Dürr and Krause (2002) Proc. 5th Int. Conf. CLAWAR, Paris, in press. Manuscript PA 077

Design of a Biomimetic Active Tactile Sensor for Legged Locomotion

V Dürr and A Krause
Abt. Biologische Kybernetik und Theoretische Biologie, Fakultät für Biologie, Universität Bielefeld, Germany

ABSTRACT

Many insects actively move their antennae during locomotion. In case of the stick insect, these movements are known to aid efficient leg coordination when walking on rough terrain. Based upon design principles of an insect antenna, we suggest to employ a biomimetic active tactile sensor to guide leg movements of walking machines. We analyse the impact of various kinematic parameters on the workspace of the sensor, and suggest an evolutionary optimisation technique for selecting an appropriate set of parameters for a given environment. Finally, we introduce a control circuit using parallel self-organising forward models of the antenna for active targeting- and tracking-movements. This artificial neural network controller allows online adaptation of targeting accuracy and, to some extent, extrapolation of the target trajectory.

1 WHY BUILD FEELERS? - LESSONS FROM AN INSECT

Insects and crustaceans use leg-like active tactile feelers for wall-following (1) and obstacle detection (2, 3). Because these feelers carry sensory hairs of several modalities, and therefore act as receivers of various external signals, biologists call them ‘antennae’. Many insects, like stick insects and crickets, have rather long antennae that can be actively moved by means of two simple hinge joints. In stick insects, there is a typical rhythmic movement pattern that is temporally coupled to the stepping rhythm of the front legs (4). It has been shown that the spatial sampling pattern is suitable to detect obstacles at a height range at which the animal needs to alter its locomotion strategy in order to climb the obstacle. Moreover, the sampling pattern is altered in response to loss of ground contact of a front leg, revealing a context-dependent switch of action that can be useful to aid locomotion on rough terrain (5).

In a previous study (6), we have argued in favour of a technological application of biomimetic active tactile sensors on walking machines for four reasons: Firstly, their control is rather simple but effective. Secondly, the fixed morphology reduces computational effort for retrieval of obstacle location and height. Thirdly, the gathered information is always relevant to leg movement control, because only the working-range of the legs is sampled. Fourthly, they reliably work irrespective of light and other environmental conditions.

To date, there are only few studies on active tactile probes (e.g. 7) and most of these focus on the problem of how to retrieve the obstacle location by means of an insensitive beam. In the present study, we analyse the design principles of biomimetic insect-like antennae, showing how their kinematic parameters shape their workspace, i.e. the tactile sensing range (section 2), and how these parameters can be chosen to design specialised obstacle detectors for a given environment (section 3). Finally, we discuss the use of a parallel set of self-organising forward models for the control of active tracking and pointing movements (section 4).

2 MORPHOLOGY AND WORKSPACE OF AN INSECT ANTENNA

The antenna of many insects (e.g. stick insect, cricket, locust) can be viewed as a two-segment manipulator with two simple hinge joints (see Fig. 1, where the box indicates the head of the animal). In this case, the morphology of the insect antenna is defined by six kinematic parameters: the segment lengths S_1 and S_2, the Euler-angles φ_1 and ψ_1 which define the orientation of the α–joint axis in the head coordinate system, and the Euler-angles φ_2 and ψ_2, orientating the β–joint axis in the S_1-coordinate system. The proximal joint rotates the entire antenna by angle α, the distal joint rotates the long distal segment by angle β. The joint axes of the α- and β-joints are the y–axes of the local coordinate systems of segment 1 and 2, respectively. For a biomimetic antenna based on this morphology, the general form of the forward kinematics is $P(\alpha, \beta) = R_Z(\varphi_1)\ R_X(\psi_1)\ R_Y(\alpha)\ T_X(S_1)\ R_Z(\varphi_2)\ R_X(\psi_2)\ R_Y(\beta)\ T_X(S_2)\ (0,0,0,1)^T$, where R and T are homogenous rotation and translation matrices, respectively, with their index indicating the affected axis.

