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Fast and Robust: Hexapedal Robots via Shape Deposition Manufacturing

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 four body-lengths per second) and robust (traversal over hip-height obstacles) performance begins to compare to that seen in nature. We describe the design and fabrication of the robots and we present the results of experiments that focus on their performance and locomotion dynamics.

KEY WORDS—biomimetic robots, locomotion, shape deposition manufacturing

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1. Introduction

1.1. 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.

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 design of the robots. 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 and disturbance rejection (van Soest and Bobbert 1993; Brown and Loeb 2000).

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.

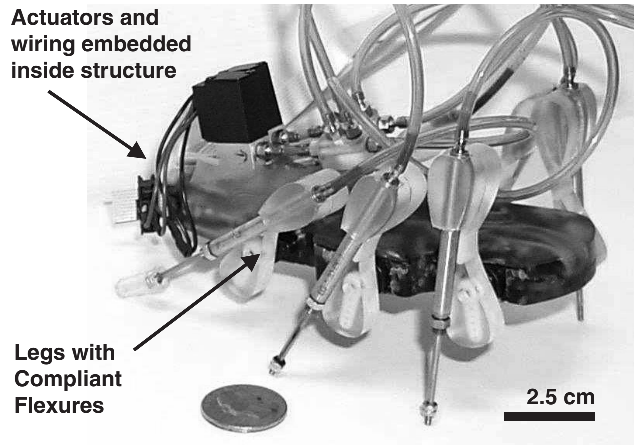

Fig. 1. Sprawlita, a dynamically-stable running hexapod based on functional principles derived from biomechanical studies of the cockroach. The original prototype is capable of running at 3.5 body-lengths per second.

1.2. 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 viscoelastic 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, Heglund, and Taylor 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 four 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. Parts of the work in this paper have been reported previously in Clark et al. (2001) and Bailey et al. (2000).

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 and Wettergreen 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, the bouncing robots of Raibert (1986) 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 viscoelastic structural elements;
4. timed, open-loop/feedforward control;
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).

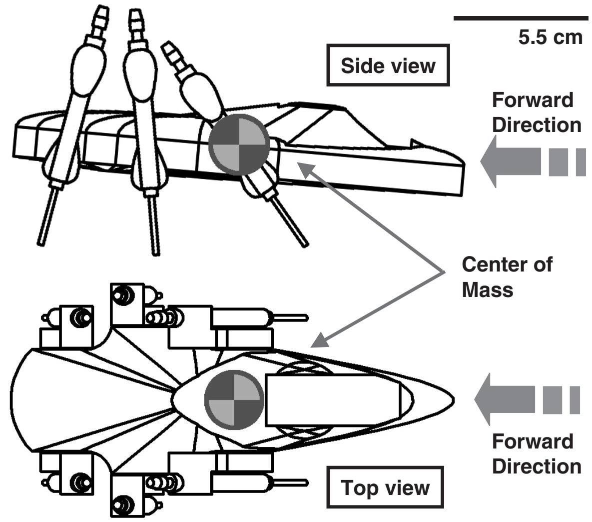

Fig. 2. Self-stabilizing posture: a rear and low center of mass and a wide base of support contribute to the overall stability of locomotion.

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, Blickham, and Full 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 and Holmes 2000a, 2000b).

Our first-generation prototype robot, approximately 16 cm 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 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, Blickham, and Ting 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 decelerate during the stride. The creation of large internal forces may be inefficient for smooth, steady-state running, but there is evidence that 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 viscoelastic material that allows rotation mainly in the sagittal plane, as shown in Figure 3.

