

Leg Coordination Mechanisms in the Stick Insect Applied to Hexapod Robot Locomotion

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*Three of the mechanisms believed to be responsible for leg coordination in the stick insect, *Carausius morosus*, are used to control the straight-line locomotion of a hexapod robot on a smooth surface. The robot walks with a continuum of statically stable insectlike gaits in response to a single, scalar user input that controls the speed of locomotion. This control strategy is highly robust in the sense that the controller continues to maintain its basic function of causing the robot to walk effectively despite large perturbations to the controller. This controller robustness was demonstrated by inducing a wide variety of lesions (severing of connections) and performing parameter sensitivity studies.*

Key Words: hexapod robot; coordination mechanisms; stick insect; robust control; locomotion

1 Introduction

Potential solutions to engineering problems can be found by investigating how these problems are solved in nature. In the last two decades, neuroethologists have identified mechanisms underlying the coordination of legs in the walking stick insect, *Carausius morosus*. Cruse (1990) reviewed mechanisms that he and others have described for the control and coordination of legs in this insect. Dean (1991b) simulated these mechanisms and demonstrated that together they can account for many experimentally observed aspects of walking stick insect locomotion. However, his simulation was based on kinematic leg models, and thus the effects of inertia and friction were ne-

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glected. In this article, we applied these mechanisms to the control of the locomotion of a hexapod robot, and we report that these mechanisms are remarkably effective for producing straight-line locomotion on a smooth surface. The locomotion of legged robots has been an area of interest for the past several decades. Examples include one-legged hopping robots (Raibert, Brown, & Chepponis, 1984; Raibert, 1986), bipeds (Hodgins & Raibert, 1991; Miura and Shimoyama, 1984), quadrupeds (Liston & Mosher, 1968; McGhee, 1967; Frank, 1968; Hirose, 1984; Raibert, Chepponis, & Brown, 1986; Hirose & Kunieda, 1991), and hexapods (McGhee, 1985; Sutherland & Ullner, 1984; Byrd & DeVries, 1990; Song & Waldron, 1989; Brooks, 1989; Quinn & Espenschied, 1992). Hexapods have been of particular interest due, in part, to the fact that six legs are the fewest required to support the body in a statically stable fashion using half the legs while stepping with the other half.

Most of the robots just cited are mechanically successful, but their performance is limited by the control method. A human-operated robot (Liston & Mosher, 1968) has the advantage of human intelligence in the control loop. However, the coordination of such a complex machine can be very taxing. In telerobotic operation (Byrd & DeVries, 1990; Song & Waldron, 1989), this problem is partially relieved by using computers for some portion of the control task. For many purposes, autonomous operation is desirable. For almost every purpose, however, all basic locomotion tasks should be performed by a computerized control system, which puts a considerable demand on the control system.

Some robots use mechanical means to simplify the control problem of coordination of multiple legs, each with multiple degrees of freedom. To this end, the vertical and horizontal motions of the foot have been decoupled by pantograph mechanisms (Hirose, 1984; Song & Waldron, 1989) or hydraulic circuitry (Sutherland & Ullner, 1984). However, insects display remarkable locomotion ability without decoupling joint motions in this manner. In fact, insect leg kinematics permit a large work space relative to their leg segment lengths. Insects use this range of motion for locomotion on very rough terrain and for manipulation of objects.

The traditional approach is *centralized control*, wherein a central computer controls all joint motions based on a particular fixed gait (sequence of leg movements). This requires a high flow rate of data and a very powerful computer. Furthermore, this control strategy is not robust to damage to the computer itself, sensory inputs, or motor outputs. Also, any single fixed gait is not suitable for all situations. For example, the tripod gait is the fastest, but loss of a middle leg precludes static stability.

Recently, several investigators have begun to use distributed control paradigms, inspired by the biology of insects. For example, Donner (1987) utilized inhibitory and excitatory influences between independent leg controllers to generate statically stable gaits in a hexapod robot. The influences were based on Wilson's (1966) model

