

## Eyes and Ears: Combining Sensory Motor Systems Modelled on Insect Physiology

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### Abstract

*Integrating sensorimotor systems is still a difficult problem for robotics. Biological inspiration, which has been effectively used to address single sensorimotor tasks, could also be applied to this problem. Several studies on the cricket suggest that it integrates an optomotor response to improve its sound localization behaviour. We have taken two existing 'biorobots' - one that uses an aVLSI circuit to reproduce the optomotor behaviour and another that models in hardware and software the sound localization of the cricket - and combined their capabilities to investigate whether an additive combination will reproduce these effects. We report the initial results and discuss a number of issues raised by this investigation.*

### 1 Introduction

Many robot systems have been 'inspired' by biology. Some recent systems have investigated a closer connection, building robot hardware and software intended as direct models of specific biological systems. Examples include the 'Sahabot' model of the desert ant (Lambrinos et al, 1997 [10]); the 'robolobster' model of underwater odour tracking (Grasso et al, 1996 [4]). In previous work, the authors of this paper have respectively built an auditory localization system that mimics the cricket (Webb, 1995 [15]; Lund, Webb & Hallam, 1998 [11]), and an optomotor analog VLSI chip that mimics the fly (Harrison and Koch, 1999 [7]). Both systems have been successfully tested in real robots, under the same stimulus conditions used to test

the animal. Important insights from this work are that appropriate sensory preprocessing can greatly simplify control problems, and that the sensory mechanisms are best understood in the context of a motor task, rather than viewed as extracting general-purpose information from the environment.

This approach should also have application to the problem of 'sensor fusion' or how different sensory motor capabilities can be integrated. That is, we can investigate this problem by attempting to explicitly model a biological example of multimodal integration. The 'fusion' should be considered in the context of a motor task rather than characterised as a problem of producing a representation that merges information from diverse modalities. Utilising the preprocessing mechanisms or 'matched filters' we have previously built should simplify the problem of how to combine behaviours. The mechanisms derived can be applied to autonomous robot navigation.

This paper describes a pilot investigation of a combined visual and auditory system, implemented on a robot, that models the cricket behaviour of sound source localization with optomotor corrections. In what follows, we briefly review the biological background, which points to a simple linear integration mechanism. The hardware used to copy the peripheral sensory mechanisms, and their implementation on a robot will then be described. The results of using the linear combination of the two sensor systems to control the robot behaviour will be presented, and we will discuss the issues raised by this initial investigation and the direction of future work.

## 2 Background

Although crickets are best known for their ability to localize mating partners by approaching specific calling songs (phonotaxis), they share with most animals the basic optomotor response that to date has been most thoroughly investigated in flies. That is, they respond to rotation of their visual field by self-rotation, which in normal conditions serves as an 'auto-correction' for unintended course deviations. This visual behaviour may play a significant role in phonotaxis. Weber et al (1981) note that "the female cricket seeks the calling male on temperate evenings, in conditions that can offer a sharply structured visual surround" [17] and compare the behaviour of crickets tracking sound in the light and in the dark. Without visual information the cricket produces a zigzag path to the sound, meandering 30°-60° from the sound direction. In the light, it can produce relatively straight runs in the speaker direction, with deviations of only around 6°.

Bohm et al (1991) further investigated this behaviour using an 'open-loop' paradigm in which the cricket was fixed in position above a treadmill, to measure its turning tendency to stimuli from different locations [1]. They found that the presence of visual stimuli increased the turning tendency exhibited by the cricket to sound. When a moving visual grating provided a strong optomotor signal, the turning response of the animal to sound would be shifted in the corresponding direction. They conclude that the "turning tendency can be explained as the weighted sum of the two turning tendencies evoked by the two individual stimuli".

These studies, combined with the known mechanisms for pure phonotaxis (e.g. Schildberger, 1988 [14]) and optomotor (e.g. Egelhaaf & Borst, 1993 [3]) behaviour, suggest the following action of the optomotor and phonotaxis responses (illustrated in figure 1):

- Phonotaxis uses the difference between the ears to bias the motor output: a louder signal in one ear causes a turn towards it.
- The optomotor response uses the velocity of the visual field to bias the motor output: the cricket turns in the direction of visual motion.
- These two biases are summed with the forward motion tendency to determine the actual turn.
- The phonotaxis response should be more heavily weighted than the optomotor response so that a turn towards sound is not immediately counteracted by an optomotor correction.
- When facing directly to the sound there is little difference between the ears so the optomotor response is used to keep a direct course.

