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Architectures for a biomimetic hexapod robot

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Abstract

This paper describes a six-legged robot based on the features of an agile insect, the American cockroach, *Periplaneta americana*. The robot is designed with insect-like leg structure and placement, and actuators that mimic muscles. A test leg is also described that shows how sensory feedback can serve as the basis of the control system for the robot in order for it to achieve the degree of adaptability of locomotion over rough terrain exhibited by insects. ©2000 Elsevier Science B.V. All rights reserved.

Keywords: Walking robot; Biomimetic robot; Hexapod; Cockroach

1. Introduction

In recent years, a number of robotics engineers have taken an interest in building legged robots whose designs are based at least in part on biological principles of structure or control (see [31]). In principle, legged robots can go where wheeled ones cannot, so they have a potential utility that justifies the extra effort required to control their locomotion. The rationale for the interest in biology is that legged animals can easily outperform the most agile robot over rough or irregular terrain. By looking to the physical structure and control mechanisms of successful biological systems, engineers may be able to improve the performance of walking robots [2,6,11,28,31]. Hence, a number of collaborations between neurobiologists who have information about the biological basis of animal locomotion and robotics engineers who design the robots have been established (e.g., [28,29]). In these collaborations, the biologists typically contribute their expertise on the animals they study while the engineers try to implement the relevant biological concepts in hardware and software.

The experience of these groups suggests that *adaptive* locomotion is much harder to generate and coordinate than had been thought. If interactions of a few simple sensors and actuators regulated by a simple control system were sufficient to achieve the level of performance that insects show, it seems likely that engineers would by now have achieved walking performances by machines that would rival that of insects. That this level of performance has yet to be achieved suggests that there is more to locomotor control than neurobiologists and engineers have yet fully identified.

Neurobiologists have been slower in establishing collaborations with engineers for the converse purpose, to use robots as models to study biological

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mechanisms. For example, the possibility that studying robots might provide insights into neurobiology has been recognized for some time [31], but has only rarely been implemented (e.g., [36]). A walking robot can provide information of interest to neurobiologists in two ways. First, the nature of the problems that arise in constructing a robot and developing a robust locomotion controller can illuminate the neurobiological problems faced by animals [3], such as the need to stiffen a joint before ground contact [25,30]. Second, a walking robot can used to address important questions in motor control [7]. For example, a major issue in neurobiology is how the nervous system selects, times, and coordinates muscle action. Hypotheses about how this is achieved in the nervous system can be tested directly by implementing them on a physical robot (e.g., [12]).

A second issue in motor control research is the role of the physical plant in the control mechanisms that are used by an animal [4]. By varying the physical structure of the robot that is being controlled it is possible to study the effects of such changes on its performance. For example, it may be that the multiplicity of muscles and sense organs present in insects may serve to confer more versatile and stable movement to the legs during walking. Although sensory feedback is most commonly considered in its role in timing leg movements during walking, there is evidence that it helps stabilize gaits [14]. It would be worthwhile to test these types of system–level hypotheses on a physical robot.

In this paper we describe a six-legged robot whose design is based on the biomechanics of an insect. The robot is powered by pneumatic actuators that use a unique valving mechanism to mimic important muscle characteristics such as force development and compliance, in addition to providing greater strength and higher acceleration compared to many motorized actuators. Our ultimate objective is to use the structure of an insect in addition to known biological principles for controlling insect walking as models on which to base the structure of the robot and the organization and operation of its controller. However, in order that we might build a functioning robot reasonably quickly, we have initially aimed for simplicity in our design. Hence, although we have been guided by the insect's structural and functional features in developing our robot, we have not attempted to reproduce the insect faithfully in every detail, and our current locomotion controller does not yet embody all biological principles that we know to be important.