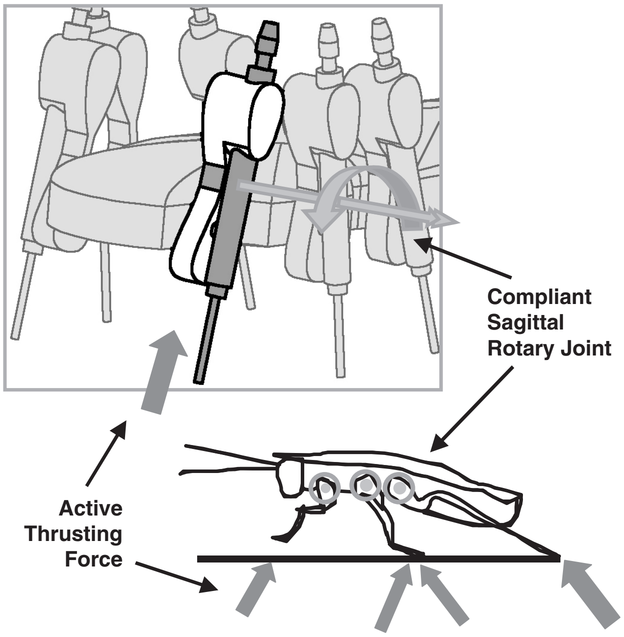

Fig. 3. Studies of the cockroach's locomotion show that ground reaction forces are directed towards the hip joints, indicating that the legs essentially act as thrusters. In addition, each leg performs a different function: front legs act as decelerators while hind legs act as accelerators; middle legs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

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 Viscoelastic 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 1999, 2000). This viscoelasticity resides not only in the limb 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.

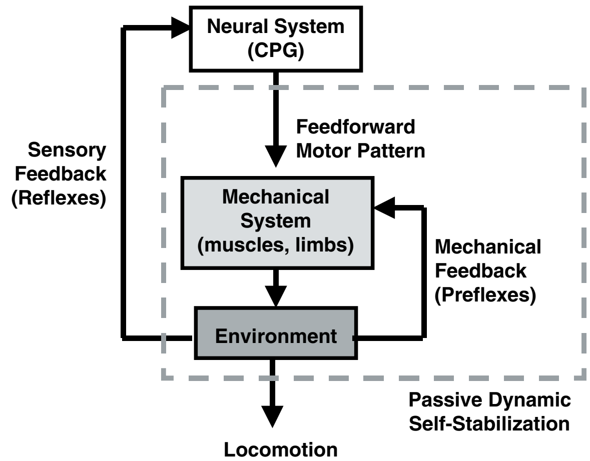

Fig. 4. Suggested roles of a feed-forward motor pattern, preflexes and sensory feedback. Here, disturbance rejection is the result of the mechanical system and not an active neural control loop. Adapted from Full and Koditschek (1999).

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 viscoelastic 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, Bailey, and Cutkosky 2000; Ringrose 1997). Sensory information is then used to modify 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 three-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.

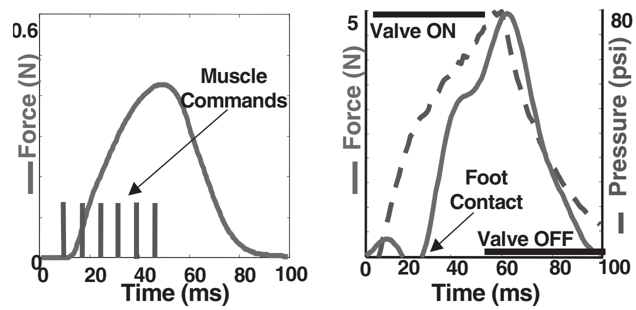

Fig. 5. A comparison of isometric muscle force output (Full and Meijer 2000) in response to motor commands and pneumatic piston force output in response to solenoid valve input on Sprawlita.

3. Fabrication of Biomimetic Structures

The preflexes, 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. Secondly, 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. In this section, we describe a manufacturing process that circumvents these problems and makes practical the application of nature's design lessons in our prototype robots.

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) and Binnard and Cutkosky (2000).

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 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).