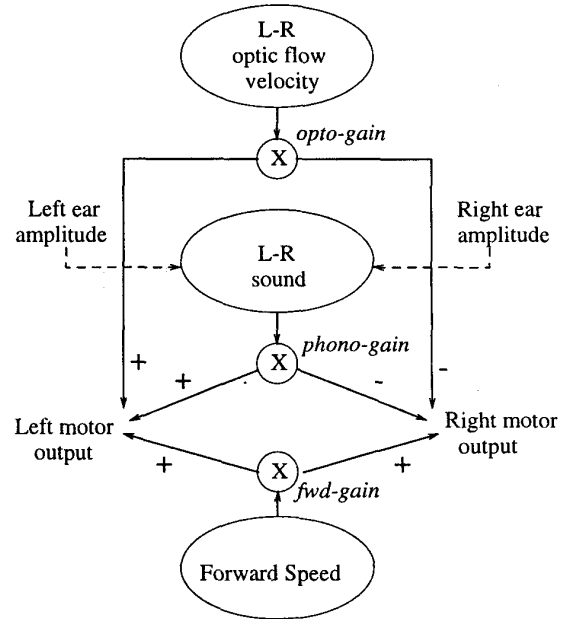


Figure 1: the combination of optomotor and phonotactic information

## 3 Implementation

Our implementation of the combined visual and auditory behaviour reflected the neural architecture found in the cricket. Visual motion processing occurs in the cricket's optic lobes and is then routed to the protocerebrum, from which descending neurons command motor control. The visual processing on our robot was done on a separate chip and the velocity signal sent to the main processor that produced motor commands. Auditory processing in the cricket occurs in the prothoracic ganglion from which signals ascend to the protocerebrum and are combined with other modalities. The auditory processing on our robot was done on a separate microprocessor and the output sent to the main processor to be combined with the visual signal. We will describe each of these parts in more detail.

### The phonotaxis system

The cricket has a unique auditory system that acts as a pressure difference receiver to provide a strongly directional response despite the small spacing between the ears. The eardrums, located on the forelegs, are connected by a tracheal tube through which sound waves can propagate. Consequently the vibration of the ear drum results from the combination of the direct sound and the delayed sound travelling from the other ear. This delay is tuned to the frequency of cricket song such that the relative phase of the waves reflects the direction of the sound

source, and thus the summed vibration has an amplitude that reflects the direction of the sound source.

An electronic circuit that mimicks this system has been built (figure 2; see (Lund et al, 1997 [11]) for further details.) Two microphones separated by 18mm (1/4 wavelength of the carrier frequency - 4.7kHz - of cricket song) receive and amplify the sound. The signal from the left microphone is delayed by 53 microseconds (1/4 the phase of 4.7kHz) and then subtracted from the right; and vice-versa. The resulting waves are sent through an RMS circuit to measure the amplitude and passed to the A-D port on a robot.

This auditory circuit was designed to interface with a Khepera™ (Kteam, 1994 [9]) robot. A software simulation of the subsequent neural processing of sound is run on the Khepera's microprocessor. This uses a simple state-based integrate-and-fire neuron model. The left and right ear signals produced by the auditory circuit cause respective auditory interneurons to fire with a latency and firing rate correlated to the amplitude of the signal. The auditory interneuron that fires first excites an ipsilateral motor neuron which signals a turning response. The details of this neural simulation, and a description of how it is capable of explaining the cricket's selectivity for sound, are given in Webb & Scutt (1999) [16].

