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Biologically based distributed control and local reflexes improve rough terrain locomotion in a hexapod robot

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Abstract

Distributed control and local leg reflexes enable insects to cope easily with terrain that would defeat many legged robots. An insect-like hexapod robot incorporating biologically based control effectively responded to mechanical perturbations using active and passive compliance and a local stepping reflex. An elevator reflex and a searching reflex addressed unexpected obstacles and loss of support, respectively. The robot exhibited a range of gaits using stick-insect-based distributed control mechanisms and negotiated irregular, slatted and compliant surfaces with this biologically based control strategy.

Keywords: Hexapod; Legged robots; Rough terrain locomotion; Stick-insect; Biologically inspired control

1. Introduction

Because legged locomotion allows us to access many areas that cannot be reached by wheeled vehicles, there has been a long-standing interest in the construction of legged devices for locomotion. Despite decades of effort, however, the abilities of legged robots to negotiate irregular terrain is still rather limited as compared to that of insects. Natural terrains are often not level, may be slippery, provide poor support, have significant vertical variations, large obstacles, and provide sparse footholds [26]. A common solution for legged robots on rough terrain is to allow operators to remotely place each leg [27]. Other solutions utilize extensive pre-planning based on prior knowledge of the characteristics of the terrain [27,1]. As a consequence, most existing legged robots progress slowly on rough terrain, are nonautonomous and cannot easily cope with rapidly changing environment conditions.

In contrast, legged animals can effectively locomote over extremely rough terrain. Even insects manifest impressive capabilities for dealing with rough terrain. For example, using a variety of local leg reflexes, *Locusta migratoria* can negotiate a wire mesh, an irregular surface of wooden blocks (height irregularity between blocks was approximately 0.1 of the locust's body length), a hexagonal array of flat head nails (40% solid surface; minimum gap of approximately 0.1 body length), a ditch (width of approximately 0.16 body length), an elevated step (height of approximately 0.2 body length), and a vertical rod with projecting side branches [23]. Insects also have the advantage that both the biomechanics of their periphery and their neural control are tractable to detailed experimental analyses, as indicated by the considerable amount of literature available (for example, [3, Chs. 1–9]).

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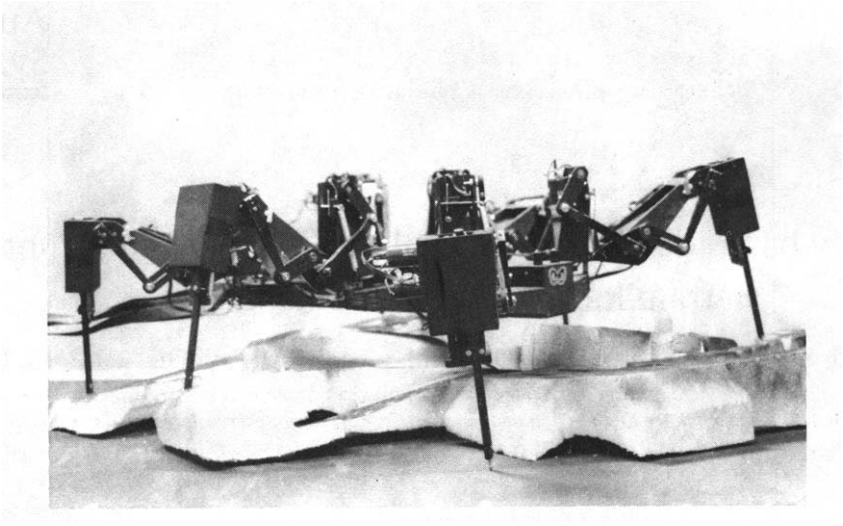

Fig. 1. Photograph of robot on irregular terrain. Robot is approximately 50 cm long, 50 cm wide, and 25 cm high. Joints are powered by 6-Watt DC motors with attached planetary transmissions (motors and gearing account for approximately 65% of the mass), and potentiometers sense joint positions. Semiconductor strain gages measure axial load in the most extreme leg segment.

For this reason, a number of robotics researchers have begun to incorporate biological principles into the biomechanics and control of legged robots. Raibert has demonstrated that incorporating biologically inspired dynamics can lead to effective monopedal, bipedal and quadrapedal hopping and running robots [26]. Donner, Brooks, and Pfeiffer have demonstrated some of the advantages of using distributed mechanisms to control hexapod robots. Donner controlled a large hydraulically actuated hexapod using distributed connections that changed the likelihood that different legs would engage in a swing/stance cycle, and observed that the robot could still walk if one leg was disabled [15]. Brooks has not only built several hexapod robots controlled by augmented finite-state machines, but he has emphasized the value of distributed vs. centralized control, and the value of horizontal vs. vertical task decomposition for improving robot performance [8], i.e., closely integrating sensors and effectors to guarantee low-level competencies that serve as building blocks for higher order behaviors. Pfeiffer et al. have built a stick-insect-like robot whose control is based on mechanisms that have been observed in these insects, and is currently implementing leg reflexes [28,24].

