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Biomimetic Design and Fabrication of a Hexapedal Running Robot

Jonathan E. Clark[1], Jorge G. Cham[1], Sean A. Bailey[1], Edward M. Froehlich[1], Pratik K. Nahata[1], Robert J. Full[2], Mark R. Cutkosky[1]

[1]Center for Design Research, Stanford University, Stanford, California 94305-2232
[2]Dept. of Integrative Biology, University of California at Berkeley, Berkeley, California 94720
clarkj@cdr.stanford.edu; http://www-cdr.stanford.edu/biomimetics

ABSTRACT

The design of legged robots has long drawn on nature for inspiration. However, few of these robots exhibit the speed and robustness seen in even the simplest of animals. This paper presents the design and fabrication of a novel class of six-legged running robots based on biologically-inspired functional principles. We first describe recent findings in biological research that motivate our robots' design, leg configuration, and control structure. We then describe an emerging layered-manufacturing technology that allows us to fabricate the robots with passive mechanical properties like those found in nature. Finally, we present preliminary tests over different terrains and conditions which show speed and robustness approaching the performance of small animals.

1. INTRODUCTION

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). Indeed, the speed and versatility of legged animals when traversing over uncertain terrain provide a daunting precedent from which to draw inspiration. This bio-mimicry has taken several forms over the years. The most common instance 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 pioneering work (Raibert, 1986) made use of symmetry in running for the design of bouncing monopods. More recently, RHex (Buehler et al, 2000) a prototype built on biological principles similar to the ones described here also demonstrates the possibility of simple, robust dynamic running machines. These approaches have imitated, in varying degrees, observed animal behavior and animal morphology.

We argue that, in looking at biology for design inspiration, the fundamental principles of effective animal locomotion should be distilled and then appropriately applied to the robots' design. It is impractical to attempt a direct mapping between morphologies, actuators or control schemes since the tools biology uses to build systems are fundamentally different than those used by engineers. Furthermore, the requirements of biological systems include many tasks such as growth, reproduction, and respiration which may not be germane to robot design.

This paper outlines some principles of locomotion taken from the study of small invertebrates, especially cockroaches. We describe their application in the creation of a new class of running robots for fast robust locomotion through uneven and uncertain terrain. We then discuss the fabrication of a prototype robot using a manufacturing process that allows many of these principles to be integrated into the structure of the robot itself, much like the biological systems that inspired it (Figure 1). Finally, we present initial experimental results and conclusions.

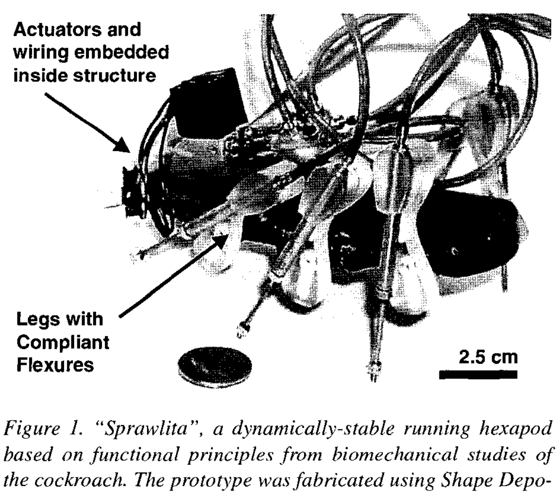

Figure 1. "Sprawlita", a dynamically-stable running hexapod based on functional principles from biomechanical studies of the cockroach. The prototype was fabricated using Shape Deposition Manufacturing and is capable of speeds of approximately 3 body-lengths per second.

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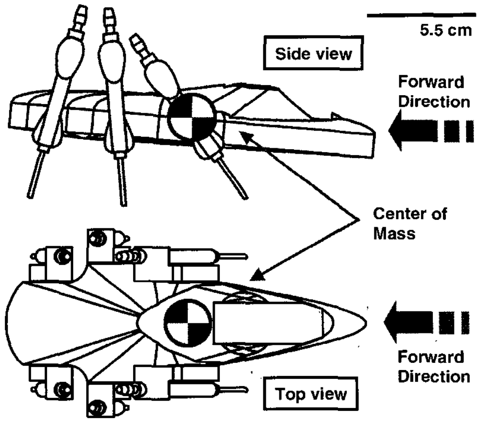

Figure 2. Self-stabilizing posture: A rear and low center of mass and wide base of support contribute to the over-all stability of locomotion.

