Control of Hexapod Walking in Biological Systems

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Abstract. To investigate walking we perform experimental studies on animals in parallel with software and hardware simulations of the control structures and the body to be controlled. In this paper, we will first describe the basic behavioral properties of hexapod walking, as the are known from stick insects. Then we describe a simple neural network called Walknet which exemplifies these properties and also shows some interesting emergent properties. The latter arise mainly from the use of the physical properties to simplify explicit calculations. The model is simple, too, because it uses only static neuronal units. The system is currently tested using an adapted version of the robot TARRY II.

Keywords: walking, stick insect, decentralized control, Walknet, positive feedback

1 Walking: a nontrivial behavior

From a cognitive standpoint, walking seems to be rather uninteresting because it appears to be a fairly automatic behavior. We do not have to think consciously about moving the joints when walking. Nevertheless, we will argue that walking in a natural environment requires considerable ,,motor intelligence“ and can be regarded as a paradigm for control of behavior in general. First of all, walking, as almost all behavior, has to deal with redundancy. In most biological systems for motor control, particularly those concerned with walking, the number of degrees of freedom is normally larger than that necessary to perform the task. This requires the system to select among different alternatives according to some, often context-dependent optimization criteria, which means that the system usually has to have some autonomy. Therefore, the experimenter does not have direct control of some important inputs to the motor system. Further, such natural systems are physical systems "situated" in complex, often unpredictable environments, which means that any movement may be modified by the physics of the system and the environment. In turn, adapting to real environments requires the use of sensory information about the environment and the results of the system's actions. Together, these two factors create a loop through the environment which means that the actual behavior is determined by the properties of the environment as well as those of the walking system. Despite these experimental and theoretical difficulties, the complexity makes the study of motor mechanisms especially challenging, particularly because they illustrate to a high degree the task of integrating influences from the environment, mediated through peripheral sensory systems, with central processes reflecting the state and needs of the organism. In a walking insect at least 18 joints, three per leg, have to be controlled. Because the environment may change drastically from one step to the next, and even the geometrical properties of the body may change, the control of walking is all but a trivial task. Traditional technical solutions take sensory input into account only to a small degree and usually use hierarchically structured control architectures. In both respects these solutions differ strongly from solutions found by biological systems. Most probably, this difference is the main reason for the failure of traditional solutions when being tested in a realistic environment. Biologically inspired autonomous systems appear to be the solution when one searches for systems being able to act in unpredictable and hostile environments.

The control system explained here consists of a number of distinct modules which are responsible for solving particular subtasks. Some of them might be regarded as being responsible for the control of special ,,microbehaviors“: for example, a walking leg can be regarded as being in one of two states, namely performing a swing movement or a stance movement. During stance, the leg is on the ground, supports the body and, in the forward walking animal, moves backwards with respect to the body.

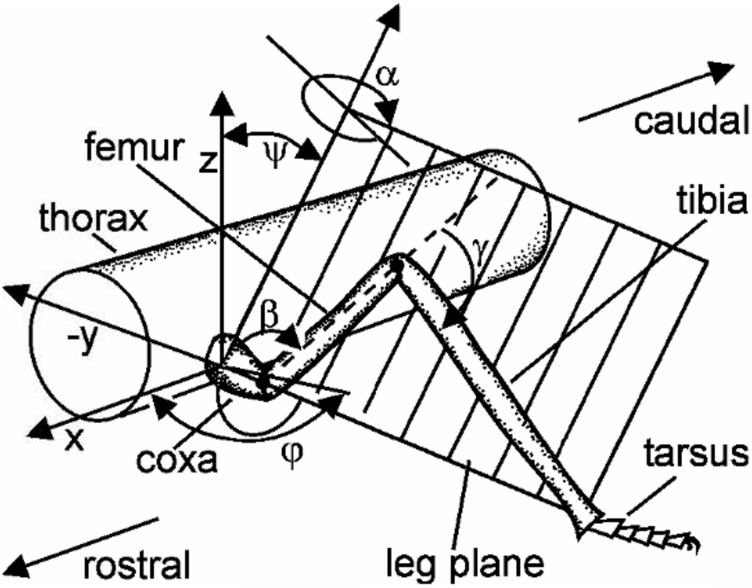

Fig. 1. Sketch of a stick insect leg showing the arrangement of the joints and their axes of rotation.

