

A walking machine using coordinating mechanisms of three different animals: stick insect, crayfish and cat.

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Abstract

Mechanisms for interleg coordination described for three species of animals were tested in a simulation of a hexapod walking machine originally developed for the stick insect. Both the temporal pattern and the postural stability of the hexapod were considered. The coordination mechanisms of the stick insect, a natural hexapod, provided better coordination than those of the crayfish, a decapod normally using eight legs to walk under water, or the cat, a terrestrial quadruped often relying on dynamic stability.

Introduction

To walk in a natural environment an animal or a robot must be able to deal with obstacles and uneven terrain. Large obstacles can be avoided by finding a suitable path. Small obstacles, or disturbances they may cause to movements of individual legs, can be surmounted if the legs are moved in such a way as to maintain geometric stability of the body. This paper will concern only the latter capability.

The application of biological knowledge to technical development might lead to significant progress in constructing a walking machine. To reach this goal, several problems have to be solved. One question concerns the way the movement of the individual leg is controlled. The second question refers to the coordination between legs. Experiments with stick insects and other animals suggest the following answers. First, each leg has its own control system which generates rhythmic step movements (review Bässler 1983). The behavior of this control system corresponds to that of a relaxation oscillator in which the change of state is determined by thresholds based on leg position. (To date, most studies have focused on the state transitions between swing and stance and on the kinematics of the foot movement; no detailed information is available concerning the control of the individual leg joints of the walking animal and the control of the dynamics.) Second, the coordination of the legs is not determined by a separate control system hierarchically superior to the step pattern generators of the individual legs. Instead, the gait pattern emerges from the cooperation of these separate control systems. This cooperation is based on different types of signals which convey information on the actual state of the sender to the control systems of the neighboring legs. The receiver collects this information and, on this basis, decides on its own action. This distributed architecture results in stable gaits but nevertheless allows the whole system to react flexibly to disturbances. These interleg influences differ in different animals.

Most experimental data on leg coordination were obtained for the stick insect. Therefore, the model presented here is based on this animal. However, in developing a control system for an actual walking machine, we do not plan to build an exact copy of this animal. To make a working model we introduce simplifications or, where not enough experimental information exists, use ad hoc assumptions. Hence, it might be useful to implement coordination mechanisms found in other animals. In the work described here, we tested the efficiency of coordinating mechanisms found in crayfish and cats for controlling the hexapod walking machine.

The movement of the individual leg consists of two parts, the power stroke (PS) and the return stroke (RS). During the power stroke, the leg is on the ground, supports the body and, in the forward walking animal, moves backward with respect to the body. During the return stroke, the leg is lifted off the ground and moves in the direction of walking to where it can begin a new power stroke. The anterior transition point, i.e. the transition from return stroke to power stroke in the forward walking animal, has been called the anterior extreme position (AEP) and the posterior transition point has been called the posterior extreme position (PEP). Either as a hypothesis or on the basis of experimental results several authors (Bässler 1977, Cruse 1985b, Graham 1972, Wendler 1968) proposed the idea that the transition from one state to the other occurs when the leg reaches a given criterion position and that the step generator can thus be considered a relaxation oscillator. The role of load in modifying this position criterion will be neglected here (see however Bässler 1977, Cruse 1983, Dean 1991a).

As in the model of Müller-Wilm et al. (1992), each leg is represented by three segments which are connected to each other and to the body by three simple hinge joints. Contact with the ground is assumed to occur at a non-slipping hemisphere at the end of the distal segment. This simplified leg omits the set of short segments forming the tarsus or foot of the insect. The structure of the leg and the definition of the angles are shown in Figure 1. The axes of rotation of the basal joints are arranged in the same way as in the stick insect and, therefore, are not orthogonal with respect to the body-fixed coordinate system shown in Figure 1. In the stick insect the basal joint actually is a ball-and-socket joint. However, the primary movement during walking involves only one axis of rotation (Cruse 1976). Therefore, for the present model we assume that the basal joint is used only to move the leg in the forward-backward direction and that all the upward-downward movement is performed at the coxa-trochanter joint.

