Evolving Spiking Neuron Controllers for Phototaxis and Phonotaxis

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Abstract. Our long-term goal is to evolve neural controllers which reproduce in behaving robots the kind of phonotaxis behaviour seen in real animals, such as crickets. We have previously studied the evolution of neural circuitry which, when implanted in a Braitenberg type 2b vehicle, promoted phototaxis behaviour in the form of movement towards flashing lights of different frequencies. (It was simpler to study light-driven than acoustic-driven behaviour.) Since this is not truly sequential behaviour, we now describe new work to discriminate between particular mark-space ratio patterns of the same basic (flash or on-off) frequency. The next step will be to integrate the two behaviours so that robot taxis is driven by a signal with temporal structure closer to that of the cricket 'song'.

1 Introduction

In previous work (Damper, French, and Scutt 2000; French and Damper 2002), we have used an autonomous robot to study the links between the 'neurophysiology' of a robot and its external behaviour in the belief that this can inform us about the links between neurophysiology and behaviour in real animals. This dictates that we use spiking neurons in the robot controller. Since real nervous systems are evolved rather than designed, we study the evolution of spiking neuron circuitry for our robot. Evolving spiking neural circuitry remains something of an unusual activity; the only other work we know of is that of Floreano and Mattiussi (2001). Our long-term goal is to evolve neural controllers which reproduce in behaving robots the kind of phonotaxis behaviour seen in real animals, such as crickets. Female crickets move towards the 'song' of a male conspecific or an artificially-produced 'song' provided it shares a similar temporal structure. This behaviour has been extensively modelled in robot studies (e.g., Lund, Webb, and Hallam 1997; Kortmann 1998; Webb and Scutt 2000; Reeve and Webb 2002). Since our robot is not currently equipped with acoustic sensors, we have switched modalities to study the evolution of phototaxis behaviour.

We have previously studied the evolution of neural circuitry which, when implanted in a Braitenberg type 2b vehicle, promoted phototaxis behaviour in the form of movement towards flashing lights of different frequencies (French and

Damper 2002). However, these simple signals are quite unlike the more complex cricket song. Hence, in the current work, we study a task specifically designed to promote sequence-discrimination behaviour. The approach is very similar to French and Damper (2002), and the reader is referred to this earlier publication for details of the genetic programming (data structures and algorithms) used to evolve the controllers. Specifically, in this new work, we require the robot to move towards an on-off pattern of flashing light (of a fixed flash frequency) with a given mark-space ratio while ignoring an on-off pattern of another mark-space ratio.

2 Evolving a Mark-Space Discriminator

In our recent work (French and Damper 2002), circuits of model spiking neurons were evolved to detect a sensory (light) signal with a particular flash frequency. A simple extension to this work is to evolve a neural circuit to process a signal that varies in duration—it has a variable mark-space ratio.

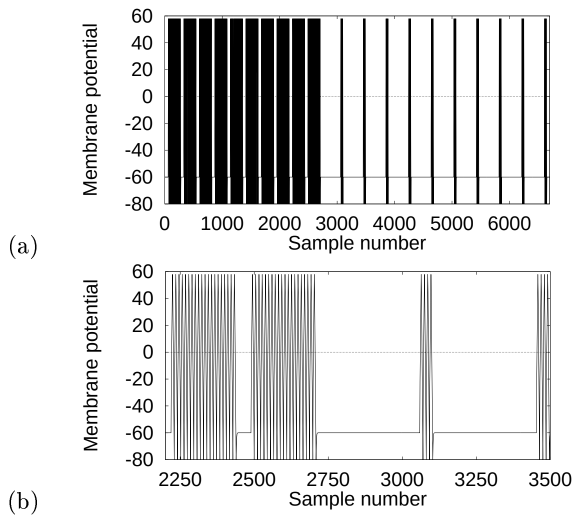

Fig. 1. (a) Neuron activity showing two mark-space burst-firing patterns and (b) close-up of the spike train showing individual spikes.

Figure 1 shows the activity of a neuron that alternates between two mark-space patterns. This is taken to represent the output of a sensory neuron that is being depolarised by a stimulus from an environment and forms the input to our evolving neural circuit.

The fitness function for this evolutionary task simply increments a counter by a small amount every time a particular input firing activity coincides with firing of a designated output neuron. The fitness counter is similarly decremented by small amount for an incorrect output response. Because the input neuron's burst trains differ in length (giving rise to two different mark-space patterns), the amount by which the counter is incremented or decremented is weighted to reflect the length of the spike train. For example, when evolving a discriminator for a long spike train the counter is decremented for an incorrect response by an amount greater than that used for an increment. If this safeguard is not used then the discriminator will not filter out the short spike train properly.

