

# Kinematic Model of a Stick Insect as an Example of a Six-Legged Walking System

Uwe Müller-Wilm  
University of Bielefeld\*

Jeffrey Dean  
University of Bielefeld\*

Holk Cruse  
University of Bielefeld\*

Hans-Jürgen Weidemann  
Technical University, Munich†

Jürgen Eltze  
Technical University, Munich†

Friederich Pfeiffer  
Technical University, Munich†

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*The model proposed here describes the control of the leg movement of a six-legged walking system. It is based on biological data obtained from the stick insect. The model represents a combined treatment of realistic kinematics and of biologically motivated, adaptive gait generation. In contrast to previous biologically motivated models, it includes realistic legs with three joints and natural geometry and, with some simplifying assumptions, describes the movement of the joints and the tarsi.*

*The results show that the information obtained from biological experiments can be incorporated into a model for a six-legged system that is able to walk at different speeds over irregular surfaces. The model shows a stable gait even when the movement of the legs is disturbed. The system can start walking beginning from arbitrary starting positions of the legs. Thus, the control system described here can be used to control a real walking machine.*

*Key words: Walking machine, leg coordination, motor control, stick insect*

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## 1 Introduction

Nature provides us with an immense variety of extremely skilled walkers. In the technical domain several walking machines exist, but these are much less skilled than real animals (for review, see Berns and Fiegert, 1991). This is presumably related to the obvious differences in the mechanical and control systems of walking machines compared to those found in animals. In recent years, much information has been collected on how animals control the movement of their legs during walking (Cruse, 1990).

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\* Department of Biologic Cybernetics, Faculty of Biology, University of Bielefeld, D-4800 Bielefeld 1, Germany

† Institute B of Mechanics, Department of Mechanical Engineering, Technical University, Postfach 202420, D-8000 Munich 2, Germany

The application of biological knowledge to technical development might lead to significant progress in constructing a walking machine. To reach this goal, some questions have to be answered. One question concerns the way the movement of the individual leg is controlled. A second question refers to the coordination between legs. From biological experiments, the following answers can be gleaned. First, each leg has its own control system that generates rhythmic step movements (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. Second, the coordination of the legs is not determined by a hierarchically superior control system. Instead, the gait pattern emerges from the cooperation of the separate control systems of the individual legs. This cooperation is based on different types of signals that convey information about the actual state of the sender to the control systems of the neighboring legs. The receiving system collects this information and, on this basis, decides on its own action. This distributed architecture results in a very stable gait but nevertheless allows the whole system to react flexibly to disturbances. At the present time, no detailed information is available concerning control of the individual leg joints of the walking animal and control of the dynamics.

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 the stick insect. Rather we introduce simplifications or, where not enough experimental information exists, use ad hoc assumptions to make a working model.

The properties of these biological solutions have already been incorporated into several qualitative and quantitative models (Cruse and Graham, 1985; Dean, 1991b,c, 1992a,b; Cruse, 1976a; Cruse, Riemenschneider, and Stammer, 1989). However, these models do not consider the natural movement of the leg and the coordination of movement at the three leg joints. They consider only the horizontal or vertical projection of the connection between the tip of the leg, the tarsus, and the basis of the leg, the thoracic-coxal joint. Such models exist for both the control of individual leg movement (Bässler, 1977; Cruse, 1985a) and the coordination between legs.

The movement of the individual leg consists of two parts, the power stroke and the return stroke. 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 is moved in the direction of walking to begin a new power stroke. In the literature on stick insects, 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) (Bässler, 1972). Either as a hypothesis or on the basis of experimental results, several

authors (Wendler, 1968; Bässler, 1977; Graham, 1972; Cruse, 1985b) proposed the idea that the transition from one mode 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 criterion will not be considered here (Bässler, 1977; Cruse, 1983; Dean, 1991a).

