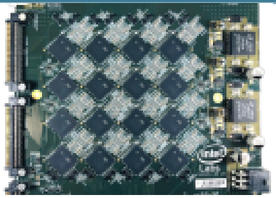
SAND2021-13350PE

Lessons from a dragonfly’s brain for neuromorphic computing



Frances S. Chance

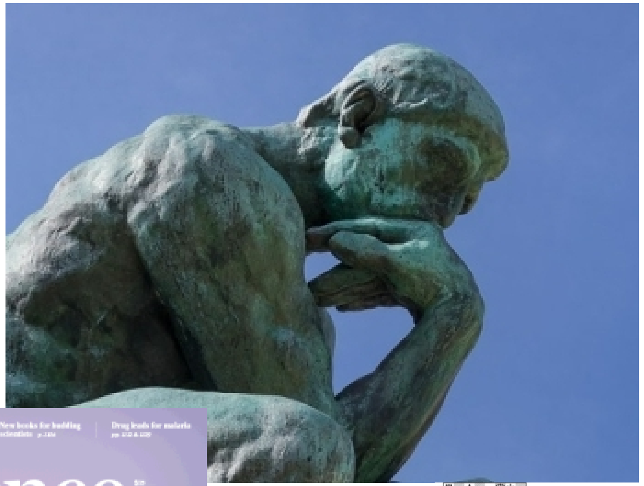
October 26, 2021
Lockheed Martin

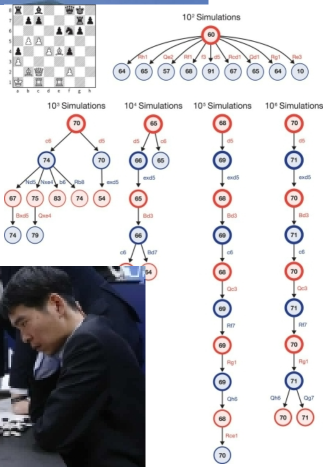
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

How to use brains to inspire neuromorphic computing?

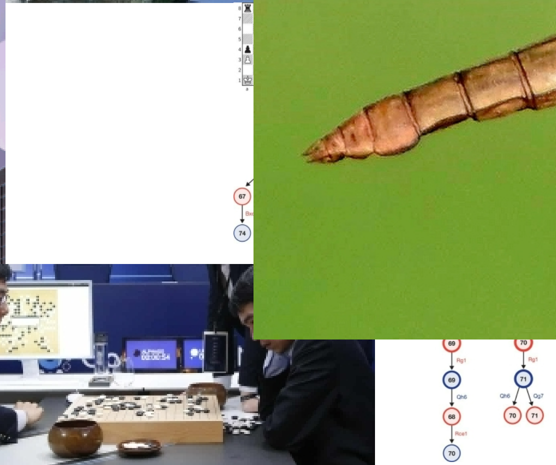
Neural-inspired algorithms

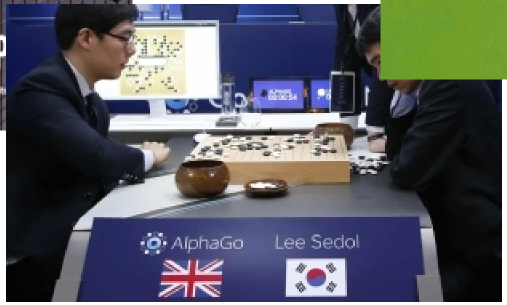




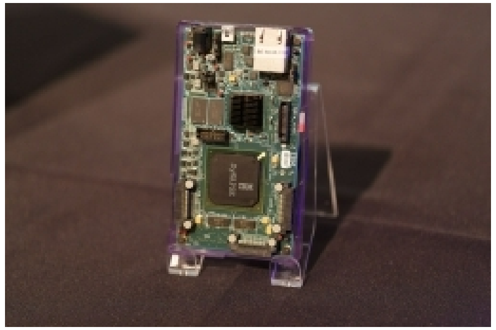
How to use brains to inspire neuromorphic computing?

