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The Stick Insect Antenna as a Biological Paragon for an Actively Moved Tactile Probe for Obstacle Detection

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ABSTRACT

We propose the stick insect antenna as a biological model for the study of the tactile sense and its active use in guiding leg movements. During walking, stick insects perform rhythmic antennal movements which are well-coordinated with leg movements. Antennal contact with an obstacle can lead to rapid adaptation of the ongoing leg movement, e.g. by re-targeting of a swing movement. The typical antennal movement pattern is sufficient to reliably detect obstacles of critical height, i.e. where leg reflexes alone will not suffice to overcome the obstacle. The technical application of insect-like actively moved tactile probes on a legged robot may provide a simple, fast and reliable means of object detection within the working range of the front legs.

1 INTRODUCTION

Stick insects of the species *Carausius morosus* carry two long antennae (feelers) which they continuously move during locomotion (1). Because the antennae are of approximately the same length as an extended front leg, tactile contact of an antenna with any object will signal the presence of a potential obstacle within reach of the front legs. In other words, contact information is always relevant for the control of locomotion. Because the geometry of the antenna is inherently known by the insect (or the robot), contact location can be retrieved with little computational cost. Moreover, other than visual or ultra-sonar obstacle detection methods, tactile localisation is largely independent of environmental conditions and surface properties of the obstacle.

In spite of these advantages, only few legged robots are equipped with tactile feelers, like the hexapod robot Genghis (2). To our knowledge, actively moved feelers have not been used at all. This may because of the required additional control of two degrees of freedom per antenna, but also due to the apparent drawback of low sampling density compared to vision. In the course of this study, evidence is provided suggesting that the latter can be compensated by an appropriate sampling strategy, taking account of what spatial information is relevant to immediate locomotor control.

So far, only few biological studies have dealt with the use of antennal movements in locomotion. Apart from studies on the stick insect (1, 3), the antennae were shown to be involved in body axis adjustment to forthcoming obstacles in beetles (4), in tactile localisation in crayfish (5) and wall-following behaviour in cockroaches (6). Interestingly, a number of engineering studies have dealt with questions concerning tactile localisation of a contact point using an insensitive mechanical probe (e.g. 7, 8, 9). All of these studies indicate a large potential in the use of actively moved tactile probes.

2 PROPERTIES OF THE BIOLOGICAL MODEL

In an evolutionary view, insect antennae are specialised limbs of the head that underwent the functional transition from a locomotor leg into an actively moveable, multisensory probe. The close relationship between legs and antennae is reflected by the fact that stick insects with an amputated antenna sometimes regenerate a leg-like appendage instead of an antenna (10). Accordingly, the principle ‘construction’ of antennae and legs is rather similar, particularly concerning the kind of joints, the muscle innervation and most types of sensory hairs.