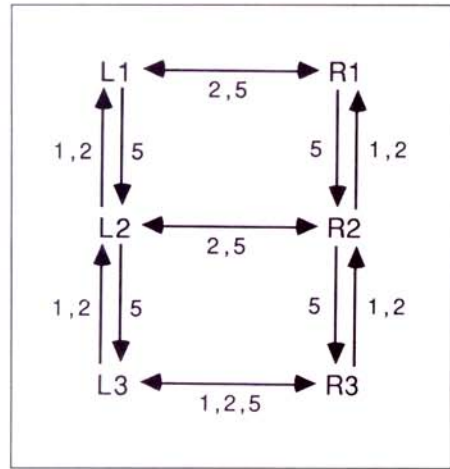


Figure 1

Influences of the mechanisms (1, 2, and 5) implemented for robot leg coordination. (L1, L2, L3 = left front, middle, and rear legs, respectively; R1, R2, R3 = right front, middle, and rear legs, respectively).

of the generation of multiple gaits in insects. More recently, Brooks (1989) used a partially distributed controller with local leg reflexes and a centralized gait sequencer to generate stable locomotion in a hexapod robot. His controller was implemented using networks of finite-state machines augmented with registers and timers.

In previous work, we used a distributed neural network, based on experimental studies of cockroach locomotion by Pearson, Fournier, and Wong (1973), to control the locomotion of a hexapod robot (Beer, Chiel, Quinn, Espenschied, & Larsson, 1992; Quinn & Espenschied, 1992). The network generated a continuous range of statically stable insectlike gaits as the excitation of a single command neuron was varied. The network was extremely robust in the sense that the controller continued to maintain its basic function of causing the robot to walk effectively despite large perturbations to the controller (Chiel, Beer, Quinn, & Espenschied, 1992). Thus, biological inspiration has proved very useful for the design of controllers for robot locomotion.

2 Coordination Mechanisms

For this article, we applied three of the mechanisms reported by Cruse (1990), which are believed to be responsible for stick insect locomotion, to the control of a mechanical hexapod. Note that, in contrast to our previous work, in this study we did not use a neural network. These mechanisms, which Dean (1991b) designated 1, 2, and 5, were implemented as shown in Figure 1. In Figure 1, the arrows indicate the direction of the influences from a sending leg to a receiving leg. An influence originates at a sending leg and is communicated to a receiving leg. Thus, *sending* and

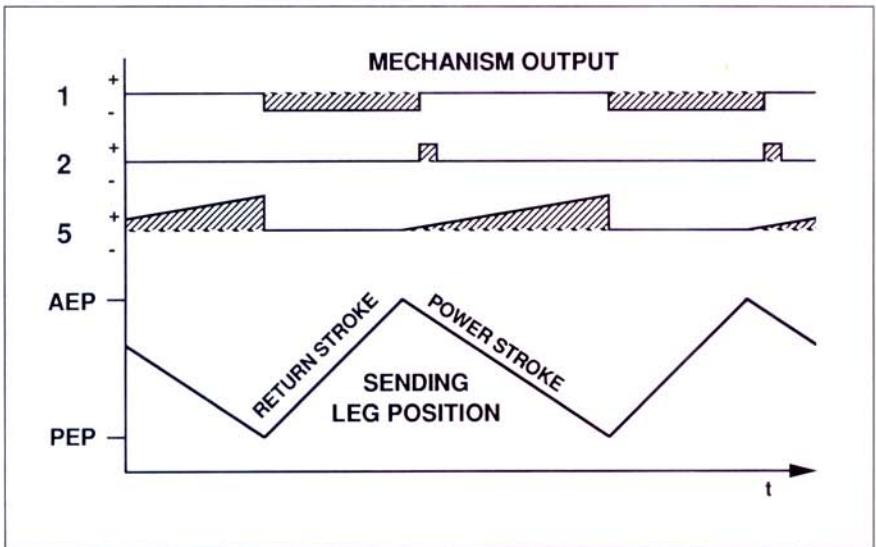


Figure 2

Mechanisms. Sending leg position versus time is plotted for 2 stepping cycles. Plotted above are corresponding outputs from mechanisms 1, 2, and 5. (*AEP* = anterior extreme position; *PEP* = posterior extreme position.)

receiving are terms relative to a particular influence under consideration. *R1*, *R2*, and *R3* refer to the right front, middle, and back legs, respectively. Similarly, *L1*, *L2*, and *L3* refer to the left front, middle, and back legs, respectively.

A leg in the return stroke swings forward until it reaches the anterior extreme position (*AEP*), where it switches to the power (stance) stroke and begins moving backward until it reaches the posterior extreme position (*PEP*). The speed of a leg in the power stroke (and thus the speed of locomotion) is proportional to a single input to the controller. This single scalar input is specified by the user. The *AEP* is not altered by any of these mechanisms. The *PEP* of each receiving leg is adjusted based on the sum of the interleg influences (see Fig. 1) affecting that leg; the strength of each influence equals the sending leg mechanism output multiplied by a weighting factor.