2. Physical design

The mechanical structure of our hexapod robot (Fig. 1) is modeled after the American cockroach, *Periplaneta americana*. We selected this insect as a model because of its extraordinary speed and agility and because the structure and physiology of this insect are reasonably well known (e.g., [5]). The body of the robot measures 58 cm × 14 cm × 23 cm length, width, and height. It has an additional 15 cm ground clearance when standing. The legs, projecting laterally and to the front, add about 38 cm to the width and 18 cm to the length. The robot weighs approximately 11 kg, most of the weight being in the valves that control the pneumatic actuators (see Section 3). The physical dimensions of the robot body and legs are generally between 12 and 17 times the size of the comparable dimensions of the cockroach. The robot, however, is considerably heavier in relation to its size due to the weight of the valves.

We designed the legs of the robot with three segments each, corresponding to the three main segments of insect legs: coxa, femur, and tibia. The coxa articulates with the body, the femur with the coxa, and the tibia with the femur. Insect legs also have a foot-like tarsus, but in order to keep the legs relatively simple, we did not model it. All leg segments are fashioned of aluminum tubing about 1.9 cm on a side. Each of the joints between leg segments and between the coxa and the body is a simple hinge joint.

In addition to employing six legs with three segments each, we also emulated specific features of the legs of our model insect that we considered important for a robot that is to be capable of flexible and adaptable locomotion, as have other designers of biomimetic robots [18,26]. Two features seemed especially relevant. First, the three pairs of legs in cockroaches are different in length and in structure [23,32]. The front legs of *Periplaneta* measure about 2.2 cm. The middle and rear legs are longer, yielding a ratio of front : middle : rear leg lengths of 1 : 1.2 : 1.7. We made the front legs of our robot about 38 cm long, and scaled the middle and rear legs slightly shorter

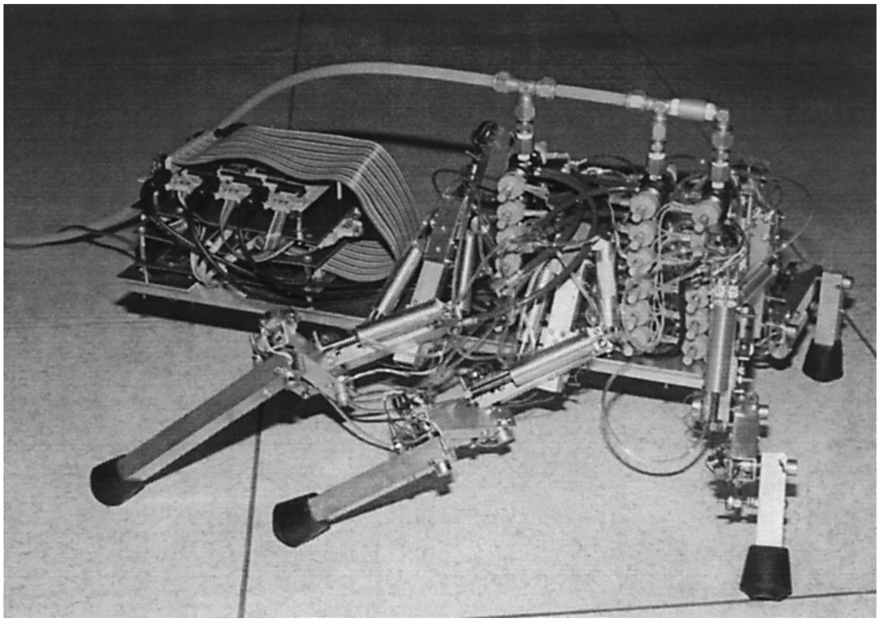

Fig. 1. Biobot, a biomimetic robot physically modeled after the American cockroach, *Periplaneta americana*. It is powered by pressurized air, supplied through the tube at the top of the photo.

than their insect counterparts, so the length ratio for the robot's legs is 1 : 1.1 : 1.5.