Model

The movement of the individual leg is controlled in the following way. In arthropods the step pattern generator can be described as a relaxation oscillator which depends on sensory feedback. This means that the periphery has to be included in the system. As proposed by Cruse et al. (1993), a simple recurrent system is used to control the state of the leg; Figure 2 shows a slightly different form. As illustrated, the proprioceptive signals can provide appropriate feedback to produce a rhythmic movement (Bässler 1977, Land 1972; for a general discussion see Bässler 1986). The recurrent signals from the motor unit outputs act to maintain the on-going state; the recurrent paths via the movement and sense organs control state changes. The output of the return stroke motor unit RS, interpreted as a velocity moving the leg forward, is applied to the leg until a sense organ signals that the AEP has been reached. This sensory unit, AEP, turns off the RS motor unit and switches on the PS motor unit, causing the leg to move to the rear until a second sense organ signals that the PEP has been reached. This sense organ turns off PS and switches on RS, completing the cycle. As a result the system oscillates rhythmically, moving the leg between the AEP and PEP, although there is no central oscillator in the system.

The actual 3-dimensional movement of the leg is determined by the trajectory generation unit (Fig. 2). In order to simplify the model for the straight walking considered here, we assume that the tarsus always moves in a vertical plane parallel to the long axis of the body. The rhythmic movements of the tarsus parallel to this axis (the x-axis, see Fig. 1) and the vertical axis (z-axis) are controlled by signals derived from the state variable. To make the reversals in the direction of movement less abrupt and therefore more realistic, the state value is first put through a low-pass filter. The filtered output is used as a reference signal to control the movement of the leg tip in the horizontal and vertical directions. In the stick insect the forward and backward movement of the tarsus during return and power strokes appears to be determined by a velocity-controlling feedback system (Cruse 1985a, Dean 1984, Weiland and Koch 1987). Therefore, to control movement in the x-direction, the reference signal is interpreted as velocity. To control the height of the tarsus (z-direction), it is interpreted as position. During walking on irregular surfaces, the timing of ground contact is uncertain, so the end of the downward movement during the final part of the return stroke has to be determined by an additional sensor ("ground contact", abbreviated as GC in Fig 2). (For further details on the determination of the tarsus trajectory, see Müller-Wilm et al. (1992).)

Once the trajectory of the tarsus relative to the body is selected, the values of the joint angles can be calculated. Here, because the leg has no redundant degrees of freedom, joint angles are computed by solving the inverse kinematics explicitly, as described by Pfeiffer et al. (1990). Alternatively, the problem can be solved by a hard-wired, recurrent network implementing the mean of multiple calculations method (Cruse and Steinkühler 1993).

In order to simulate height control during walking over uneven surfaces, the model makes a distinction between features of the environment and those of the animal, as indicated by the dashed horizontal line in Figure 2. The control systems of each leg specify reference values for the three joint angles of the leg, as described above. However, height control is determined using data on vertical force as a function of the configuration of the whole leg. Therefore, to simulate the mechanical effects, the direct kinematics is solved for each leg and then the actual height and inclination of the body is computed by treating each leg as a cantilever of variable length supported by a vertical spring of constant stiffness located over the tarsus. Vertical loads or unevenness in the substrate are added in this computation. External disturbances to the movement of a leg are included subsequently. These two steps determine the actual positions of the tarsi relative to the body. The inverse kinematics is applied again to compute the actual joint angles, which are the natural input signals from the animal's proprioceptors.