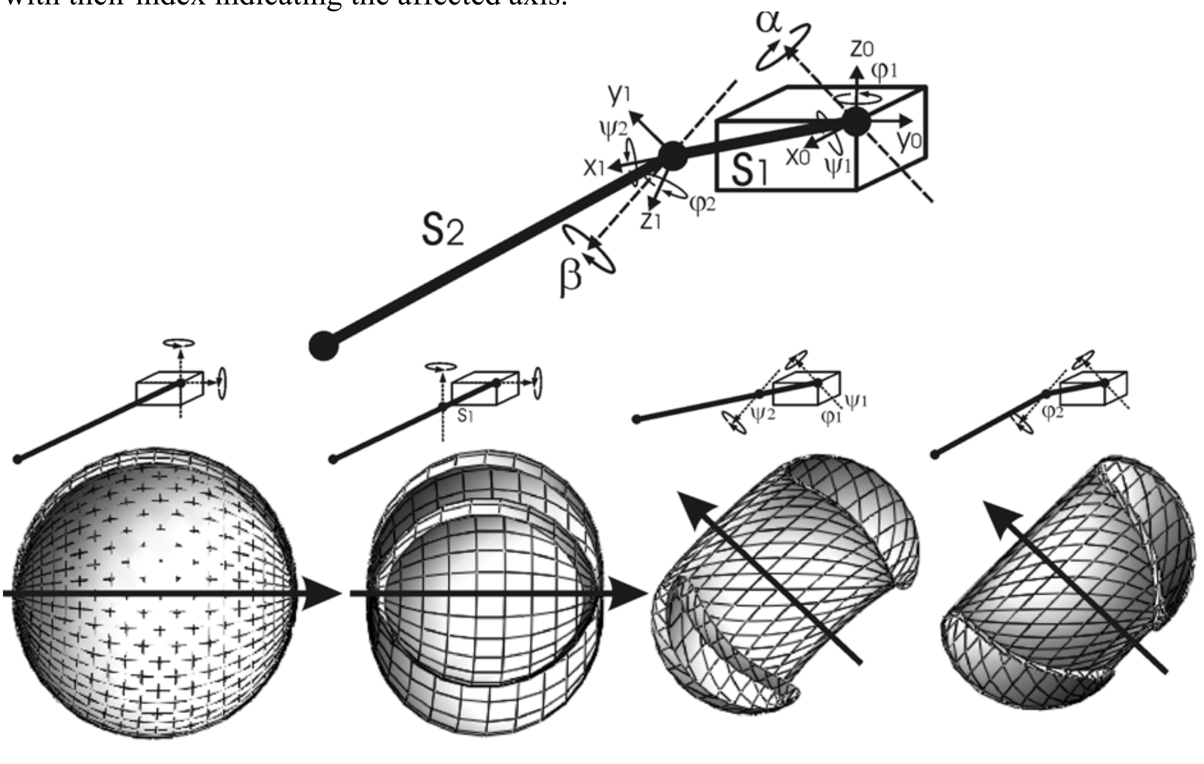

Figure 1: The workspace of an antenna with two hinge joints

As the tactile action range is determined by all of these parameters, it is important to understand how each one of them affect the workspace of the antennal tip. The four small drawings in Fig. 1 show the location and orientation of the joint axes as increasingly more parameters get changed. The sphere and torus-like shapes below these figures show the impact of the indicated parameters (from left to right): If S_1 and all Euler-angles are zero, the workspace is that of a cardanic joint, i.e. a sphere. As S_1 is increased, the sphere is doubled and, if S_1+S_2 is kept constant, compressed along the α-axis. By increasing ψ_2, the two spheres separate into a torus. ψ_1 and φ_1 rotate the entire torus such that the holes are aligned with the α-joint axis (arrow). φ_2 introduces an asymmetry by narrowing the torus on one side and widening it on the other. Note that, for reasons of better comparison, all of the displayed workspace figures assume unconstrained rotation around both joints (0 through 2π rad), and all shapes are cut open along the drawing-plane. In a real antenna, only a part of the displayed workspace can be used. For example, in case of a torus, typically only the outer surface will be feasible to reach.