A population of 1000 individuals was used running for 500 generations across a MOSIX cluster of nine Athlon-based disk-less PCs. The evolutionary process was repeated 10 times for the short mark-space discrimination task and 10 times for the long mark-space discrimination task. All runs generated circuits that could distinguish between the mark-space patterns.

Figure 2 shows a typical circuit evolved with a fitness function configured to select the long mark-space component of Fig. 1. In the same way, Figure 3 was evolved with a fitness function configured to select the short mark-space component of Fig. 1. Figures 4 and 5 show how the best fitness obtained so far increases during evolution.

3 Analysis of the Evolved Circuits

We will first consider the short mark-space circuit of Fig. 3 because, after so doing, we will be in a better position to understand the workings of the circuit in Fig. 2. The significant element underlying the circuit of Fig. 3 is the habituating excitatory synapse between `input` and `interneuron` cells. During the long mark-space firing pattern of the input neuron, the habituating synapse weakens to a point where it can no longer depolarise and fire the output neuron via the interneuron. This is shown in Fig. 3 (b). Critically though, during presentation of the short mark-space firing pattern, the habituating synapse recovers (`Rec. = 0.009`, a slow recovery rate) to a point where it can depolarise and fire the interneuron. Interestingly, the interneuron has evolved a low threshold of $-58\,\mathrm{mV}$, which is close to resting potential. This increases the chances of the interneuron firing during the short spike train (when the degree of temporal summation is low.)

Turning to the long mark-space circuit of Fig. 2, this circuit has a simpler operation. The low value of the synaptic weight between the input and interneuron cells (with respect to that in Fig. 3) means that more spikes from the input neuron are needed to depolarise the interneuron beyond threshold than in the circuit of Fig. 3. Hence, the operation of this circuit depends upon a relatively large degree of temporal summation. Additionally and in contrast with the previous circuit, the interneuron has evolved a high threshold of $-43\,\mathrm{mV}$. This requires greater depolarisation of the membrane for the neuron to fire making it less likely to fire during the short spike train.

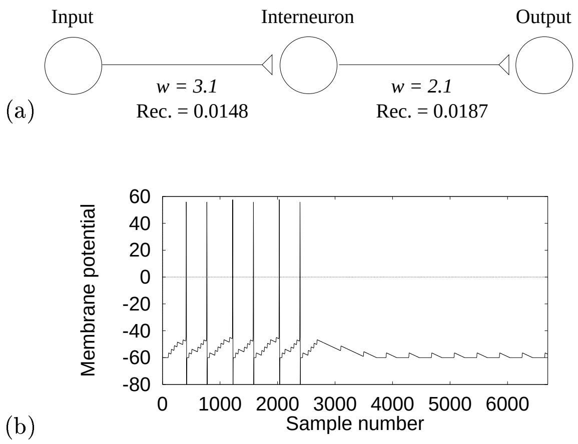

Fig. 2. (a) Nervous system evolved to select the long mark-space input signal (Fig. 1) with synaptic weight and recovery parameters shown and (b) its output. Redundant components have been removed for clarity.

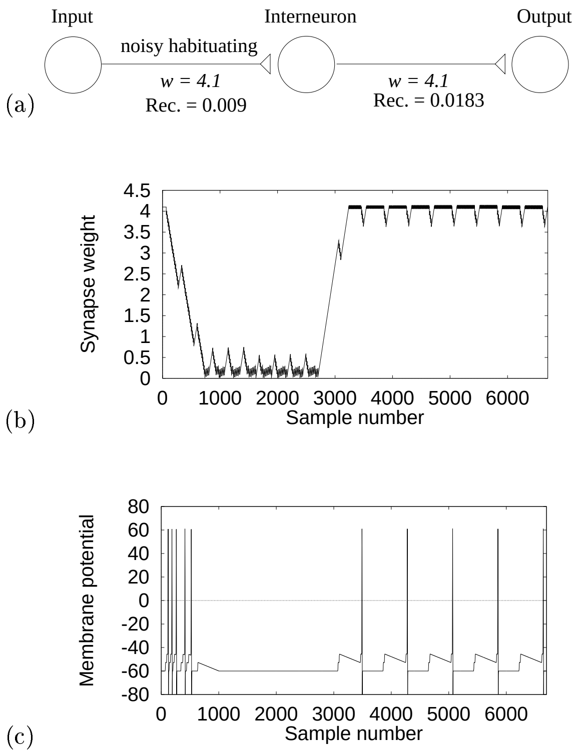

Fig. 3. (a) Nervous system evolved to select the short mark-space input signal (Fig. 1), (b) habituating synapse weight and (c) the circuit's output. Redundant components have been removed for clarity.