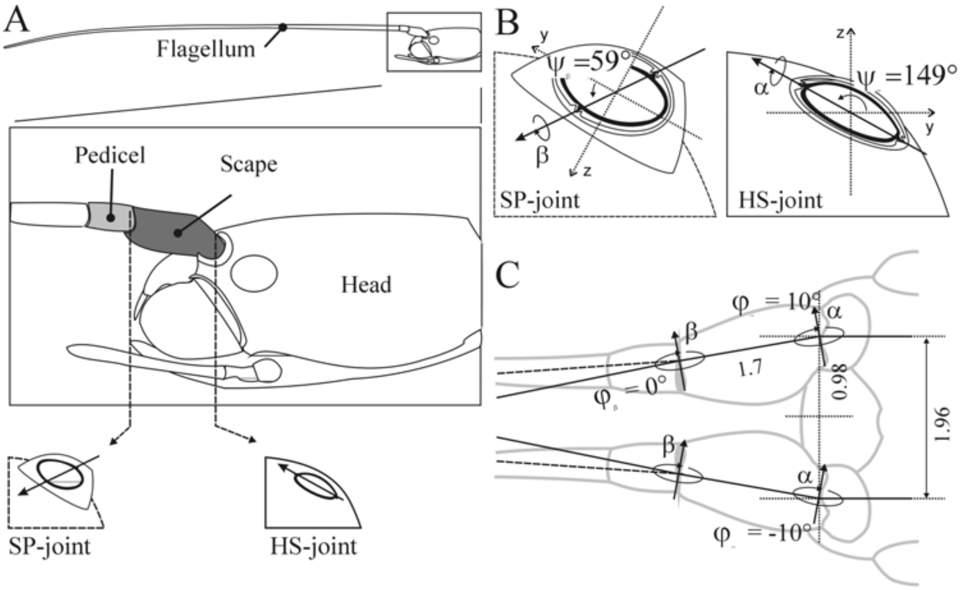

Figure 1: ‘Construction’ of the stick insect antenna.

As in all higher insects (Pterygota), the antenna of the stick insect consists of three functional segments: two short, moveable segments at its base called scape and pedicel, and a long, thin flagellum (Fig. 1A). The latter carries most of the sensory hairs. The sensory repertoire of these hairs ranges from olfaction (11), hygro- and thermoreception (12) to mechanoreception (13). Because neither pedicel nor flagellum contain muscles, the flagellum itself can not be actively moved. Rather, the pointing direction of the flagellum is determined by means of two simple hinge joints, located between the head an the scape (HS-joint) and between the scape and the pedicel (SP-joint). The arrangement of the joint axes, along with the anatomy of the inserting muscles and their innervating motoneurons is known (1).

Fig. 1A shows a side view of the stick insect head, illustrating the insertion site of the left antenna and its three functional segments. Schematic cross-sections at the level of the HS-joint and SP-joint are drawn in Fig. 1B (right and left, respectively), showing the location and orientation of the two hinge joint axes in a frontal view (α-axis of HS-joint; β-axis of SP-joint). Fig. 1C shows a top view of the head with grey lines indicating cuticular structures. Distances are given in mm. The α-axis is defined by shifting the body-centred coordinate system to the base of the scape and rotating it around the z- and x-axes by φ_α and ψ_α, respectively. The ß-axis requires a further shift to the base of the pedicel and rotation around the x-axis by ψ_β. Thus, the forward kinematics of the antenna can be calculated using standard robotics equations (e.g. 14, see section 3).

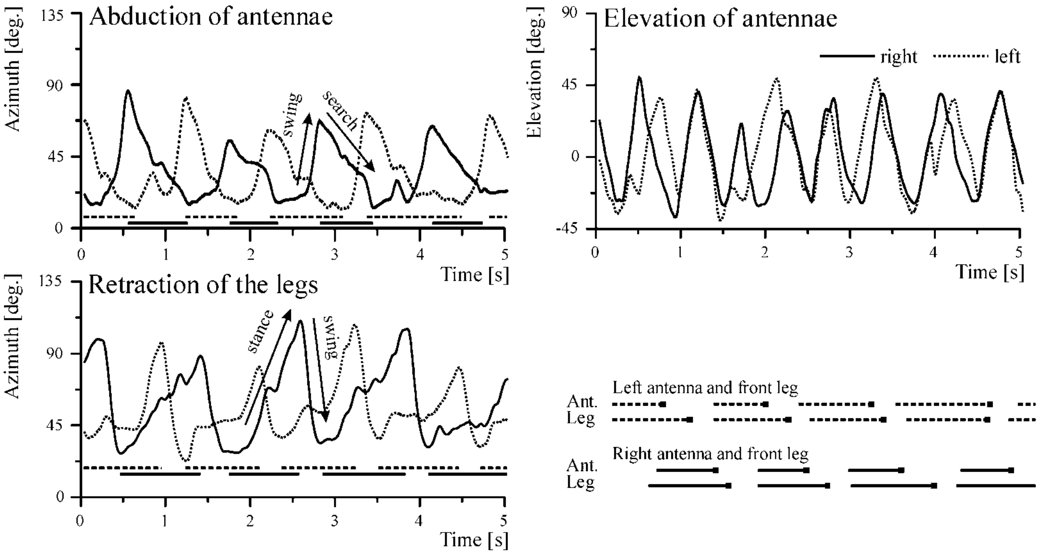

Figure 2: Coordination of antennae and front legs.