Figure 2 illustrates the three mechanisms. In response to the return stroke of a sending leg, mechanism 1 shifts the *PEP* of a receiving leg backward, delaying the onset of the receiving leg's return stroke. Mechanism 1 output is a step function beginning with the onset of the return stroke of the sending leg and ending 60 ms after that leg's power stroke begins. On the other hand, mechanism 2 shifts the *PEP* of the receiving leg forward, encouraging its transition from power to return stroke. Mechanism 2 output is also a step function, beginning 60 ms after the onset of

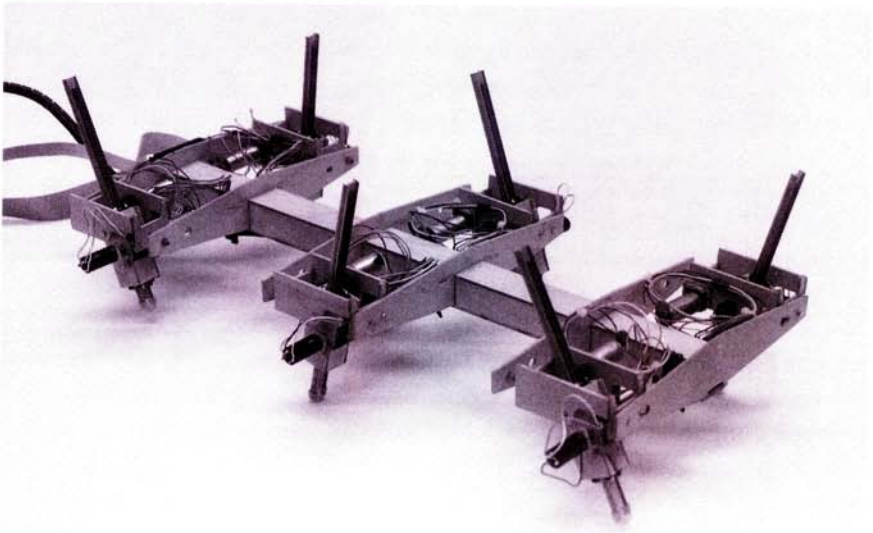


Figure 3
The hexapod robot.

the sending leg power stroke and ending 60 ms later. While a sending leg is in its stance phase, mechanism 5 acts to shift the PEP of the receiving leg forward, thus encouraging it to begin its return stroke. Unlike mechanisms 1 and 2, mechanism 5 is a ramp function; the output begins to climb with the onset of the power stroke of the sending leg.

3 Hexapod Robot

The hexapod robot used in our study and depicted in Figure 3 is 50 cm long by 30 cm wide and weighs 1 kg. Twelve 2-watt DC motors drive 2 degrees of freedom per leg to permit straight-line locomotion. Each leg moves in the vertical plane: The leg can swing front to back along the body, and the foot can extend and retract radially. Potentiometers are used for position sensing.

The control program, which runs on a personal computer, reads leg positions, computes mechanism outputs, and updates leg positions. These new leg positions are sent to proportional feedback position control circuits to drive the motors. Each of the motors has a dedicated analog circuit board for position control (the power stage is included in this circuit). The position control circuit is designed to simulate musclelike behavior. As in the biological muscle control model reviewed by Bizzi and Mussa-Ivaldi (1990), the output leg positions from the control program are treated