Second, the front, middle, and rear legs of cockroaches articulate differently with the body of the insect. In front legs, the coxa, the leg segment that articulates with the body, is oriented almost vertically at rest and moves through about ±30° relative to the vertical during walking [23]. However, the front coxae have more than one degree of freedom of motion, and hence can swing the leg laterally as well. The middle leg coxae typically swing through angles of about 10–30° from the vertical, pointed toward the rear. These legs are used as struts to support the weight of the body. The coxae of the long rear legs are angled even further posteriorly, moving through angles of about 30–50°. The rear legs provide much of the propulsive force required during walking. Although the coxae of the legs move through angles of only 20–30° during walking, they are all capable of moving through considerably greater angles. Even the middle and rear legs, with only a single degree of freedom at the coxal-body articulation, are able to move from about 10–90° from the horizontal, giving the legs great flexibility when the insect attempts to climb over obstacles.

We did not attempt to emulate in our robot every aspect of the articulation of the legs with the body in the insect, but we did adjust the articulation to generate functionally similar movements. First, we attached the coxae of the front legs vertically, but arranged for them to swing laterally rather than parallel to the long axis of the body. This gives the front legs an excursion of from about 55–100° from the longitudinal body axis measured from anterior to posterior. Second, we attached the middle leg coxae at an angle of about 75° from horizontal; this allows the foot to swing through an angle of about 10–80° from the horizontal during the transition from full flexion to full extension around the coxa. Third, we attached the rear legs at an angle of about 30° from horizontal, allowing the rear foot to swing through an angle of about 10–90° from horizontal from flexion to extension of the coxa.

An important consequence of this physical arrangement is that the legs can be attached relatively close to one another along the body without mechanical interference between them. The different lengths of the legs and the different angles through which the coxae move as a cockroach walks means that each