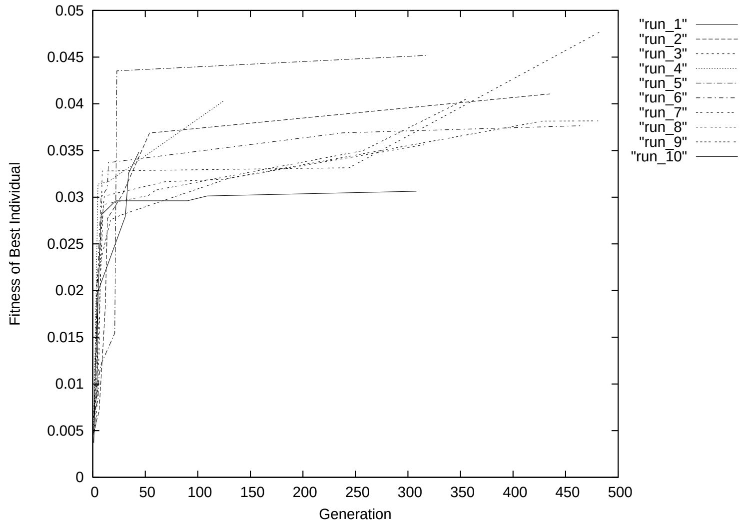

Fig. 4. Increase of best fitness of the evolved neural circuit to detect the long mark-space ratio versus generation. For clarity, the best fitness is indicated only up to point at which it stabilises.

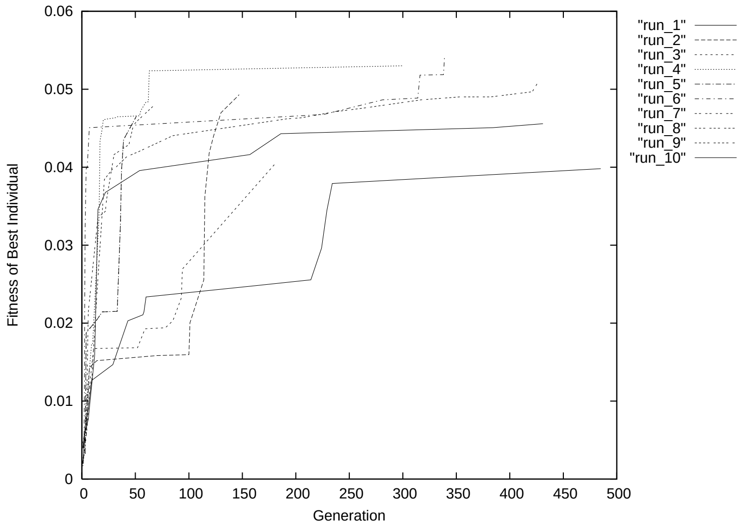

Fig. 5. Increase of best fitness of the evolved neural circuit to detect the short mark-space ratio versus generation. For clarity, the best fitness is indicated only up to point at which it stabilises.

4 Phototaxis in a Braitenberg Vehicle

Now that we have evolved neural circuits 'in isolation' that can discriminate between different mark-space patterns, they were incorporated in a Braitenberg type 2b vehicle (Braitenberg 1984, p. 7). This should result in a vehicle that can seek out the source of a stimulus, e.g., a light source flashing with a particular mark-space ratio, so exhibiting phototaxis.

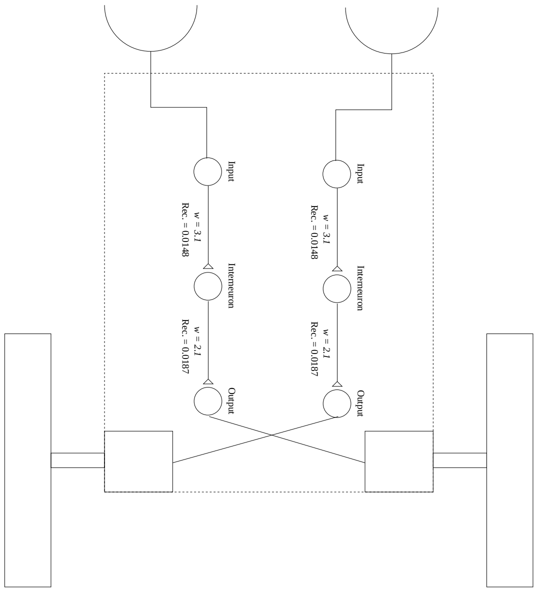

Fig. 6. A Braitenberg type 2b vehicle architecture with spiking neurons that seeks long mark-space signals.