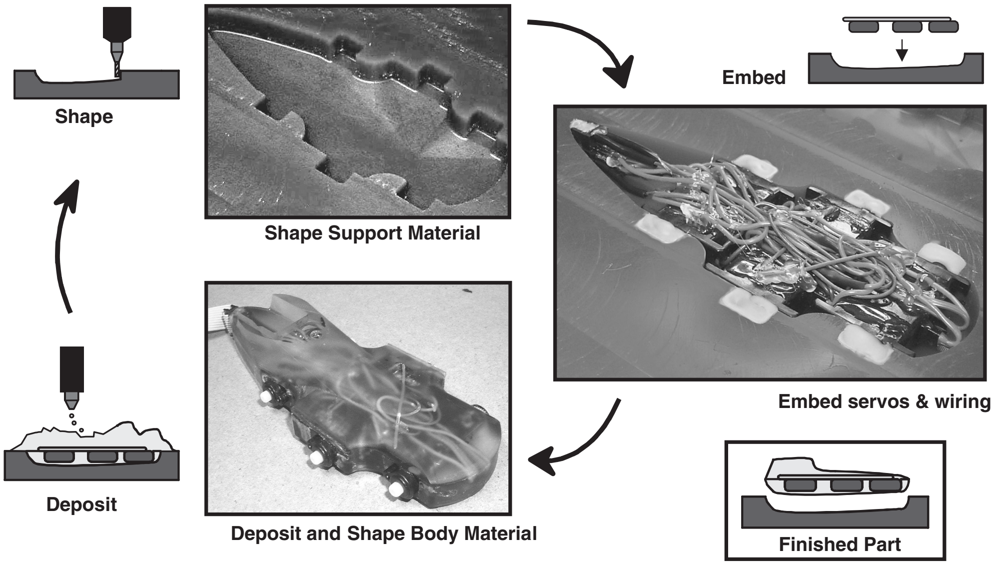

Fig. 6. SDM consists of alternating cycles of material deposition and shaping. The hexapod's servos and wiring were embedded inside the structure of the body. As shown in the figure, they were first placed in a shaped geometry of support material and then encased by depositing material in the following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

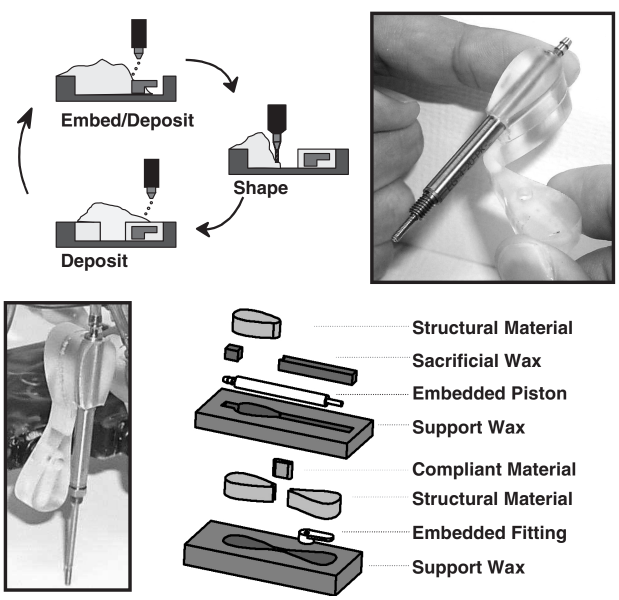

Fig. 7. Process plan for the robot legs. The figure shows the alternating layers of hard and soft material and embedded components used to make the compliant legs.

4. Results: Performance Testing

In this section we present the results of velocity tests and we discuss 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 per second (see Extensions 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.

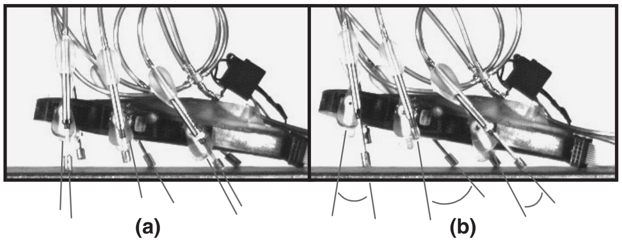

Fig. 8. High-speed footage of the running robot in (a) mid-stance and (b) full extension. As shown, the compliance in the legs plays an important role in the locomotion, as evidenced by the large deflections during the stride.

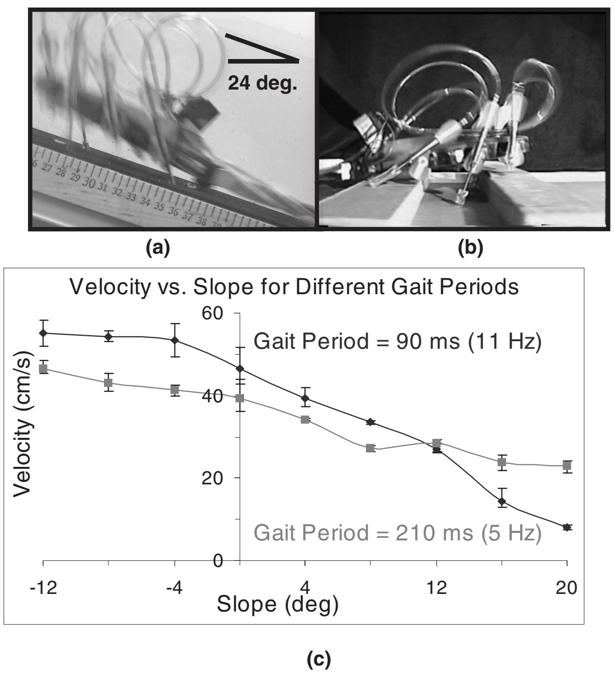

Fig. 9. Performance test results. The prototype is capable of surmounting (a) uphill slopes of up to 24 degrees and (b) hip-height obstacles. (c) Tests over different slopes indicate the need to adapt the variables of locomotion to environmental conditions.