Owing to possible temporal delays in the system, the position at which the leg actually touches down or lifts off the ground does not necessarily correspond to the criterion position. To distinguish these positions, we call the criterion positions *threshold AEP* (thAEP) and *threshold PEP* (thPEP) and retain AEP and PEP for the positions of the leg when ground contact begins and ends, respectively. As the leg might continue to move somewhat to the rear after leaving the ground at the end of the power stroke, the absolute PEP where the leg changes the direction of movement might differ from both of the above. The same is possible at the end of the return stroke. These turning points will be called *absolute posterior* or *anterior extreme position* (aPEP, aAEP), respectively. (Many behavioral measurements of insects do not distinguish clearly between extreme position (e.g., AEP) and actual extreme position (e.g., aAEP) but, in the insect, the difference does not appear to be large.) As will be shown later, in our model the transition to return stroke (PEP) equals the threshold position (thPEP), but all other position values are different in general.

Several authors presented models that describe interleg coordination of these relaxation oscillators (for review, see Cruse and Graham, 1985). More recently, Müller and Cruse (1991), using the crayfish, and Dean (1991b,c 1992a,b), using the stick insect, have published model simulations based on experimental evidence of several coordinating mechanisms found in these animals. As mentioned, all these models concern only the projection of the legs in the horizontal plane—that is, they consider, more or less, only the movement parallel to the long axis of the body. Another model considers only the projection in the vertical plane. This model was proposed to describe the control of body height for the standing (Cruse et al., 1989) and the walking animal (Cruse, 1976a). Based on experimental results, this model assumes that each leg controls the distance between body and leg tip in the sense of a proportional feedback controller (i.e., one with springlike properties). This means that the properties of the individual controllers and the mechanical connections of the legs via the rigid body and the ground are sufficient to explain the system's behavior. No neuronally mediated interactions are necessary. Using this simple method, this model successfully describes standing and walking on irregular surfaces.

Besides the intraleg step generator and interleg coordination, a third problem concerns the true kinematics of leg movement and the dynamics of joint control. Pfeiffer, Weidemann, and Danowski (1990) presented a mechanical model of the stick insect in the form of a rigid multibody system consisting of a central body and

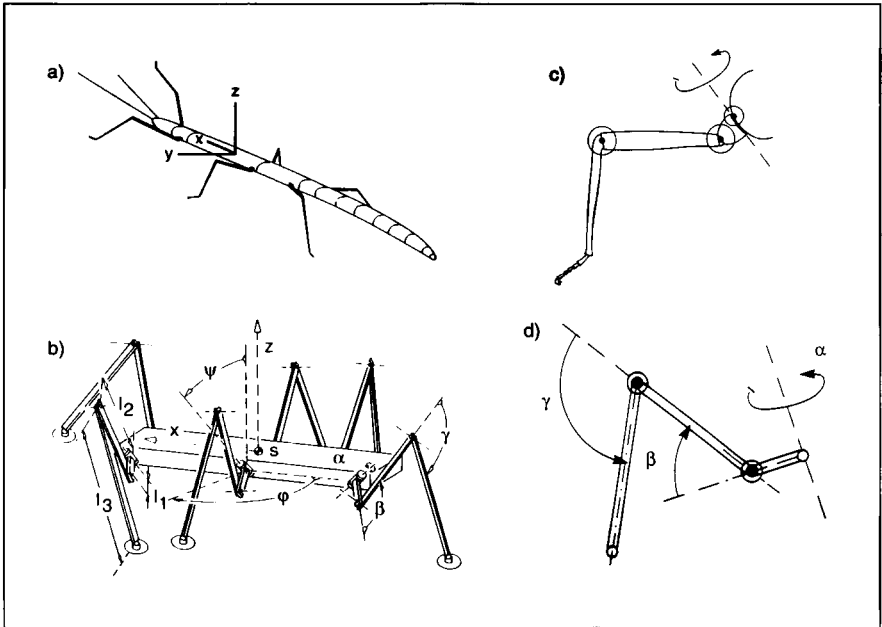
six legs with three segments each. Using this model, they computed the kinematics and dynamics of the system under various assumptions concerning the distribution of the forces produced by the legs. These assumptions were necessary to compute the otherwise underconstrained system. When certain criteria were optimized, the forces applied by the animal to the ground agree qualitatively with those calculated using the model. This result provides insight into the control strategy used by the animal. It also supported the validity of the mechanical model.