2. DESIGN INSPIRATION FROM BIOLOGY

For the task of quick and robust traversal over uneven and uncertain terrain, we draw design inspiration from small arthropods. In particular, cockroaches are capable of remarkable speed and stability. For example, it has been shown that *Periplaneta americana* can achieve speeds of up to 50 body-lengths per second (Full and Tu, 1991). *Blaberus discoidalis* is capable of traversing uneven terrain with obstacles of 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 structure
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.

2.1 Self-stabilizing Posture

A sprawled hexapedal posture has many obvious advantages. As utilized by most six-legged walking robots, maintaining the center of mass within the support polygon formed by the feet of at least three rigid legs ensures static stability. The use of this approach, however, has limited many of these robots to very slow, near-static speeds.

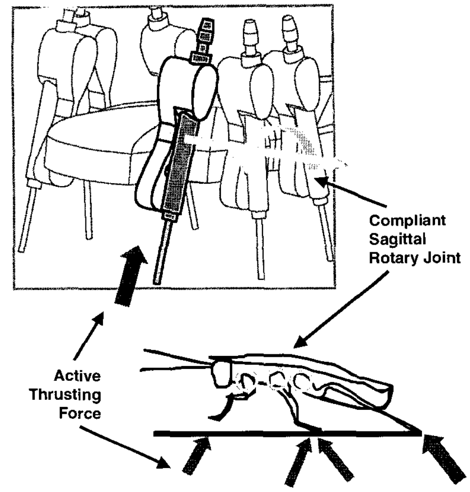

Figure 3. Leg Function: Studies of ground reaction forces in cockroach locomotion show that forces are directed towards the hip joints, essentially acting as thrusters. In addition, each leg performs a different function: front legs act as decelerators while hind legs act as accelerators; middle legs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

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. Their studies suggest that 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.

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 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). Furthermore, 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 wide 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 this contributes to dynamic robustness to perturbations (Kubow and Full, 1999) and to 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. This 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 prototype, the compliant hip joint 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. Servo motors rotate the base of the hip 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

The advantages of low impedance, or compliance, for interaction with an unknown environment have long been recognized (Hogan, 1985). A popular approach, even in locomoting robots, has been active impedance control of rigidly-built robot appendages. Even with active control, the high transient forces due to impacts involving stiff links cannot be precluded because of limitations in servo bandwidth.

Instead, animals are commonly anything but rigid. In particular, studies of the cockroach *Blaberus discoidalis* are revealing the role of the viscoelastic properties of its muscles and exoskeleton in locomotion (Garcia et al., 2000; Meijer and Full, 2000; Xu et al., 2000).

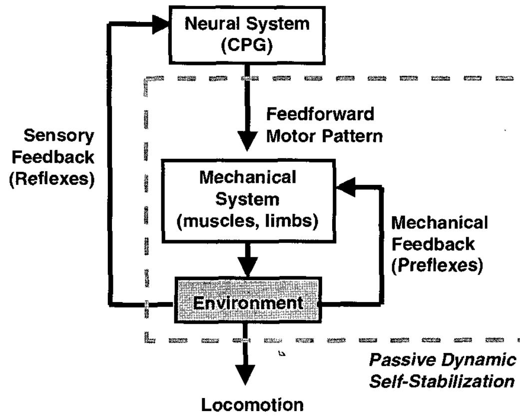

Figure 4. Suggested roles of a feedforward motor pattern, preflexes and sensory feedback. Here, disturbance rejection is the result of the mechanical system and not an active neural control loop. Adapted from (Full and Koditschek, 1999).

Our prototype's leg design contains a passive compliant and damped rotary hip joint fabricated as a flexure of soft viscoelastic polymer urethane embedded in a leg structure of stiffer plastic. This is an initial attempt at integrating desired impedance properties passively through 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/Feed-forward 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 during running over uneven terrain suggest that these preflexes play a dominant role in the task of locomotion. For example, it has been shown that 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, period, or 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"