Hexapod model implementing the coordination mechanisms of the stick insect

In the stick insect, six different coupling mechanisms coordinate the movements of the individual legs (review Cruse 1990). These mechanisms are mediated through the CNS; they act between adjacent legs. Two mechanisms will not be considered here. (One serves to correct errors in leg placement, the other has to do with distributing propulsive force among the legs). The other four mechanisms were successfully implemented in an earlier model (Dean 1991bc, 1992ab) which formed the basis for the coordination module in the first version of the present model. The beginning of a return stroke, and therefore the end-point of a power stroke (PEP), is modulated by three mechanisms arising from ipsilateral legs: (1) a rostrally directed inhibition during the return stroke of the next caudal leg, (2) a rostrally directed excitation when the next caudal leg begins active retraction, and (3) a caudally directed influence depending upon the position of the next rostral leg. The beginning of the power stroke (AEP) is modulated by a single, caudally directed influence (4) depending on the position of the next rostral leg; this mechanism is responsible for the targeting behavior. Influences (2) and (3) are also active between contralateral legs. (Besides these interleg mechanisms mediated through the CNS, several intraleg mechanisms responding to position and load also contribute to maintaining coordination and stability, but these will not be considered here. See Bässler 1977, Cruse 1985b)

As expected from previous results with similar models, the present model shows a proper coordination of the legs when walking at different speeds. As in the stick insect the step pattern shifts from the tetrapod to the tripod gait with increasing walking speed (Graham 1972). The movements of the legs are not shown here because they are very similar to those previously described for the algorithmic model (Müller-Wilm et al. 1992).

The coordination pattern appears stable. For example, when the movement of the right middle leg is interrupted briefly during the power stroke, the normal coordination is regained immediately at the end of the perturbation (Fig 3a). Another critical test of

stability is to consider the behavior of the model in starting from arbitrary leg positions. Starting is particularly difficult when contralaterally neighboring legs begin from the same x- position because, uninfluenced by any coordinating mechanism, they would reach their PEP thresholds at the same time, not alternately as in normal coordination. Nevertheless, the normal coordination is regained after very few steps (Fig 3b). The complete simulations of the 3-dimensional leg movements, which are not shown here, demonstrate that the model also maintains postural stability except for starts from some, for the stick insect (Dean and Wendler 1984), unusual starting configurations. As previously noted (Dean 1992a), intraleg mechanisms appear necessary to cope with these exceptions.

Hexapod model implementing the coordination mechanisms of the crayfish

Three coordinating mechanisms are found in the crayfish (Cruse and Müller 1986, Müller and Cruse 1991). All act between adjacent legs and influence the transition from return stroke to power stroke. Two act between neighboring ipsilateral legs. One of these is rostrally directed: for as long as the posterior leg performs a power stroke, it forces the anterior leg has to perform or continue a return stroke and also reduces the velocity of this return stroke. As a result, the return stroke is prolonged so that normal coordination is regained in the next step. The second ipsilateral mechanism is caudally directed. As the anterior leg nears the end of its power stroke or begins its return stroke, this mechanism exerts an increasing influence tending to terminate and thus shorten the return stroke of the posterior leg. This influence ends abruptly about 200 ms after the anterior leg begins its return stroke. The third mechanism acts between contralateral legs. It closely resembles the ipsilateral caudally directed influence, acting to shorten the return stroke of the receiver. In contrast to the ipsilateral mechanism, the contralateral influence is active during most of the cycle. Moreover, contralateral coupling is symmetric: it acts in the same way in both directions but one leg is often slightly dominant. Contralateral coupling is weaker than ipsilateral coupling.

These coordinating mechanisms were substituted for the stick insect algorithms in the hexapod model. The rostrally directed influence adjusts the return stroke velocity of the receiver so that it reaches its AEP at the same time as the sender reaches its PEP. Two versions of the caudally directed mechanism were employed; they differed only in the time delay. In the first version, the influence increases continuously during the power stroke of the sender once the sender retracts past a certain threshold but the effect on the receiver follows with a fixed delay of 200 ms, corresponding to the experimental results. Qualitatively, these coordinating mechanisms produce a regular spatio-temporal pattern for different walking speeds. When the pattern is perturbed by holding one leg stationary for some fraction of the step period, normal ipsilateral coordination is regained within three to four steps, allowing for the propagation to all ipsilateral legs (Fig 4a). Because contralateral coordination is weaker, recovery requires between one and five steps. However, when judged on the basis of postural stability, these coordinating mechanisms are much worse than those of the stick insect. One problem lies in a small range of phase relationships which are unaffected by either ipsilateral mechanism. In a simulation, the ease with which both natural and unnatural starting configurations can be tested, together with the unvarying retraction and protraction velocities, means that the unnatural and posturally unstable phase relationships in this range often occur. This deficiency can be rectified by increasing the delay in the caudally directed mechanism to 500 ms so it is active throughout the return stroke of the sender. In the crayfish, the