In summary, the effects of the kinematic parameters are the following: The Euler-angles of the β-joint axis define the width and asymmetry of the torus. Provided that both joint rotations are of limited angular precision, the width of the torus determines the positioning accuracy and maximum sampling density of the antenna. The narrower the torus, the more accurate will be the positioning. The Euler-angles of the α-joint axis set the symmetry axis of the torus. Because the hole in the torus delimits a region that is out of reach, the orientation of the α-joint axis determines the tactile sampling range relative to the body coordinate system.

3 CHOICE OF MOTOR PATTERN AND ADAPTATION TO PARTICULAR ENVIRONMENTS

Insect antennae are transformed, specialized legs, a fact that is illustrated by experiments in which stick insects regenerate a leg to replace an amputated antenna (8). It is likely that the ancestors of insects carried limbs in the head region of the body, where they proved to be unnecessary for maintaining posture or propulsion. Thus, these limbs were free to assume other functions, for instance contact sensing. As the new functions were beneficial to the animals, the morphology and movement physiology of antennae evolved to adapt to the specific circumstances that a given insect species encountered. Following this evolutionary interpretation of the natural design of insect antennae, we suggest to use evolutionary algorithms to choose the construction and motor parameters of an active tactile obstacle detector. In case of a walking machine, the main purpose of such a sensor will be to safely guide a leg during protraction, and to adapt ongoing movements to forthcoming environmental features, such as obstacles. Therefore, morphology and movement pattern of an antenna should be adapted to the stepping pattern of the ipsilateral front leg, but also to characteristic features of the environment.

Fig. 2 shows how both the morphological and the movement parameters of a model antenna can be optimised for obstacle detection in a given environment. While the drawing in Fig. 2A shows the side-view of a real stick insect antenna (approx. 3 cm length; arrows indicate the location of the two hinge joints), the model of the stick insect antenna in Fig. 2B consists of two cylinders that are connected to a cylindrical body by a pair of slanted joint axes (long arrows, labelled α and β). The white, torus-like shape shows the workspace of the antennal tip, similar to the asymmetrical torus in Fig.1 (cut open at the drawing plane).

