Sandia National Laboratories

Modeling Coordinate Transformations in Dragonfly Nervous Systems

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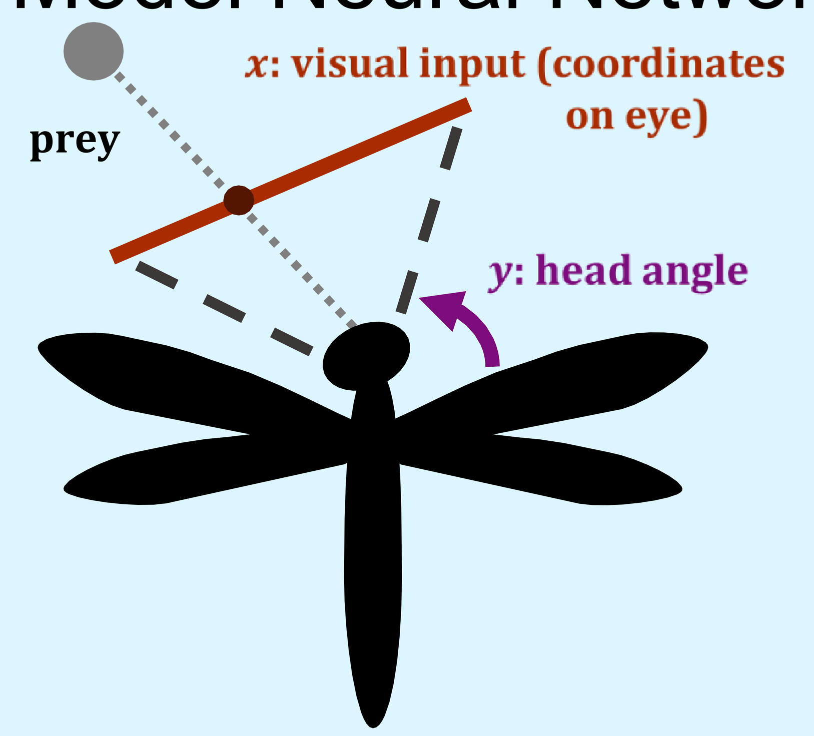
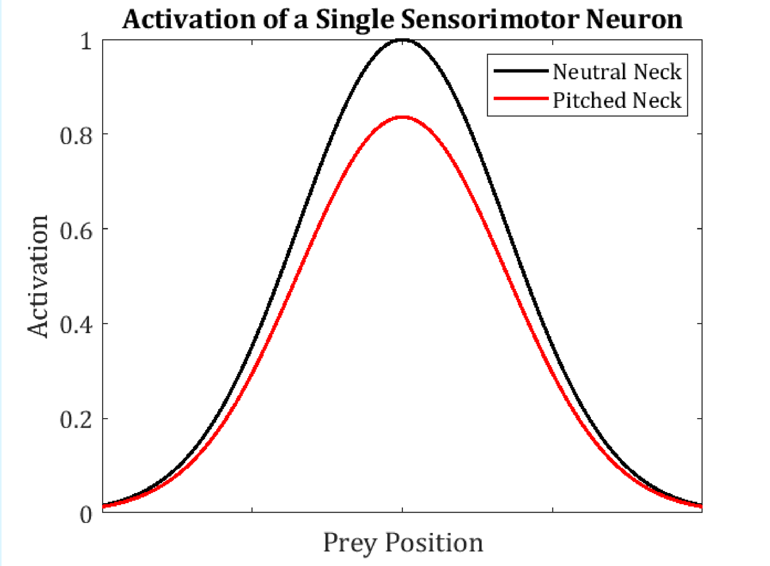
Introduction

Dragonflies are highly specialized hunters, and experimental data suggests they approximate parallel navigation, a geometric rule, for interception (6, 10, 11). We are interested in how the dragonfly nervous system calculates turns during hunting.

Effective interception requires coordinate transformation computations, from the eye's reference frame to the body's reference frame. We propose a model neural network that integrates both visual and proprioceptive (head angular position) inputs to calculate motor commands for interception. This model multiplicatively combines visual and proprioceptive inputs (inspired by gain fields observed in primate parietal area 7a (1, 2, 3, 4)). We compare the results of this model to electrophysiology data recorded from awake dragonflies to validate this model and to gain understanding of the biological mechanisms for performing these computations. The validated model will be used to inform new neuromorphic architectures.