contralateral coupling tends to produce a single, asymmetric phase relationship between the two legs of a segment, but this influence is weak. In the simulation, this mechanism generally suffices to achieve postural stability with 5 steps at the most from any starting configuration (Fig 4b).

Hexapod model implementing the coordination mechanisms of the cat

Behavioral studies point to four coordination mechanisms in the slow-walking cat (Cruse and Warnecke 1992). As in the stick insect and crayfish, these act between adjacent legs. Two mechanisms affect the coordination of contralateral legs. The first prevents the receiver from starting a return stroke during the return stroke of the sender. This mechanism corresponds to the first ipsilateral mechanism described for the stick insect. The second increases the probability that the influenced leg starts a return stroke as the sender moves backward during its power stroke. This corresponds to the third ipsilateral influence of the stick insect. As in the other animals these contralateral influences are symmetric. The two ipsilateral mechanisms are asymmetric. In the first, the front leg is influenced to start a return stroke when front and hind legs have approached each other to a given distance, d . In the second, the hind leg is influenced to start a stance movement after the front leg has begun its return stroke.

The ipsilateral mechanisms as described tend to produce a brief moment when both ipsilateral legs are in the air. For the cat, this momentary instability is presumably resolved by the dynamics. For our hexapod model, which continually tests static stability, a delay must be introduced to allow the rear leg to end its return stroke before the front leg terminates its power stroke. Furthermore, implementing these mechanisms in the hexapod model showed that the ipsilateral mechanisms are not sufficient to ensure a biologically natural pattern of coordination. If d was large, then when the movement of one leg was disturbed, the ensuing step periods showed a regular alternation between short and long steps but never converged to a single value. This occurs because the criterion based on the relative distance does not specify that the approach of the two legs occur at a particular place. If d was small, the pattern of leg movements was regular with not alternation in step period, but the moment of instability at the transition between the power strokes of neighboring ipsilateral legs remained. The alternation in step periods could be removed by modifying the ipsilateral mechanism to make the value of d vary with the distance of the actual front leg position from a fixed value corresponding to the desired PEP. This provides a restoring influence which moves the relative phase toward a single, steady value. The postural instability could also be avoided by adding the condition that a leg can only begin a return stroke when the adjacent caudal leg is on the ground (Fig 5).

A further problem with implementing the cat mechanisms in the hexapod relates to geometrical differences. The efficiency of the rostrally directed ipsilateral mechanism depends upon the amount of spatial overlap in the ranges of the front and hind legs. In the geometrical model of the stick insect, this overlap is relatively small. In summary, the postural stability of the model is about the same as that of the stick insect model, but it has an unnatural origin in the fact that legs are made to slide over the ground if they have to wait to begin a return stroke (e.g. Fig 5).

Discussion

Although some improvements in the various coordination mechanisms is doubtless

possible, the results indicate that the mechanisms of the stick insect provide the best postural stability in the hexapod walker. This is perhaps not surprising. The crayfish, of course, has eight rather than six legs. Moreover, it normally lives under water, which reduces the requirement for support and probably slows falling in case of instability. On the other hand, because cats and other mammals have only four legs, they must rely on dynamic rather than static stability in fast locomotion. Although quadrupeds can maintain continuous static stability during slow walking, cats apparently use the dynamics even in this gait. In summary, the results show that the coordinating mechanisms of the cat and crayfish by themselves are not appropriate for a six-legged walking machine. One direction of future research is to consider whether they might be profitably combined with those of the stick insect.