During swing, the leg is lifted off the ground and moved in the direction of walking to where it can begin a new stance. These two ,,microbehaviors“ are mutually exclusive. A leg cannot be in swing and in stance at the same time, a situation also holding for many ”macrobehaviors” such as fight or flight, for instance. Therefore, the control structure has to include a mechanism for deciding whether the swing or the stance module is in charge of the motor output. To solve this problem, a simple network, based on positive feedback, is used. This network works like a ,,two-way“ subsumption system [1], although there is no direct suppression and subsumption influence. Note that no central oscillator is used.

2 Control of the step rhythm of the individual leg

As mentioned, the step cycle of the walking leg can be divided into two functional states, stance and swing. The anterior transition point, i.e., the transition from swing to stance in the forward walking animal, is called the anterior extreme position (AEP) and the posterior transition point is called the posterior extreme position (PEP). Differences in the constraints acting during the two states and in the conditions for their termination suggest that the leg controller consists of three separate control networks. Two low-level networks, a swing network and a stance network, control the movement of the leg during swing and stance, respectively. The transition between swing and stance is controlled by a selector network. The swing network and the stance network are always active, but the selector network determines which of the two networks controls the motor output.

3 Control of the selector network: coordination between legs

The pattern of leg movement in insect walking is usually described as tripod or tetrapod gait (Fig. 2). These terms may suggest a rigid central control structure. However both gaits should rather be considered as extremes of a continuum (e.g. [2]). Actually very different step patterns can be observed e.g. after a brief disturbance of the movement of a single leg or when animals start walking from different leg configurations [3, 4]. Insect gaits may therefore better be described by the term ”free gait” [5]. The usually observed tripod or tetrapod patterns represent limit cycle solutions that are only apparent in undisturbed situations [6]. For insects and crustaceans, it has been shown that a small number of local rules acting between neighboring legs suffice for the emergence of different gaits and the recovery from different disturbances. In the following these rules will be summarized briefly.

In all, six different coupling mechanisms have been found in behavioral experiments with the stick insect (Fig. 5a). One mechanism serves to correct

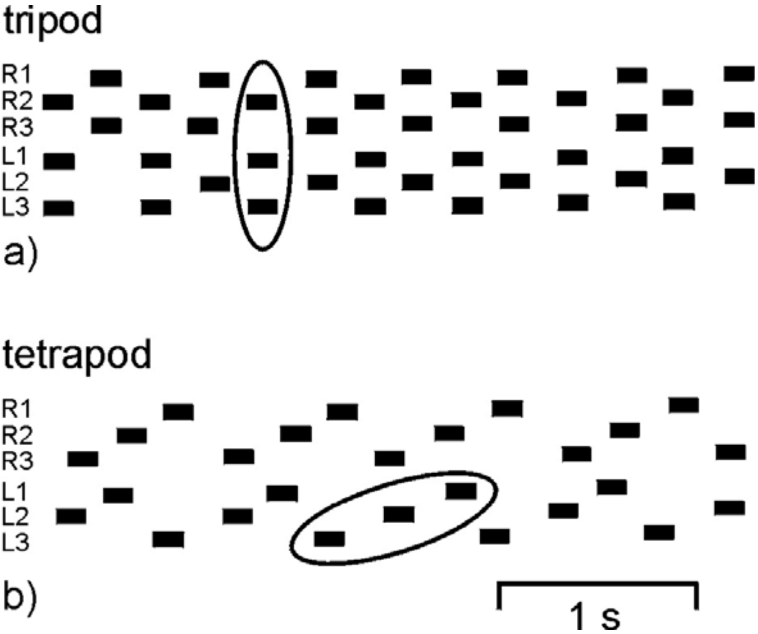

Fig. 2. The step patterns of a tripod (a) and a tetrapod (b) gait as produced by a stick insect. The latter is also referred to as a wave gait. The six traces represent the six legs. Black bars correspond to swing movement. Legs are designated as left (L) or right (R) and numbered from front to rear. Left and right legs on each segment (e.g., L1 and R1) always have a phase value of approximately 0.5. The phase value of adjacent ipsilateral legs (e.g., L1 and L2) is 0.5 in the tripod gait but differs in the tetrapod gait (after [2]).

