Testing a model of cricket phonotaxis on an outdoor robot platform

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Abstract

If biological inspiration can be used to build robots that deal robustly with complex environments, it should be possible to demonstrate that 'biorobots' can function in natural environments. We report on initial outdoor experiments with a robot designed to emulate cricket behaviour. The work integrates a detailed neural model of auditory localisation in the cricket with a robot morphology that incorporates principles of six-legged locomotion. We demonstrate that it can successfully track a cricket calling song over natural terrain. Limitations in its capability are evaluated, and a number of biologically based improvements are suggested for future work.

1. Introduction

The ability of animals to deal flexibly with complex environments is often advanced as a reason to adopt a biology-based approach to robotics. This suggests that robots designed to emulate biological systems should be tested in natural conditions. But to date there are only a few examples of such evaluations e.g. the Sahabot using polarised light navigation in the Tunisian desert (Lambrinos et al., 2000); or recent testing of Robolobster in the Red Sea (Frank Grasso, personal communication).

We have built a series of robots based on cricket phonotaxis, that is, the ability of female crickets to locate a mate by moving towards male calling songs. These robots have been shown to reproduce many aspects of the insect's behaviour, including sound localisation in noisy conditions, preference for conspecific pattern in the calling song, distinguishing between competing sound sources, and using optomotor correction to do phonotaxis with motor output biased or randomly disturbed (Webb, 1995; Lund et al., 1998; Webb and Scutt, 2000; Webb and Harrison, 2000). The most recent robot uses an auditory processing circuit closely based on cricket ears and is controlled by a realistic neural network that replicates known neural connectivity in the cricket (Reeve and Webb, 2002). In this paper we aim to evaluate the performance of this system when implemented and tested on an outdoor robot, to explore the issues raised by the natural habitat for this behaviour.

These issues fall into three broad areas. The first concerns the nature of the stimulus - how the sound is propagated and what kinds of interference and distortion occur. To what extent does the auditory localisation system we have implemented on the robot to date need to be altered to deal with this? The second area (which will not be addressed in this paper, but is the subject of ongoing research) is how the animal or robot detects and deals with obstacles that might block its path towards the sound. The third area is motor capability. The six-legged cricket can traverse rough terrain. Can we control a robot with a cricket-like morphology using the algorithms developed for a wheeled robot on a flat floor?

The robot platform we use here is inspired by insect walking. Insects such as cockroaches and crickets typically use a tripod gait, in which the front and rear legs on one side of the body move in phase with the middle leg on the other side. Close studies of cockroach locomotion (Watson et al., 2002) also reveal that the front legs normally swing head-high to surmount many obstacles without changing gait, but when larger barriers are encountered the gait changes, and contralateral legs move in phase. These strategies have been incorporated into a robot morphology called "Whegs", that unlike RHex (Saranli et al., 2000), uses only a single drive motor and embedded passive compliance (Quinn et al., 2002). It uses six hubs which each have three protruding legs that rotate as the robot moves (see details below). The three-spoke design and torsional compliance in the drive train allow it to climb up and down shallow stairs and inclines and easily traverse most terrains, such as asphalt, grass, mud, gravel, and light brush. The platform used in this

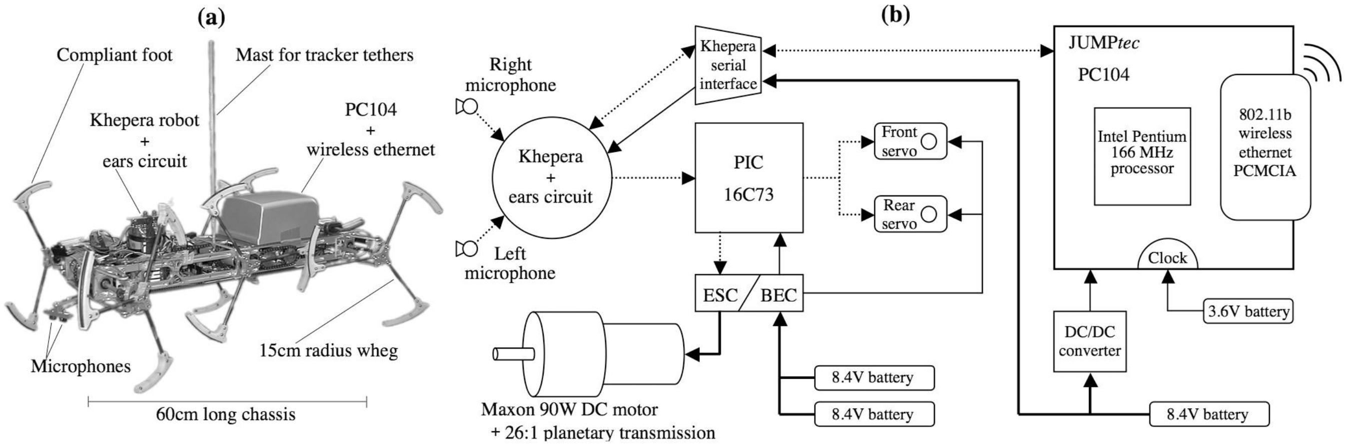


Figure 1: The Whegs Autonomous Sensor Platform: a) robot b) hardware used in outdoor phonotaxis experiments

study could move at a speed of up to 4 body-lengths per second and has a turning radius of 1.5 body-lengths.