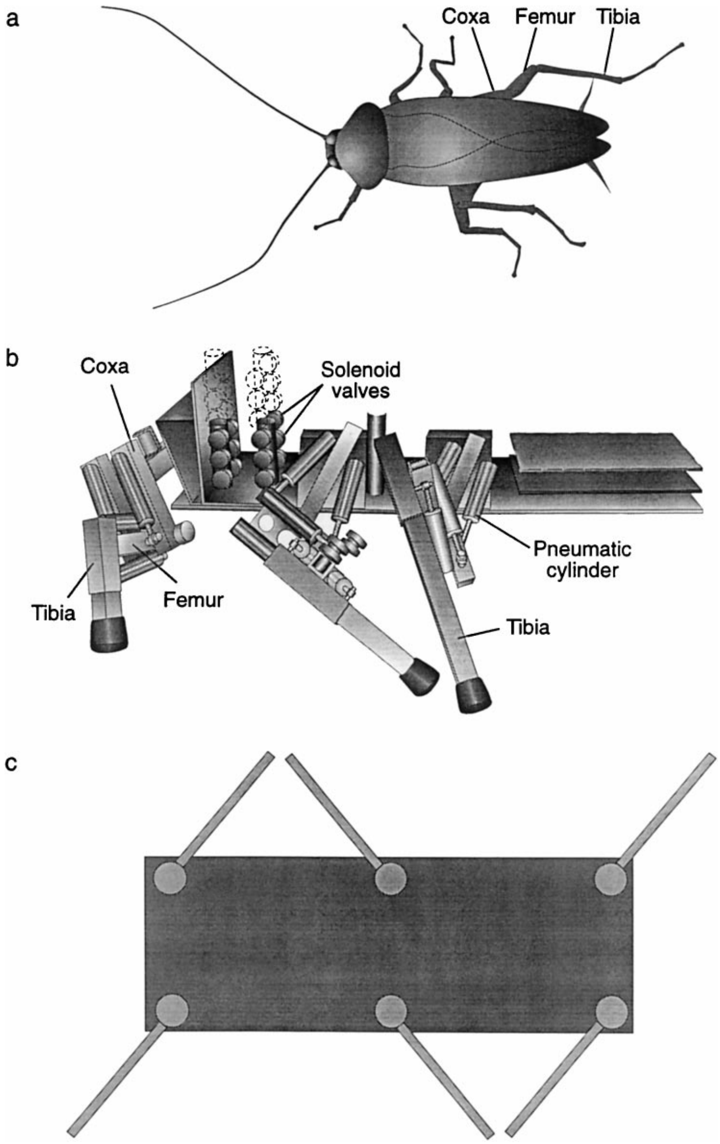

Fig. 2. The positions of legs during walking in an insect and two types of robots. (a) In the cockroach, the angled attachment of the legs to the body and the different sizes of front, middle, and rear legs allows the legs to be positioned close to one another on the body without suffering mechanical interference during walking. (b) A similar design in our robot also allows relatively close placement without mechanical interference. (c) An earlier type of robot design in which the legs move in horizontal arcs. The legs must be placed some distance apart to avoid collisions during walking.

leg can move through its full cycle without significant chance that it will interfere with the movement of any of the other legs (Fig. 2a). Angling the legs of the robot in a similar way allows us to place the legs relatively close together (Fig. 2b), in contrast to the positions that the legs would have to take if they were attached orthogonally so as to move in a plane horizontal to the walking surface (Fig. 2c). Some elongated insects, such as the stick insect, do have legs attached in this way, but these animals gen-

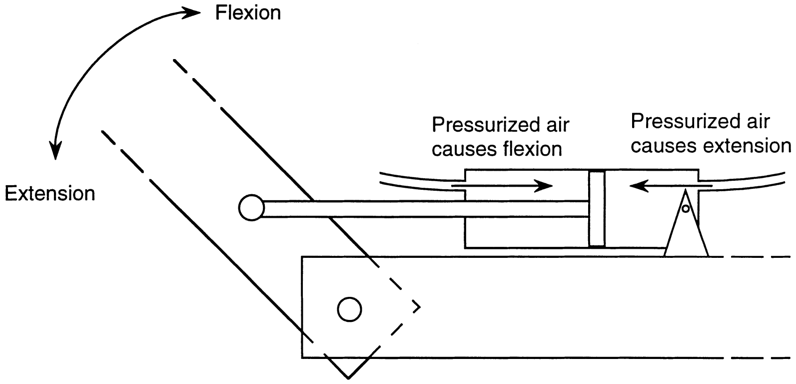

Fig. 3. Functional use of a single dual action cylinder to provide movement in two directions. The cylinder will generate either flexion or extension of the next limb segment depending on which chamber is filled with pressurized air.

erally live in the open and hence apparently have not faced selection pressure for a compact body/leg arrangement.

3. Actuators

Muscles in insect legs, like voluntary muscles in other animals, are controlled by impulses from motor neurons that innervate them. We chose a pulsed pneumatic system for our actuators, partly in order to adhere to this feature of insect systems in our robot. Actuators consist of double action cylinders (Robart) that are powered by pressurized air (nominally 90 lbs/inch^2). Double action cylinders allow a single cylinder to produce movement in both directions. Allowing pressurized air into one side of the cylinder forces the piston in one direction, and allowing pressurized air into the other side forces the piston in the other direction. Hence, one cylinder can serve to extend or to flex a single joint (Fig. 3).

Commercially available, fast-acting, computer-controlled electronic (solenoid) valves are used to control the flow of pressurized air into a cylinder. Each valve is opened briefly when the actuator is to be “activated”, allowing a direct connection between the pressurized air supply and the cylinder. When the valve is closed, the chamber of the cylinder is open to the atmosphere, allowing any accumulated pressure to dissipate (Fig. 4). We use pulses of constant 10 ms duration and vary their frequency in order to vary the force output of the cylinder.