errors in leg placement; another has to do with distributing propulsive force among the legs. The other four are used in the present model. The beginning of a swing movement, and therefore the end-point of a stance movement (PEP), is modulated by three mechanisms arising from ipsilateral legs: (1) a rostrally directed inhibition during the swing movement 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. Influences (2) and (3) are also active between contralateral legs. The end of the swing movement (AEP) in the animal 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–the placement of the tarsus at the end of a swing close to the tarsus of the adjacent rostral leg. These signals are used be the selector network to decide on swing or stance. Mechanisms (1) to (3) are illustrated in Fig. 3.

4 Control of the swing movement

The task of finding a network that produces a swing movement is simpler than finding a network to control the stance movement because a leg in swing is mechanically uncoupled from the environment and therefore, due to its small mass, essentially uncoupled from the movement of the other legs.

A simple, two-layer feedforward net with three output units and six input units can produce movements (see Fig. 5b, swing net) which closely resemble the swing movements observed in walking stick insects [7]. The inputs correspond to three coordinates defining the actual leg configuration and three defining the target–the configuration desired at the end of the swing. In the simulation, the three outputs, interpreted as the angular velocities of the joints, $\mathrm{d}\alpha/\mathrm{dt}$, $\mathrm{d}\beta/\mathrm{dt}$, and $\mathrm{d}\gamma/\mathrm{dt}$, are used to control the joints. The actual angles (for definition see Fig. 1) are measured and fed back into the net.

Through optimization, the network can be simplified to only 8 (front and middle leg) or 9 (hind leg) non-zero weights (for details see [8]). We believe this represents the simplest possible network for the task; it can be used as a standard of comparison with physiological results from stick insects. Despite its simplicity, the net not only reproduces the trained trajectories, it is able to generalize over a considerable range of untrained situations, demonstrating a further advantage of the network approach. Moreover, the swing net is remarkably tolerant with respect to external disturbances. The learned trajectories create a kind of attractor to which the disturbed trajectory returns. This compensation for disturbances occurs because the system does not compute explicit trajectories, but simply exploits the physical properties of the world. The properties of this swing net can be described by the 3D vector field in which the vectors show the movement produced by the swing net at each tarsus position in the workspace of the leg. Fig. 4 shows the planar projections of one parasagittal section (a), and one horizontal section (b) through the work space.

This ability to compensate for external disturbances permits a simple extension of the swing net in order to simulate an avoidance behavior observed in insects. When a leg strikes an obstacle during its swing, it initially attempts to avoid it by retracting and elevating briefly and then renewing its forward swing from this new position. In the augmented swing net, an additional input similar to a tactile or force sensor signals such mechanical disturbances at the front part of the tibia (Fig. 5b, r1) or the femur (Fig. 5b, r2). These units are connected by fixed weights to the three motor units in such a way as to produce the brief retraction and elevation seen in the avoidance reflex. Other reflexes can been observed when the tibia is mechanically stimulated laterally (r3) or when the femur is touched dorsally (r4). These reflexes have been implemented in an analogous manner (Fig. 5b).

In the model, the targeting influence reaches the leg controller as part of the input to the swing net (Fig. 5b). These signals can be generated by a simple feedforward net with three hidden units and logistic activation functions