We have emphasized the synergies that can emerge when the conceptual tools and techniques of biology and engineering are simultaneously brought to bear on the problem of legged locomotion [2,4]. In our previous work, we demonstrated that a robot incorporating either a neural network controller, or distributed, biologically based control mechanisms, could walk with a range of insect-like gaits on horizontal surfaces, and was robust to lesions of central connections, single sensors or single effectors [25,17,11]. In order to deal with rough terrain, we extended our previous work by incorporating biological principles into the biomechanics and control of a new hexapod robot.

2. Robot mechanics

The mechanics of a robot are crucial for implementing many biological control mechanisms. This consideration dictated many of our design decisions for the robot. First, its kinematic construction was qualitatively similar to that of a walking stick insect, so that its body was suspended from its legs (Fig. 1). The low center of mass of this design enhances the stability of the robot. Second, since the degrees of freedom of each leg of an insect are decoupled, we did not use the common approach of a pantograph or frame design which couples degrees of freedom to simplify control

[27,21]. Instead, we provided each leg with three independent, active, revolute degrees of freedom, and one passive spring-loaded linear degree of freedom. These additional degrees of freedom were crucial for implementing many of the reflexes described below. Third, since insect reflexes rely upon an extensive range of proprioceptors, each leg was equipped with angle sensors for each active degree of freedom, and a force sensor for the passive degree of freedom.

3. Compliance

Maintaining a posture on a complex, irregular terrain requires an ability to conform to that terrain. Insects are capable of doing this using the flexible biomechanics of their legs and bodies, as well as local leg reflexes. Passive and active compliance mechanisms were incorporated into the robot so that it could conform to irregular surfaces. Passive compliance results from the incorporation of springs into each leg. Additional compliance is produced by using a spring-like proportional feedback control law at each revolute joint. As a consequence, these joints exhibit muscle-like properties in accordance with the moving equilibrium point hypothesis for musculoskeletal systems [6].

Active compliance is due to two strategies: first, joint control stiffnesses are reduced when excessive loads are encountered to help prevent joint damage. Compliance in the horizontal direction is achieved by reducing the stiffness of the joints primarily responsible for motion in the horizontal direction. This allows the stiffness to be increased when the perturbing force is removed, causing the leg to return to its original position, contributing to the swaying reflex.

The second strategy for active compliance is to distribute vertical load among the supporting legs by altering the equilibrium points instead of the stiffnesses for the joints of those legs, allowing the robot to conform to large vertical height variations. This strategy is suitable for this purpose since the new equilibrium positions serve as a reference for the stepping height and consequently the placement of the foot on the next step. The combination of active and passive compliance makes its possible for the robot to conform to terrain containing large disparities in height (25 cm).

4. Swaying and stepping reflexes

Rough terrain locomotion also requires a legged device to adjust rapidly to mechanical perturbations of the legs. Insects do this using two strategies: in response to small perturbations, they activate muscles to oppose the change in angle of a perturbed joint [30]. The active compliance mechanisms described above led to a swaying reflex in the robot. As the robot is pushed, these mechanisms induce it to comply to the forces, and if the displacements are not too large, the robot returns to its original position once the perturbation is removed. If the displacement of a leg is large enough, insects move a perturbed leg so that it is again capable of supporting load [30]. To re-establish a stable posture in response to larger displacements, a stepping reflex was also incorporated into the robot's control (Fig. 2(A)). This reflex is a direct consequence of the distributed mechanisms for gait generation, which will be described next. As a consequence of these mechanisms, a push from any direction causes swaying responses if the displacements are small; otherwise, the robot's leg lifts and moves towards the center of its range of movement, improving the stability of the posture. Indeed, if a substrate upon which some of the legs of the robot are resting is pulled from underneath it, the legs initially comply, and then step off of the retreating substrate, maintaining postural stability.