Full details of the methods used to integrate the previous robot controller onto this platform have been described in Horchler et al. (2003). Here we analyse the performance of this implementation, to address some of the issues of hearing and responding to sound outdoors.

2. Methods

2.1 Hardware

2.1.1 Robot base

The robot base was the Whegs Autonomous Sensor Platform (Whegs ASP), shown in figure 1a. It is based upon a lightweight 60cm long by 15cm wide aluminium chassis. It has six 15cm-radius three-spoke whegs, each of which is arranged 60 degrees out of phase from adjacent whegs. This allows the robot to move with a nominal tripod gait with all six whegs powered by a single 90W Maxon motor and transmission. The torque delivered to each wheg passes through a torsionally compliant mechanism that permits a wheg to comply if an obstacle is encountered, thus moving into phase with the contralateral wheg. Additionally, large compliant feet at the tip of each spoke cushion and smooth the robot's vertical motion without seriously compromising its climbing ability. To turn, front and rear rack-and-pinion steering is activated with two electrically coupled Futuba servomotors. Two 3000mAh battery packs connected in parallel provide 5V to the servos and 8.4V to the drive motor via an Astro-Flight electronic speed controller (ESC). A third electrically isolated battery pack was used to power the control system (see below).

2.1.2 Sensors

A pair of miniature microphones were mounted to a four-bar mechanism attached to the front steering, allowing them to pivot with the front whegs. They were positioned about 10cm above the ground surface, facing forward, separated by 1.8cm (one quarter the wavelength of the carrier frequency of cricket song, which is 4.8kHz). The output from these microphones was processed with a customised electronic circuit (Lund et al., 1997) based on the ear morphology of the cricket. The input from each microphone is delayed by 52μs (a quarter cycle of 4.8kHz sound) and then subtracted from the other, effectively performing a phase comparison and thus providing directional information. The microphone separation and delay times make the directional output accurate for the typical cricket song signal.

2.1.3 Control system

Figure 1b shows the main hardware elements of the control system for this robot. The auditory circuit had been designed to interface to a Khepera robot, and it proved simplest to mount this small robot directly on the Whegs ASP base, and use it to do the sensory pre-processing. This consisted of converting the signal amplitudes to Poisson spike trains, with programmable threshold and saturation levels, and transferring these via a serial line to a PC104 processor running a neural simulator under Linux. The motor output was also encoded as a spike train and transferred back to the Khepera, where it was interfaced to the Whegs steering servos and electronic speed controller via a programmable PIC. The robot carries the entire processing system, including power supply, and operates autonomously except for start and stop signals and configuration commands between experiments. To communicate with a laptop, a PCMCIA 802.11b wire-

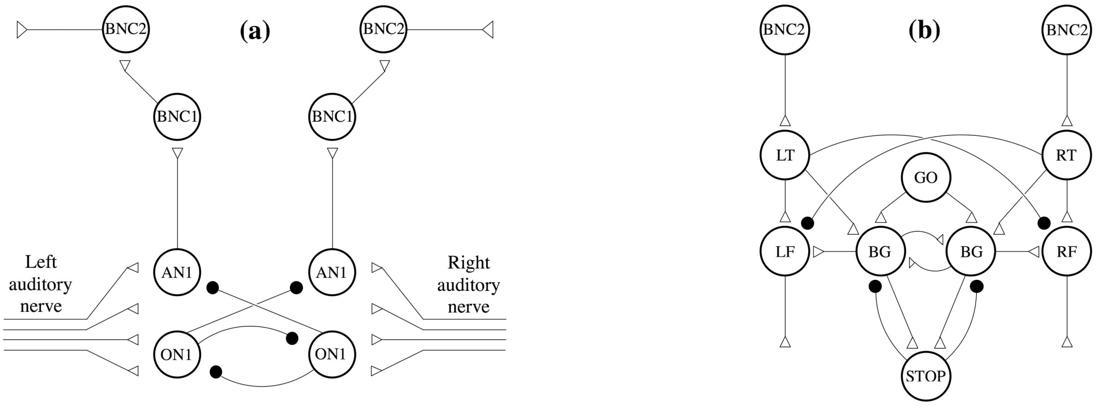


Figure 2: Neural circuits based on cricket neurophysiology, for a) auditory processing and b) motor control

less ethernet card is installed in the PC104 onboard the robot. The laptop also runs a tracking system based on triangulation using retractable tethers (see below).