However, to simplify the calculation, this model did not contain the natural control structures previously described. Rather, the model “walked” in a fixed kinematic pattern, repeating the coordination and leg movement in a step measured from an animal. To achieve the flexibility of biological systems, the model must be changed to adopt some of the solutions found in animals.

The goal of the present research is not only to combine the coordination and height control model to form a unified model that can walk over irregular surfaces and automatically correct for disturbances but also to make the model more realistic by simulating the movements of a real leg. As in the model of Pfeiffer et al. (1990), each leg is represented by three segments that are connected to each other and to the body by three simple hinge joints. Contact with the ground is assumed to occur at a nonslipping 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. 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 up-down movement is performed at the coxa-trochanter joint.

## 2 Model

The movement of the individual leg is controlled in the following way. As only straight walking is considered, to simplify the model we assume that the tarsus always moves in a vertical plane parallel to the long axis of the body. The movement in the direction of the  $x$  axis (see Fig. 1) (i.e., the axis parallel to the long axis of the body), is controlled according to the following mechanism (Cruse, 1985a): The controller switches from one state to the other (return stroke, power stroke) when the tarsus has reached a given position (thAEP or thPEP, respectively). The state (Fig. 2a, upper trace) in the model is represented by a positive (return stroke) or negative (power



**Figure 1**

(a) Schematic drawing of a stick insect. The tripod shows the body coordinates. (b) Mechanical model: 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.

stroke) value. During each state, the movement of the tarsus is controlled by a velocity-controlling feedback system. Here we assume that the reference input to this velocity controller does not switch like the step function of the state variable but rather corresponds to a low-pass filtered version of the state value and thus follows an exponential function at the change in state (see Fig. 2a). This causes the change in direction of movement to be less abrupt and therefore more realistic. At the same time, this means that the actual turning point in the tarsus movement (aAEP, aPEP) occurs somewhat after the tarsus reaches the thAEP or thPEP.

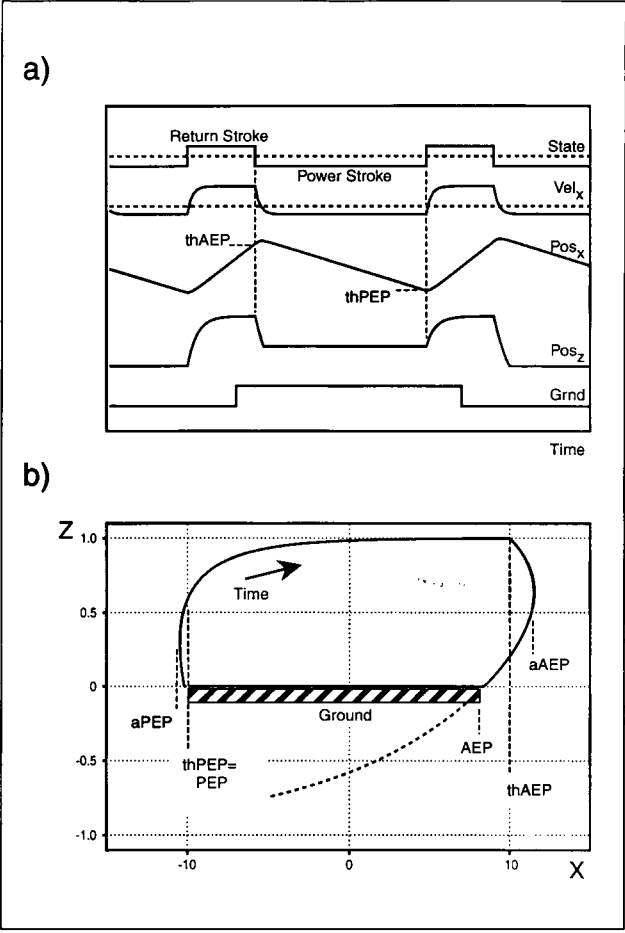
When the movement of the real leg is simulated, the length of the leg sets an absolute limit to retraction. This problem was not considered in the earlier model calculations. Dean (1991a) considered the problem and speculated that the naturally occurring variation in retraction velocity is nature's way of meeting this constraint. Obviously, a fully extended leg that maintains a fixed contact with the ground would brake the forward motion of the insect. Since the present simulation does not include the dynamics, two alternative strategies have been used. First, a fully extended leg is excited to begin a return movement if no neighboring leg is in return stroke. Second,