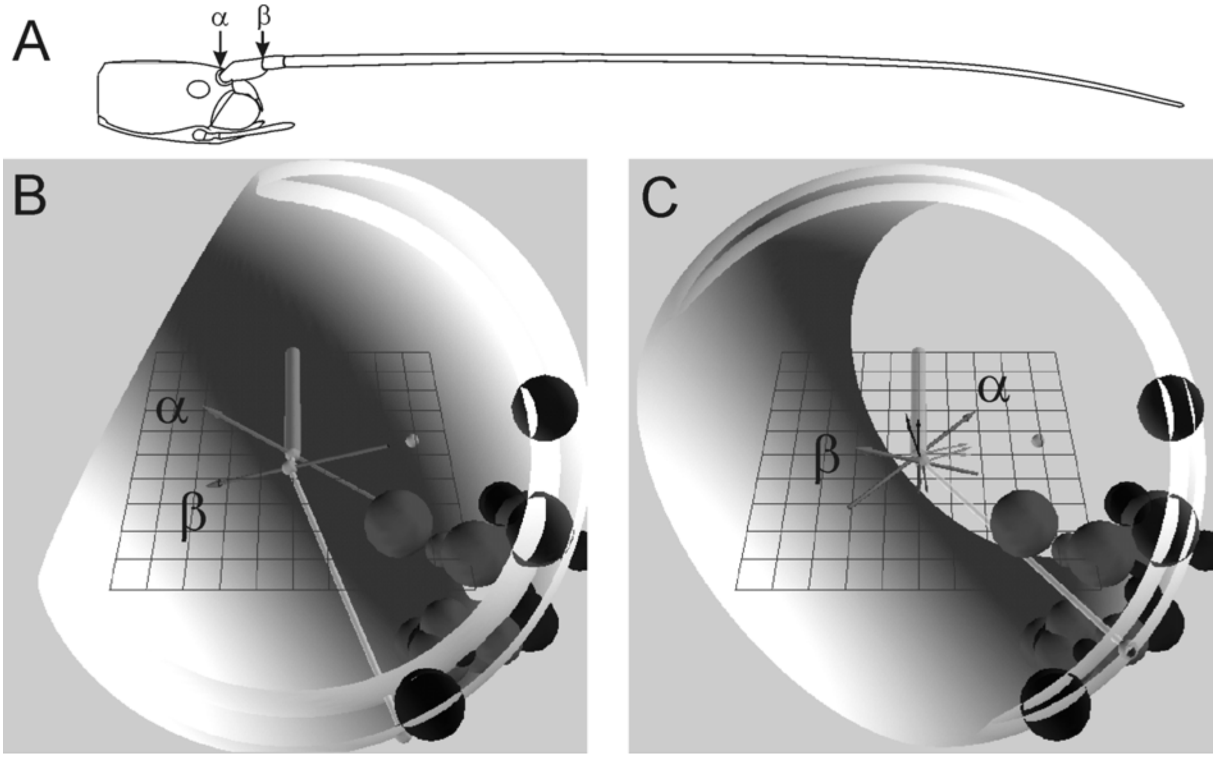

Figure 2: Evolving antennal morphology to adapt to a given environment

Fig. 2B shows the result of a design experiment, in which the efficiency of a particular morphology (joint axis orientation and segment lengths) and of the movement pattern (joint angle modulation frequency, amplitude and phase) was optimised for a given environment. In an attempt to simulate steady forward walking through unpredictable terrain, the environment consisted of a random cloud of balls, moving towards the antenna at constant speed (parallel to the x-axis of the body coordinate system). Because an insect carries two antennae with symmetrical morphology, the cloud was restricted to one side of the antenna, assuming that the other side would be sampled by symmetrical action of the second antenna. The performance of an antenna with a given parameter set was measured by counting the number of balls that were detected. The model parameters were then optimised by means of an evolutionary algorithm. The aim was to maximise the number of detected balls in the environment, while minimising the segment lengths, the modulation frequencies and movement amplitude. Therefore, the fitness function by which the performance of each individual in a population of 200 got evaluated, weighed the benefit of efficient obstacle detection against the cost of the required movement energy. Fig. 2C shows the most successful antenna after 1000 generations. Similar to the stick insect morphology, the winner has evolved non-orthogonal joint axes and a very short first segment. The Euler-angles of the α-joint axis were such that the torus aligned towards the centre of the cloud. Because non-orthogonal joint axes narrow the action range of the antenna, appropriate choice of joint axis orientation can significantly decrease movement effort while, at the same time, increase sampling efficiency.

Thus, given a particular structure of the environment, the design principles that were explained in section 2 can be applied to make a ‘first good guess’ of how to design an active tactile sensor. In a second stage, an evolutionary algorithm can help to fine-tune the parameter set, particularly in the light of a cost-benefit trade-off.

4 PARALLEL FORWARD MODELS FOR ADAPTIVE APPROXIMATION OF AN INVERSE MODEL

Apart from active sampling of the environment, some insects also perform active tracking movements with their antennae (9). The act of pointing a sensory probe towards an object increases the chance to gather further sensory information about it that can not be retrieved visually. Therefore, tracking and pointing movements can support exploratory behaviour of a walking machine. Tracking a target with a multi-joint manipulator requires the ability to solve the inverse kinematics problem. Fig. 3 shows an Artificial Neural Network (ANN) of parallel, self-organising forward models of the manipulator, that can approximate the inverse kinematics problem in a closed-loop tracking-behaviour. Each forward model is implemented by an extended Kohonen map (10) that transforms the joint angles of the current antennal posture into the pointing direction of the antennal tip (Fig. 3). The output allows estimation of the distance to the target. Systematic variation of the joint angles is used to choose the movement direction that leads to the largest decrement in pointing error (distance to the target).