2.2 Software

2.2.1 Neural simulator

The PC104 is running a spiking neural simulator that we have developed to test hypotheses of auditory processing in the cricket (Reeve and Webb, 2002). The behaviour of the basic neural model is related to single compartment 'leaky integrate and fire' models, but based more closely on the models described by Koch (1999). The neuron is considered to be an RC circuit with a fixed membrane capacitance and membrane conductance and a base potential across the membrane to which it will decay exponentially in the absence of external input. If the membrane potential rises above a threshold, the neuron will 'fire', sending a spike to any output synapses. The synapses are modelled as a variable conductance with a battery potential which corresponds to the reversal potential of the ion channel opened by the synaptic neurotransmitter. Their properties include a delay (corresponding to the sum of possible axonal, neurotransmitter, and dendritic delays), a variable time course for the exponential decay of conductance, as well as a more standard weight determining the standard conductance change in the affected ion channel. They also allow short-term adaptation of the weight through mechanisms of facilitation and depression. Despite this complexity, the model can run in real time for robot control.

2.2.2 Auditory circuit

We have designed a neural circuit based on the physiological mechanisms known to underlie phonotaxis behaviour in the cricket (reviewed in Pollack (1998)). It is shown in Figure 2a. For each of the two 'auditory nerve' inputs (left and right), there were four pairs of Poisson spiking neurons with differing threshold and saturation levels. This meant the subsequent processing could deal with a larger range of input amplitudes, which was necessary given the substantial attenuation of the sound signal over the distances we wanted to run the robot. The spiking input from the auditory pre-processing excites one pair of auditory interneurons (ON) and one pair of ascending neurons (AN). The first (mutually inhibitory) pair performs cross-inhibition of the other to sharpen the directionality of the signal. An important effect of this was to produce a form of gain control. Louder sounds were more likely to activate auditory neurons on both sides so mutual inhibition would reduce the overall response as well as increase the relative difference. The AN pair conveys this signal to 'brain' neurons (BN1 and BN2) that use dynamic synapse properties to filter the song for the appropriate temporal pattern. BN1 requires the correct gap to occur between sound bursts for it to recover from synaptic depression and thus fire efficiently at the onset of each burst. BN2 requires the onsets signalled by BN1 to occur sufficiently close together before it will respond. The filtered output indicates, through the activity of the left and right brain neurons, if a male of the correct species is calling from the left or the right. Therefore, the BN2 output needs to connect to the motor control neurons in order to cause a turn in the direction from which the louder and/or clearer song can be heard.

2.2.3 Motor control circuit

The motor control circuit (figure 2b) is based upon a 'burst-generator' (BG) consisting of a pair of neurons coupled by mutual excitation, so that sufficient input to either produces continuous spiking of both. This is eventually terminated because the pair also excites a STOP neuron that eventually becomes active and inhibits the bursting pair. In theory, a variety of sensory stimuli or internal factors can activate a motor response, either by direct excitation of the burst generator or via the GO neuron, which modulates the sensitivity of the burst pair by low frequency tonic excitation. In the experiments below, the GO neuron receives a constant input, representing a response to a high ambient light level, so that the robot's default behaviour will be to move forward.

The two burst-generator neurons (BG) excite, respectively, a left forward (LF) and a right forward (RF) motor neuron. These normally connect directly to the speed controllers for the independently driven wheels of a Koala or Khepera robot. For Whegs ASP however, both neurons provide excitation for a forward signal that controls the drive motor, while LF excites and RF inhibits a signal that controls the position of the servomotors that steer the robot. If LF and RF are balanced then the robot steers forward, otherwise it turns according to the difference in activity (LF-RF). The activity of the LF and RF neurons is modulated by the output of the auditory processing described above, via left turn (LT) and right turn (RT) neurons that produce appropriate excitation and inhibition to affect the robot's direction.

2.3 Experimental methods

Our aim was to demonstrate that the robot could perform the basic task of the female cricket: to recognise and track towards a male cricket calling song over a reasonable distance in a natural outdoor environment. The robot was tested on a grass-covered (later frost-covered) area between one of the University of Stirling's buildings and a small lake bordered by trees. For the main results given below, the area used was approximately 10 meters by 7 meters. This area was fairly level but not a smooth lawn. There was little wind. The air temperature was below 0C.