**Figure 2**

Control of the movement of the tarsus. (a) Tarsus position and velocity versus time. The five traces show, from above:

(1) internal state (power stroke–return stroke); (2) tarsus movement parallel to the  $x$  axis: reference input to the velocity controller; (3) position of the tarsus; (4) tarsus position parallel to the  $z$  axis, which is terminated when a touchdown signal records ground contact; (5) height of the ground. At the beginning of the second power stroke, the leg steps on an obstacle.

(b) Side view of the tarsus movement. ( $thAEP, thPEP =$  position thresholds that, when reached, change the internal state of the control system;  $AEP, PEP =$  tarsus position when the leg reaches or leaves the ground;  $aAEP, aPEP =$  anterior and posterior turning point, respectively.) See Figure 1 for definition of the coordinates. For the sake of clarity, the movement in forward direction during the downward movement at the end of the return stroke is shown with a larger amplitude than in the actual model.



if one or more neighbors are in return stroke, the fully extended leg drags along the ground until the return stroke can begin. Bässler (1977) describes observations in the stick insect that are consistent with this latter behavior. Full extension can also occur during the return stroke if the target leg is far forward. In this case, the  $thAEP$  is adjusted to cause a transition to power stroke.

During the return stroke, the vertical position of the tarsus (i.e., the movement along the  $z$  axis [see Fig. 1]) is calculated in the following way: Like the reference

signal for the velocity controller, that for the height controller is a low-pass filtered form of the state signal. However, for the change from power stroke to return stroke, the state signal is rectified before low-pass filtering. This causes the leg to lift off the ground immediately at the PEP, which therefore corresponds to the thPEP. At the change from return stroke to power stroke, the state signal is not rectified. Thus, the leg can move beyond the zero level (i.e., below the level where the ground is to be expected when walking on a horizontal plane). This enables the leg to find ground contact when stepping in a hole. As is shown in Figure 2, the tarsus moves downward after having reached the thAEP. The zero velocity in the  $x$  direction is reached somewhat above the ground level. This position corresponds to the anterior turning point or aAEP. The actual  $x$  position of ground contact depends on the height of the surface. At the end of the return stroke, the tarsus reaches the retraction velocity, which corresponds to that of the power stroke only at a height very much below the ground level at the start of the return. Thus, the tarsus usually touches the ground with a forward velocity that is slower than the velocity of the body relative to the ground. This means that, at the beginning of the power stroke, the leg acts to brake the forward motion of the body. This too corresponds to findings in stick insects (Graham, 1972; Cruse, 1976b).

For an irregular surface, the actual end of the return stroke has to be determined by a touchdown signal that triggers the transition to power stroke. During the power stroke, the height is then determined by a proportional feedback controller. This means that the height is controlled as if the leg were replaced by a spring with a given elasticity. The actual height of the body, of course, depends on the total number of legs in power stroke, their position relative to the body, and the form of the surface. This mechanical problem is not a part of the control structure of the walking machine but has to be included in our simulation of walking over irregular surfaces.

Once the trajectory of the tarsus relative to the body is determined, the values of the joint angles can be calculated. This is done here using the inverse kinematic solution described by Pfeiffer et al., (1990). The first and second derivatives of the joint angles can also be calculated, but these are not used in the present kinematic model.