An neural controller describing a type 2b vehicle architecture was created using two of the networks in Fig. 3 to connect contralateral *proximal* sensory-motor pairs (i.e., the sensors respond to changes in light level) as shown in Figure 6. Proximal light sensory neurons were selected to reduce the risk of spurious sensory input. This is because ordinary light-sensor neuron firing is proportional to light intensity.

Minor changes to the evolved nervous system circuitry were made to match the circuit's response to 'live' input from real light sensors. As indicated above, sensory and motor neurons were added in place of input and output neurons. Experiments were carried out to test the expected phototaxis behaviour.

The experimental setup was as follows. A Khepera robot was placed in a test environment facing the mid-point between two 2.5 V filament lamps, approximately 10 cm away. The lamps were positioned 15 cm apart. A driver circuit controlled by software via a PC's parallel printer port switched the lamps (pulsed at 50 Hz via bits D0 and D1) with on/off-times of 1 s/1.02 s and 2 s/0.02 s giving the short and long mark-space patterns, respectively. Software control also allowed toggling of the patterns between the two lamps, i.e., the long mark-space pattern could be presented on the left lamp with the short on the right, or vice versa. This arrangement gave a usable optical signal for the proximal sensory neurons of the Braitenberg vehicle. Although these timings proved adequate for the real-world experiment, however, there are undoubtedly better alternatives that more closely match the simulated sensory-input signals presented during evolution. The nervous system models and lamp controller software ran concurrently on a 80486 Linux PC.

During initial tests it became clear that ambient light influenced the robot's phototaxis performance: Bright background light disrupted the ability to discriminate between long and short mark-space signals. Hence, final runs took place in low levels of lighting. The inability to cope robustly with ambient light is probably because the discrimination circuits of Figs. 2 and 3 were evolved in isolation, without the input noise generated by the Khepera simulator sensor models.

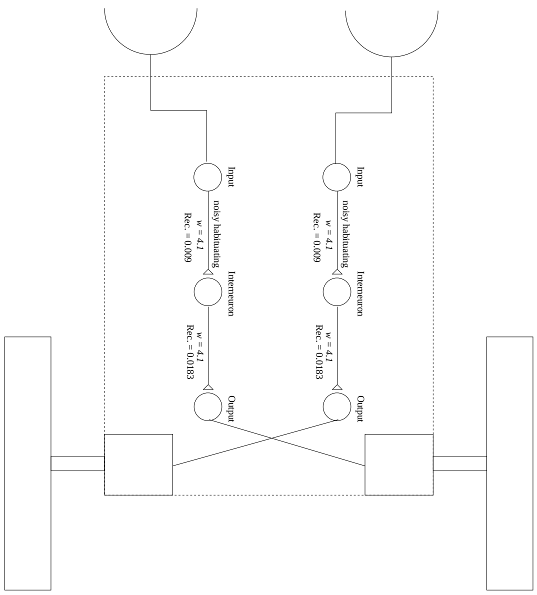

Fig. 7. A Braitenberg type 2b vehicle architecture with spiking neurons that seeks short mark-space signals.

The experiments started with a Braitenberg type 2b vehicle (shown in Figure 7) that favoured the short mark-space signal. Twenty trials were carried out to observe the robot's behaviour with both toggle-settings of the lamp control software. For the first 10 trials the short mark-space signal was on the robot's left; for the second group of 10 trials, the short mark-space signal was moved to the robot's right. This was then repeated with a vehicle that favoured the long mark-space signal (shown in Figure 6).