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Figure legends

Fig. 1. (a) Schematic drawing of a stick insect showing the location of the body-centered coordinate system, (b) mechanical model of the stick insect: arrangement of the joints and their axes of rotation, (c) single leg of a stick insect showing the axes of rotation, (d) the joints of the simplified leg of the model.

Fig. 2. A model for the control of rhythmic leg movement using mutual feedforward inhibition and recurrent self-excitation of the motor units RS (return stroke) and PS (power stroke). Rostral-caudal leg position is obtained by integration of the low-pass filtered version of the output of RS and PS. Once the leg has reached a given threshold (AEP or PEP), the system switches from one state to the other. This oscillator controls the state and the forward-backward movement of the leg. The complete tarsus trajectory is determined by a trajectory generator, described in the text, and the corresponding joint angles are found by solving the inverse kinematics. The sensory input GC registers ground contact. See Cruse et al. (1993) for further explanation.

Fig. 3. Step pattern for the hexapod model using the coordination mechanisms of the stick insect. The traces illustrate the forward and backward movement of the tarsi (upward and downward changes in the traces, respectively) versus time. Legs are designated as left or right and numbered from front to back. (a) Movement of the legs when the power stroke of the right middle leg (R2) is interrupted for a short time (bar). (b) Illustration of how the coordination pattern is established when contralateral pairs of legs start from the same rostrocaudal position.

Fig. 4. Step pattern for the hexapod model using the coordination mechanisms of the crayfish. The format is the same as that of Fig 3. (a) Movement of the legs when the return stroke of the left rear leg (L3) is interrupted for a short time (bar). (b) Illustration of how the coordination pattern is established when contralateral pairs of legs start from the same rostrocaudal position.

Fig. 5. Step pattern for the hexapod model using the coordination mechanisms of the cat. The format is the same as that of Fig 3. (a) Movement of the legs when the return stroke of the left middle leg (L2) is interrupted for a short time (bar). (b) Illustration of how the coordination pattern is established when contralateral pairs of legs start from the same rostrocaudal position.

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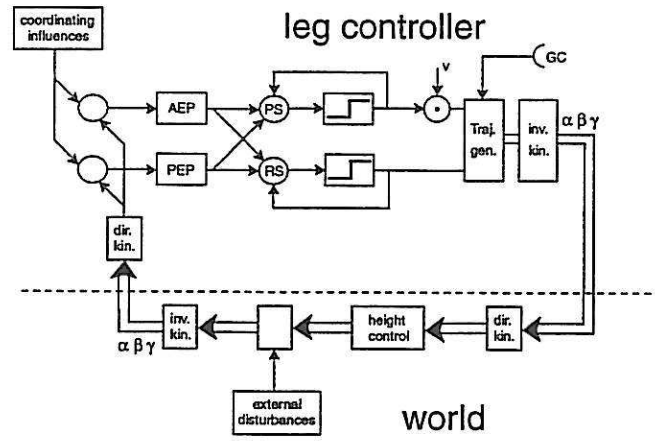
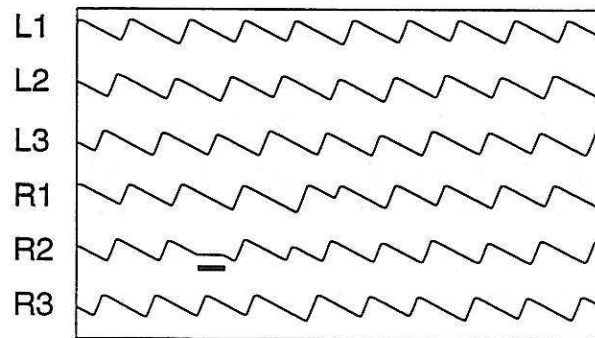
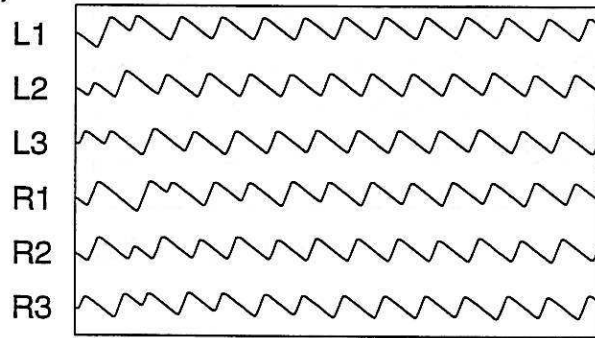