The target was a speaker placed on the ground and connected to a laptop computer, through which we played a simulated male cricket song. This consisted of two "chirps" per second, where each chirp is four cycles ("syllables") of 25Hz square wave amplitude modulation of a 4.8kHz tone. The sound amplitude was approximately 85dB at the speaker and 65dB at the robot's starting points.

The neural simulation program automatically recorded the inputs and activity of all the neural elements during trials. In addition, the position of the robot was tracked using retractable lines that tether the robot to fixed points. The robot's position is then calculated by triangulation. This position information is automatically synchronised with the internal data. Details of the implementation of this tracking system are given in Horchler et al. (2003).

3. Results

Figure 3 shows the tracks produced by the robot in thirty trials, from three different starting positions as shown: 7 meters straight ahead (facing the speaker) 3.5 meters to one side with the speaker on the left, and 4.5 meters to the other side, with the speaker on the right. It is evident that the robot can track towards the sound source. Defining success as getting within one body length of the speaker, there was only one trial in which the robot did not find the sound source, and only one other trial with significant indirectness in the path taken. Paths took an average time of 43.8±11.8 seconds from the centre, 28.6±8.6 seconds from the right, and 24.0±12.4 seconds from the left. The average forward speed over the 30 trials was 0.2m/sec. There was an average of 12 direction corrections made per trial, although as discussed below, not all of these are clearly reflected in the tracks.

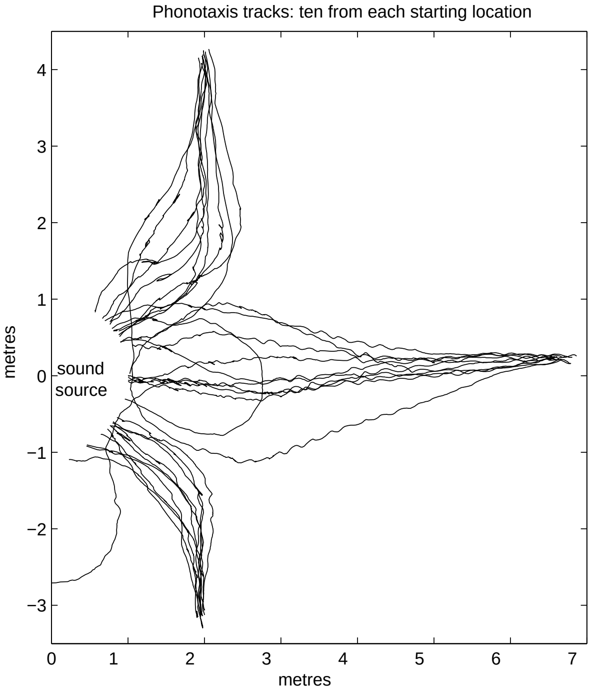


Figure 3: Tracks of the robot towards the sound source in 30 outdoor trials, from 3 starting positions.

The spiking activation of the neural circuits during approach to the sound is illustrated in figure 4 for two successful tracks, one taking 50 seconds from the central starting position (left plots) the other a fast 5 second track from the right side (right plots). The upper plots show the different response thresholds of the different fibres in the auditory nerve, with more fibres becoming active as the robot approaches the sound. On the left side the time scale only shows the chirp pattern in the song (repeated firing bursts at 2Hz); on the right side the four syllables that make up each chirp can be seen in the