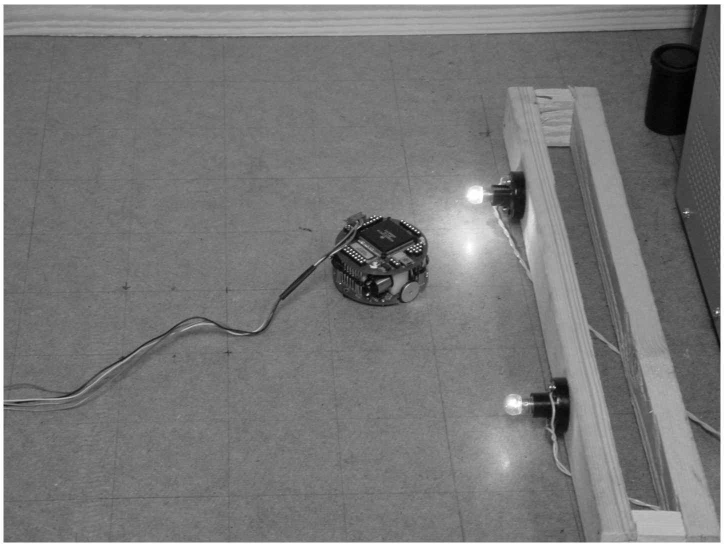

Fig. 8. Khepera in the test environment used for phototaxis experiments.

Figure 8 shows the vehicle (Khepera) in the test environment. It was noticed that the response of the short mark-space circuit was not as vigorous as its long mark-space counterpart, taking approximately 4 minutes to reach the target lamp. This was entirely due to the slow recovery of the habituating synapses. In contrast, the long mark-space vehicles took approximately 2 minutes to reach the target lamp.

In all trials, the vehicles performed their tasks well. During the short mark-space ratio trials, only three vehicles lost view of the target lamp and halted. This is likely to be an indication that the 'on' time for this target signal is too long. For the long mark-space ratio trials, the vehicles performed without error.

5 Towards the Evolution of Phonotaxis

In cricket phonotaxis, a female insect seeks the calling song of male conspecifics in a noisy environment. This has been extensively studied by Webb and colleagues (Lund, Webb, and Hallam 1997; Webb and Scutt 2000; Reeve and Webb 2002). However, throughout their work, the circuitry underlying the behaviour of their robots has been manually designed. This prompts the question: "Can we evolve neural circuits that allow a robot to perform phonotaxis behaviour?" This is interesting because a neural controller generated through evolutionary computation may operate using principles that had previously not been considered for manual designs.

The work presented here on phototaxis is intended as a stage in the evolution of circuitry to drive cricket phonotaxis. We note that Kortmann (1998) has conducted preliminary work on the evolution of phonotaxis in a robot cricket, but his work merely evolves parameters controlling high-level behaviour (*delay* and *turning time*) in a circuit of predetermined structure rather than, as here, evolving the circuit structure itself. The analysis in Section 3 shows that the operating principles of the evolved spiking-neuron circuits is quite different from that of more conventional 'neural networks' using artificial neurons of the type made popular by (McCulloch and Pitts 1943), based on simple activation functions. By their ability to encode time information in terms of time of firing, and richer endowment of parameters, spiking neuron circuits ought to display enhanced ability to learn and process complex temporal patterns (Bugmann 1997; Koch 1998) such as the cricket song.

6 Conclusions

We have described work to evolve spiking neural circuits that can discriminate between two mark-space patterns. Light-seeking Braitenberg vehicles were constructed that used these circuits as the basis of phototaxis. Although the Braitenberg vehicles were unable to deal with strong ambient light, this is probably because their circuitry was evolved 'in isolation' (for computational convenience) and not onboard a vehicle situated in a real or simulated environment. We intend to extend this work to simulate phonotaxis in the cricket, where the temporal patterning of the relevant signals is considerably more complex. The next stage of this work will focus upon the coupling of evolved frequency discrimination circuitry (French and Damper 2002) and the evolved mark-space discriminators described in this paper.

The evolved controllers in this paper rely on properties of biological neurons which are not modelled in conventional artificial or formal 'neurons' (e.g., recovery rates and/or time of arrival differences between spikes). Hence, as part of future work, we intend to evolve non-spiking neural solutions and to compare them with their spiking counterparts. It also remains to assess the sensitivity of our evolved circuits to small changes in flash frequency and mark-space ratio in their inputs.

Although the circuits evolved in the work so far, and the tasks which they allow the robot to perform, are relatively simple, we envisage that these simple circuits will exploit evolutionary and computational principles which can be combined hierarchically to produce more complex circuits and behaviours. This is much in the flavour of the concept of "a cell biological alphabet" for learning and learned behaviour espoused by Hawkins and Kandel (1984). If so, this would offer at least the prospect of moving from simple small-scale behaviours in insect-like animats to more interesting large-scale behaviours.

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