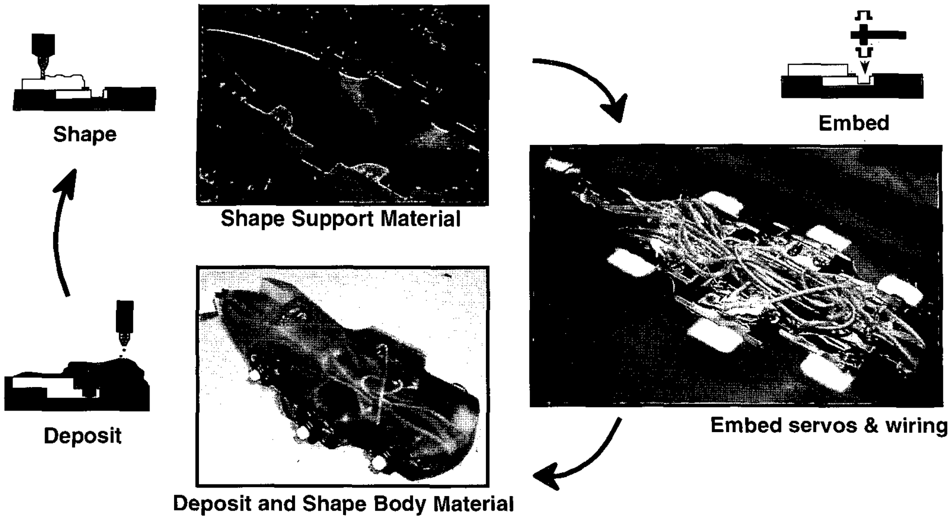

Figure 5. Shape Deposition Manufacturing (SDM) consists of alternating cycles of material deposition and shaping. The hexapod's servos and wiring were embedded inside the structure of the body. As shown in the figure, they were first placed in the shaped geometry of the previous step, and then encased by depositing material in the next step.

that is sufficient to maintain stability in the face of sudden perturbations or terrain changes (Cham et al., 2000). 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 location of feet touchdown locations (Jindrich and Full, 1999).

Our robot is controlled by alternately activating each of the leg tripods, where a leg tripod is made up 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. These valves are operated at a frequency and duration determined respectively by the stride period and duty cycle.

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 relative nominal angles of each hip. In a later section, we will see the performance of this simple control scheme, and the effects of changing this feedforward pattern.

2.5 Integrated Construction

We argue that biomimetic design must also be accompanied by biomimetic fabrication (Bailey et al., 1999). A common mode of failure for today's robots lies in the numerous fasteners and fittings that hold them together. This is especially problematic in smaller robots, where much of the design space is dominated by fasteners. Fundamentally, a mechanism designed to be assembled can also disassemble itself.

Nature, on the other hand, composes its designs in a different manner. Actuators, sensors and structural members are compactly packaged in an integrated fashion and protected from the environment. In addition, nature's compliant materials are capable of large strains without failure (Vogel, 1995). Material properties are also varied to meet local loading requirements. For example, bone is hard and dense at the joints but porous in between.

Of course, we may never be able to achieve the complexity and elegance of biological structures. However, the emerging manufacturing technology adopted to fabricate our prototype robos does allow us to build integrated assemblies with embedded components and material variations. This yields a structure that is rugged enough to withstand the collisions and falls that are inevitable in running through an unstructured environment. The following section describes the manufacturing process and how it was used to implement the "preflexes" described above.

3. BIOMIMETIC FABRICATION

Shape Deposition Manufacturing (SDM) is a layered prototyping method where parts or assemblies are built up through a cycle of alternating layers of structural and support material. After a layer of material is added, it is then shaped to a precise contour before the next layer is added. The intermittent addition of support material allows for the construction of nearly arbitrary geometries. Unlike many other layered processes, the material is shaped after it is added. This allows for high precision features and avoids

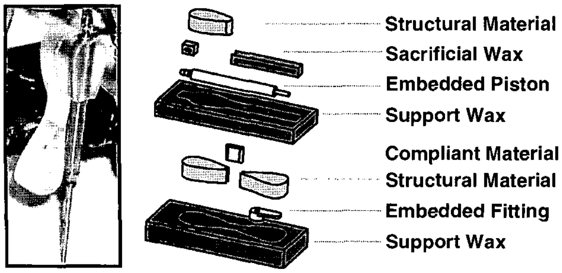

Figure 6 - Process plan for the robot legs. The figure shows the alternating layers of hard and soft material and embedded components used to make the compliant legs.

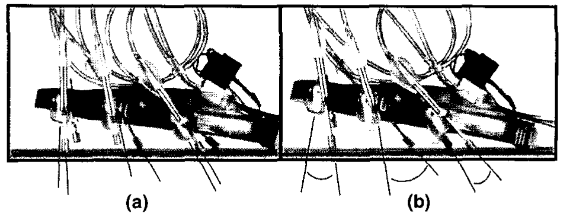

Figure 7 - High-speed footage of the running robot in a) mid-stance and b) full extension. As shown, the compliance in the leg plays an important role in the locomotion, as evidenced by the large deflections during the stride.

the common stair-stepping effect. The process is described in greater detail in (Merz et al., 1994; Binnard and Cutkosky, 2000).

Figure 5 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. As shown, the robot's servos, wiring and connectors were embedded within the body. 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 and protected by sacrificial material (low melting-temperature wax). A layer of structural material (pourable polyurethane) was then deposited and shaped, thereby encasing the embedded components. Finally, the sacrificial material was removed to access the finished part.

