior. While the vertical force patterns for individual limbs are similar, forces in the fore-aft direction are quite different. In general, the front legs decelerate, the rear legs accelerate, and the middle legs do both, as shown in Figure 13.

When we examine the plots in Figure 13, we see that there are some differences between the individual leg functions in the cockroach and the robot. While the rear legs accelerate during the first part of the half-stride, there is a negative fore-aft force during the latter part of the half-stride due to dragging. When we consider the middle leg force profile, we see that it is almost the opposite of the cockroach’s. The middle legs initially provide acceleration, and then deceleration. As shown, the front legs do not provide much deceleration.

## 6. Results: Discussion

Sprawlita has demonstrated the feasibility of small, sturdy, biomimetic robots that exploit passive properties in combination with an open-loop controller to achieve fast, stable locomotion over obstacles. As shown, this performance is highly dependent on the robot’s compliant elements and mechanical configuration, and underscores the

importance of SDM’s ability to tailor these passive properties.

While Sprawlita’s scurrying is insect-like, a comparison of the ground reaction forces reveals some differences to its exemplar, particularly in the horizontal direction. A closer inspection of the individual leg forces shows some differences to the cockroach in the behavior of the front, middle and rear legs. Instead of being decelerated primarily by the front and middle legs at the end of each stride, Sprawlita is partly decelerated by foot dragging in the rear legs. As a consequence, the robot does not display the typical phasing of horizontal and vertical forces associated with the SLIP model found in running animals. In essence, the rear legs are “running out of stroke length,” resulting in a pseudo-flight phase with dragging feet.

These observations suggest modifications for incorporation into the next generation of biomimetic hexapods. In particular, we can increase the stroke length of the middle, and especially the rear legs by embedding custom pistons with a longer stroke length or by fabricating a compliant SDM linkage that multiplies the pistons’ motion, such as the one shown in Figure 14. We anticipate that if we can prevent the pseudo-flight phase and foot dragging, the front and middle legs will be able to take on the role of compliantly decelerating the robot at the end of each stride, and a more elegant SLIP-like motion will be observed. Whether this motion will truly be faster or more robust remains to be verified, but given its ubiquity in running animals it is certainly worth investigating.

## 7. Conclusions and Future Work

At the moment, state-of-the-art legged robots, including ours, are not capable of much better performance than small wheeled vehicles with suspensions and treaded tires. Nonetheless, the advantages of legged systems are well established. Cockroaches are capable of faster speeds and traversal over more rugged terrain than any wheeled system of similar scale. The prototypes presented here begin to approximate that performance, and are faster, more robust and simpler than most previous legged robots. The success of these running hexapedal robots is based on design principles taken from biological studies of function in running animals.

These principles were made realizable in a robust manner through the use of Shape Deposition Manufacturing. The use of this technology allowed us to embed functional components and create visco-elastic flexures in structures without fasteners and connectors that are often the cause of failures due to stress concentrations. The use of traditional assembly-based manufacturing methods would have limited the robot’s performance and robustness.

The application of SDM in these prototypes represents a simple demonstration of the capabilities of the process. SDM allows roboticists to embed actuators and sensors in structures of arbitrary geometry, while tailoring the structures' passive properties. Future work in the area of SDM continues to explore the process' capabilities and to develop a design interface that allows roboticists that are new to the process to quickly generate and modify manufacturing plans [Clark et al, 2001]. Furthermore, we advocate that the use of SDM is not limited to robots whose design is directly inspired by biology. Rather, SDM can provide a solution in any robotic application where integration of the robot's structure and active components would improve its performance and robustness, especially at small scales. The relative advantages of the process for larger-scale mechanisms remain an open question.

Future work will also continue on the development of robust running robots. As shown, the simple open-loop control scheme is sufficient for straight-ahead running over smooth and uneven terrain. However, our results also show the need for adaptation. Different environmental conditions such as slope and texture require different sets of operational parameters for optimal traversal. Future work will focus on augmenting the current control structure to allow adaptation to changes in environment and task.