This system allows us to mimic several features of insect muscle [8]. First, muscle contracts (develops force) upon the arrival of a nerve impulse from a motor neuron that innervates it. Our actuator develops force when a single pulse of pressurized air enters the cylinder. Just as a single nerve impulse will generate only a brief twitch in muscle, a single pulse of air will generate only a brief “twitch” in our actuator, since the pressurized air that enters the cylinder will begin to dissipate as soon as the valve closes. Second, a contracting muscle has compliance, yielding if it is subjected to a force greater than that which it is generating. Pneumatic cylinders behave similarly. A force greater than that being generated by the piston of a cylinder will simply force the cylinder back in the opposite direction. This movement will be resisted as the air in the non-active chamber is compressed, producing life-like behavior without causing damage to the system. Third, in insect muscle, variations of force are produced by varying the frequency of the nerve impulses that are delivered to the muscle. The same relationship holds in our system (Fig. 5). At low frequencies of pulses, a low level of force is generated. As frequency increases, the level of force generated also increases, until at high frequencies the system develops the maximum force possible given the pressure of the air being used.

Although we have not implemented it, our system of actuators allows another feature of biological systems to be emulated. Many types of muscle show the phenomenon of facilitation, in which successive nerve impulses produce successively stronger effects on the

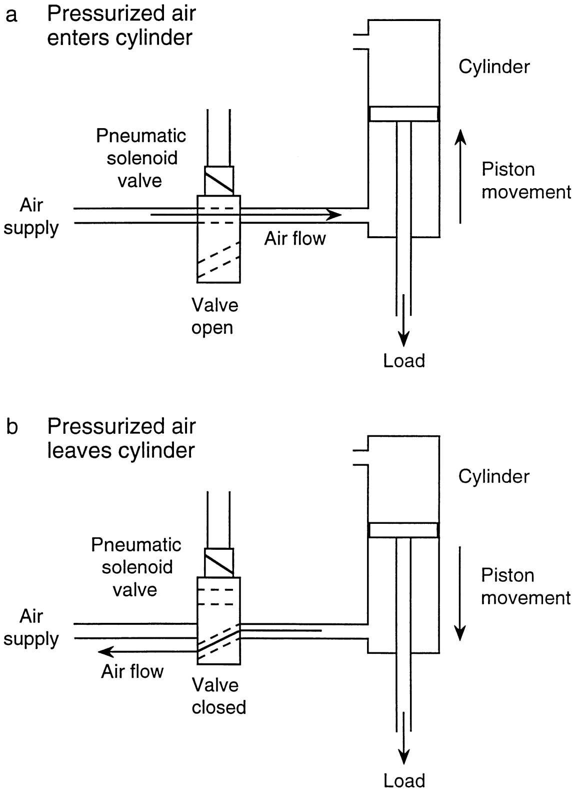

Fig. 4. Valve operation for control of a cylinder. When the valve is open, pressurized air is allowed to enter one chamber of the cylinder. When the valve is closed, the chamber is opened to the atmosphere, allowing the accumulated pressure to dissipate.

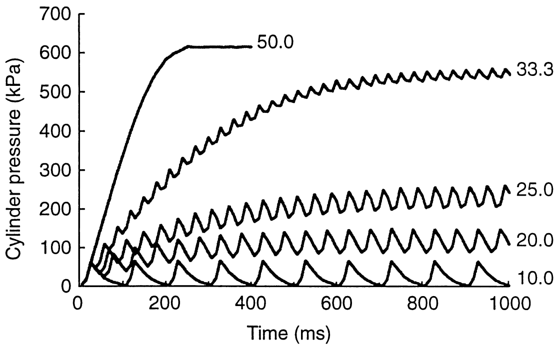

Fig. 5. The pressure generated in one chamber of a cylinder in relation to the frequency of pressurized air pulses introduced into it. Pulses are 10 ms in duration. Adapted from [8].

muscle (see, e.g., Chapter 5 in [22]). In some cases, the effect of a single nerve impulse may be augmented by several hundred percent at maximal facilitation. This feature can be emulated with our actuator system by increasing the duration of the valve open time. At present we use pulses of 10 ms. We can increase the force generated by one or more pulses by increasing the pulse duration to, say, 15 or 20 ms. This allows greater force to be generated at low frequencies of activation, which seems to be the functional effect of facilitation in biological systems.