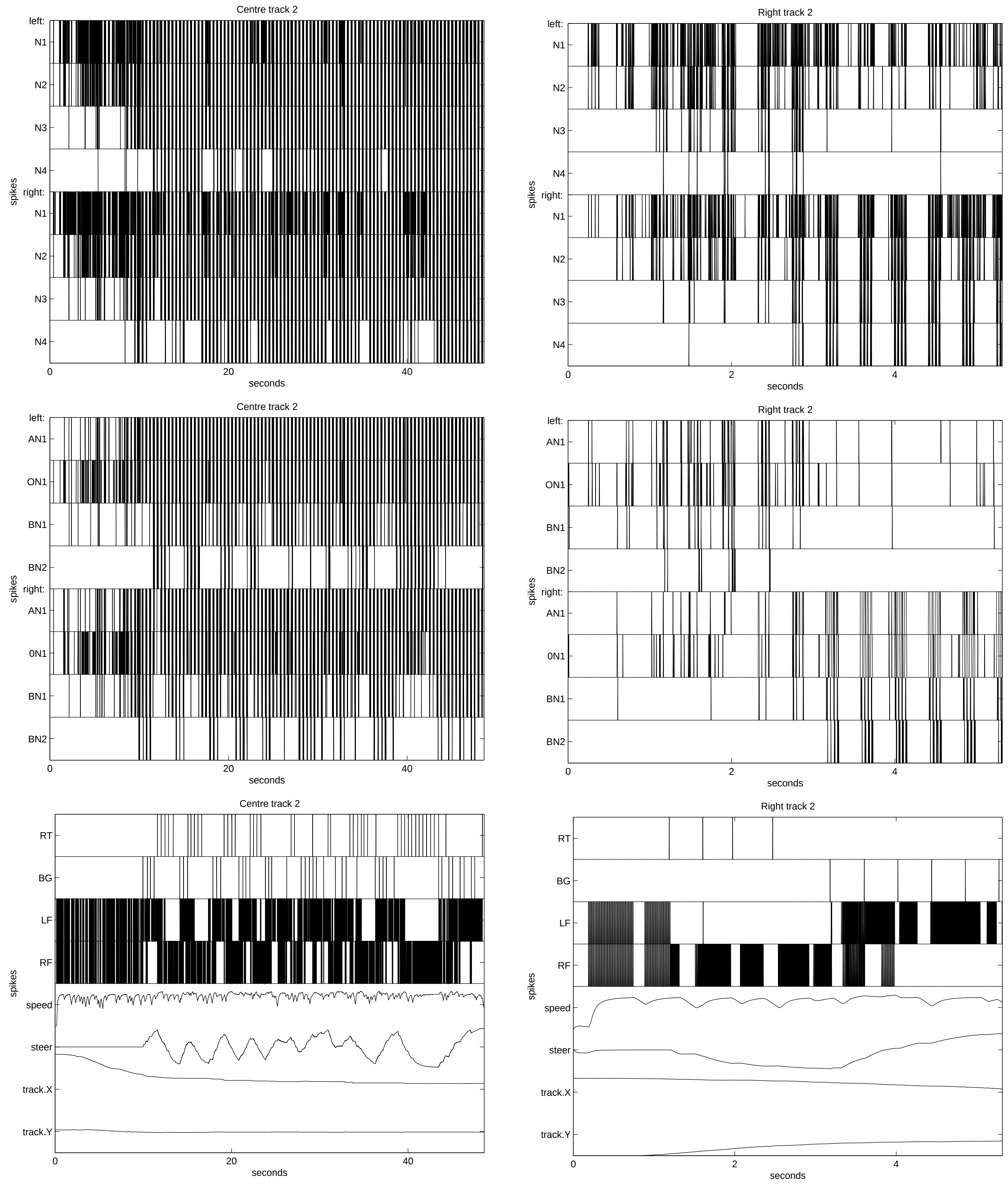


Figure 4: Activation patterns of the neurons during sound tracking: left, a track from the centre: right, a track from the side (note different time scales). Upper plots show the auditory nerve, middle plots the auditory processing circuit in figure 2a, lower plots show critical elements from the motor circuit in figure 2b, the control signals sent to the robot, and the X and Y co-ordinates of the robot's actual track as recorded by the tether system.

firing patterns. It is evident that those fibres with a low enough threshold to respond to sound from a distance (N1 and N2) also encode more noise, and consequently it is harder to see the sound pattern in their response than in N3 and N4. As a consequence the activation of the AN and ON interneurons is also more noisy at the start of the track.

A clear encoding of several consecutive syllables by AN1 is needed before BN1 and BN2 start to fire. It can also be seen that BN2 firing shows strong directionality, with almost no overlap in activity between the left and right neurons. For each chirp indicated in the firing of BN2 there is at most one spike in the appropriate RT or LT neuron to signal a turn. In the centre track it can be seen that these spikes alternate from one side to the other as the robot turns back and forth; whereas in the track from the right, consecutive turn signals in one direction are followed by similar signals in the other direction, resulting in only two changes in steering direction during the track.

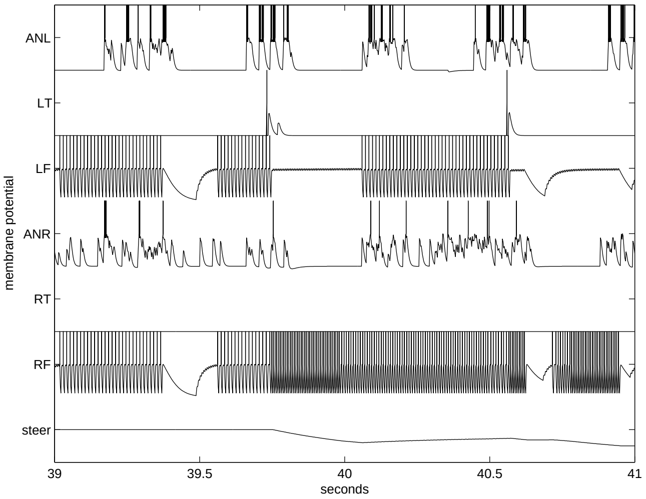


Figure 5: Membrane potential of three neurons on each side during a turn. Response to a chirp in ANL causes a spike in LT which inhibits LF and excites RF, sending a steering signal to the robot.