## Acknowledgements

The authors thank the members of the Berkeley PolyPEDAL lab and the Stanford CDR and RPL teams for their contributions to the work documented in this paper. In particular, we thank Kenneth Meijer, Mike Binnard, Roger Goldman and Motohide Hatanaka. Sean Bailey is supported by an NDSEG fellowship. This work was supported by the National Science Foundation under grant MIP9617994 and by the Office of Naval Research under N00014-98-1-0669.

## References

Anderson J M, Streitlien K, Barrett D S, Triantafyllou M S  
 "Oscillating foils of high propulsive efficiency." *J FluidMech.*360:41-72, 1998  
 Bailey, S. A., Cham, J. G., Cutkosky, M. R., and Full, R. J.,  
 "Biomimetic Mechanisms via Shape Deposition  
 Manufacturing," in *Robotics Research: the 9th  
 International Symposium*, J. Hollerbach and D.  
 Koditschek (Eds), Springer-Verlag, London, 1999.  
 Bares, John E. and Wettergreen, D. S. "Dante II: technical  
 description, results, and lessons learned" *International  
 Journal of Robotics Research* v 18 n 7 p 621-649, 1999.  
 Binnard, M. and Cutkosky, M. R., "A Design by  
 Composition Approach for Layered Manufacturing"  
*ASME Transactions, J. Mech. Design*, vol. 122, no. 1,  
 March 2 p. 91-101, 2000.

Blickhan, R., and Full, R.J., "Locomotion energetics of the  
 ghost crab. II. Mechanics of the centre of mass during  
 running and walking," *J. exp. Biol.*, 130, 155-174, 1987.  
 Box, G. and Bisgaard, S., *Statistical tools for improving  
 designs. Mechanical Engineering Magazine*, 110(1):32-  
 40, January 1988.  
 Brown, I.E. and Loeb, G.E., "A reductionist approach to  
 creating and using neuromusculoskeletal models." In  
*Biomechanics and Neural Control of Posture and  
 Movement*. (Eds. Winters, J. M. and Crago. P. E.), 1999.  
 Buehler, M., Saranli, U., Papadopoulos, D., and Koditschek,  
 D. E., "Dynamic locomotion with four and six-legged  
 robots," *International Symposium on Adaptive Motion of  
 Animals and Machines*, Montreal, Canada, August, 2000.  
 Cavagna, G. A., Heglund, N. C., and Taylor, C. R.,  
 "Walking, Running, and Galloping: Mechanical  
 Similarities between Different Animals," *Scale Effects in  
 Animal Locomotion, Proceedings of an International  
 Symposium*, T. J. Pedley (Ed.), 111-125, Academic Press,  
 New York, USA, 1975.  
 Cham, J. G., Karpick, J., Clark, J. E., and Cutkosky, M. R.,  
 "Stride Period Adaptation for a Biomimetic Running  
 Hexapod," *10th International Symposium of Robotics  
 Research*, Lorne, Victoria, Australia, November 9-12,  
 2001  
 Cham, J. G., Bailey, S. A., and Cutkosky, M. R., "Robust  
 Dynamic Locomotion Through Feedforward-Preflex  
 Interaction," *ASME IMECE Proceedings*, Orlando,  
 Florida, November 5-10, 2000  
 Cham, J. G., Pruitt, B. L., Cutkosky, M. R., Binnard, M.,  
 Weiss, L. E., Neplotnik, G., "Layered Manufacturing with  
 Embedded Components: Process Planning Issues," *ASME  
 Proceedings, DETC '99*, Las Vegas, Nevada, September  
 12-15, 1999.  
 Clark, J., Xia, L. and Cutkosky, M. R., "An interactive aid  
 for designing and planning heterogeneous layered  
 prototypes," To be published in *ASME Proc., DETC 2001*,  
 Pittsburgh, PA, 2001.  
 Full, R. J. and Meijer, K., "Artificial muscles versus natural  
 actuators from frogs to flies," In *Smart Structures and  
 Materials 2000: Electroactive Polymer Actuators and  
 Devices (EAPAD)* (ed. Yoseph Bar-Cohen). *Proc. SPIE*  
 Vol. 3987, p. 2-9, 2000.  
 Full, R. J., and Tu, M. S., "Mechanics of a Rapid Running  
 Insect: Two-, Four-, and Six-legged Locomotion," *Journal  
 of Experimental Biology*, 156, 215-231, 1991.  
 Full, R. J., and Tu, M. S., "Mechanics of Six-legged  
 Runners," *J. Exp. Bio.*, 148, 129-146, 1990.  
 Full, R. J., Autumn, K., Chung, J. I., Ahn, A., "Rapid  
 negotiation of rough terrain by the death-head cockroach,"  
*American Zoologist*, 38:81A, 1998.  
 Full, R. J., Blickhan, R. and Ting, L. H., "Leg design in  
 hexapodal runners" *J. exp. Biol.* 158, 369-390, 1991.