Altogether, six different types of coupling mechanisms have been found for the stick insect (for review, see Cruse, 1990). Two of these—one that serves to correct errors in leg placement and the other having to do with distributing propulsive force among the legs—will not be considered here. The other four mechanisms were successfully implemented in an earlier model (Dean 1991b,c, 1992a,b), which formed the basis for the coordination module in the present model. The beginning of a return stroke, and therefore the end point of a power stroke (thPEP), 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 on the position of the next rostral leg. The beginning of the power stroke (thAEP) is modulated by a single caudally directed influence depending on the position of the next rostral leg (targeting behavior). Influences (2) and (3) are also active between contralateral legs.

### 3 Results

The model shows a proper coordination of the legs when walking at different speeds on a horizontal plane. The movement of the tip of all six legs, projected onto the  $x$  axis, is shown in Figures 3 and 4b. With increasing walking speed, the typical change of coordination from the tetrapod to the tripod gait is found (Graham, 1972).

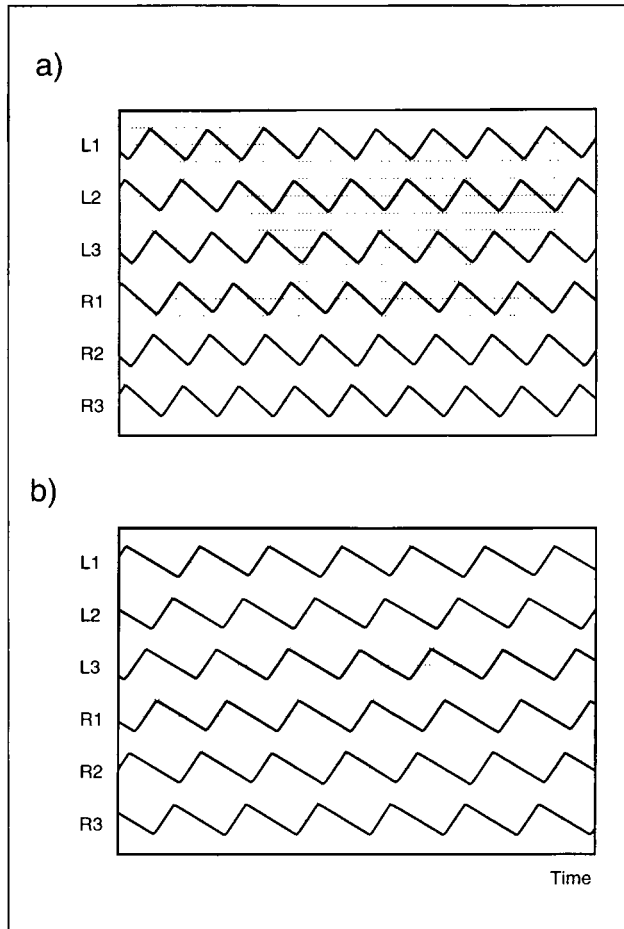
The coordination pattern is very stable. Figure 4a demonstrates the brief interruption of movement of the right middle leg during the power stroke. As can be seen, normal coordination is regained immediately at the end of the perturbation. A critical test of the stability of the coordination pattern is to consider the behavior of the model when starting to walk from arbitrary leg positions. The start is particularly difficult when contralaterally neighboring legs begin with the same  $x$  position. In this case, contralaterally neighboring legs reach the PEP at the same time, whereas in normal coordination they should alternate. Figure 4b shows such a case, and it can be seen that normal coordination is regained after only a small number of steps. The three-dimensional plot, which is not shown here, demonstrates that the model maintains vertical stability as well.

The height control can be seen in Figure 5. Here the model has to step over an obstacle. This figure depicts both top (upper part) and side views (lower part) and represents two sections of a video film. Different frames are superimposed here to give a better impression of the movement of the whole model. The figure also indicates that the leg glides over the ground for a short time after touchdown. This gliding would correspond to a decelerating force if the tarsi were fixed to the substrate. Figure 6 shows the time course of the leg angles for the hind leg when the model walks on a horizontal plane.