During walking, the cyclic movement pattern of the antennae is temporally coupled to that of the legs, such that for each step cycle of a front leg there is a distinct movement cycle of the ipsilateral antenna (1). An example of the typical coordination between antennae and front legs is shown in Fig. 2, where the top panels graph the elevation and azimuth of the antennae, and the bottom left panel graphs the concurrent azimuth of the front leg tarsus (solid lines: right limbs; dotted lines: left limbs). Corresponding to the forward swing phase of a front leg, there is a fast backward swing of the antenna. The slow stance phase of the leg has its counterpart in a forward directed search phase of the antenna, including a second up-and-down movement. Therefore, the antenna performs one in-out cycle per step and, on average, two up-down cycles. The in-out cycle has a stable phase shift relative to the step cycle. This is illustrated by lines drawn below each search phase of the antennae and each stance phase of the front leg. For easier comparison, these lines are grouped together of Fig. 2 (lower right). The posterior extreme position (PEP), i.e. the largest azimuth, is marked by a square symbol.

Although consistent between animals, the typical movement pattern of the antenna is not rigid. First, the up-down cycle has a variable phase shift relative to the in-out cycle. As a result, the antennal trajectory does not stay on the same track in each cycle but sweeps through the entire ipsilateral frontal sector. Second, the movement pattern changes markedly upon obstacle contact or upon loss of foothold of the ipsilateral leg.

In case of loss of foothold, for instance after having stepped across an edge, the front leg engages in rhythmic searching movements (3). Fig. 3 shows a representative sequence of antennal movement during a normal step (left) and the subsequent change that takes place during a searching-movement of the front leg. The spheres indicate the body coordinate system with the body long axis pointing towards 0° azimuth (see inset; spheres are centred on the base of the antenna). The dots in Fig. 3 mark antennal positions during 15 step cycles and 25 searches, sampled at 25 Hz. The density of the dots therefore reflects the spatial distribution of the sampling density of the antenna. The right diagram in Fig. 3 illustrates the fact that the sampling density shifts forward during searching movements of the leg (relative frequency of dots per 30 degree longitudinal sector). Thus, the antenna appears to alter its typical movement pattern and to back up the searching-effort of the front leg in the adjacent region above the area searched by the leg.

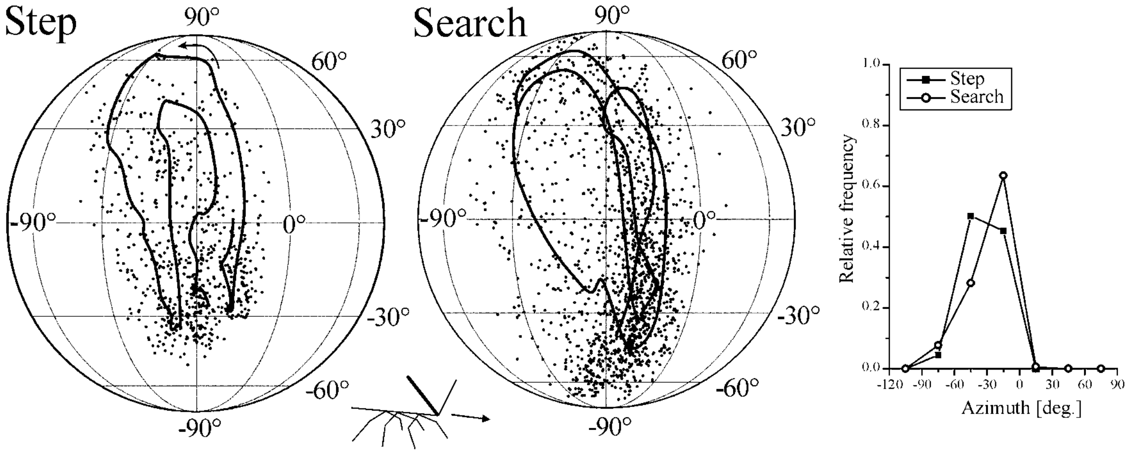

Figure 3: Sampling density during stepping and searching.