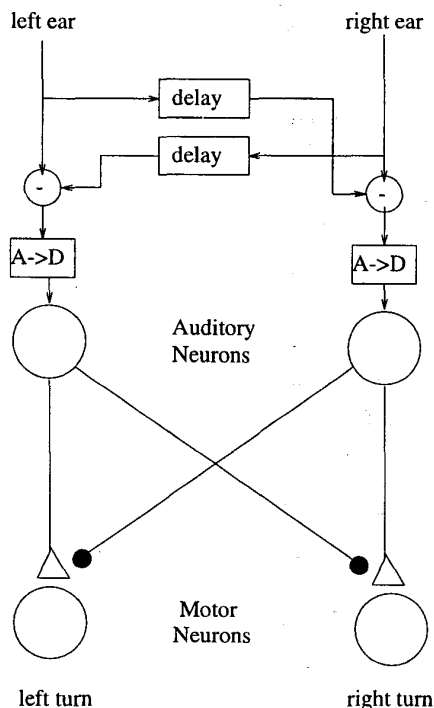


Figure 2: Schematic of the phonotaxis system

### The optomotor system

Visual motion detection has been studied most extensively in flies, but similar systems are found in a wide variety of insects (O'Carroll 1996). The best studied cells are wide-field motion sensitive neurons in the lobular plate of the optic lobe. It is known that a subset of these cells -- the HS, or "horizontal system", neurons -- in the fly estimate the animal's yaw rotation and send this information to the wings, which produce a stabilizing compensatory torque (Egelhaaf and Borst 1993). One of these HS neurons has been modelled in 1.2 micron analog VLSI (Very Large Scale Integration) technology (Harrison and Koch 1998). The silicon model has been compared directly with a behaving fly in a closed-loop flight simulator (Harrison and Koch 1999a) [6], and has been used to stabilize the trajectory of an asymmetric robot (Harrison and Koch, 1999b) [7].

The chip used in our experiments contains a 24 x 6 array of photoreceptors. A local measure of motion is computed between adjacent pairs of photoreceptors in each of six rows across the chip. We use the Reichardt model of insect motion detection to process photoreceptor signals. First, these signals are bandpass filtered to remove the DC illumination levels. In the Reichardt model, photoreceptor signals are delayed, then correlated with non-delayed signals from neighboring photoreceptors. We use the phase lag inherent in a lowpass filter as the delay, and multiplier circuits as the correlators. This motion detection is performed in opponency, and the results across the chip are summed (see Figure 3). The results of the chip are lowpass filtered ( $\tau = 100$  ms) to remove residual pattern dependencies from the response. All of these operations are performed on a single analog VLSI chip that dissipates less than 1 mW of power.

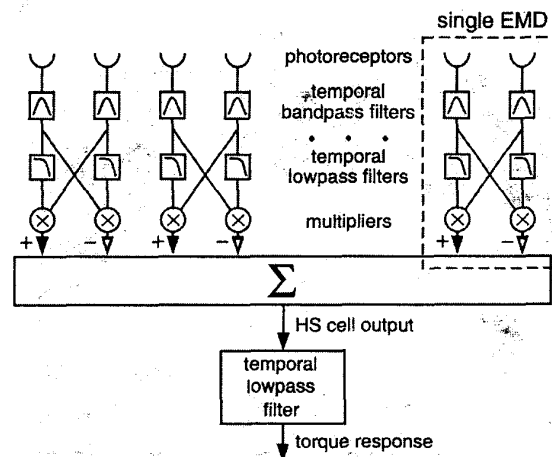


Figure 3: Schematic of the optomotor chip

The chip, with its support circuitry and a lens, was mounted on a Rug-Warrior Pro™ (Jones, 1999) [8] robot, with the time-averaged velocity signal connected to an analog-to-digital port.

### Combining the outputs

The output of the phonotaxis system is a pair of binary signals indicating a left or right turn if there is a left or right difference between the ears. Instead of using this signal to control the motors of the Khepera robot, the Khepera was mounted on top of the Rug Warrior and the turn signals routed via LED circuitry on the Khepera to two digital ports on the Rug Warrior. There they were combined as  $\text{ears} = \text{left} - \text{right}$ , i.e. ears would equal +1 for a left turn, -1 for a right turn, or 0 for no turn. The output of the optomotor circuit is simply the value read from the AtoD port minus the initial 'zero' set-point value, i.e. will be positive for leftwards motion and negative for rightwards motion.

The motor output was then calculated as:

Left\_speed =

default speed + opto\_gain\*opto\_signal + ear\_gain\*ears

Right\_speed =

default speed - opto\_gain\*opto\_signal - ear\_gain\*ears

The default speed could be set so that the robot, in the absence of sound or visual signals, either moved forward (default speed = +30, equivalent to about 20 cm/sec) or stayed on the spot. The ear\_gain was set at 30, so that in the absence of the opto-motor signal, the robot would: if travelling forward respond to a turn signalled from the ears by stopping one wheel and doubling the speed of the other; if on the spot respond by setting one wheel forward and one wheel backward, thus turning toward the sound. The optomotor gain was set at 1, so that the robot would slow down one wheel and speed up the other by the size of the visual velocity signal. Alternative gain settings were tried but not systematically explored.