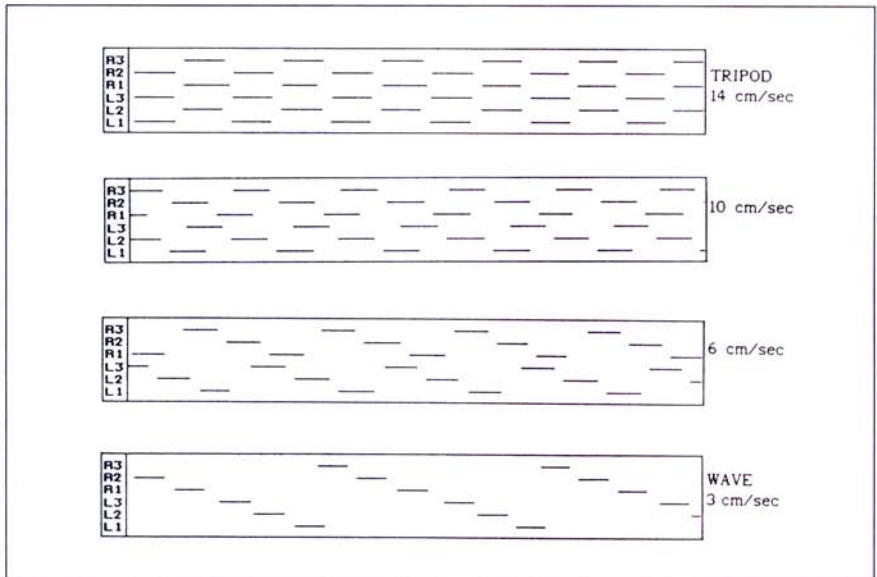


Figure 4

Typical robot gaits. Black lines represent return strokes; no line represents the power stroke. Each figure displays 6 seconds of locomotion.

as equilibrium positions for the joints, which the feedback controllers cause the joints to follow. Furthermore, this approach is consistent with the findings of Cruse, Riemenschneider, and Stammer (1989), wherein the body height of the stick insect is controlled in a proportional feedback manner. Quinn and colleagues (1991) and Quinn and Espenschied (1992) provide a more detailed description of the robot and electronics.

4 Results

The robot can begin to walk starting from any arbitrary leg configuration. A single input to the controller varies the robot speed from zero to the maximum speed, which is approximately 14 cm/sec. As the speed is varied, a continuous range of statically stable insectlike gaits are produced, as shown in Figure 4. The gaits range from the wave gait to the tripod gait, all of which display the metachronal wave (a middle leg swings after the adjacent rear leg, and a front leg swings after the adjacent middle leg). In the wave gait only one leg is in the return stroke at any time. In the tripod gait, the front and rear legs on one side of the body step in unison with the middle leg on the other side. Dean (1991b) reported a similar range of gaits when he applied these mechanisms to control a kinematic model of a hexapod in simulation.

Lesion studies provide insight into the function and robustness of a distributed control system. Biologists often perform lesion studies of an organism's nervous system for the purpose of analyzing the function of a biological neural network. In this article, a *lesion* may be defined as the removal of a particular interleg influence or an entire mechanism from the controller.

We performed lesion studies on our controller to determine the roles of the stick insect mechanisms in generating particular gaits in the robot (Table 1). The tripod gait is the most robust. However, the robot walks effectively throughout the range of speeds despite the removal of any single interleg influence. By *effective* locomotion, we mean that the robot walks in a gait that is primarily statically stable but may experience occasional brief periods of static instability. For example, two adjacent legs may lift simultaneously. Removal of entire mechanisms showed that mechanism 2 promotes normal back-to-front metachronal waves, and mechanism 5 promotes 180-degree phasing between cross-body leg pairs. Removal of mechanisms 1 and 2 showed that mechanism 5 alone can produce effective locomotion over a range of speeds.

Parameter optimization was not necessary for locomotion because the controller is insensitive to most parameters (Fig. 5). The baseline value of an influence was initially and arbitrarily chosen to produce metachronal waves and 180-degree cross-body leg phasing. The vertical axis of Figure 5 represents the ratio of the perturbed value to the baseline value of an influence. For example, the strength of mechanism 1 can be varied over a large range without impairing the robot's ability to walk. However, a relatively small decrease in the along-the-body influences of mechanism 2 renders the robot unable to maintain normal metachronal waves. A small increase of mechanism 2 cross-body influences causes cross-body leg phasing to shift away from 180 degrees, generating asymmetrical phasing, which is observed in walking stick insect locomotion (Dean, 1991a). Locomotion is most sensitive to changes in the strength of mechanism 5. A relatively small increase in the strength of either the along-the-body or the cross-body influences disrupts the coordination such that the robot cannot walk effectively.