In order to examine the effect of antennal contacts with obstacles during walking, we conducted experiments in which the animals were left to walk over a bridge towards a vertical rod. Video-recording the animals from two sides allowed a 3D-analysis of the movement sequence. Upon antennal contact with the rod, animals often re-directed an ongoing swing movement of the front leg. The cartoon in Fig. 4 shows an example of such an altered swing movement. Three snapshots of the animal are indicated by the animal's body axis (circles mark the head) and the left front leg. The instances correspond to the time of the PEP (solid circle on bridge), the time of antennal contact (open circle on trajectory) and the time of leg contact (solid circle on rod). The tarsus trajectory (solid curve) and the ipsilateral antennal tip (dotted curve) are drawn to illustrate the sudden upward movement of the tarsus, compared to the course of a normal swing movement (dashed arrow). The upward bend in the tarsus trajectory occurred within 60 ms of the first antennal contact with the rod. Because swing movements of the legs are known to be targeted (15), we interpret this re-directing of the swing movement as a sign of a re-targeting mechanism, i.e. a continuous updating of the target location.

Because the entire experimental setup was kept in black and an infrared spotlight was used for illumination, visual cues can be considered to have a negligible input to the observed behaviour. Furthermore, because the visual acuity of the compound eyes is rather low (approx. 7° of inter-ommatidial angle in the horizontal plane) the stick insect is unlikely to see much of its own antenna. Moreover, because *Carausius morosus* is a nocturnal species, it is usually active at dusk and at night, i.e. under rather poor lighting conditions.

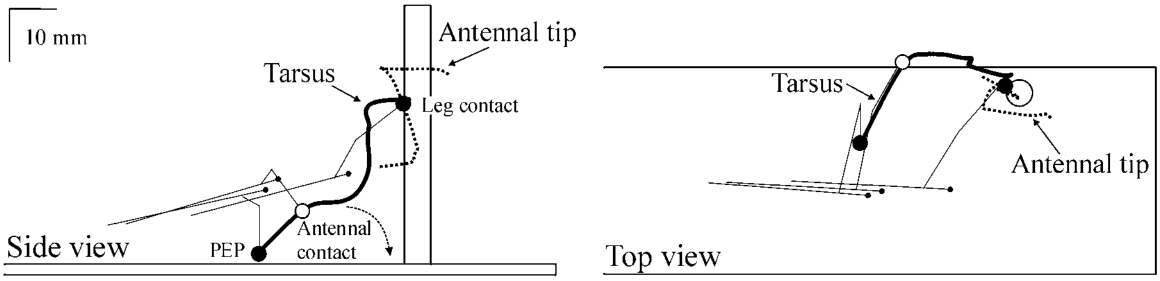

Figure 4: Rapid re-targeting of a swing movement triggered by antennal contact.

Based on the experimental data of simultaneous antennal and leg movements (such as shown in Fig. 2), it was possible to determine the probability of the antenna to touch an obstacle of a given height before leg contact, thus leaving the legs enough time to react to the contact information. The result is a sigmoidal function of obstacle height (dotted line in Fig. 5). The obstacle height of 6 to 7 cm, at which the function reaches its half-maximum value, is equivalent to half the 'clearance' of the body at the level of the front legs. An experimental test of the frequency of the event 'antennal contact leads leg contact' confirmed the predictions (1, open circles in Fig. 5). These findings match simulation results of Cruse et al. (16) who tested the success rate of a virtual stick insect without antennae in climbing steps of variable height (solid line in Fig. 5). At obstacle heights where the simulated hexapod without antennae frequently became unstable for longer than one swing period, the probability of the event 'antennal contact leading leg contact' markedly increased. This suggests that the typical movement pattern of the antennae is well suited to reliably detect obstacles of critical height, i.e. obstacles that can not be climbed without appropriate early adaptation of the locomotor program. The fact that real stick insects do much better in climbing high obstacles than the simulated hexapod, together with the frequent observation of contact-induced rapid changes in leg movements, suggest that active antennal movements of the stick insect strongly contribute to efficient locomotion on rough terrain.