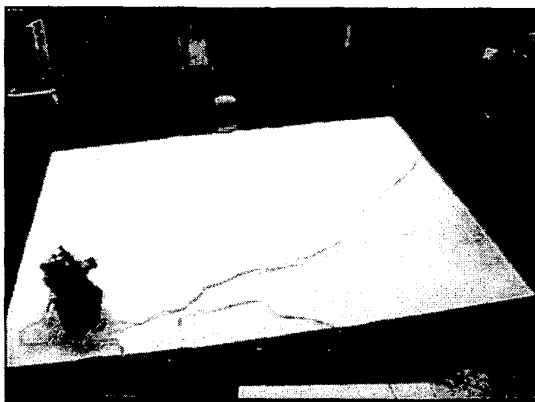


Figure 4: The robot (left) in the experimental situation, speaker is at center

## 4 Results

The robot behaviour was tested in the normal lab environment. The auditory stimulus was constructed from a recorded cricket song. A single 'syllable' of the male cricket song is a 20ms burst of almost pure 4.7kHz sine wave. The syllables occur in groups of 4, with intersyllable gaps of 20ms; and the groups ('chirps') repeat at approximately 3 Hz. A song of 20 seconds total duration was played back from a .wav file through a speaker. The speaker was placed on the floor of the lab. No special sound-proofing or other controls for noise or echoes was used. The visual stimulus was simply the lab furniture, including at times the experimenters (see figure 4).

Some of the tracks were recorded using a pen attached to the back of the robot, and transcribed by hand. We also attempted to use the shaft-encoders to record tracks but they were not sufficiently accurate to reconstruct the path taken by the robot. Consequently the results discussed below can only be considered preliminary observations. Further experiments and quantification of the behaviours are being pursued.

Using only the phonotaxis response (figure 5), the robot was quite reliably able to locate the sound source when started from various positions 1.5m from the speaker. When the optomotor response was added, the paths became slightly more direct, and included a larger number of small adjustments - see figure 6. However the difference between the conditions was small, because the phonotaxis response alone was generally sufficient to produce quite a direct path, i.e. there wasn't much room for improvement.

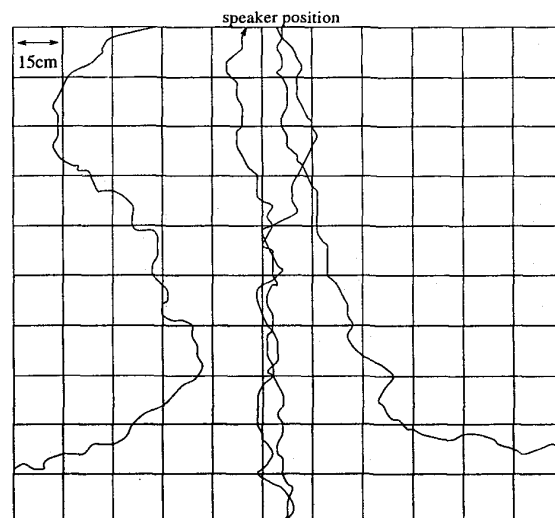
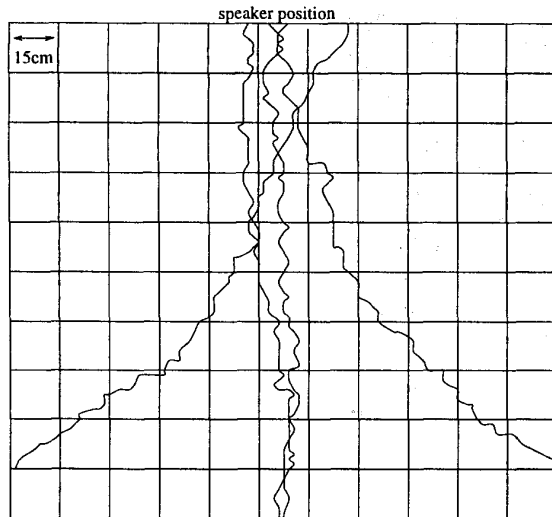