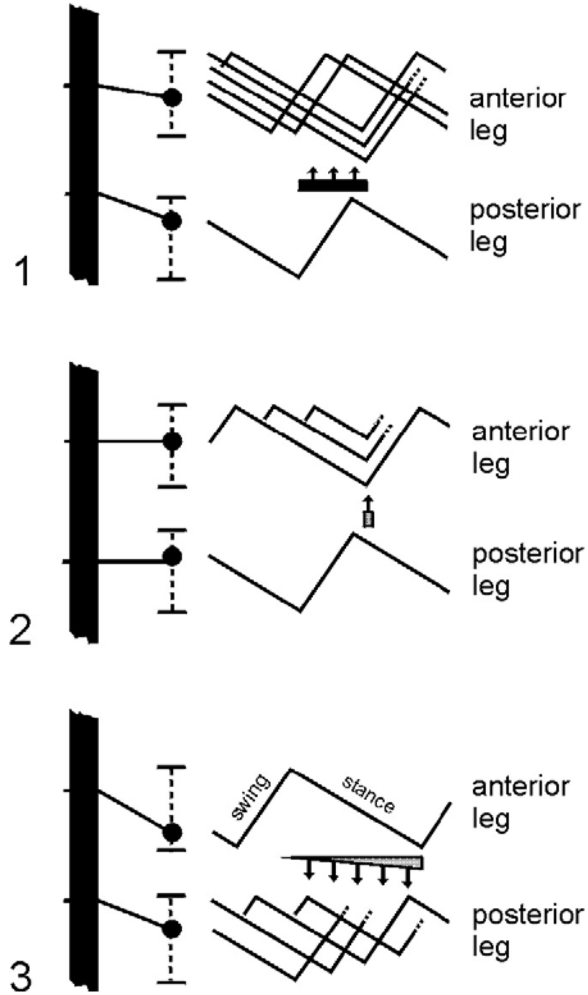

Fig. 3. Illustrations of the mechanisms 1 to 3 (see Fig. 5a) as shown from above to below.

(Fig. 5b, "target net") which directly associates desired final joint angles for the swing to current joint angles of a rostral leg such that the tarsus of the posterior leg is moved in the direction of that of the anterior leg. Compared to a first version [9] the new target net has direct connection between the input and the output layer. There is no explicit calculation of either tarsus position. Physiological recordings from local and intersegmental interneurons [10] support the hypothesis that a similar approximate algorithm is implemented in the nervous system of the stick insect.