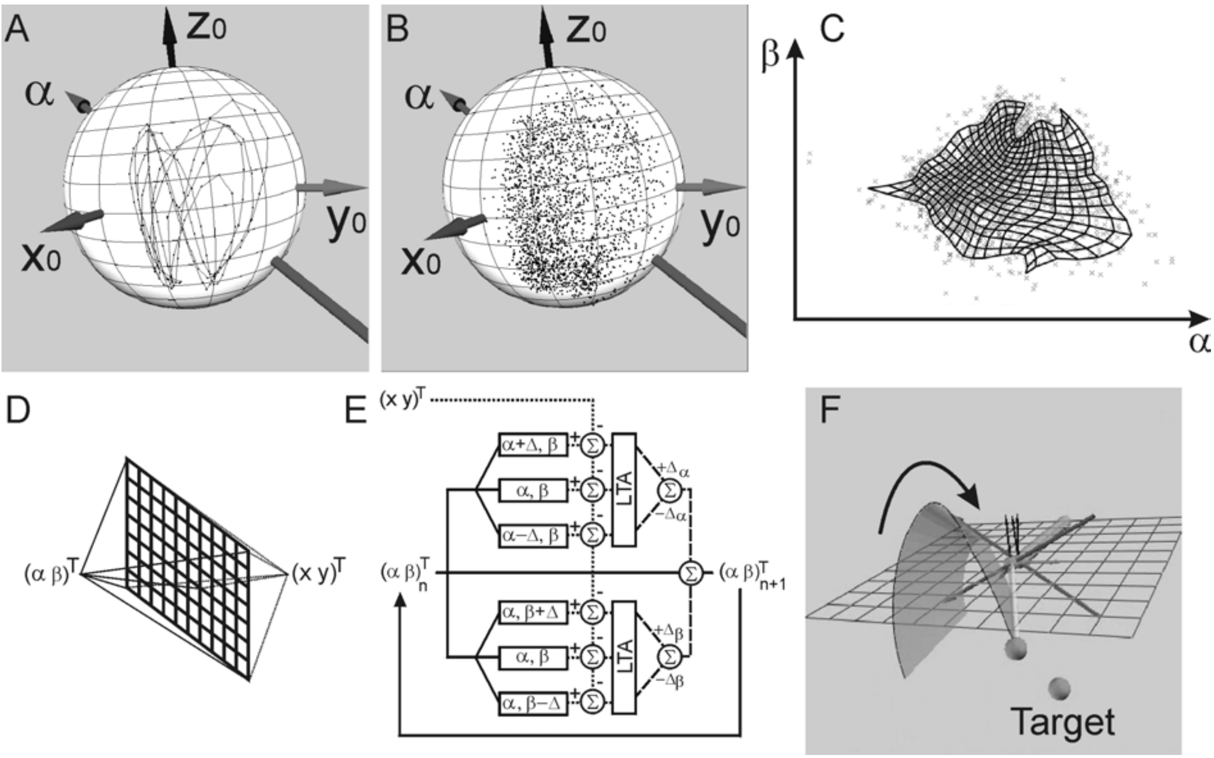

Figure 3: Parallel self-organising forward models for iterative inverse kinematics

In order to demonstrate the process of self-organisation, we have trained an extended Kohonen map to learn the forward model of a stick insect antenna. Trajectories of the antennal endpoint were measured during walking sequences of the stick insect *Carausius morosus* (Fig. 3A, plotted as polar coordinates in a body-fixed coordinate system, centred on the base of the antenna). Superimposing trajectory points from 10 walking sequences results in a probability distribution of antennal pointing directions during walking, revealing that sampling density is largest in the lower frontal region (Fig. 3B). In a next step, a Kohonen map was trained to span the joint angle range of the measured data, simulating off-line learning of a natural sequence of inputs (Fig. 3C). Extension of the Kohonen map (10) allows simultaneous self-organisation of an input and an output layer (Fig. 3D). In other words, it is trained to associate the joint angles, i.e. the motor command, with the endpoint of the antenna. The result is a forward model of the stick insect antenna. In principle, a similar learning procedure could be used to learn an inverse model of the antenna. However, because the inverse kinematics problem may have either no unique solution or no solution at all, the learning algorithm would have to deal with exceptions. In comparison, the forward kinematics problem always has a unique result and, therefore, allows learning of unique associations. The control architecture shown in Fig. 3E uses six 'clones' of the learned forward model in parallel. Each forward model receives the joint angle vector $(\alpha\ \beta)^T$, but with an added or subtracted angular offset Δ (which can be made dependent on the target distance to speed up convergence). The output of each forward model, a position vector, is subtracted from the target vector $(x\ y)^T$ and its length is fed into a 'least takes all network' (LTA). The winner, that is the altered input with the smallest deviation from the target, adds its offset component to the original joint angles, which are then fed back into the forward models.