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 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 experimental conditions, the maximum speed on smooth level ground was 42 cm/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 feedforward pattern to match changes in the environment.

On flat, even terrain, the robot is able to clear obstacles 3.5 cm high corresponding to its ground clearance, or one "belly-height" (see Extension 9). As the slope increases, the height of the maximum obstacles decreases. The ability to move across various ground conditions was also tested. 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. In this section we detail 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, Heglund, and Taylor 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 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, Heglund, and Taylor 1975).

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 0.0026 kg) 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 per 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 0.275 kg) 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 six-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 143 Hz. Forces were filtered by an analog fourth-order Butterworth filter at 100 Hz, and then sampled at 1000 Hz and converted to a digital signal. Forces were then digitally filtered at 50 Hz by a Butterworth filter with zero phase shift. The minimum resolution of the force plate is approximately 0.1 N 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, Heglund, and Taylor 1975) and 50% in crabs (Blickhan and Full 1987). This measure can be calculated by

$$\frac{(\Sigma \mathrm{HKE} + \Sigma \mathrm{GPE} - \Sigma \mathrm{TE})}{\Sigma \mathrm{HKE} + \Sigma \mathrm{GPE}} \times 100\%. \qquad (1)$$

Here, ΣHKE is the sum of the positive changes in horizontal kinetic energy during one stride, ΣGPE is the sum of the positive changes in gravitational potential energy during one stride, and ΣTE 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, Heglund, and Taylor 1975). Thus, this metric is a quantitative indication of whether the observed locomotion is well represented by an inverted pendulum model, indicating walking dynamics.

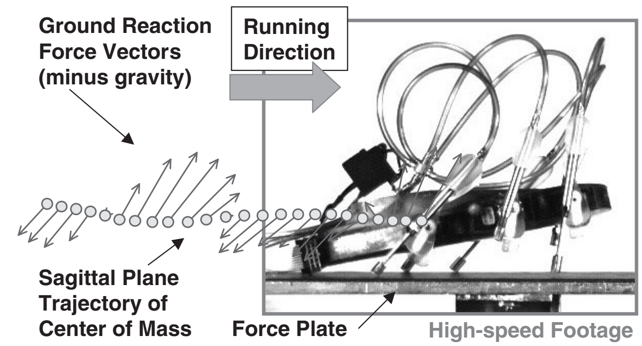

Fig. 10. Apparatus for experiments: high-speed video and markers were used to track the robot's trajectory; a force plate measured ground reaction forces for both the whole body and for individual feet.

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 surprising for the animal during fast locomotion, it is interesting that even at one-quarter the maximum stride frequency (3 Hz), 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 we 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