5 Discussion

Using a kinematic simulation, Dean (1992a,b) independently investigated walking stick coordination mechanisms by conducting perturbation and lesion studies. In addition to the mechanisms used here, Dean also included a mechanism to target foot placement to the position of the next rostral foot by adjusting the AEP of the receiving leg (e.g., the middle leg is encouraged to place its foot near the foot

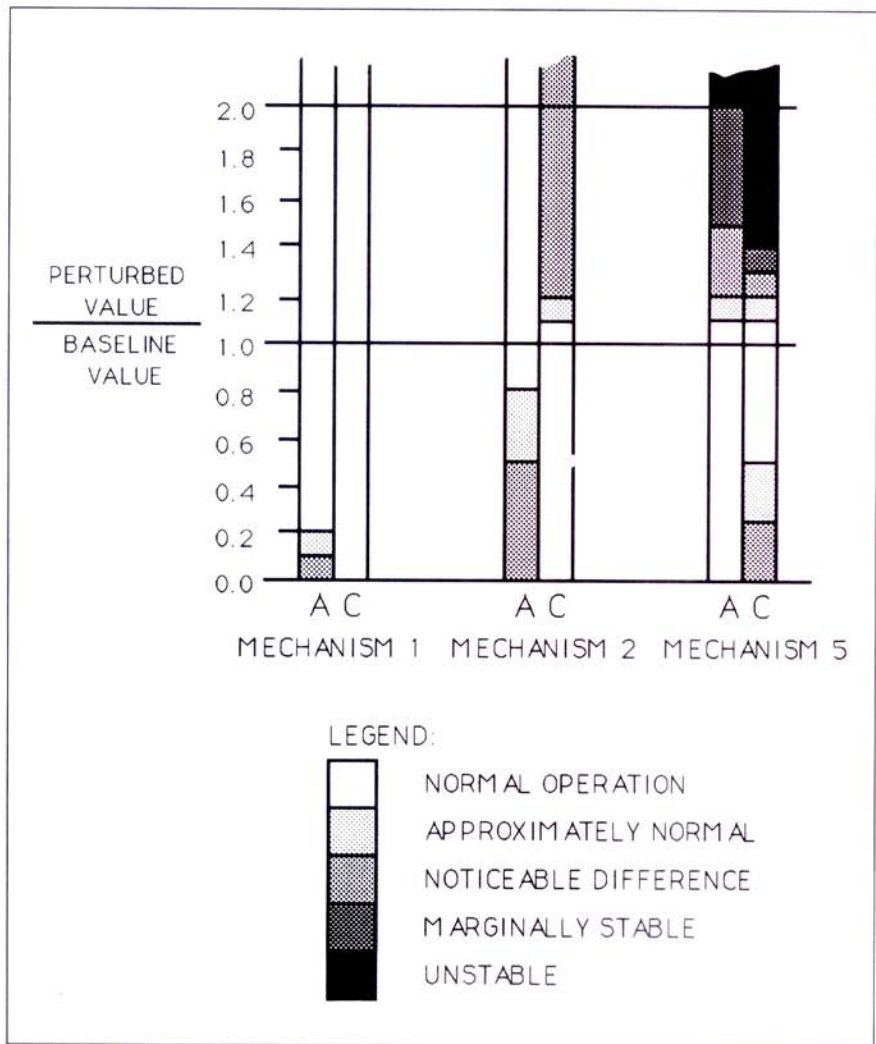


Figure 5

Results of the sensitivity study. The columns denoted by *A* and *C* represent the along-the-body and cross-body interleg influences, respectively, of the indicated mechanism. An influence strength of 1.0 corresponds to a shift in the posterior extreme position (PEP) of approximately half of a typical stroke length. The baseline values of the along-the-body (cross-body) strengths of mechanisms 1, 2 and 5 are: 0.59 (0.12), 1.00 (0.10), and 0.58 (0.77), respectively. Each strength was altered independently while the others remained at the baseline value. The black portions of the columns associated with mechanism 5 indicate periods of static instability long enough to cause the robot to fall. The along-the-body and cross-body influences of mechanisms 1 and 2 can be increased without limit or decreased to zero without impairing effective locomotion.

Table 1 Results of lesion analysis. Entries give a qualitative description of gait properties based on observations of the robot's walking. The four gaits and speeds correspond to those shown in Figure 3. Lesions were induced by setting the strengths of the influence(s) of interest to zero. The upper section of the table contains single lesions and covers all the possible single influences (based on symmetry). The designation *all* in the influence column indicates that all influences for the particular mechanism were removed. The quality of coordination (gait and speed) is ranked as follows: 0 = operates normally; 1 = abnormal tripod, statically stable gait; 2 = impaired formation of metachronal waves; 3 = weak cross-body phasing; 4 = backwards metachronal waves; 5 = unsteady gait (gait varies over time with occasional brief periods of static instability); 6 = frequent brief periods of static instability; X = statically unstable. Note that the tripod gait is the most robust. (*L1, L2, L3* = left front, middle, and rear legs, respectively; *R1, R2, R3* = right front, middle, and rear legs.)