Neural-inspired algorithms

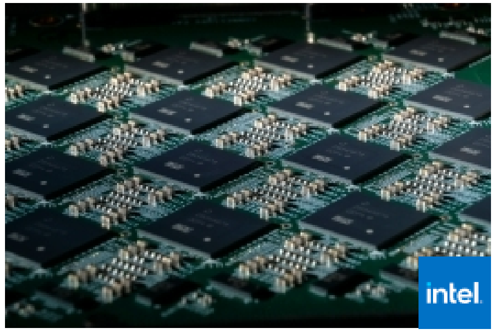


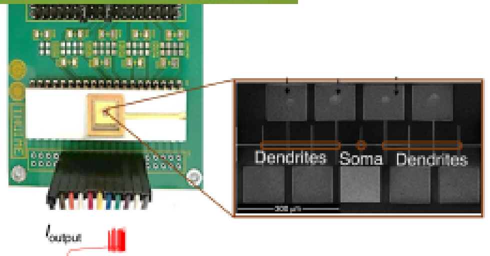


Neuromorphic hardware



76: 776



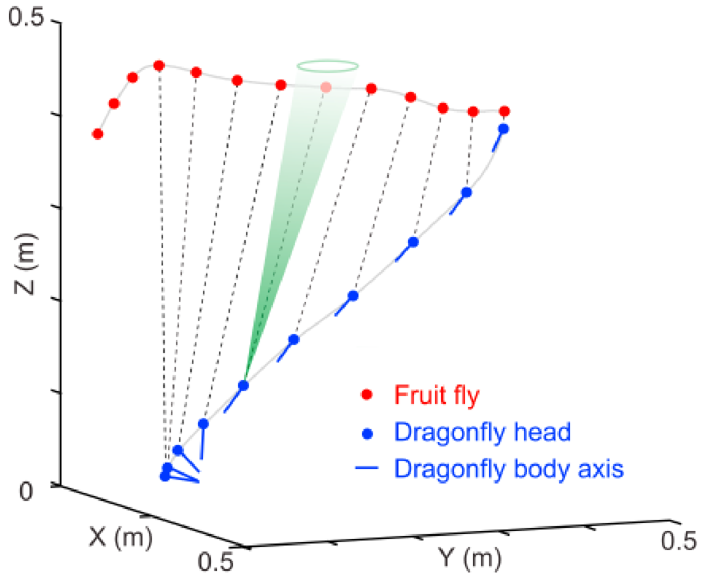


from Li et al (2020) Nature Nanotechnology 15: 776

Why dragonflies?

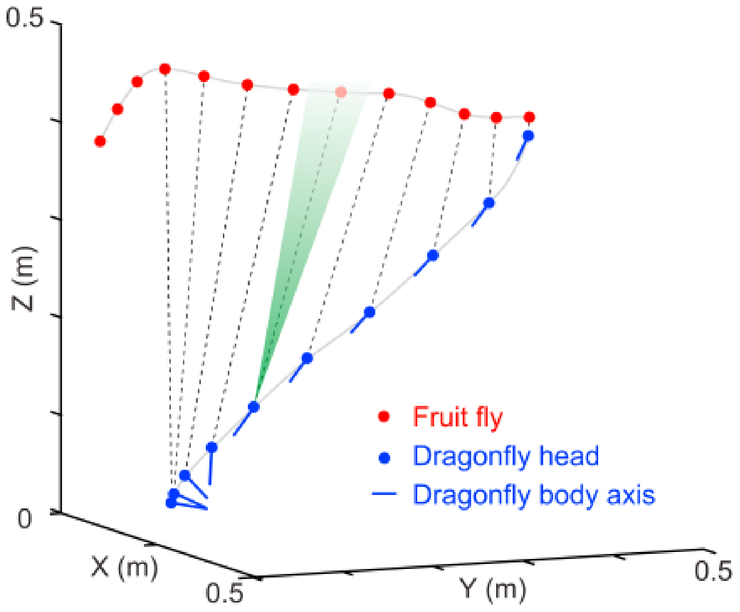
Good at hunting (90-95% capture rate)

When hunting, dragonflies use interception strategies similar to modern defense systems