4. Control and pattern generation

Most roboticists would likely agree that the greatest challenge in developing an autonomous walking robot is to design a control system that will allow adaptive walking over virtually any type of walking surface. It is the prospect of developing such a flexible control system that attracts roboticists to biomimetic designs, since current robots still fall short of animals in their ability to handle variations in terrain that animals handle with ease.

Neurobiologists interested in the neural basis of rhythmic behavior have generally focused on the means by which the rhythmic alternation of activity in antagonistic muscle groups is achieved [24]. In the course of developing the controller for our robot, we have come to realize that this emphasis ignores important issues if the objective is to understand how the insect generates coordinated and adaptive locomotion. For example, we have found that for adaptive locomotion in the robot we need to have a means of moving each leg through a specific trajectory during the swing and stance phases of a leg cycle without rigidly specifying what that trajectory should be. Insects have considerable flexibility in their leg movements, and the path taken by a leg can easily be modified if the leg strikes an obstacle or must adapt to irregular terrain.

At present we have taken the shortcut of preprogramming desired trajectories. We determined a target trajectory for each leg by taking videotapes of cockroaches walking over a flat surface, digitizing the images, and measuring the angles of the joints as they extended and flexed through a complete cycle of stance and swing (see [34,35] for another and more detailed description of this approach). We then moved each leg of the robot passively through a trajectory close to the natural trajectory determined from the behavioral study. During the passive movement of an individual leg, values of the three joint angle sensors were recorded and saved in a look-up table to establish a desired trajectory for that leg. During locomotion, a proportional-integral-derivative (PID) feedback control algorithm is used to track the desired trajectories and to bring the movements of the legs back to the planned paths if they deviate from them. All legs move through their desired trajectories with the same cycle period, about 2–4 seconds depending on walking speed, but the relative phases of the legs are adjusted to generate an alternating–tripod gait [13]. Establishing a stable walking gait in this manner is not particularly difficult so long as the robot is restricted to moving on uniform flat surfaces with no obstacles. However, to achieve a truly flexible insect-like locomotor control system in which each leg has considerable freedom to adapt to substrate variability poses a significant challenge for leg coordination and control (e.g., [33]).

To negotiate uneven terrain, the robot demands more from a locomotion controller than the simple ability to generate fixed motor patterns. Agility over rough terrain requires the generation of leg movements that are adaptively modulated by sensory feedback from leg sensors. Insect legs have a rich array of sense organs that provide the nervous system with detailed information about the dynamic state of the leg and its interactions with the environment [15]. These sense organs play a significant role in the coordinated and adaptive walking of insects (review: [13]). One of the key requirements for agile locomotion is to ensure that individual legs have adequate contact with the substrate before attempting to generate forward thrust. When attempting to establish a new foothold in rough terrain, or when support is suddenly removed from an individual leg, many insects generate stereotyped searching movements to find a new foothold. This substrate-finding reflex has been particularly well characterized in the stick insect [1].

The substrate-finding reflex is a useful model system for studying how sensory feedback from leg sense organs can adaptively modulate the output of a central pattern generator. To explore this issue, we have implemented a biologically inspired model of the substrate-finding reflex in a 2-joint robot leg [16,17]. The mechanical design of the robot leg is shown in Fig. 6. The leg has two servo motors, one for the coxa–femur joint and one for the femur–tibia joint. The response characteristics of the servo motors have been modified to have compliant actuation characteristics that are dynamically equivalent to a Hill-type muscle model [21]. This was accomplished