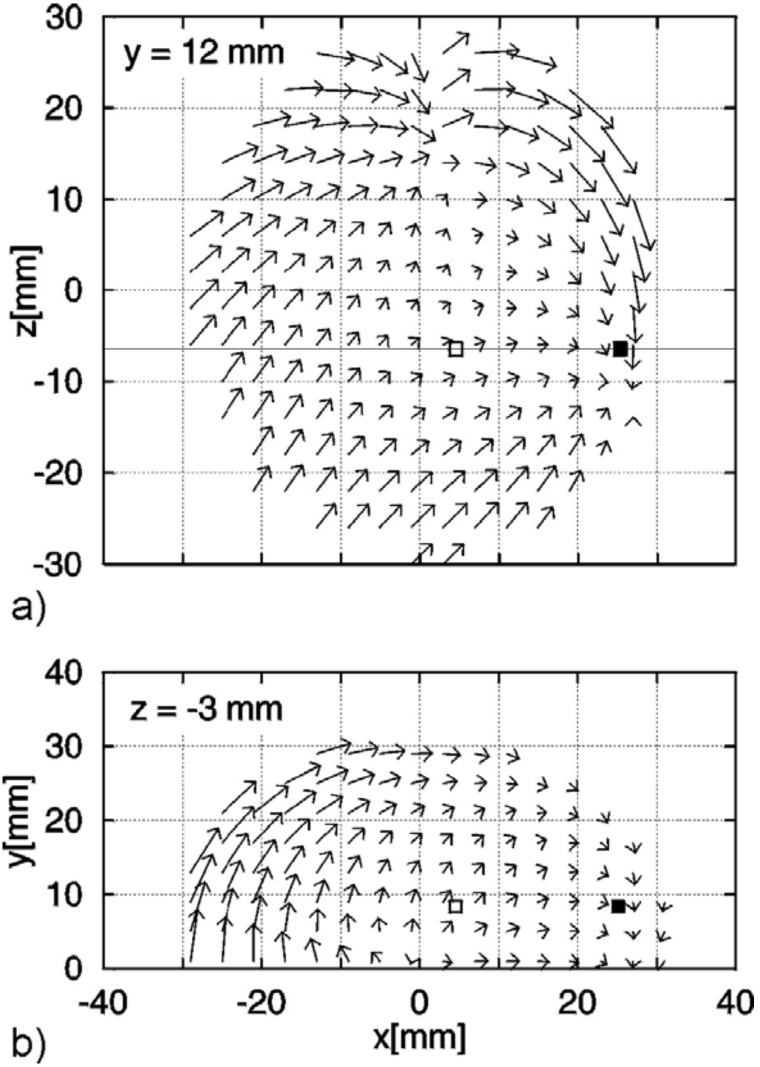

Fig. 4. Vector field representing the movement of the tarsus of a left front leg produced by the swing net. (a) Projection of a parasagittal section (y = 12 mm, for coordinates see Fig. 1). (b) Projection of a horizontal section slightly below the leg insertion (z =-3mm). Left is posterior, right is anterior. The average posterior extreme position (start of swing movement) and of the average anterior extreme position (end of swing movement) are shown by an open square and by a closed square, respectively.

5 Control of the stance movement and coordination of supporting legs

For the stance movement, simple solutions can be found for straight walking on a flat surface [11]. In more natural situations, the task of controlling the stance movements of all the legs on the ground poses several major problems. It is not enough simply to specify a movement for each leg on its own: the mechanical coupling through the substrate means that efficient locomotion requires coordinated movement of all the joints of all the legs in contact with the substrate, that is, a total of 18 joints when all legs of an insect are on the ground. However, the number and combination of mechanically coupled joints varies from one moment to the next, depending on which legs are lifted. The task is quite nonlinear, particularly when the rotational axes of the joints are not orthogonal, as is often the case for insect legs and for the basal leg joint in particular. A further complication occurs when the animal negotiates a curve, which requires the different legs to move at different speeds.

In machines, these problems can be solved using traditional, though computationally costly, methods, which consider the ground reaction forces of all legs in stance and seek to optimize some additional criteria, such as minimizing the tension or compression exerted by the legs on the substrate. Due to the nature of the mechanical interactions and inherent in the search for a globally optimal control strategy, such algorithms require a single, central controller; they do not lend themselves to distributed processing. This makes real-time control difficult, even in the still simple case of walking on a rigid substrate.

Further complexities arise in more complex, natural walking situations, making solution difficult even with high computational power. These occur, for example, when an animal or a machine walks on a slippery surface or on a compliant substrate, such as the leaves and twigs encountered by stick insects. Any flexibility in the suspension of the joints further increases the degrees of freedom that must be considered and the complexity of the computation. Further problems for an exact, analytical solution occur when the length of leg segments changes during growth or their shape changes through injury. In such cases, knowledge of the geometrical situation is incomplete, making an explicit calculation difficult, if not impossible.

Despite the evident complexity of these tasks, they are mastered even by insects with their "simple" nervous systems. Hence, there has to be a solution that is fast enough that on-line computation is possible even for slow neuronal systems. To solve the particular problem at hand, we propose to replace a central controller with distributed control in the form of local positive feedback [8]. Compared to earlier versions [12], this change permits the stance net to be radically simplified. The positive feedback occurs at the level of single joints: the position signal of each is fed back to control the motor output of the same joint. Earlier experiments [13] have shown that body height in the stick insect is controlled by a distributed system in