To illustrate in close-up how the turning is implemented, figure 5 shows the membrane potentials of a subset of the neurons shown in figure 4. Right forward RF and left forward (LF) neurons normally produce synchronised bursts of spikes to drive the robot forward. In this plot, the sound is on the left, so the left auditory neuron (ANL) encodes the song pattern (with some noise) while the right AN is less activated (due both to quieter input and to the cross inhibition from ON). Two of the chirps in ANL are clear enough to produce (via the BN neurons, not shown here) a spike in the left turn (LT) neuron. Each spike in LT inhibits the firing of LF, and increases the firing rate of RF, for about 0.5 seconds. The difference in firing rate between LF and RF determines the steering signal.

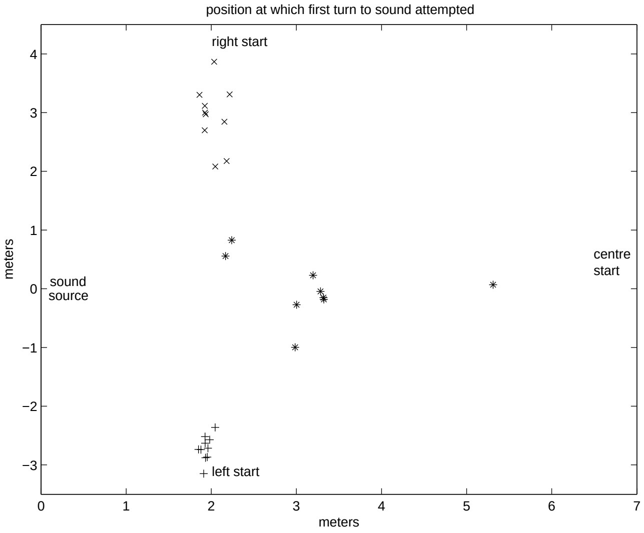
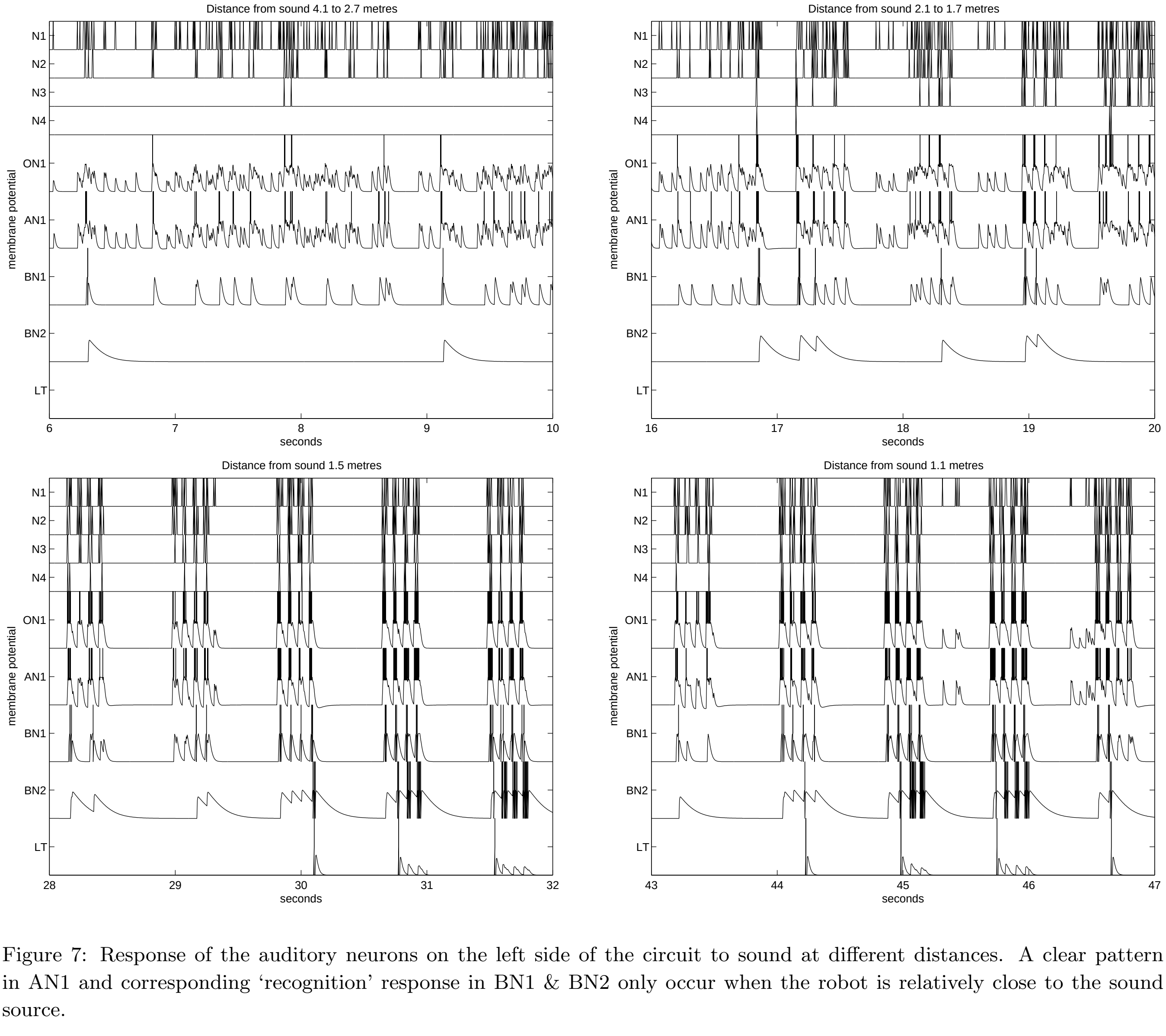