Figure 2

a)



b)



Time (Rel. Units)

Figure 3

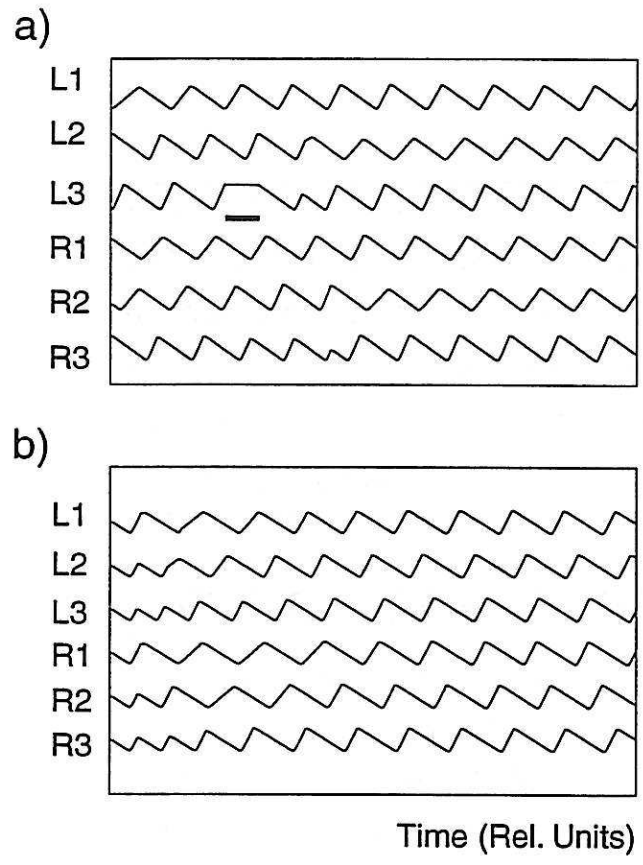
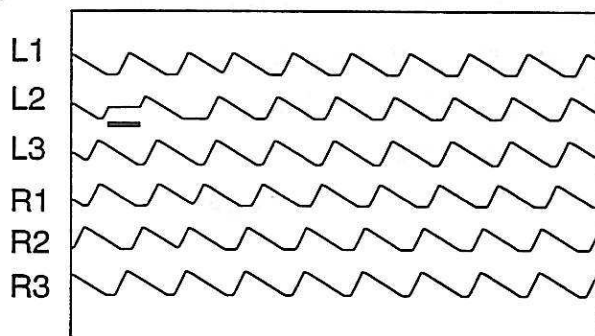
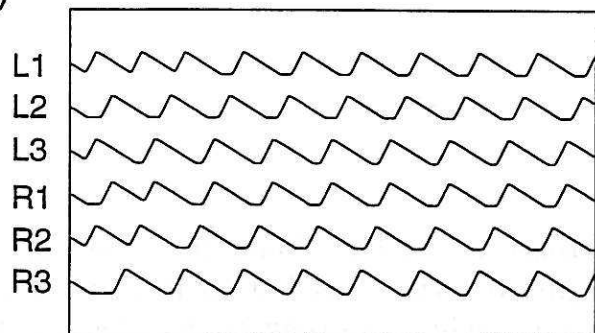


Figure 4

a)



b)



Time (Rel. Units)

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