Mimicking the worm – an adaptive spiking neural network for contour tracking inspired by C. Elegans thermotaxis

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Introduction

- A widely studied model organism, nematode C. Elegans, can track regions with constant temperatures or chemical concentrations.
- A nearly complete structure and connectivity of the neural network of C. Elegans has been known for two decades.
- However, there have been no neural models that completely and quantitatively explain non-trivial behaviors such as thermotaxis arising from basic neural networks.
- We demonstrate a spiking neural circuit inspired by the architecture of the network believed to control thermotaxis in C. Elegans.
- We quantify the performance of our model for discovering and tracking contours, in terms of accuracy and energy efficiency.

Model for Spiking Neurons and Synapses

\[
\frac{dF(t)}{dt} = -g_e (F(t) - E_e) + g_i (F(t) - E_i) + \exp \left( \frac{F(t) - F_{th}}{\Delta E} \right) - U(t) + I_{syn}(t) + I_{inh}(t)
\]

\[r_e = \frac{1}{V_e} \frac{d}{dt} [F(t) - E_e] - U(t)
\]

\[r_i = \frac{1}{V_i} \frac{d}{dt} [F(t) - E_i] - U(t)
\]

If \( V \geq 0 \) then \( F \to F_e \) and \( U \to U(t) + b \)

Synaptic current induced by spike at time \( t' \):

\[I_{syn}(t) = I_i \left[ \exp \left( \frac{t - t'}{\tau_e} \right) - \exp \left( \frac{t - t'}{\tau_i} \right) \right] \delta(t - t')
\]

The Dynamics Model

We assume that the worm is continuously moving. The speed and direction of the worm is controlled by the neural network.

 Comparator circuit

\[I_{N1}(t) = \alpha_T (T - T_b)
\]

\[I_{N10} = \alpha_T (T - T_b) + \beta_T (T - T_b)
\]

A complementary comparator can be realized by making \( \alpha \) negative and \( \beta \) positive.

Neural circuit for contour tracking

- At every spike of N10, the worm turns by a random angle uniformly distributed over \([-\pi/2, +\pi/2]\).
- The bias current into N10 alone is not sufficient to elicit any spiking. N2 and N3 inject excitatory currents into N10 when worm is not within a band around the cultivation temperature \( T_b \).
- Worm should move faster if it is away from \( T_b \).
- At every spike of either N2 or N3, the speed exponentially decays to 1 mm/sec.
- In absence of any spike at either N2 or N3, the speed exponentially decays to 1 mm/sec.
- Spike patterns in the network during random exploration (left) and tracking (right).
- N6 and N9 spike in response to negative and positive temperature gradients. Their spikes actuate deterministic turns causing isothermal tracking.
- N10 spikes when they are quiet, prompting random exploration.
- When away from \( T_b \), heavy spiking at comparator neurons causes the average speed to increase thus leading to faster exploration.

Results and performance evaluation

- For a memoryless forager, the optimal strategy to detect randomly distributed revisitable targets is to make the flight lengths between random turns follow the heavy-tailed Levy distribution. For a fair comparison with our model, we kept launch point, minimum run length and average speed for both models identical. Results were as follows:

<table>
<thead>
<tr>
<th>Methods</th>
<th>Levy Flight</th>
<th>Our model</th>
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<tbody>
<tr>
<td>1. Isometric discovery success rate</td>
<td>35%</td>
<td>82%</td>
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<tr>
<td>2. Time to locate the isotherm</td>
<td>51.08 ± 36.16 s</td>
<td>40.70 ± 27.83 s</td>
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This justifies the energy expended by the worm in neural computations. The energy consumed by this circuit depends on the number and frequency of spikes needed to make decisions. The average firing rate over the whole population of neurons is 73.89 Hz. The worms spike sparsely. Local spiking frequencies rarely go above 150 Hz and never above 260 Hz, ensuring that our model is biologically plausible.