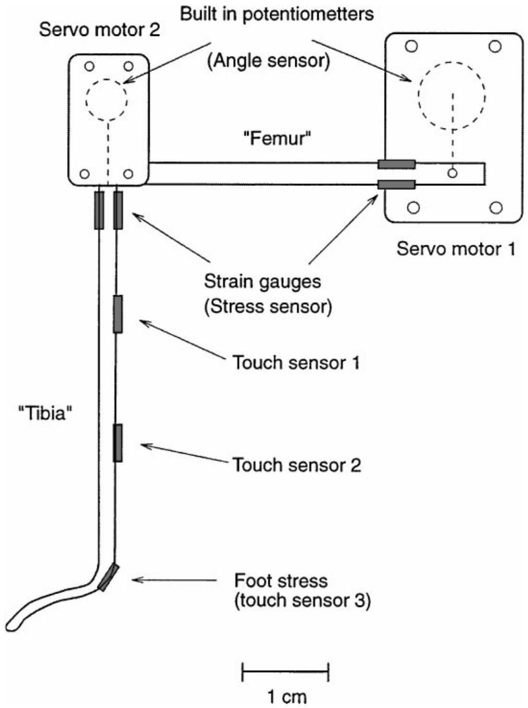

Fig. 6. A 2-joint robot leg equipped with multiple sensors and muscle-like actuators. A neural controller implements a substrate-finding reflex using sensory feedback. The leg will "search" for a foothold if it has none, and will reflexively place its foot on top of any solid object encountered during the search phase. Adapted from [16].

by opening the position feedback loop of the servo motor and replacing it with a custom analog feedback circuit. The leg has three types of sensors. Potentiometers contained within each servo motor provide measurements of joint angle, analogous to information provided by the insect chordotonal organ. Pairs of strain gauges placed near the joints provide information about the load on each segment, analogous to that provided by insect campaniform sensilla. Finally, individual strain gauges provide information on local leg contact, analogous to that provide by tactile hairs in the insect.

The substrate-finding behavior of the robot leg is mediated by a neural controller with four layers of units: a sensory input layer with nine units (one per leg sensor), a 5-unit sensory interneuron layer (analogous to spiking interneurons in the insect thoracic ganglia), a 5-unit premotor layer (analogous to non-spiking interneurons) and a 4-unit output layer (one flexor–extensor pair per joint). The connections within the network are predominantly feed forward, with recurrent connections occurring only between units within the premotor layer. The central pattern generator (CPG) for searching movements of the leg is established by recurrent lateral interactions between these premotor units. The individual neural units are continuous-valued adaptive threshold neurons with five parameters per neuron: baseline firing rate, gain, membrane time constant, adaptation time constant, and degree of adaptation (0.0 = tonic, 1.0 = phasic). After establishing the basic network architecture, a genetic algorithm technique [20] was used to search the parameter space of gains, time constants, and synaptic connection strengths in order to optimize the substrate-finding behavior (for details, see [16]).

With no substrate present, the searching CPG generates coordinated movements of the two joints, such that the leg repetitively sweeps out an arc through the space where a foothold might be encountered. This sweeping motion is illustrated in Fig. 7a. When the leg encounters an object during the search phase (typically signaled by touch sensors on the tibia and an increase in tibial strain), the output of the premotor layer is altered in such a way that the leg slides up along the object, maintaining a relatively constant tibia strain (Fig. 7b) until it just clears the object. The change in sensory input when the leg briefly loses contact with the object causes a subsequent change in premotor activity such that the tarsus comes down on top of the object and a foothold is established (Fig. 7c).

Incorporating such a flexible system of reflexes into a legged robot should confer to the robot many of the features of flexibility and adaptability desired by engineers, at the same time as it provides a robust basis for locomotion.