5. Gait generation

Steady progression of a legged device requires coordination of leg movements (gaits) such that legs both propel and support the device. Insects locomote using a continuous range of stable gaits [29]. In the stick insect, Cruse and colleagues [12] have described a series of distributed local influences between adjacent legs that induce them to move in a range of gaits. In simulation [13,16] and in a robot [17,18], it has been shown that these distributed control mechanisms generate a continuous range of insect-like gaits, and are robust to lesions [17,18,14]. These distributed control mechanisms are organized around two kinematic parameters, the anterior extreme position (AEP) and the posterior extreme position (PEP), which control the switch from swing to stance, and

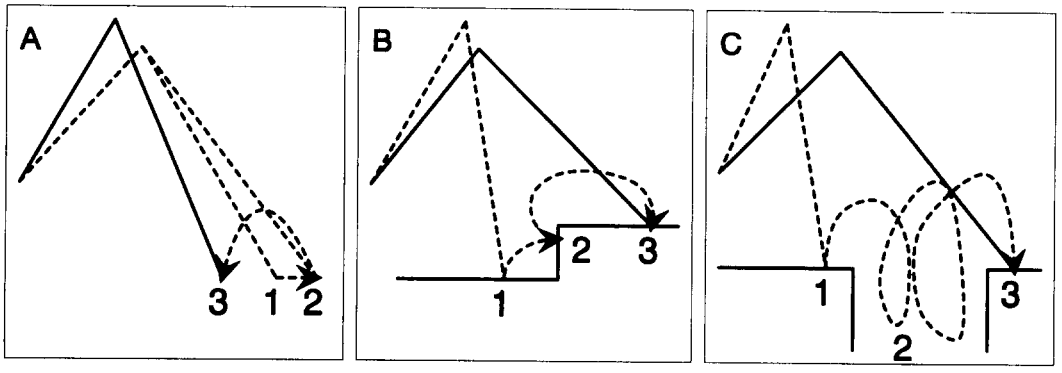

Fig. 2. Postural and rough terrain reflexes. (A) Stepping reflex. When the leg is perturbed, it initially complies (from position 1 to 2); if the perturbation is sufficiently large, the leg steps to a position that better supports the body (3). (B) Elevator reflex. If the leg encounters an obstacle during the return stroke (2), it retracts and lifts the foot higher to step on or over the obstacle. (C) Searching behavior. If the foot does not touch the ground at the expected location (2), it searches for a foothold (3).

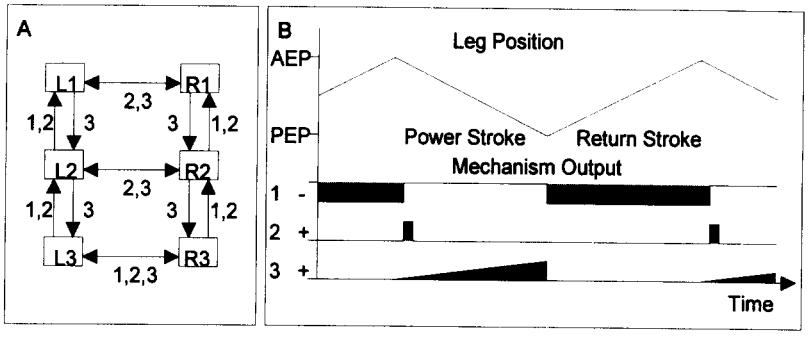

Fig. 3. Stick insect mechanisms. A leg in the return stroke swings forward until it reaches the anterior extreme position (AEP), at which time it switches to the power stroke and begins moving backwards until it reaches the posterior extreme position (PEP). The speed of the leg in the power stroke is based on the desired motion of the body. (A) Network of influences. Each arrow indicates one or more influences; L1, L2, and L3 indicate left front, middle, and back legs, respectively; R1, R2, and R3 indicate right front, middle, and back legs, respectively. Each influence consists of a positive weight times a particular mechanism output (indicated by number) from sending leg to receiving leg (sending and receiving are terms relative to the influence being discussed; all legs act as both). The PEP for a particular leg is then adjusted by an amount equal to the sum of the influences affecting that leg. Since the crossing of the PEP threshold determines the time of the switch from power stroke to return stroke, the influences can serve to adjust the phase relationship between adjacent legs. (B) Mechanisms. Each leg controller produces three mechanism outputs as a function of the leg position. Mechanism 1 shifts the PEP of the receiving leg backward, delaying the onset of the receiving leg's return stroke. Mechanism 2 shifts the PEP of the receiving leg forward, encouraging the receiving leg to take a step. As a sending leg progresses through its power stroke, mechanism 3 acts with increasing influence to encourage the receiving leg to take a step.

stance to swing, respectively [12]. We again utilized these distributed control mechanisms in the new robot (Fig. 3), and extended our previous work by generalizing these kinematic parameters to two dimensions. Despite the increased numbers of degrees of freedom in each leg of the new robot as compared to our previous robot, it successfully generated a continuous range of insect-like gaits (up to 14 cm/s) as a single activation parameter was varied. These gaits ranged from the slow wave gait to the fast tripod gait [29]. These coordination mechanisms also allowed the robot to continue to make forward progress even if one of its legs was mechanically prevented from unloading, so that leg never swung forward. Similar results have been observed in stick insects [20].