### 4 Discussion

The model proposed here represents a combined treatment of realistic kinematics and biologically motivated, adaptive gait generation. In contrast to earlier biologically motivated models, it contains the joint geometry and, with some simplifying





**Figure 3**

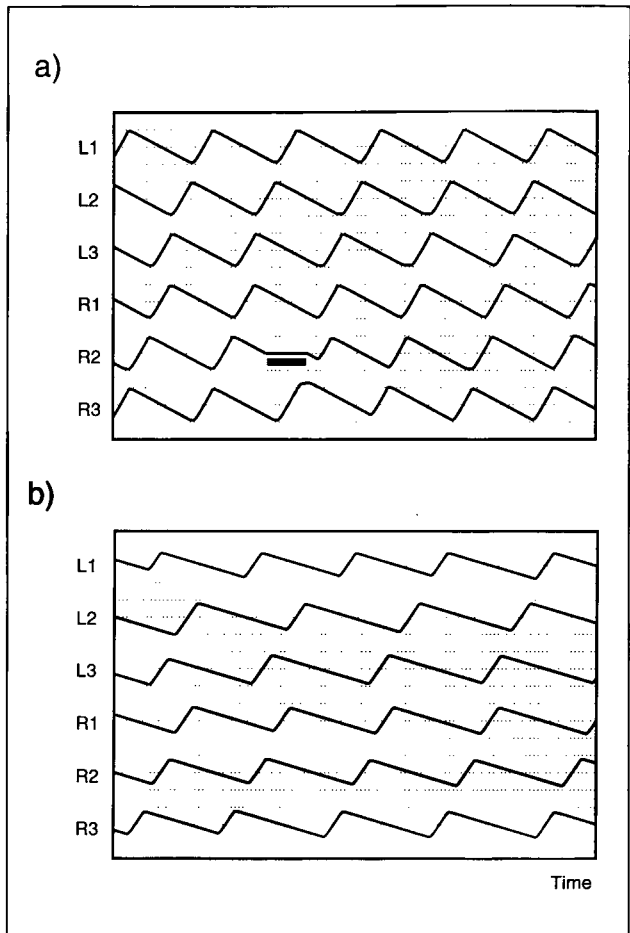
Movement of the leg tip at two different walking speeds. Abscissa is time, ordinate is leg position. (a) high velocity. (b) middle velocity. (A slow walk is presented in Figure 4b.) Leg position is shown here as the position of the leg tip projected onto the  $x$  direction (i.e., the direction parallel to the long axis of the body). Upward deflection means return stroke, downward deflection means power stroke. The legs are numbered from front to rear. ( $R$  = right legs;  $L$  = left legs.)

assumptions, describes the movement of the joints and the tarsi. The movement of the tarsis is made more realistic in the sense that the velocity profile is rounded at the transition points. The results show that the information obtained from biological experiments can be incorporated into a six-legged model that is able to walk at different speeds over irregular surfaces. The model displays a stable gait even when the movement of the legs is disturbed. The system can start walking beginning from arbitrary leg positions. Thus, the control system described here can be used to control a real walking machine.

Two restrictions in the model may be alleviated through further studies on biological systems. First, in this model, the movement of the tarsus is restricted to a vertical