- Full, R.J. and Farley, C. T., "Musculoskeletal dynamics in rhythmic systems - a comparative approach to legged locomotion," in *Biomechanics and Neural Control of Posture and Movement*, J. M. Winters and P. E. Crago (Eds.), Springer-Verlag, New York, 2000.
- Full, R.J., Koditschek, D. E., "Templates and Anchors - Neuromechanical hypotheses of legged locomotion on land." In *Designs for Life. The Journal of Experimental Biology*. In press.
- Garcia, M., Kuo, A., Peattie, A. M., Wang, P. C. and Full, R. J., "Damping and Size: Insights and Biological Inspiration" in *Proc. of the Intl. Symp. on Adaptive Motion of Animals and Machines*, Montreal, Canada, August 2000.
- Hogan, N. *Impedance Control: An Approach to Manipulation: Part I-Theory*. *Journal of Dynamic Syst., Measure, and Cont.*, 107(1):1-7, 1985a.
- Jindrich, D.L. and Full, R.J. Many-legged maneuverability: dynamics of turning in hexapods. *J. exp Bio.* 202, 1603-1623, 1999.
- Kubow, T.M., Full, R.J., "The role of the mechanical system in control: A hypothesis of self-stabilization in hexapedal runners." *Phil. Trans. Roy. Soc. London B.* 354, 849-862, 1999.
- Kumar, V. and Waldron, K., "Force Distribution in Walking vehicles," *ASME Transactions, Journal of Mechanical Design*, Vol. 112, pp. 90-99, March 1990.
- McGeer, T., "Passive dynamic walking," *IJRR*, Volume 9, 62-82, April 1990.
- McMahon, T. A., "Muscles, Reflexes and Locomotion" University Press, Princeton NJ.
- Meijer, K. and Full R. J., "Stabilizing properties of the coxa-femur extensor muscles of the cockroach (*Blaberus Discoidalis*). *Society of Experimental Biology*, Exeter, England, 2000.
- Meijer, K., Full, R. J., "Stabilizing properties of invertebrate skeletal muscle," *American Zoologist*, Volume 39, Number 5, 117A, 1999.
- Merz, R., Prinz, F.B., Ramaswami, K., Terk, M., Weiss, L., "Shape Deposition Manufacturing," *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, August 8-10, 1994.
- Nelson, G. M., Quinn, R. D., Bachmann, R. J., Flannigan, W. C., Ritzmann, R. E., and Watson, J. T., "Design and Simulation of a Cockroach-like Hexapod Robot," *Proceedings of the 1997 IEEE International Conference on Robotics and Automation*, Albuquerque, NM, 1106-1111, 1997.
- Raibert, M. H., "Legged robots that balance." MIT Press, Cambridge, MA, 1986.
- Ringrose, R., "Self-stabilizing running," *IEEE ICRA Proceedings*, Albuquerque, NM, 1997.
- Ritzman, R. E., Quinn, R. D., Watson, J. T. and Zill, S. N., "Insect Walking and Biorobotics: A Relationship with Mutual Benefits" January / Vol. 50 No. 1 of *BioScience* 23-33, 2000.
- Schmitt, J. and Holmes, P., "Mechanical models for insect locomotion: dynamics and stability in the horizontal plane I, Theory," *Biol. Cybern.* 83, 501-515, 2000a.
- Schmitt, J. and Holmes, P., "Mechanical models for insect locomotion: dynamics and stability in the horizontal plane II, Application," *Biol. Cybern.* 83, 517-527, 2000b.
- Ting, L.H., Blickhan, R. and Full, R.J. Dynamic and static stability in hexapedal runners. *J. exp Bio.* 197, 251-269, 1994.
- van Soest, A. J., Bobbert, M. F., "The contribution of muscle properties in the control of explosive movements" in *Biol. Cybernetics* 69: 195-204, 1993
- Vogel, S. "Better bent than broken" *Discover*, p62 - 65, May 1995.
- Waldron, KJ "Force motion management in legged locomotion." *IEEE Trans on Robotics and Automation.* 2 (4): 214-220, 1986.
- Xu, X., Cheng, W., Dudek, D., Hatanaka, M., Cutkosky, M. R., and Full, R. J., "Material Modeling for Shape Deposition Manufacturing of Biomimetic Components," *ASME Proceedings of DETC/DFM 2000*, Baltimore, Maryland, September 10-14, 2000.
- Yan, J., Wood, R. J., Avadhanula, S., Sitti, M. and Fearing, R. S., "Towards Flapping Wing Control of a Micromechanical Flying Insect", *IEEE ICRA*, Seoul Korea, 2000.