Figure 6: Location of the first attempted turn in response to sound for each of the thirty tracks. Active tracking of the sound only occurs within a radius of about 3 metres from the speaker.

The distance over which the robot could track was more limited than we had originally hoped. Although the straight-ahead trials started the robot at a distance of 8 metres, the robot did not actually start responding to the sound till somewhat closer. If it was started from a position and direction that did not bring it within a few metres of the sound, it was unlikely to track it successfully. We could quantify this more precisely by using the internal neural data to determine where in each track the robot made the first turning response to the sound signal. These positions are shown in figure 6. For the central tracks the mean distance was 3.19m (min. 2.23, max. 5.31) from facing to the right, 3.34m (min. 3.12, max. 3.68) and facing left, 3.58m (min. 2.92, max. 4.37).

The main cause of this limitation was that the amplitude of the sound signal beyond this distance was not sufficient for the robot to detect the song pattern above background noise. This can been seen in figure 7 which shows the activation of the neurons on one side of the auditory circuit at different distances from the sound source. As the sound pattern in AN becomes increasingly clear, BN1 & BN2, which filter for this pattern as described in the methods, start to respond. The main cause of background noise was the motors of the robot, which caused both electromagnetic distortion and auditory interference. The former was partially reduced by shielding the microphone leads but could perhaps be further reduced. Several possibilities for dealing with the latter problem are discussed below.

An additional problem with the system is also evident



Distance from sound 4.1 to 2.7 metres

Distance from sound 2.1 to 1.7 metres

Distance from sound 1.5 metres

Distance from sound 1.1 metres

Figure 7: Response of the auditory neurons on the left side of the circuit to sound at different distances. A clear pattern in AN1 and corresponding ‘recognition’ response in BN1 & BN2 only occur when the robot is relatively close to the sound source.

from close inspection of the lower left traces in figure 4. The spiking behaviour in RT and LT is producing appropriate alterations in the steer signal. The robot is effectively travelling along the X-axis of its track. At the beginning it moves fairly rapidly towards the origin (the X value decreases), with little deviation (the Y value stays constant). Once it starts responding to the sound by steering, it slows down its approach (the X value decreases more slowly). However, there still appears to be little deviation. If it was actually zigzagging to the sound, as the steer signals seem to indicate, each change in direction should be visible as a change in the Y-value of the track, but it remains almost constant.

What is occurring? From observing the robot it became evident that when it started reacting to sound, it would often come to a stop and take several seconds to move again, and make further stops while approaching the sound. During the stops, the front axle and the ears would be turned towards the sound source, or might oscillate back and forth several times around the sound source direction. It appeared that when the whegs base was turning, the level of forward motor torque being supplied was not always sufficient to overcome the extra friction of the unaligned whegs. This could also be a problem in starting from a stop, where overcoming the initial inertia could take a few seconds. On the other hand, when already moving straight, the same level of torque would make the robot move so fast that it risked exiting the critical area before noticing the sound. What was lacking was any form of motor feedback to allow the system to regulate its torque to deal appropriately with the different situations. As this robot base had previously only been used under remote control, it had not been appreciated how much trimming of the speed signal was needed to allow it to cope smoothly with starting, turning and other changes such as slopes or differences in ground friction. It is evident from the fact that the robot did, largely, succeed in tracking the sound that it could manage to turn sufficiently often. Nevertheless the tracking could have been faster and more efficient if the actuators had actually performed correctly according to the motor signals that were sent.