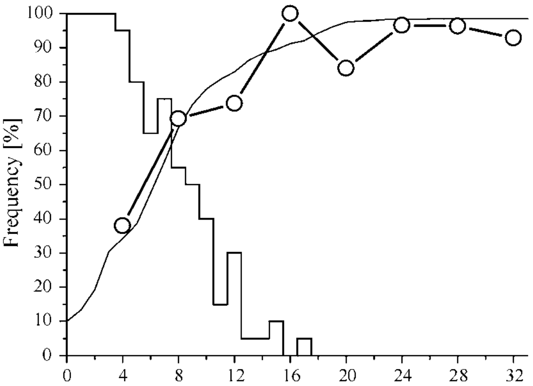

Figure 5: Dependence of object detection on obstacle height and climbing success of a hexapod without antennae.

3 MODEL SIMULATION OF THE STICK INSECT ANTENNA

As the geometry of the antennal segments and their connecting joints is known (Fig. 1), the forward kinematics could be incorporated into a computer simulation (Fig. 6A), allowing Open GL visualisation and experimental variation of antennal 'construction' and movement parameters. This allows us to systematically vary segment lengths of the antenna, axis orientation of the HS- and SP-joints, but also the amplitude, frequency and phase of the rotation cycles of each joint. Thus, the impact of each of these parameters on the efficiency of obstacle detection can be investigated. The purpose of such a study is twofold. First, it allows us to compare the antennal 'design' of different insect species and to assess is role in adaptation to a specific environment. Second, the simulation will allow to test and optimise the appropriate movement strategy for a hardware implementation of an actively moved tactile probe for a given environment.

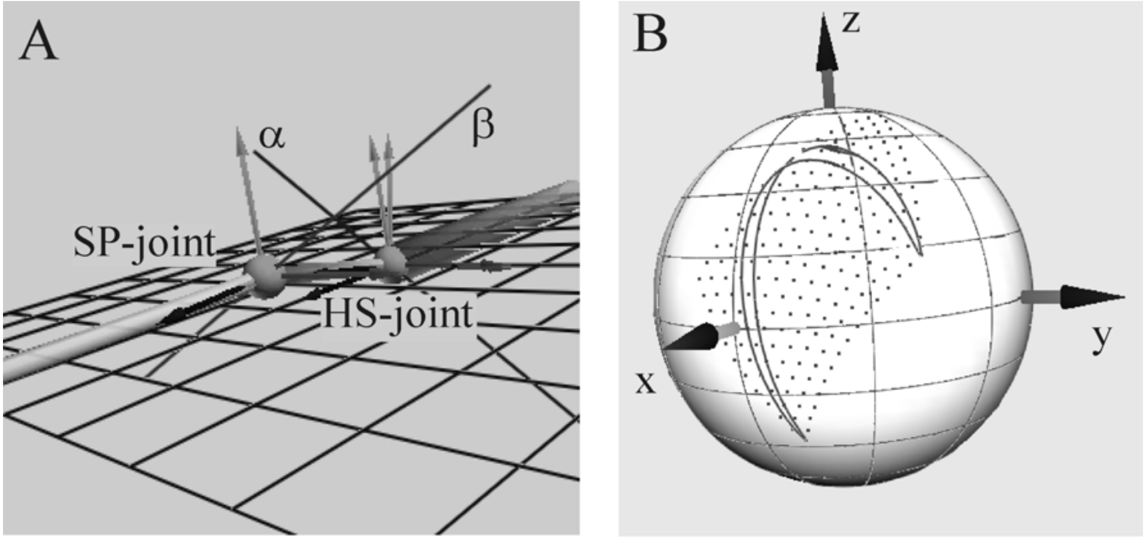

Figure 6: Model simulation of the stick insect antenna.