Figure 5: paths with only the phonotaxis system enabled



**Figure 6: paths with the phonotaxis and optomotor systems combined**

One effect of the optomotor input was to make the robot turn less directly towards the sound when at a significant angle to it. Hence the path would tend to be a curve towards the speaker rather than a zigzag meander. It might be argued that the same effect could simply be achieved by reducing the phonotaxis gain so that the robot turned more gradually to sound. However, testing the phonotaxis behaviour with a reduced gain and no optomotor response produced a quite different response. A very smooth curve, without the micro-adjustments seen in the optomotor path, was observed. This was in fact insufficient to get the robot successfully to the sound source.

To better understand the effect of the optomotor reflex on the phonotaxis behaviour we also looked at the behaviour of the robot with the default speed set to zero, so that it only rotated on the spot. By placing it on a board, we could rotate it in arbitrary ways and look at how the two sensorimotor systems could control the behaviour. When no sound was present, the optomotor response enabled the robot to correct for any experimenter imposed turns. When sound was present the phonotaxis response alone led to the robot oscillating about the speaker direction, and turning back towards it if the experimenter turned it away. When the optomotor response was added to phonotaxis there were two distinct effects discernable. If the robot was facing away from the sound, it took longer to turn towards it, because it had, in a sense, to 'fight' against the optomotor response, which tried to turn it back. On the other hand, when the robot was already facing the sound, turning it away led to a rapid correction back to the forward direction. In this case, the phonotactic and optomotor responses were acting together to turn the robot

back towards the direction from which it was deflected. It appeared as though the robot had strongly 'locked on' to the sound direction.

## 5 Discussion

We have used two pre-existing robot models of insect sensorimotor behaviour – the phonotactic response and the optomotor response – and looked at how they might be combined. Experiments on the cricket have suggested a simple additive combination of the two factors, so this is what we implemented on the robot. Although there was some indication that the optomotor reflex improved the phonotactic behaviour, the change was not as dramatic as we had hoped – certainly not as clear as that found in the cricket experiments reported above.

Several reasons for this limited result can be advanced. Perhaps the most important is that the optomotor response may be more important for real insects than it is for typical robots. The primary function of this response is to enable an animal to maintain a straight course when faced with inherent disturbances. A fly in a high wind, or a cricket walking over uneven terrain cannot rely on sending equal signals to both wings or sets of legs to obtain a straight line path. However our robot, with high friction wheels and powerful motors could maintain a relatively straight heading without much difficulty. Consequently the optomotor response at best contributed a 'fine-tuning' effect to what was already a reliable behaviour. It seems likely that in a situation that offers more challenging motor control – such as running a robot in outdoor terrain – the advantage of adding an optomotor response might become more obvious. This is one direction of future research that will be pursued.

It is also possible that the simple additive combination of responses should be reconsidered. The fact that the optomotor response tended to 'fight' against an efficient turning towards the sound suggests that perhaps the phonotaxis should generally override the optomotor, at least where these signals are acting in opposite directions. Alternatively the problem might be that the current implementation of the phonotaxis behaviour is binary – the robot either turns or does not, rather than scaling the speed or strength of the turn to the size of the difference between the ears. If the phonotaxis turn signal was relatively large when the robot was at a large angle to the sound, it would then effectively override the optomotor signal, without having to actively suppress it.

Finally we have as yet not attempted to make a careful study of, or tuning of, the relative timing of the two responses. There are several ways in which these timings might interact. The optomotor signal might tend to come after the phonotactic turn has finished, thus 'correcting' it

rather than being added to it. The optomotor response is also sensitive to the absolute velocity. Very rapid turns are not detected by the motion system, and thus provide another mechanism by which 'intended' turns can override the optomotor system. This mechanism appears to operate in flies, and corresponds to the human failure to detect motion blur during saccadic movements of the eyes.

We plan to look more closely at the biological system to address these issues in the future. For example there are a number of studies of multimodal neurons in the cricket brain (e.g. Bohm & Schildberger, 1992) [2] that may provide clues for more subtle and effective ways to combine sensory systems. In addition, the systems built also function as interesting and illuminating models in our attempts to better understand biology.

### Acknowledgments

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