Mech.	Lesion Influence	Gait and Speed			
		Wave Slow	Med. Slow	Med. Fast	Tripod Fast
1	<i>L2</i> → <i>L1</i>	0	0	0	0
1	<i>L3</i> → <i>L2</i>	0	0	0	0
1	<i>R3</i> → <i>L3</i>	0	0	0	0
2	<i>R2</i> → <i>R1</i>	2	2	2	1
2	<i>R3</i> → <i>R2</i>	2	0	0	0
2	<i>L1</i> → <i>R1</i>	0	0	0	0
2	<i>R2</i> → <i>L2</i>	0	0	0	0
2	<i>R3</i> → <i>L3</i>	0	0	0	0
5	<i>R1</i> → <i>R2</i>	0	0	0	0
5	<i>R2</i> → <i>R3</i>	5	3	3	0
5	<i>L1</i> → <i>R1</i>	0	0	0	0
5	<i>R2</i> → <i>L2</i>	0	0	0	0
5	<i>L3</i> → <i>R3</i>	5	3	3	1
1	all	6	0	0	0
2	all	5	5	4	1
5	all	3	3	3	0
2,5	all	X	X	X	6
1,5	all	X	X	X	X
1,2	all	5	5	6	6

of the front leg). He found that the removal of this mechanism had little effect on coordination; hence, our controller should be comparable to his, despite his

inclusion of this additional mechanism. Our models differed also in that Dean's form of mechanism 5 was speed-dependent, whereas ours was not.

Müller-Wilm and co-workers (1992) presented another kinematic simulation using these mechanisms. In this simulation, the joint angles of a realistic leg with natural geometry and three revolute degrees of freedom were computed via inverse kinematics. Their results show that the simulated model can negotiate an obstacle if the height of the obstacle is less than the height of the body.

The mechanisms were inferred from observations of the stick insect. Therefore, implementing the mechanisms requires the researcher to make assumptions regarding the form of the mechanisms and strengths of the influences. In his kinematic simulation, Dean (1992a,b) used different forms of mechanism 5 and found that the across-the-body leg phasing was strongly dependent on the form of this mechanism. Apparently, we used what Dean would call a relatively strong form of mechanism 5 to achieve 180-degree phasing. This reflects our disparate goals: Dean wished to simulate insect locomotion, whereas we desired to produce effective robot locomotion.

The kinematic models of Dean (1992b) and Müller-Wilm and colleagues (1992) and our robot walked successfully despite differences in our implementation of the various mechanisms. Furthermore, we found the mechanisms to play similar roles in coordinating the legs. For example, in agreement with our work, Dean found mechanism 5 to be the most effective single coordinating mechanism. Of the three rules that we used, Dean also found that mechanism 2 was the least effective.

The robot has been shown to be capable of walking on slightly rough terrain depending on the foot height during the return stroke. The musclelike position controllers provide compliance that permits small obstacles to be negotiated. However, our primary interest was the coordination of the legs on relatively flat terrain. In future work, we plan to incorporate load sensing and insectlike reflexes for negotiation of obstacles and rough terrain.

6 Conclusions

In conclusion, leg coordination mechanisms in the walking stick insect have been used to generate a highly robust straight-line locomotion controller. This robustness results from two factors. First, not all of the rules or influences are required to produce effective locomotion. Thus, if each is implemented as a distinct physical entity, physical damage to the controller could be tolerated to a certain extent. Second, the range of gaits produced is preferable to a fixed gait. The tripod gait permits quick locomotion, whereas slower gaits may permit effective locomotion even if a leg is lost.

We have demonstrated only straight-line locomotion, which is a necessary mode of operation. However, walking stick insects possess a remarkable ability to negotiate extremely irregular terrain. Hence, these mechanisms must be an integral part of a locomotion controller for complex terrain.

Based on our earlier results (Beer, Chiel, Quinn, Espenschied, & Larsson, 1992; Chiel, Beer, Quinn, & Espenschied, 1992), we predict that neural network implementation of these mechanisms may lead to an even more robust locomotion controller. In addition, as biologists gain more insight into load feedback mechanisms, this knowledge can be utilized for the development of robot locomotion controllers that can negotiate rough terrain. Finally, engineered, biologically based systems have been shown to be useful for testing biological hypotheses.

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