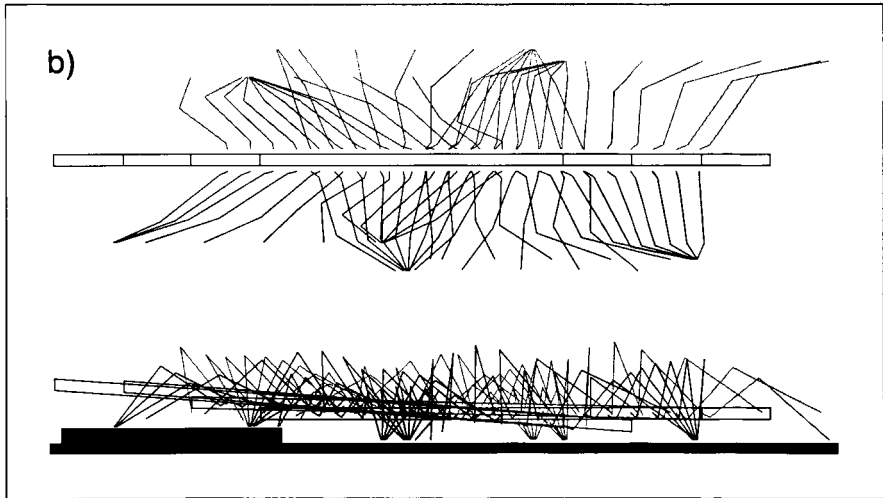
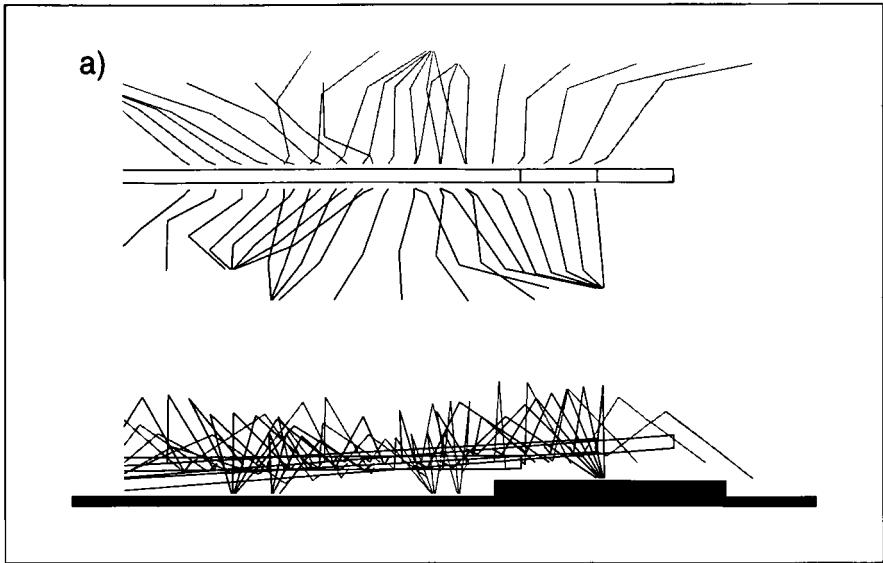
**Figure 4**

Stability of the coordination pattern.  
(a) Movement of the legs when the power stroke of the right middle leg is interrupted for a short time. (b) The legs start with contralateral neighboring legs at the same position. Slow walk. (R = right legs; L = left legs.)

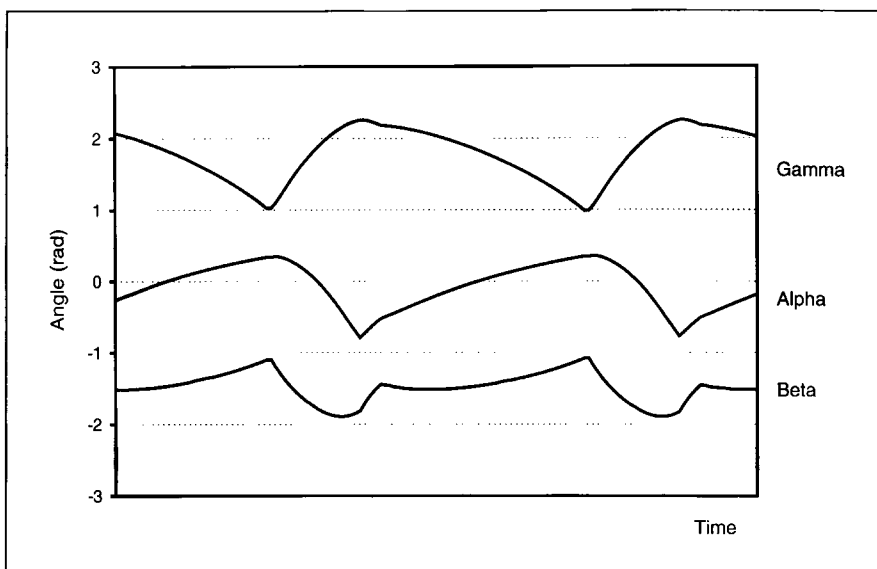


plane parallel to the long axis of the body. Preliminary investigations (Cruse, 1976b; Jander, 1985) show that this is not truly the case and it might be advantageous to introduce the actual feature into the model. A second restriction, related to the first, is that no effort was made to simulate curve walking. Although some information is known about actual tarsus trajectories (Cruse, 1976b; Jander, 1985), both questions require further biological investigation.