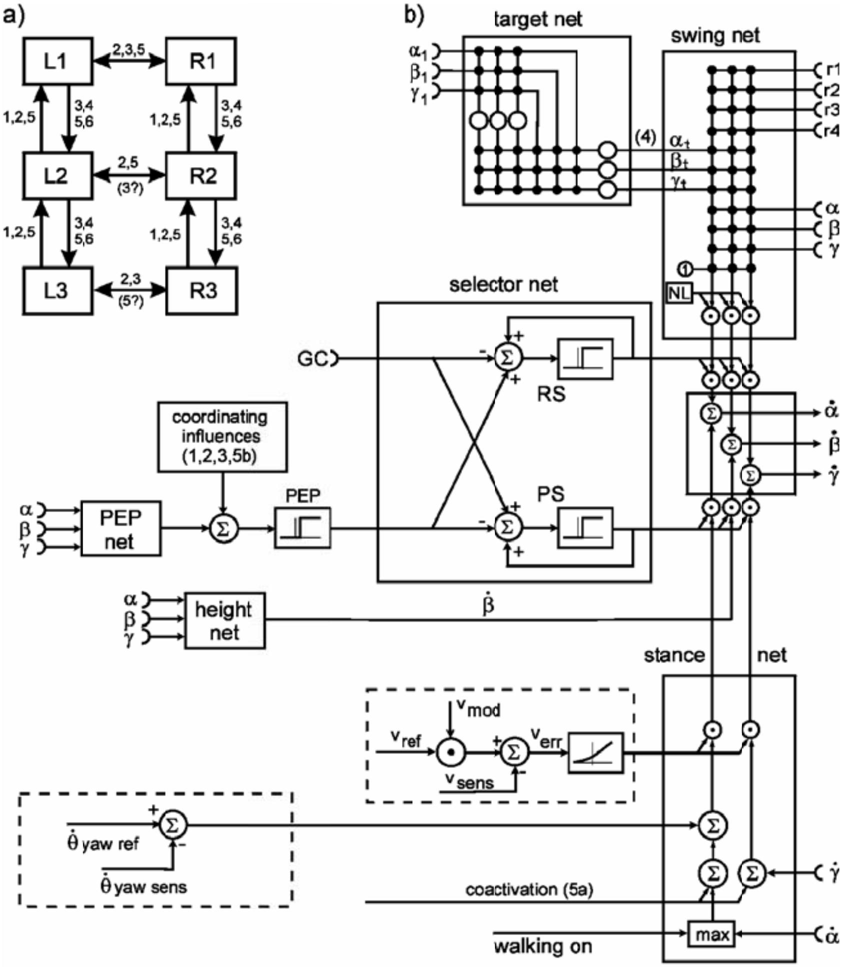

Fig. 5. Fig. 5. (a) Schematic diagram showing the arrangement of the mechanisms coordinating the movements of the different legs. (b) The leg controller consists of three parts: the swing net, the stance net, and the selector net which determines whether the swing or the stance net can control the motor output, i.e., the velocity of the three joints α, β, and γ. The selector net contains four units: the PEP unit signalling posterior extreme position, the GC unit signalling ground contact, the RS unit controlling the return stroke (swing movement), and the PS unit controlling the power stroke (stance movement). The target net transforms information on the configuration of the anterior, target leg, α_1, β_1, and γ_1, into angular values for the next caudal leg which place the two tarsi close together. These desired final values (α_t, β_t, γ_t) and the current values (α, β, and γ) of the leg angles are input to the swing net together with a bias input (1) and four sensory inputs (r1 - r4) which are activated by obstructions blocking the swing and thereby initiate different avoidance movements. A non-linear influence (NL) modulates the velocity profile. For details see Cruse et al. (1998).

which each leg acts like an independent, proportional controller. However, maintaining a given height via negative feedback appears at odds with the proposed local positive feedback for forward movement. To solve this problem we assume that during walking positive feedback is provided for the α joints and the γ joints, but not for the β joints (Fig. 5b, stance net). The β joint is the major determinant of the separation between leg insertion and substrate, which determines body height. The value for the β joint is given by a three layered feedforward network (height net) with three input units (α, β, γ), 5 hidden units and one output unit. This net has been trained using the known leg geometry and approximates data from [14], where force-height characteristics of the standing animal have been measured.

There are, however, several problems to be solved. Only two will be mentioned below. To permit the system to control straight walking and to negotiate curves, a supervisory system was introduced which, in a simple way, simulates optomotor mechanisms for course stabilisation that are well-known from insects and have also been applied in robotics. This supervisory system uses information on the rate of yaw, such as visual movement detectors might provide. Second, we have to address the question of how walking speed is determined in such a positive feedback controller. Again, we assume a central value which represents the desired walking speed v_{ref}. This is compared with the actual speed, which could be measured by visual inputs or by monitoring leg movement (Fig. 5b, boxes marked by broken lines).