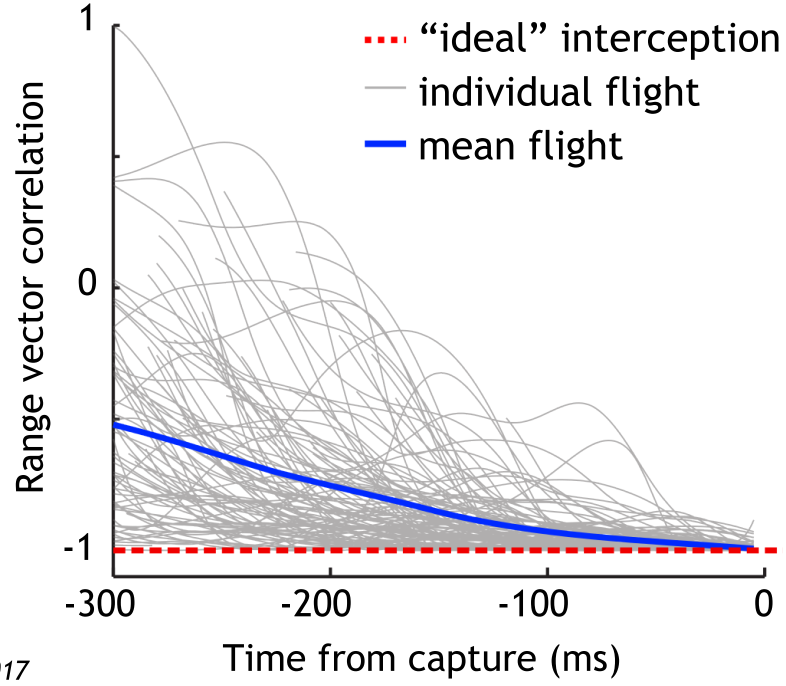


from Lin & Leonardo 2017

Dragonflies and parallel navigation

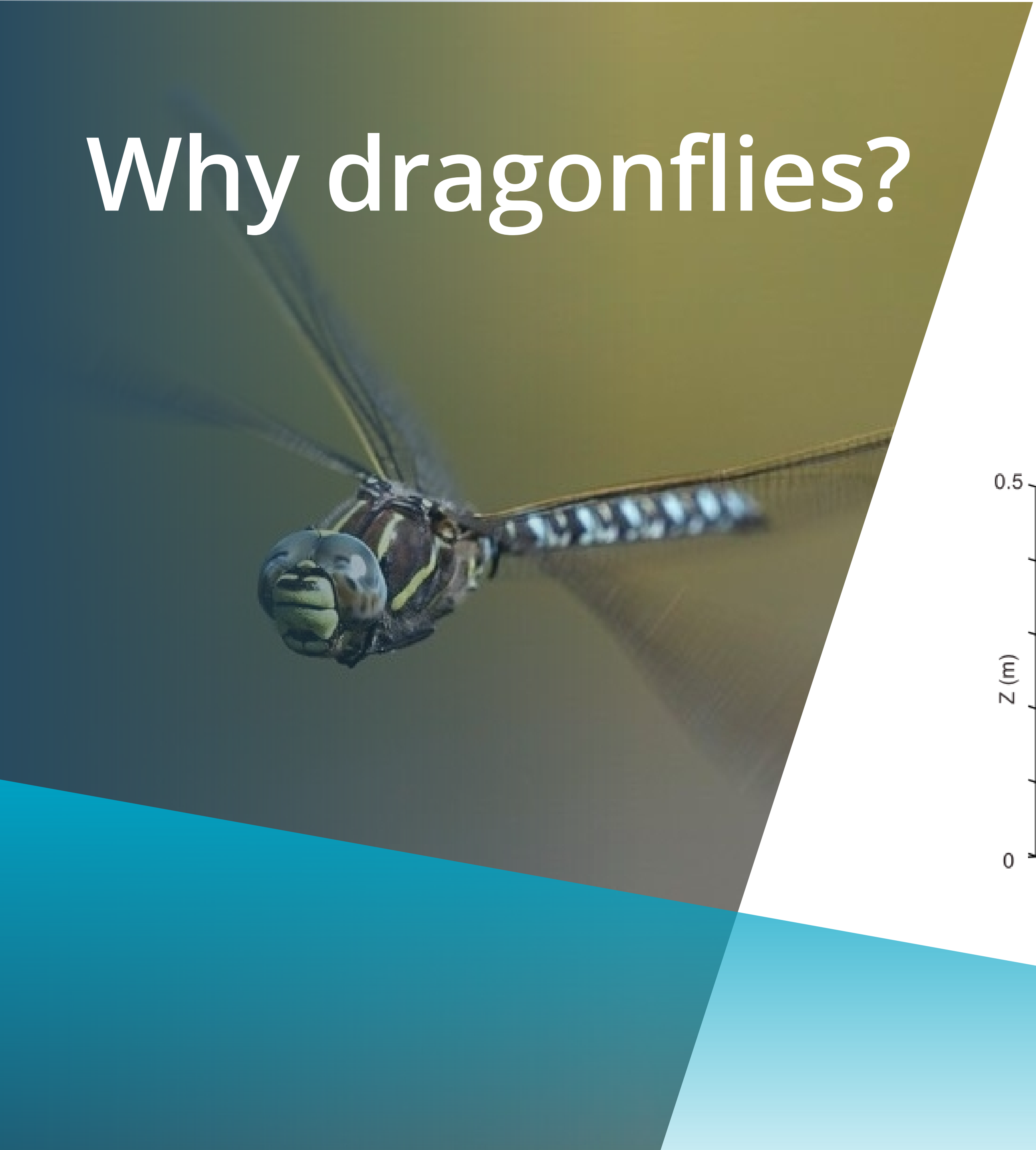


from Lin & Leonardo 2017



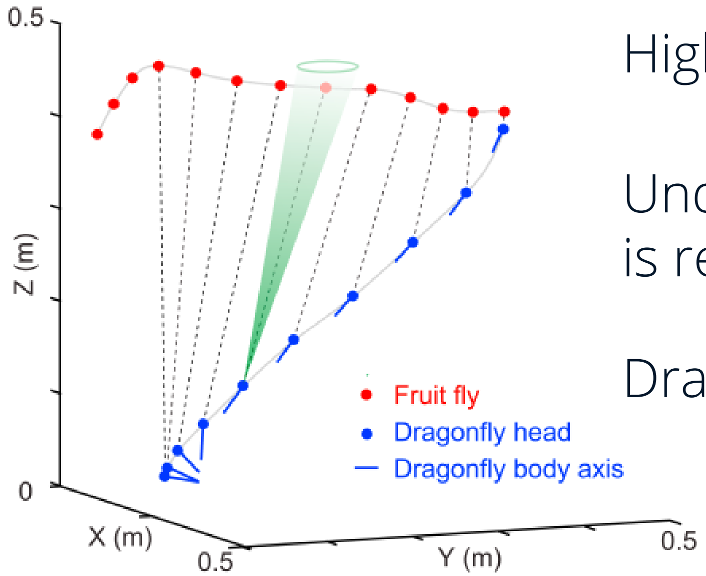
from Mischiati et al 2015

Why dragonflies?



Good at hunting (90-95% capture rate)

When hunting, dragonflies use interception parallel navigation-like strategies



Highly specialized behavior

Underlying neural circuitry is relatively simple

Dragonflies are fast

Why dragonflies?

Time scales of dragonfly interception computation

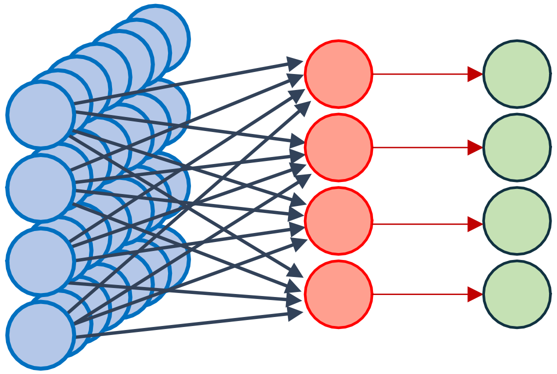
Latency to react to prey maneuver: 50 ms