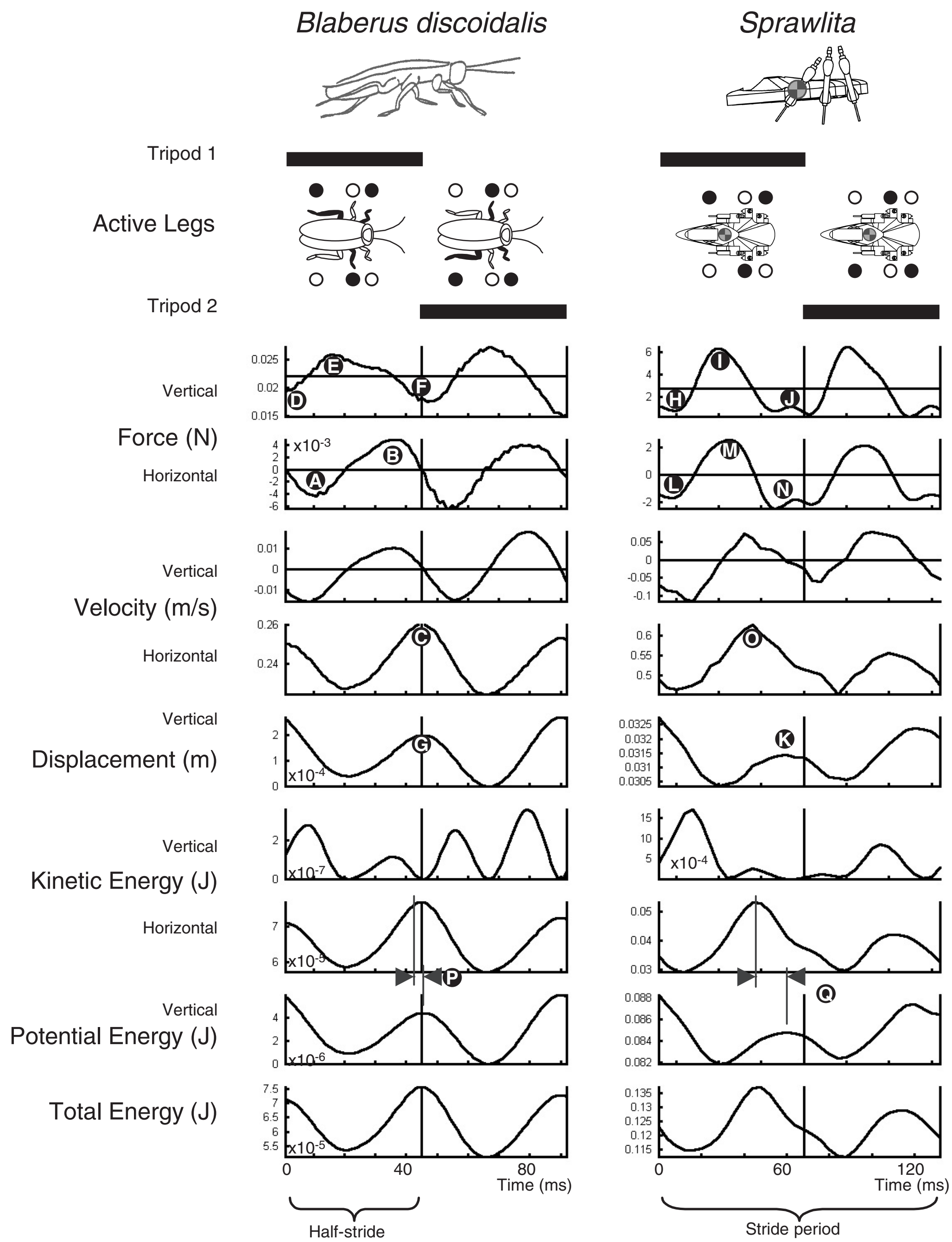

Fig. 11. The results of force plate and high-speed video experiments described in Section 5 show certain differences in the locomotion of *Blaberus discoidalis* (Full and Tu 1990) and Sprawlita. The respective amounts of pendulum-like energy recovery, calculated from the center-of-mass energetics, indicate that neither hexapod is "walking." The respective ground reaction force plots show that the standard model of animal running, the 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.

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 SLIP model and is dynamically similar to other animals during running (Cavagna, Heglund, and Taylor 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 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 piston motion, such as that 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.

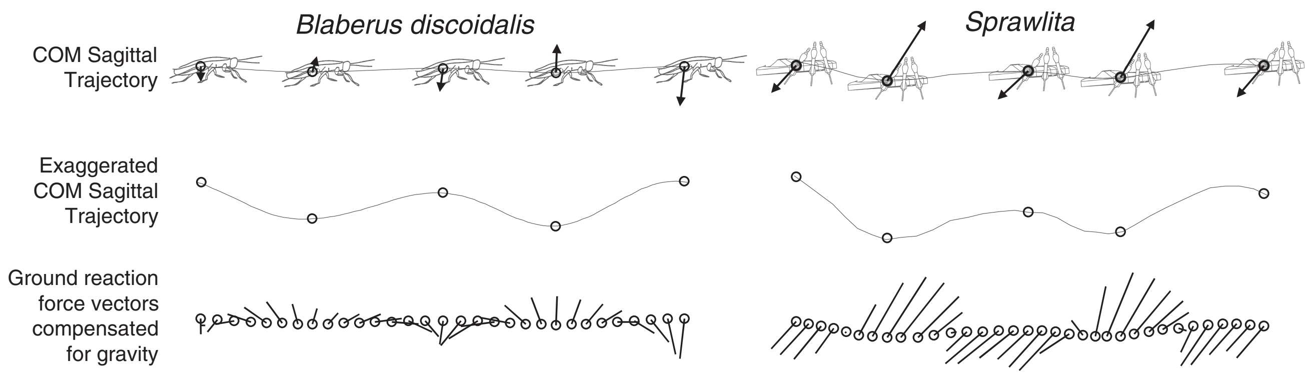

Fig. 12. Ground reaction force vectors superimposed onto position data for an entire stride period. The vertical axis of the middle plot is exaggerated for detail. The ground reaction force vectors shown have been compensated for gravity by subtracting the weight of the robot from the vertical force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