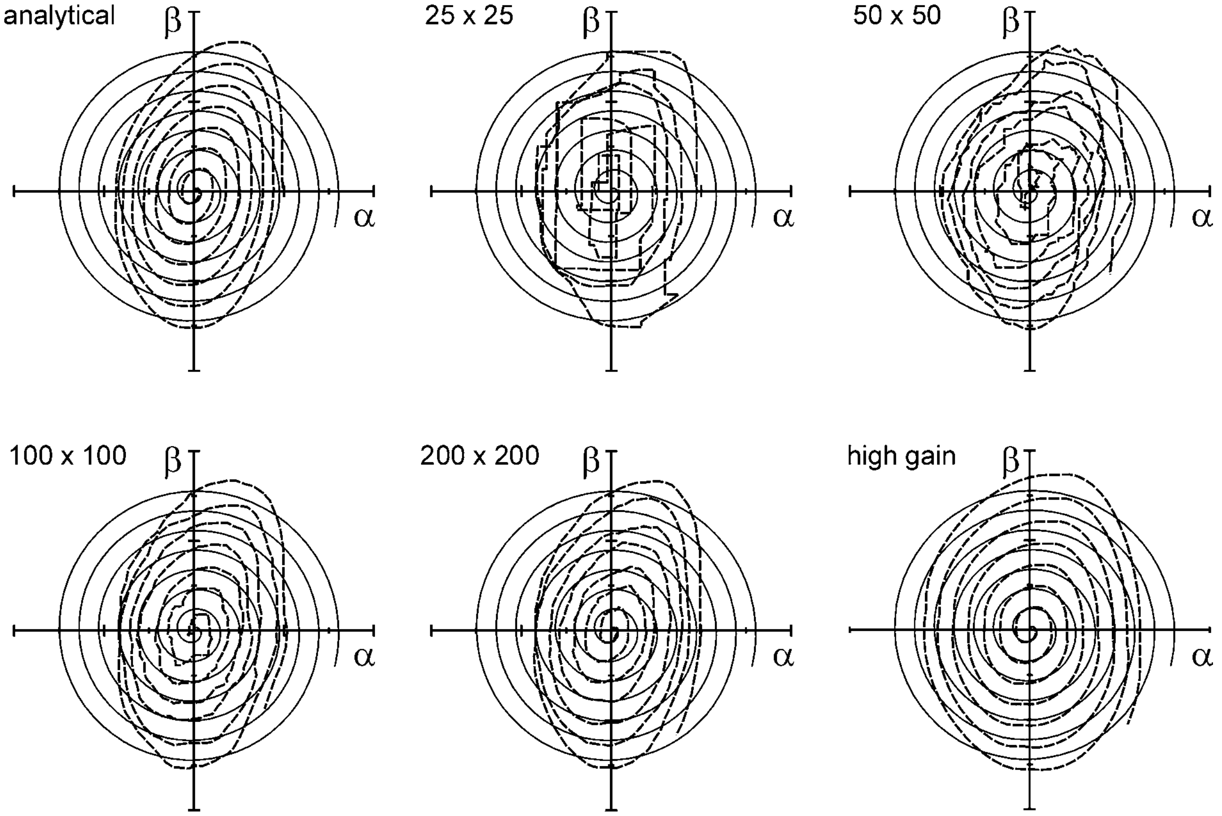

Figure 4: Trajectories of tracking movements, using parallel forward models

Fig. 3F displays a snapshot of a tracking-simulation using the parallel forward model architecture. It allows fast iterative calculation of the inverse kinematics, while allowing the network underlying the forward model to adapt to the encountered distribution of target locations. Apart from being adaptive, an interesting feature of this network is that it will not always follow the target trajectory in situations where the target takes a curve. In the phase diagrams of Fig. 4, this can be seen by the narrowed curve of the antenna that short-cuts the circular trajectory of the target angles. This is the consequence of the two-dimensional Kohonen map that captures a distance measure between all points of the workspace.