5. Future directions

Biomimetic robots may be developed for any of several purposes. On the one hand, they may be designed to take advantage of the features of animals that are presumed to be at the basis of animals' superior speed or agility over irregular terrain [4]. On the other hand, they may be built for research purposes, serving as test platforms to evaluate ideas about robotic performance

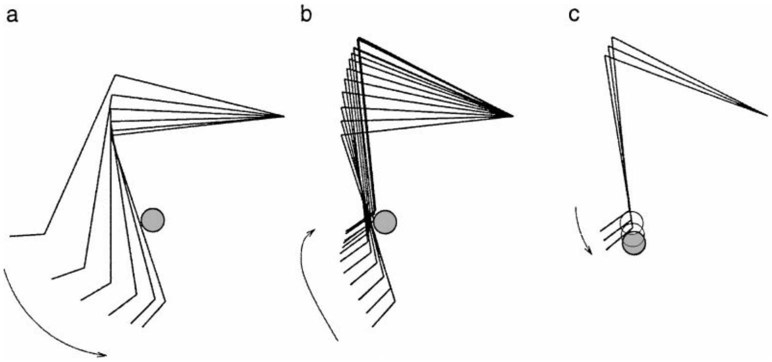

Fig. 7. The stages in searching of an insect leg as it seeks a foothold. (a) Upon loss of a foothold, the leg is lifted slightly and the foot extended. (b) The entire leg is then swept downwards, maximizing the chance that the leg will encounter a foothold. (c) Upon contact, the leg is pressed against the object and swept slowly upwards until the foot rests on it. Adapted from [16].

or control, or to test neurobiological hypotheses about how specific motor acts are accomplished [36]. These objectives are not mutually exclusive, as research may certainly reveal elements of robot design that will improve performance, and the process of building a robot for a practical application may well impact significant research questions.

The development of autonomous walking robots is still in its early stages. Based on the performance capabilities of current robots, it is clear that engineers still have much to learn about how to produce the kind of flexible control of movements that insects or other animals seem to use to such good effect. This is where biologically inspired robots can play a role [4]. Even though the neural basis of locomotor control is not completely understood, biomimetic robots can be used as research tools to test hypotheses about the relationship between body design and performance, about the role of sensors and actuators in achieving a certain level of adaptive performance, or about the most efficient way to control multiple elements (the legs) in a flexible and coordinated fashion. As knowledge of biological systems grows, this knowledge can be applied to robot design and tested to see what improvements in performance it might lead to.

At the same time, study of biomimetic robots can help the neurobiological community by providing a physical testbed for ideas about how coordinated locomotion is achieved. Hypotheses ranging from those concerning the mathematics of oscillator theory (e.g., [9,19]) to those suggesting the role of specific sense organs in regulating leg movements and coordination (e.g., [10,27]) can be tested by implementing them in hardware and software. The ability of a researcher to change a physical arrangement or rewrite software algorithms presents an opportunity to test such hypotheses in a way not possible in a living animal. The knowledge gained from such experiments should be immediately applicable to improve the design of the robot, leading to better performance.

Of course, one important driving force for work on biomimetic robots is their potential for use in places that are inaccessible to or too dangerous for humans (e.g., [37]). Off planet exploration or even exploration on earth underwater or in remote locations are frequently mentioned as possibilities. Walking robots could also be used in hazardous places such as the inside of a nuclear reactor or in buildings that have been structurally compromised. In these situations it is desirable that the robot be autonomous since it should be able to make its own way given only general instructions as to where to walk. This is a tremendous challenge.

In conclusion, biologically inspired autonomous walking robots have great potential both as research tools and as products designed for use in dangerous situations or in places inaccessible to humans or currently available machines. These two areas of potential impact interact with one another. As research suggests improvements in design the actual performance of the robots brings their use closer to being a practical reality. At the same time, improvements in performance opens vistas for research that is not yet possible. Moving forward along these parallel tracks should lead to new robots that will far outperform any that are available today.

Acknowledgements

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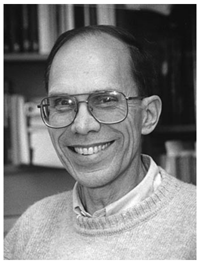

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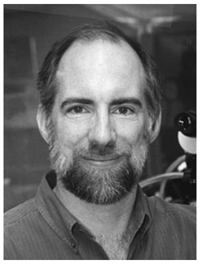

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