One major disadvantage of our simulation is its pure kinematic nature. To test the principle of local positive feedback at least for straight walking, we have performed a dynamic simulation for the six-legged system under positive feedback control during stance. The basic software was kindly provided by F. Pfeiffer, TU Munich. No problems occurred. Nevertheless, a hardware test of the walking situations is necessary. Currently, we are performing such a test by using the robot Tarry IIb, i.e., a reconstructed version of TARRY II [15]. The changes made concern the introduction of passive compliance in each leg joint, a necessary condition for application of positive feedback. For a single leg walking on a treadmill, the test turned out to be successful.

6 Conclusion

As has been shown for the case of straight walking, this network is able to control proper coordination. Steps of ipsilateral legs are organized in triplets forming "metachronal waves", which proceed from back to front, whereas steps of the contralateral legs on each segment step approximately in alternation. With increasing walking speed, the typical change in coordination from the tetrapod to a tripod-like gait is found. For slow and medium velocities the walking pattern corresponds to the tetrapod gait with four or more legs on the ground at any time and diagonal pairs of legs stepping approximately together; for higher velocities the gait approaches the tripod pattern with front and rear legs on each side stepping together with the contralateral middle leg. The coordination pattern is very stable. For example, when the movement of one leg is interrupted briefly during the power stroke, the normal coordination is regained immediately at the end of the perturbation. Furthermore, the model can cope with obstacles higher than the normal distance between the body and the substrate (see Fig. 6 for an example). It continues walking when a leg has been injured, such that, for example, half of the tibia is removed (see [16]).

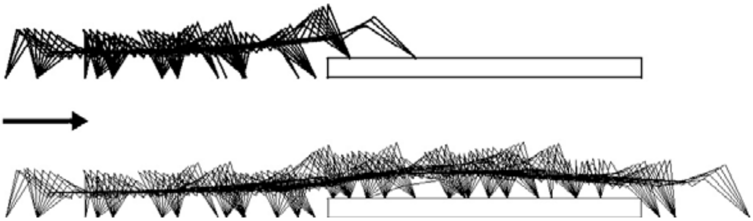

Fig. 6. Simulated walk over an obstacle. Movement direction is from left to right. Leg positions, as viewed from the side, are illustrated only during stance and only for every fifth time interval in the simulation. Upper panel: the first part of the walk until both front legs reach the top of the obstacle. Lower panel: descent from the obstacle until both front legs and one middle leg touch the lower ground.

What about curve walking? The typical engineer's solution is to determine the curve radius and the center of the curve. With these values the trajectories of the different legs are calculated and then, using inverse kinematics, the trajectories for the joint angles are determined. In our case, too, a value is required to determine the tightness of the curve. This, however, does not need to quantitatively correspond to the curve radius. The value is only used as an amplification factor for the positive feedback loop of front and hind legs. This value can deliberately be changed from one moment to the next. No further calculations are necessary.

The introduction of the local band-pass filtered positive feedback in 12 of the 18 leg joints provides a control system which as far as we can see cannot be further simplified, because it is decentralized down to the level of the single joints. This simplification has the side effect that computation time can be minimized. The essential advantage, however, is that, by means of this simplification and the consideration of physical properties of the body and the environment, all problems mentioned above (Sect. 5) can easily be solved, although they, at first sight, seemed to be very difficult.

Unexpectedly, the following interesting behavior was observed. A massive perturbation, for example by clamping the tarsi of three legs to the ground, can make the system fall. Although this can lead to extremely disordered arrangements of the six legs, the system was always able to stand up and resume proper walking without any help. This means that the simple solution proposed here also eliminates the need for a special supervisory system to rearrange leg positions after such an emergency. Some animations can be found in: http://www.uni-bielefeld.de /biologie/Kybernetik

Recent results show that internal ”motivational” states are necessary in order to enable the system to react to a given stimulus in different ways depending on the actual internal state. The state itself depends on sensory input, too.

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