6. Elevator reflex

As a legged device progresses, it may encounter an unexpected obstacle. For example, a swinging leg may be hindered by an unexpected elevation of the terrain. Insects have a variety of strategies for dealing with this problem. One strategy is to raise the leg in order to swing it over an obstacle [23]. We implemented an elevator reflex in the robot (Fig. 2(B)). If a swinging leg encounters an obstacle, it briefly reverses its motion and lifts higher before swinging forward. If triggered more than once, it lifts higher the next time. As a consequence of the elevator reflex, the robot can clear obstacles up to 8 cm.

7. Searching reflex

On rough terrain, support may be missing (e.g., if there is a hole) or may be lost (e.g., if part of the terrain slides away from under a leg). Insects can successfully negotiate terrain with large gaps. One strategy is to move rhythmically a leg in an increasing region of space to search for additional support [23]. We implemented a searching reflex in the robot (Fig. 2(C)). If a leg loses contact with substrate or fails to establish a foothold, it searches for an acceptable foothold by moving the end of the foot in circles of increasing radius for a fixed number of times. As a result of this reflex, the robot could progress over slatted surfaces with 50% missing, and could successfully deal with sudden removal of support using both the stepping and searching reflexes.

8. Turning

Other strategies for dealing with obstacles are to walk around them, recoil from them, or climb over them. Insects use all of these strategies to deal with obstacles [23]. Because of the extra degrees of freedom of the robot's legs, and the generalization of the coordination mechanisms, the robot was capable of following a curving path in response to a single commanded change in direction. That is, if the robot is commanded to turn in a particular direction, the distributed mechanisms allowed the robot's legs to remain correctly coordinated during turning movements. The same generalizations allowed the robot to walk laterally or turn in place. All of these flexible walking abilities could be used for obstacle avoidance.

9. Integration of reflexes

In natural terrains, many hindrances to locomotion may occur in combination, so that a locomotion controller must cope simultaneously with all of these difficulties. Insects are capable of integrating their localized leg reflexes and distributed coordination mechanisms to generate continuous locomotion over extremely irregular terrains. To determine whether the local reflexes and coordination mechanisms that we had developed for our robot would effectively work together to solve this problem, we placed the robot on an extremely irregular and partially compliant terrain (injection molded Styrofoam shapes with major terrain features occurring at a fundamental spatial frequency of 6 m^{-1}, and with a peak-to-peak amplitude of 11 cm). The robot was able to make steady progress: it adjusted its leg positions to comply to the irregular terrain; when legs encountered protrusions, the elevator reflex allowed them to lift and swing over them; and when legs encountered large holes, the searching reflex allowed them to find stable resting places. Thus, local reflexes can be successfully integrated with distributed control mechanisms to generate steady locomotion over rough terrain (2 cm/s).

10. Discussion

More traditional approaches to robotic control have relied on centralized controllers, and detailed advance knowledge of the characteristics of the terrain, or have utilized a telerobotic approach (Klein and Briggs, 1980; Byrd and DeVries, 1990). The approach that we have described utilizes distributed control, which has made it much easier to incrementally add localized leg reflexes. Moreover, the resulting robot can effectively deal with irregular terrain with no global knowledge of its characteristics [18,19]. As a consequence, the robot is robust to perturbations. Our prior experience with distributed control [2,4,10] suggests that it will also be robust to lesions of the

control mechanisms and that it will be very effective in coping autonomously with rough terrain.

11. Conclusions

These results demonstrate the value of basing robot control on principles derived from biology. The locality of the mechanisms, their restricted interactions with adjacent legs, and the continuous values that they exchange between legs make them quite similar to the neural network approaches we have taken previously [5]. In our future work, we plan to reimplement these mechanisms using a neural network, since this is likely to further enhance their flexibility and robustness [11]. These results also suggest that attempts to construct robots using these principles could provide insight into the mechanisms of locomotion in animals and humans. In our future work, we plan to incorporate further details of insect biomechanics and neural circuitry into the biomechanics and control of the robot as the experimental analysis of insect locomotion progresses.

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