4. Discussion

Using a robot base inspired by insect locomotion, we were able to demonstrate that our model of cricket phonotaxis could be used successfully to locate sound in an outdoor environment. The model is closely based on known neurophysiology of the animal, so this work allows us to evaluate the functional role of the various components of the network. It also demonstrates that we can capture some of the capabilities of animals and use them to achieve real-world robot tasks. The main limitations were that this only worked over a limited distance range, of around 3-3.5 metres, and that the robot did not always properly execute the motor commands generated by the neural circuit.

This second problem has several obvious solutions. It might be possible to use feed-forward control to regulate the motor output, e.g. to ensure that torque is increased proportionally to the degree of steering, given that we can to some extent predict that this is needed. However, it is likely to be more effective to use some form of feedback. For example, an encoder or tachometer speed measurement could be used with standard PID control to regulate the motor output (as is already built into the low-level control of the wheeled robots we have used previously). More interestingly, we could examine some of the ways in which insects appear to use proprioceptive feedback in controlling their actions, and see how these might best be adapted to robot control.

In a similar way, it is interesting to consider what solutions the insect itself suggests to the first problem, that of dealing with the substantial decrease in sound amplitude over longer distances, and the consequent increase in the signal to noise ratio. We have already incorporated two neural mechanisms that should contribute to solving this problem. The first is range fractionation of the input across the auditory nerve. The second is the use of cross inhibition (the ON connections) which also has the effect of gain control. However, there are several additional mechanisms that might be used. For example Römer and Krusch (2000) have demonstrated that there is a relatively slow inhibitory current that develops over several seconds allowing the ON/AN response to adapt to the prevailing sound level. Although we have included depression effects in the synaptic connections in our current model, these effects are relatively short-term and recover between chirps.

We have not as yet included further mechanisms that might allow the animal to better filter the signal from the noise. The ears circuit does not do any filtering for the carrier frequency of the sound. We have demonstrated that such filtering is not necessary to explain the carrier frequency selectivity of the cricket (Lund et al., 1997). This is because the phase comparison mechanism for localisation is itself frequency specific, thus the wrong frequency of sound simply can't be localised. However, crickets do show frequency tuning of auditory fibres, and the input to the AN and ON neurons comes specifically from receptors sensitive to the typical calling song frequency range. This may well be necessary for discriminating the sound, at low amplitudes, from background noise or noise created by the animal's own movements.

On this latter point, it should be recalled that the cricket's ears are in fact located on its forelegs. As each leg is placed on the ground, the vibrations cause substantial interference to the song signal (Schildberger et al., 1988). One strategy that may be used by the cricket, and adopted for the robot, would be to stop frequently to collect sound information without the motor noise. However, it has been shown that the cricket can make accurate course corrections without stopping (Schmitz et al., 1982). As the interference is synchronised with the stepping cycle the cricket could theoretically use corollary discharge to predict when the sound signal should be processed and when it should be ignored. As the motor noise on the robot is more continuous, either pauses in movement, or specific filtering to separate the signal and the noise are more plausible options.

The robot could detect sound from further away; the problem was the difficulty in detecting the sound pattern with sufficient clarity for recognition. It is therefore of interest to note some evidence that the cricket is less discriminating for the sound pattern when the sound amplitude is low, and only as the amplitude increases does it require the species specific pattern to maintain tracking (Doolan and Pollack, 1985). They note that this could well be an advantageous adaptation to the problem of sound distortion at a distance. It would be interesting to consider how such a mechanism could be implemented in the neural circuit we are using.

Finally, it should be noted that the distance range we achieved in the current work is not all that limited when compared to the cricket. Estimates for the cricket suggest it may be capable of tracking 2-4 times as far, but not a substantial distance further. A difficulty for us here is that the rate with which amplitude decreases with distance is fixed by the physics of the situation, so cannot be scaled to match the larger body size, and bigger turning circle, of the current Whegs implementation. The Whegs design has been used to build much smaller robot bases (e.g. "Mini-Whegs" (Morrey et al., 2003) has a body length of 8cm) but to utilise this we would also need to shrink the corresponding control hardware, or operate it off-board. Another option might be to use a more realistic six-legged robot that is capable of turning on the spot, but as yet reliable and autonomous designs that fit this specification are not available.

Our plans for future work in the short-term, therefore, will focus on implementing some of the above strategies, i.e. to improve the motor control and enable the auditory network to deal with the amplitude/noise problem more effectively. This will then allow us to test the robot on more varied terrain, e.g. with slopes or uneven footing. We also plan to implement additional sensory mechanisms on the same robot base, including the optomotor sensor used previously on the wheeled robots (Webb and Harrison, 2000) and active antennae that can be used for obstacle detection and avoidance.

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