Fig. 6B shows the working range of the left antenna based on measurements of the HS-joint and SP-joint angle ranges in walking stick insects that had one of their antennal joints fixed (Dots mark antennal tip with 5 degrees spacing of each joint angle). The superimposed trajectory shows the effect of sinusoidal movement in both joints, using twice the frequency for the SP-joint than for the HS-joint (Phase shift: 1.38, both joints cover their entire working range). The discrepancy between the action ranges covered in Fig. 3 and Fig. 6B suggests that in the stick insect the covered angular range of each joint depends on the actual angle of the other joint. Currently experiments are performed to further elucidate this inter-joint coupling during active antennal movements.

4 TOWARDS A HARDWARE IMPLEMENTATION OF AN ACTIVELY MOVED TACTILE PROBE ON LEGGED ROBOT

The following section aims to discuss the advantages of an actively moved tactile probe over other sensory systems, but also likely problems limiting the hardware implementation of active feelers.

An obvious drawback of adding two further limbs to a robot is the required additional control of at least two degrees of freedom per active antenna, plus the additional weight that needs to be carried. A promising way to incorporate the movement control of active antennae into the control scheme of the legs may be to take account of their similarity to legs, and to employ similar controllers for each antenna as they have been successfully employed for the control of single legs (16). In other words, antennae could be treated as another pair of legs. For instance, avoidance reflexes of an antenna could be handled in virtually the same way as leg reflexes.

The mechanical requirements for a tactile probe are more demanding than for a leg. The material needs to be of low weight, while exhibiting sufficient stiffness to aid localisation, and compliance, allowing for passive bending and to avoid damage after contact. Kaneko et al. (e.g. 8, 9) have successfully used piano strings for their experiments on contact localisation by means of an insensitive probe. These studies also successfully demonstrate two methods to exploit the compliance of an insensitive probe to determine contact location. The first method uses a simple active movement strategy to reduce the lateral slip between probe and object, and subsequently exploits the compliance of the probe to detect the contact distance (8). The second method analyses the fundamental and second order frequencies of the vibration pattern of the probe (9). Interestingly, insect antennae are equipped with mechanoreceptors that are potentially capable of retrieving information about the antennal vibration (by means of the so-called Johnston's organ) and bending (chordotonal organs and campaniform sensillae).

An important advantage of an active tactile probe is given by its constant geometry. This allows the knowledge about the own body shape to be exploited. A second advantage compared to visual obstacle detection is the rapid processing and availability of obstacle information. In case of a probe equipped with contact sensors along its axis, touch location is immediately available as polar-coordinates in the form of two joint angles and the touch distance. In this case, hardly any data filtering or 'expensive' image processing is required. Depth information is provided by touch distance and does not need to be computed. Another important advantage is the independence of light conditions, i.e. a tactile sensor works day and night. Moreover, tactile contact localisation is largely independent of the surface condition of the touched object. For example, wet or textured surfaces may confound the quality of information gathered by vision, ultrasound or other range detectors, but will rather provide additional tactile information about the touched surface. This can be important for the choice of the appropriate behavioural reaction to antennal contact. For example wet, slippery, or very soft surfaces may need to be avoided by a legged robot. Such surface conditions are easily detected by a tactile probe but can be difficult to analyse with other sensory systems.

Possibly the most important aspect of a tactile probe like the stick insect antenna is that all gathered information is relevant to leg movement control, because all samples lie within the action range of the leg. An actively moved antenna therefore applies two simple rules, making it beneficial for leg movement control: "Sample only where you need to" and "employ a leg-like sensor to guide a leg".

5 CONCLUSION

The stick insect antennae is a valuable model for the study of the tactile sense and its active use in locomotion. The coordination of antennae and legs in stick insects can account for a significant increase in the adaptability of their locomotor behaviour when coping with obstacles. Antennal movements in insects are living proof of the potential use of actively moved tactile probes in legged locomotion. Unlike other sensory systems, such as vision, the active tactile sense does not sample a wealth of data irrelevant to immediate locomotor control, but focuses on the working range of the legs. Thus, using an active antenna on a legged vehicle, paired with the appropriate choice of sampling strategy, may keep computational effort low while increasing reliability of obstacle detection. This can provide a robust basis for early adaptation to forthcoming changes in the environment.

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