## Appendix: Index to Multimedia Extensions

The multi-media extensions to this article can be found online by following the hyperlinks from [www.ijrr.org](http://www.ijrr.org).

**Table 1: Multimedia Extensions**

Extension	Media Type	Description
1	video	Video showing the first prototype of the "Sprawl" family of hexapedal robots (July 1999).
2	video	Video showing the second prototype of the "Sprawl" family of hexapedal robots (built October 1999).
3	video	Video showing "Sprawlita," the third prototype of the "Sprawl" family of hexapedal robots (built January 2000). Ground speed on flat terrain exceeds 80cm/s or approximately 5 body-lengths per second.

**Table 1: Multimedia Extensions**

Extension	Media Type	Description
4	video	Video showing the basic design of "Sprawlita." Hip servos and wiring and leg pistons are embedded in the structure of the robot. Viscoelastic flexures integrated into the leg structures provide a passive degree-of-freedom at the hip. Pneumatic pistons provide the leg's thrusting action, which is controlled open-loop via a fixed activation pattern.
5	video	Video showing a sample cycle of Shape Deposition Manufacturing (SDM). In the example, a pneumatic piston, valves, pressure sensor and amplifier circuit and internal passageways are embedded in the structure of a prototype linkage. For more information on SDM, please go to <a href="http://cdr.stanford.edu/biomimetics">http://cdr.stanford.edu/biomimetics</a> .
6	video	Video showing a sample sequence for creating a multi-material spatial four-bar linkage. Hard and soft material is alternately deposited and machined to create a linkage with integrated flexures.
7	video	Video showing "Sprawlita" running despite large disturbances. This disturbance rejection is accomplished without sensory feedback through the robot's passive properties and open-loop control.
8	video	Video showing a sample high-speed movie of "Sprawlita" running (shown at 1/10 normal speed).
9	video	Video showing "Sprawlita" overcoming hip-height obstacles.
10	video	Video showing "Sprawlita" running outdoors, using only a small air hose tether.
11	video	Video showing a prototype mechanism for extending the stroke length of the robot's hind legs. Assembling this mechanism using conventional off-the-shelf components results in a linkage with numerous small parts that work themselves loose over time. An alternative mechanism that uses the ability of SDM to create parts of rigid material integrated with flexures of visco-elastic material is more compact and robust.