The construction of the multi-material compliant leg used in the robot, shown in Figure 6, takes advantage of SDM's capability to vary the material properties during construction of the part. 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 joint. A stiffer grade of polyurethane was used for the structural members, which encase the piston and servo mounting.

As shown in Figure 7, this rotational viscoelastic compliance in the legs is essential for the locomotion mechanism. 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.

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 simple visco-elastic material models can be fitted to both the biological materials and the polyurethanes (Xu et al., 2000).

4. PERFORMANCE RESULTS

As Sprawlita scurries across the floor and over obstacles, the combination of the "preflexes" and control scheme mentioned above appear to result in locomotion similar to the animal it is mimicking. However, a closer examination of ground reaction forces and center-of-mass trajectory reveal differences to the cockroach's locomotion. This comparison is detailed in (Bailey et al., 2000) and suggests improvements to this particular the mapping the biological principles as described in previous sections. This section presents results of performance tests in terms of maximum forward velocity and discusses initial attempts to understand the role of the robot's "preflexes" on this performance metric.

4.1 Variation in Performance/ Tuning of Parameters

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 8 shows how the velocity varies as a function of the slope for two different gait periods. As seen the shorter period gives 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 full factorial set of experiments (Box and Bisgaard, 1988) for the following parameters: stride period, duty cycle, front hip

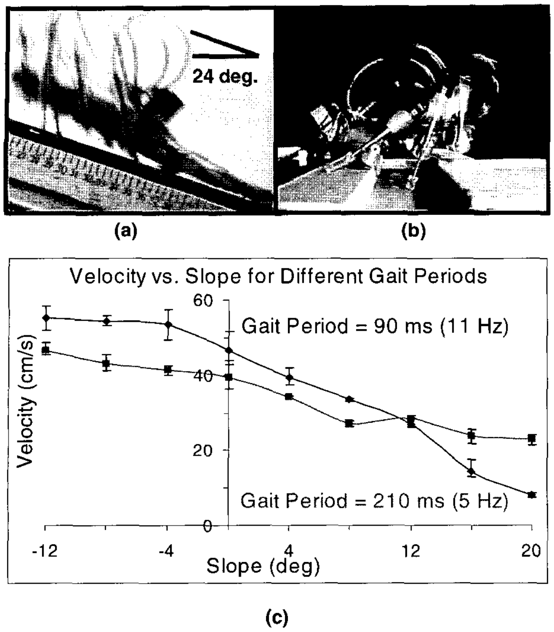

Figure 8 - Performance test results. The prototype is capable of surmounting a) uphill slopes of up to 24 degrees and b) hip-height obstacles. c) Tests over different slopes indicate the need to adapt the variables of locomotion to environmental conditions.

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 up hill 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 fig. 8 and suggests the importance of adaptation of the basic feed-forward pattern to match changes in the environment.

4.3 Unstructured Terrain

On flat, even terrain, the robot is able to clear obstacles 3.5cm high corresponding to its ground clearance, or one "belly-height". As 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.

5. CONCLUSIONS AND FUTURE WORK

Inspired by the agility, versatility and speed of legged animals, we have shown that "biomimetic" robots must mimic these animals in more than just appearance. The functional biological principles described in this paper resulted in a prototype hexapedal runner that is simple, fast, and robust. The robot incorporates these principles not only in its leg arrangement and design, but also in its construction and in the material properties of its structure.

However, the extent to which the resulting behavior of the robot is dynamically similar to its inspiration, the cockroach, is still in question. Current work focuses on comparing the dynamics of locomotion of both the robot and the cockroach. The differences may illustrate the more subtle implications of the ways in which the biological principles presented here are mapped to the robot.

As shown, the simple feedforward 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 in order to adapt to these changes in environment and task.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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.

Bailey, S. A., Cham, J. G., Cutkosky, M. R., Full, R. J., "Comparing the Locomotion Dynamics of a Cockroach and a Shape Deposition Manufactured Biomimetic Hexapod" International Symposium on Experimental

Robotics (ISER2000), Honolulu, HI, December 10-13, 2000.

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.

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.

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.

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.

Full, R. J., Blickhan, R. and Ting, L. H., "Leg design in hexapedal runners" J. exp. Biol. 158, 369-390, 1991.

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., Autumn, K., Chung, J. I., Ahn, A., "Rapid negotiation of rough terrain by the death-head cockroach," American Zoologist, 38:81A, 1998.

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.

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.

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.

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 o BioScience 23-33, 2000.

Ting, L.H., Blickhan, R. and Full, R.J. Dynamic and static stability in hexapedal runners. J. exp Bio. 197, 251-269, 1994.

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.