In order to demonstrate how the dimension of the Kohonen map affects the performance of the controller, Fig. 4 compares the phase diagrams of five tracking-movements, each one using a different version of the forward model (control as in Fig. 3E). The target was moved in an expanding spiral (axis ticks every 0.25 rad). Target angles, i.e. ideal joint angles according to the inverse kinematics of the antenna (bold line), give a spiral trajectory. The tracking- trajectory of the end effector is narrowed (broken line). The diagram labelled ‘analytical’ may serve as a ‘best performance’ reference, because it was obtained by replacing the Kohonen maps by the exact analytical direct kinematics equation (see section 2). Thus, each forward model is ideal in the sense that it has infinite accuracy throughout the entire workspace. In this case, β lags the respective target angle by six iteration steps, but follows virtually the same curve as the target angle. α does not lag the target angle but reaches smaller amplitudes and does not follow the sinus-modulation of the target angle (see slanted upper section). The intersections of the two trajectories mark postures where the antenna reaches previous locations of the target. The steep up- and downward components of the tracking trajectory mark fast short-cuts. The same principle behaviour can be observed with the Kohonen map implement (labels on each panel indicate the dimension of the map). Whereas the two smallest networks produce rather rugged trajectories, the two larger networks (100x100 and 200x200) approximate the performance of the analytical forward models quite well. Spatial interpolation techniques or temporal low-pass filtering of the output may improve the smoothness of the tracking-behaviour already with considerably smaller Kohonen maps. Moreover, the gain of the control circuit can be increased to speed up convergence and improve tracking in a closed-loop situation. An example of this is given by the panel labelled ‘high gain’ in Fig. 4, where the gain was increased by almost 50% compared to the other situations.

5 CONCLUSION

Biomimetic active tactile sensors may be as useful to walking machines as an active tactile antenna is useful to a walking insect. The design of the sensor can be easily chosen for and adapted to a particular environment. The appropriate choice of construction and movement parameters can be fine-tuned by means of evolutionary algorithms. Finally, the application of self-organising maps as integral components of a control circuit appears promising for technical application on machines walking on unpredictable rough terrain, because the weights of the map can autonomously adapt to the likelihood of encountered object contacts. Applied to an active tactile sensor, this self-organisation property can adapt the sampling accuracy to past sensory experience and, therefore, to the changing environment of the machine.

REFERENCES

1 **Camhi, J. M.** and **Johnson, E. N.** (1999) High-frequency steering manoeuvres mediated by tactile cues: antennal wall-following in the cockroach. J. Exp. Biol. 202: 631-643

2 **Pelletier, Y.** and **McLeod, C. D.** (1994) Obstacle perception by insect antennae during terrestrial locomotion. Physiol.Entomol. 19: 360-362

3 **Zeil, J., Sandeman, R.** and **Sandeman, D. C.** (1985) Tactile localisation: the function of active antennal movements in the crayfish *Cherax destructor*. J. Comp. Physiol. A 157: 607-617

4 **Dürr, V., König, Y.** and **Kittmann, R.** (2001) The antennal motor system of the stick insect *Carausius morosus:* Anatomy and antennal movement pattern during walking. J. Comp. Physiol. A 187: 131-144

5 **Dürr, V.** (2001) Stereotypic leg searching-movements in the stick insect: Kinematic analysis, behavioural context and simulation. J. Exp. Biol. 204: 1589-1604

6 **Dürr, V.** and **Krause, A.** (2001) The stick insect antenna as a biological paragon for an actively moved tactile probe for obstacle detection. In: Berns, K. and Dillmann, R. (eds) Proc. 4th Int. Conf. Climbing and Walking Robots, CLAWAR 2001, Karlsruhe. Professional Engineering Publishing, London. 87-96.

7 **Kaneko, M., Kanayma, N.** and **Tsuji, T.** (1998) Active antenna for contact sensing. IEEE Trans. Robot. Autom. 14: 278-291

8 **Cuénot, L.** (1921) Régénération de pattes à la place d'antennes sectionnées chez un Phasme. Compt. Rendus Acad. Sci. 172: 949-952.

9 **Honegger, H.-W.** (1981) A preliminary note on a new optomotor response in crickets: Antennal tracking of moving targets. J. Comp. Physiol. A 142: 419-421

10 **Ritter, H., Martinez, T.** and **Schulten, K.** (1992) Neural computation and self-organizing maps. An Introduction. Addison-Wesley, Reading/Ma