Two additional points, not considered here, are necessary to construct a control system for an actual walking machine. First, our model does not take into account the dynamics of the system—that is, the forces needed to perform the described movement. Second, we did not consider the mechanical coupling of the legs in



**Figure 5** Two sections of superimposed frames from a video film, showing the model walking over an obstacle. Top view (upper) and side view (lower) are depicted. Leg position is shown only for every fifth frame; body position is shown only for every fifteenth frame. (a) The model approaches the obstacle and places the front legs onto it. (b) The model leaves the obstacle. The left hind leg steps onto the obstacle, whereas the right hind leg touches the ground beyond the obstacle.



**Figure 6**

Time course of the three joint angles of a hind leg during an undisturbed walk. For definition of the angles, see Figure 1. Abscissa is time in relative units; ordinate is angle in radians.

power stroke through the substrate and the resulting effects when the legs attempt to move with different velocities. This was not necessary in an earlier model (Pfeiffer et al., 1990) in which the retraction velocity of the tarsi was assumed to be constant and equal for all legs. In our model, the velocity of the tarsi in the  $x$  direction, relative to the body, at the beginning of the power stroke might be somewhat smaller than the velocity of the body relative to the ground. This would cause a deceleration of the body, which is not taken into account in our simulation. For our purpose, we consider this discrepancy tolerable because we plan to use a soft velocity controller for the movement in the  $x$  direction.

Two other simplifications in this model are less important. One is the fact that the height of an obstacle is measured in body coordinates, which are only correct if the long axis of the body is horizontal. When the long axis is inclined, which generally is the case when walking over an irregular surface, the actual height of this obstacle does not correspond exactly to the calculated height. The exact calculation of these world parameters was not implemented for two reasons. First, this problem is not part of the control structure of the actual walking machine. Second, the height controllers in the individual legs of the walking animal are assumed here to be linear, though in fact, as far as is known from standing animals, they ought to have a nonlinear, sigmoid characteristic. This discrepancy alone would result in a deviation

in the behavior of the model when large inclinations occur. Another simplification is that, as mentioned earlier, the stick insect uses essentially only one of the two axes of rotation of the basal joint. As the stick insect does not use the vertical degree of freedom, it too is omitted from this model.

Finally, a general property of the model should be mentioned that has not yet been explicitly expressed. The design of the control system is based on the assumption that planning occurs using tarsus positions as the internal variables. These cannot be measured by proprioceptors, as joint angles can, but must be computed. In other words, this model is based on the assumption that the motor system of the stick insect “plans” in a world that consists of tarsus positions rather than in a world consisting of joint angles. In robotics, this is often discussed as the *work space–joint space alternative* (e.g., Hollerbach and Atkeson, 1987). A network simulation of interleg coordination in the targeting behavior (Dean, 1990) indicates that planning in joint coordinates may be simpler and sufficiently exact. One goal of our future research is to investigate whether planning in joint space is equally feasible for other coordination mechanisms as well.

### Acknowledgments

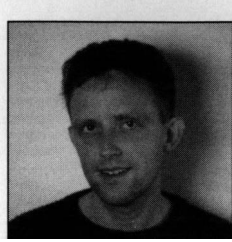
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## About the Authors



### **U. Müller-Wilm et al.**

U. Müller-Wilm (pictured at left) studied Biology at the University of Bielefeld, Germany, where he works together with J. Dean and H. Cruse in the Department of Biological Cybernetics. They study the motor control of insects, crustaceans, and vertebrates using experimental and neurophysiological techniques as well as computer simulations. H.-J. Weidemann, J. Eltze, and F. Pfeiffer work in the Mechanics Department B of the Faculty of Mechanical Engineering at the Technical University Munich, where walking dynamics and control are investigated using computer simulations and experimental testing.