Model Neural Network





Visual (prey-image location on eye) and **proprioceptive** (head angle) neurons encode prey-image location on eye and head angle, respectively.

$$f_i(x) = \exp\left(\frac{-|a_i - x|^2}{2\sigma_r^2}\right);$$

$$g_j(y) = \exp\left(\frac{-|b_j - \varepsilon \tan(y)|^2}{2\sigma_g^2}\right)$$

$f_i(x)$ and $g_j(y)$ are the response curves for the ith visual and jth proprioceptive neurons, with tuning widths σ_r and σ_g. a_i and b_j are preferred prey-image location and head angle. ε is the distance of the eye from the center of the head.

Sensorimotor neurons multiplicatively combine **visual** and **proprioceptive** inputs (inspired by gain fields observed in primate parietal area 7a (1, 2, 3, 4)):

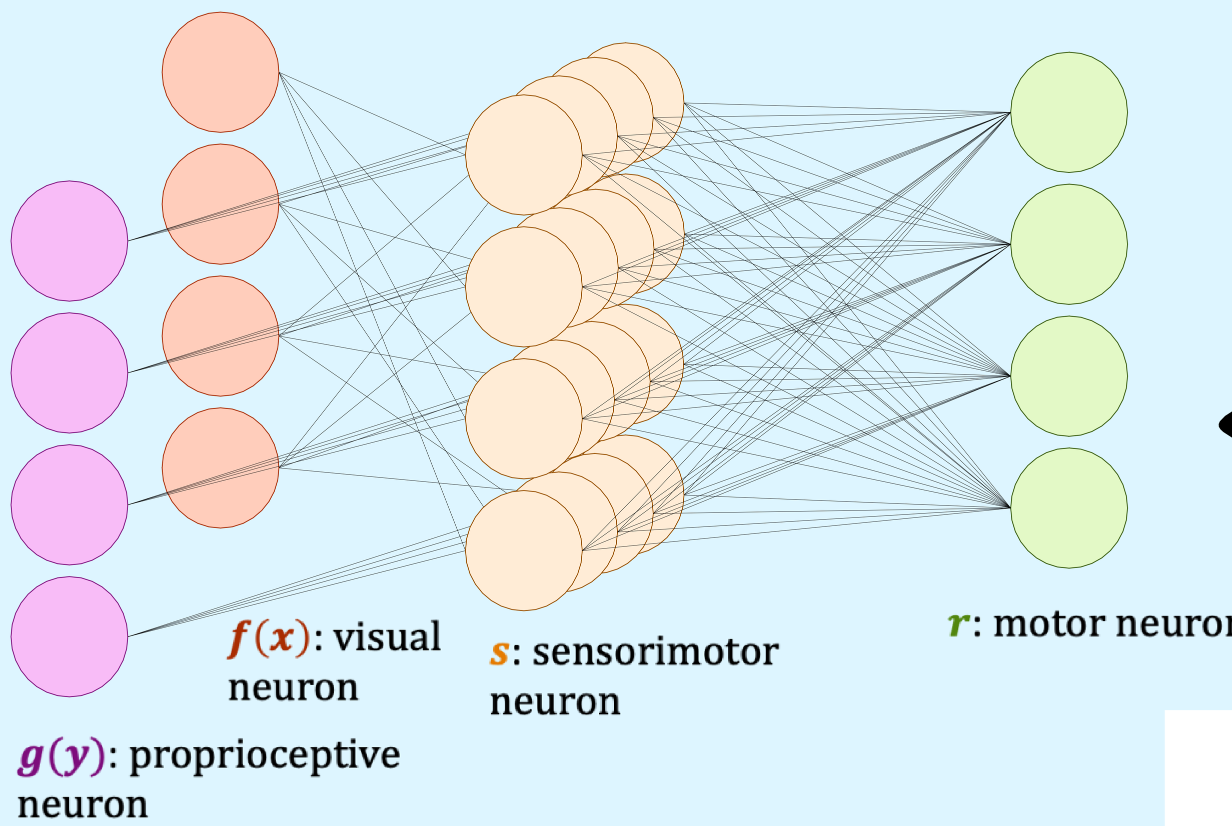
$$s_{ij} = f_i(x) g_j(y)$$

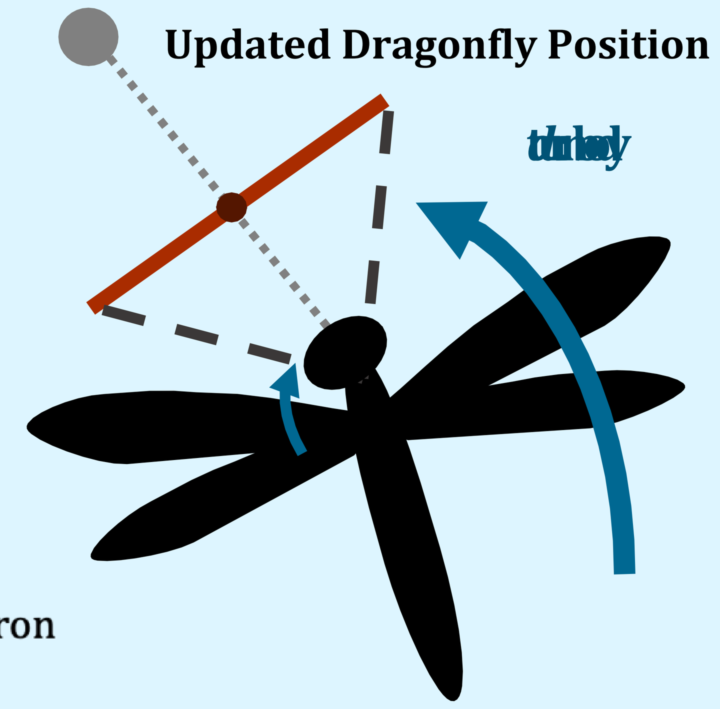