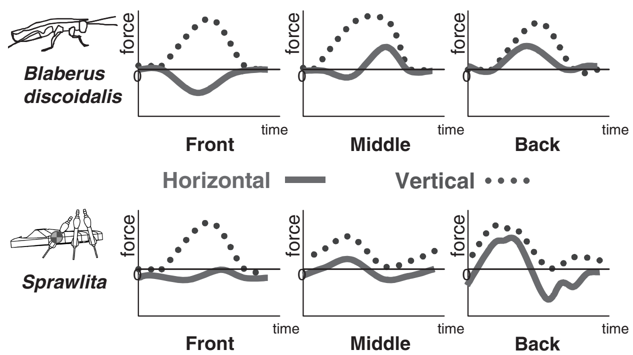

Fig. 13. Plots of the individual leg ground reaction forces for *Blaberus discoidalis* (Full et al. 1991) and Sprawlita. As indicated, dragging occurs in the middle and rear legs of Sprawlita during locomotion. This and the relative lack of deceleration provided by the front legs account for differences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

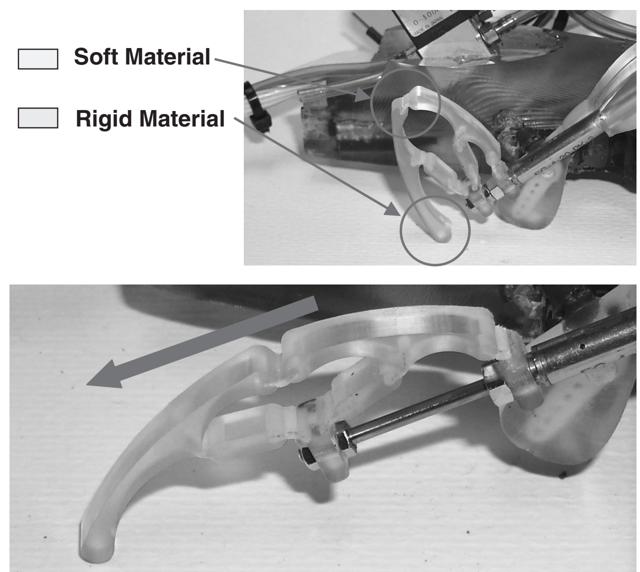

Fig. 14. Multi-material prototype leg extension mechanism made from two materials: a rigid material for the links and a soft material (reinforced with polyester fibers) for the flexures. A comparable mechanism assembled from off-the-shelf components would be more cumbersome, fragile and difficult to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

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 SDM. The use of this technology allowed us to embed functional components and create viscoelastic 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 capabilities of the process and to develop a design interface that allows roboticists that are new to the process to quickly generate and modify manufacturing plans (Clark, Xia, and Cutkosky 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.

Appendix: Index to Multimedia Extensions

The multimedia extensions to this article can be found online by following the hyperlinks from www.ijrr.org.

Table of Multimedia Extensions

Extension	Type	Description
1	Video	The first prototype of the "Sprawl" family of hexapedal robots (July 1999).
2	Video	The second prototype of the "Sprawl" family of hexapedal robots (built October 1999).
3	Video	Sprawlita, the third prototype of the "Sprawl" family of hexapedal robots (built January 2000). Ground speed on flat terrain exceeds 80 cm/s or approximately five body-lengths per second.
4	Video	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	A sample cycle of 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 http://cdr.stanford.edu/biomimetics.
6	Video	A sample sequence for creating a multimaterial spatial four-bar linkage. Hard and soft material is alternately deposited and machined to create a linkage with integrated flexures.
7	Video	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	A sample high-speed movie of Sprawlita running (shown at 1/10 normal speed).
9	Video	Sprawlita overcoming hip-height obstacles.
10	Video	Sprawlita running outdoors, using only a small air hose tether.
11	Video	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 created parts of rigid material integrated with flexures of viscoelastic material is more compact and robust.

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