Motor output neurons sum inputs from **sensorimotor neurons**:

$$r_k = \sum_{ij} W_{ijk} s_{ij}\text{, with } W_{ijk} = \exp\left(\frac{-(a_i - b_j - c_k)^2}{2(\sigma_r^2 + \sigma_g^2 + \sigma_m^2)}\right)$$

where c_k is the preferred turn direction of motor neuron k with tuning curve width σ_m.

Synaptic weights are pre-calculated (see (12) and (14) for biological motivation).



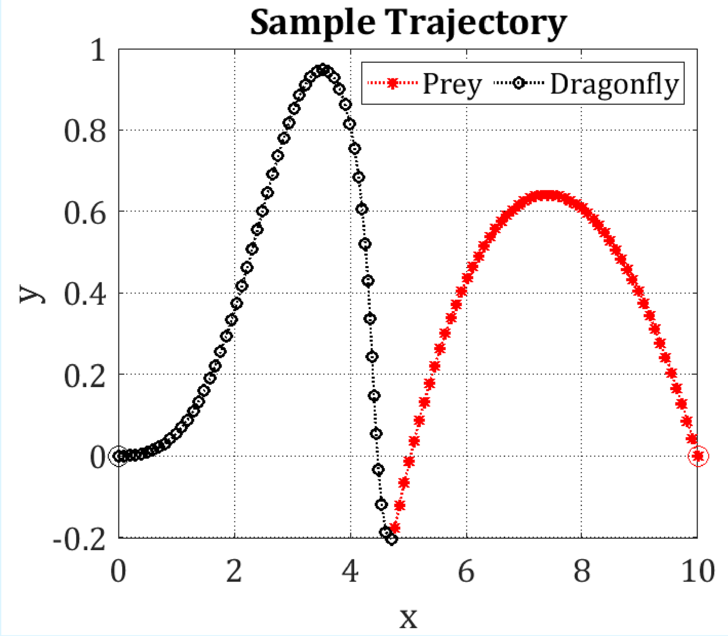


The dragonfly's body **turn** d is decoded from motor output neuron activations r.

$$d = \tan^{-1}\frac{\sum_k c_k r_k}{\sum_k r_k}$$

The head turn Δy is proportional to $-d$.

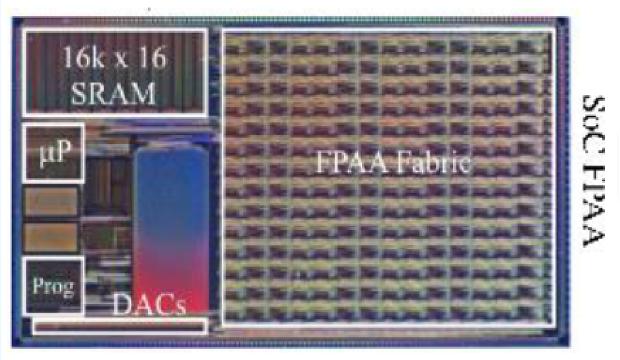
The simulation continues iteratively until the dragonfly is within distance to catch the prey in one timestep (criteria for capture) or maximum simulation time is exceeded.



Neuromorphic Computing Motivations

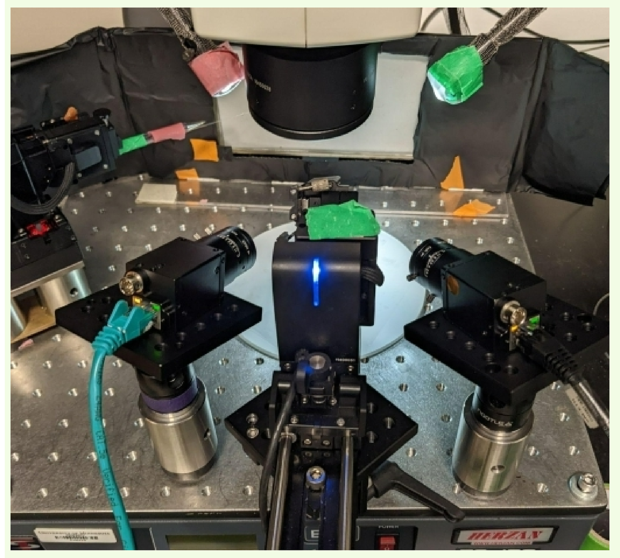
Neuromorphic systems take inspiration from biological neural networks to offer novel low-power computing techniques. The dragonfly nervous system is relatively small, allowing characterization of key features of neural circuits for specific behaviors. The neural system underlying dragonfly interception is highly efficient and accurate, making it a potential source of inspiration for new neuromorphic computing approaches.

State-of-the-art digital neuromorphic systems such as Intel's Loihi chip (7) rely upon reduced and compact neuron models such as the leaky-integrate-and-fire (LIF) neuron. Identifying where and how dragonflies perform coordinate transformations will highlight fundamental neural mechanisms, potentially at the single-neuron level, that we will leverage for developing novel neuromorphic neuron models. We are in the process of implementing a version of an earlier dragonfly model neural network (5) that will incorporate more biologically-complex neuron models on the Georgia Tech (GT) Field-Programmable Analog Array (FPAA) System-On-Chip (SoC) (8, 13).



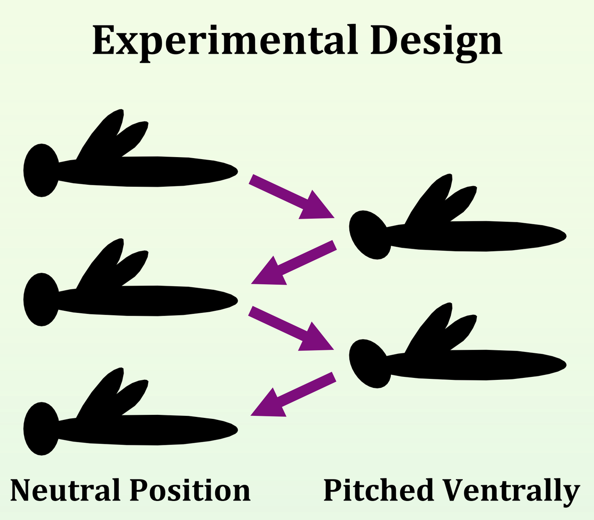
GT FPAA SoC (8)

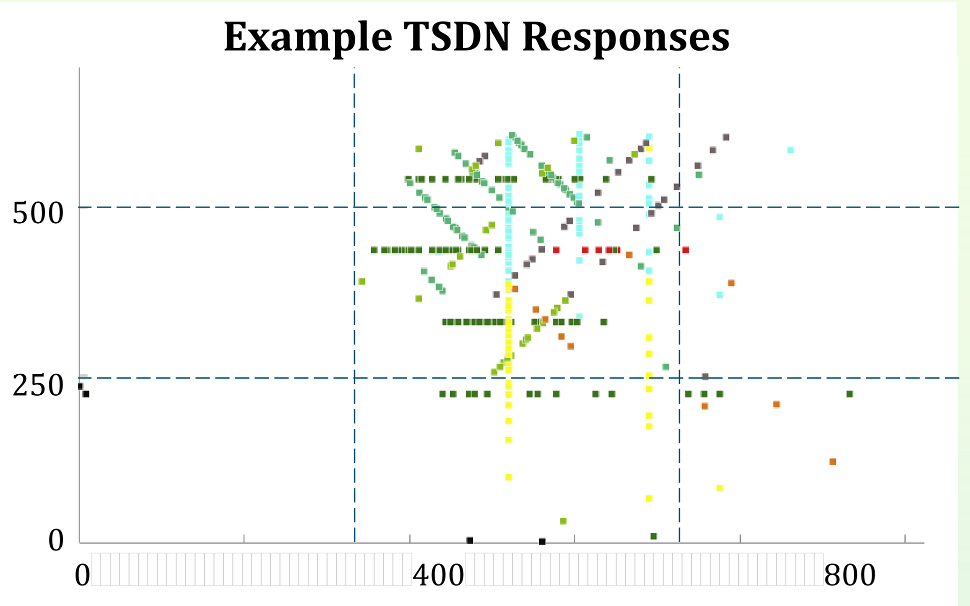
Electrophysiological Experiments

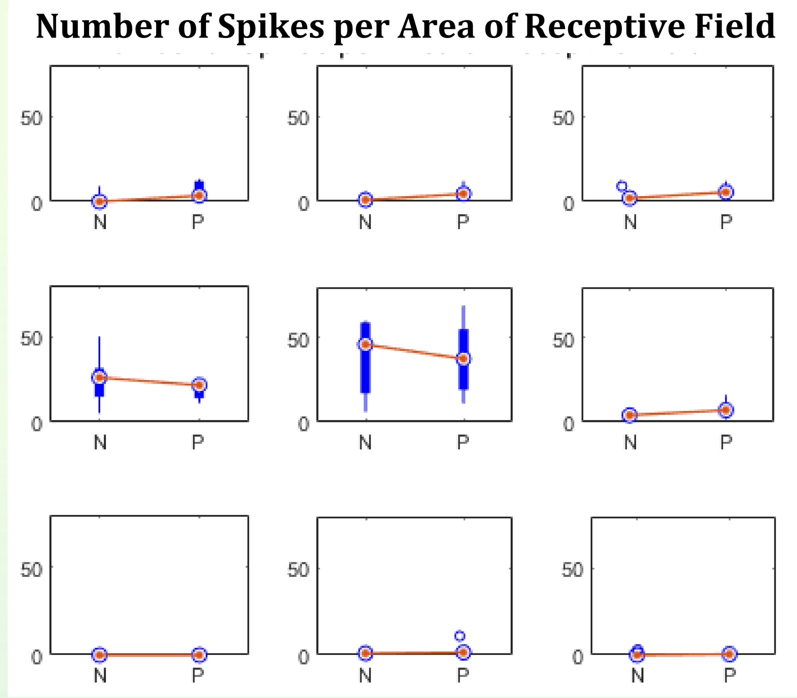


Target-selective descending neurons (TSDNs) receive visual information describing prey location and direction and send output to the motor ganglia (9). We hypothesized that TSDNs are the location where visual and proprioceptive inputs are combined for coordinate transformations. To test this hypothesis, we measured TSDN activity in awake dragonflies when shown visual stimuli for different head positions.

Our results demonstrate that TSDN activation is not affected by head position (see figure below). This data does not rule out the possibility that head position only modulates visual responses when the dragonfly is actively turning its head. Experiments to measure impact of head position on motor neuron activity are in progress.







Left: We presented 3 sets of visual stimuli (moving dots with randomized trajectories and start positions) and recorded activity from individual TSDNs. The head was then pitched ventrally and TSDN activities were recorded for 3 more sets. The head position was then returned to neutral and TSDN activity was recorded for 5 additional stimulus sets.
Center: Example TSDN responses for one set of visual stimuli. Each dot is the location of the visual stimulus at the time of one action potential (colors indicate the direction the stimulus was moving).
Right: Box plots are the number of spikes divided by receptive field area for several neurons and trials, for neural (N) or ventrally-pitched (P) head positions

Conclusion

We propose a neural network model of coordinate transformations in the dragonfly sensorimotor pathway. This model relies upon a multiplicative interaction between visual and proprioceptive input to calculate required motor commands.

Experiments to identify the location of this coordinate transformation are in progress. Identifying the coordinate transformation site will allow deeper examination of the mechanisms underlying multiplicative interactions between multimodal inputs. Our findings will be used to inspire novel neuromorphic computing architectures.

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