Time scales of a neurobiological system

Synaptic transmission: 1-5 ms

Neuronal integration: 10-50 ms

Muscle contraction: 5 ms to produce force

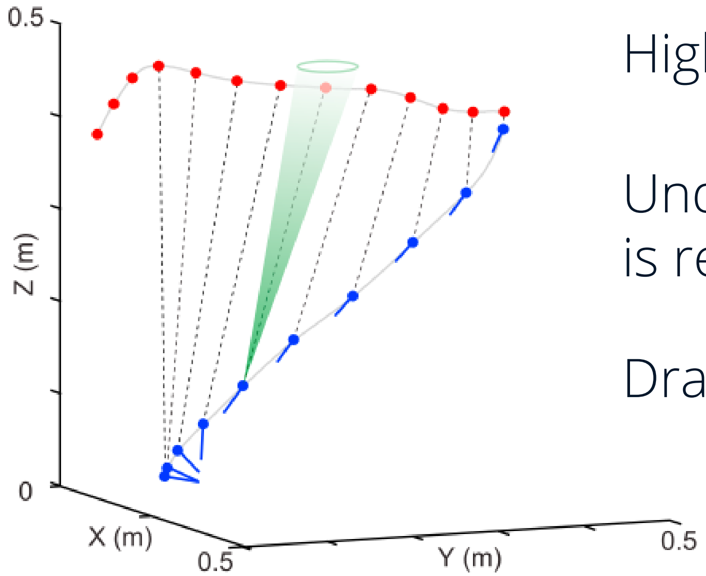


Underlying neural circuitry: 2-4 layer neural network?

Why dragonflies?

Good at hunting (90-95% capture rate)

When hunting, dragonflies use interception strategies like parallel navigation



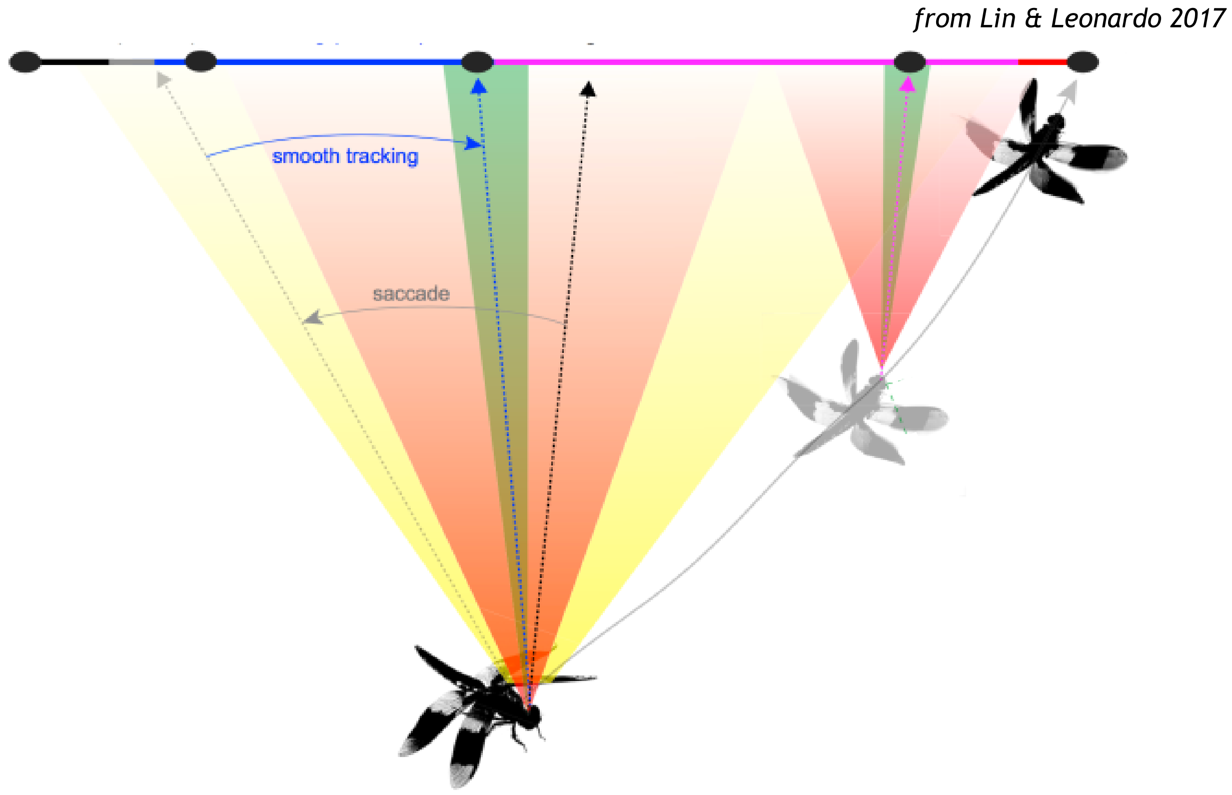
Highly specialized behavior

Underlying neural circuitry is relatively simple

Dragonflies are <u>really</u> fast

Can we learn from them to compute faster?

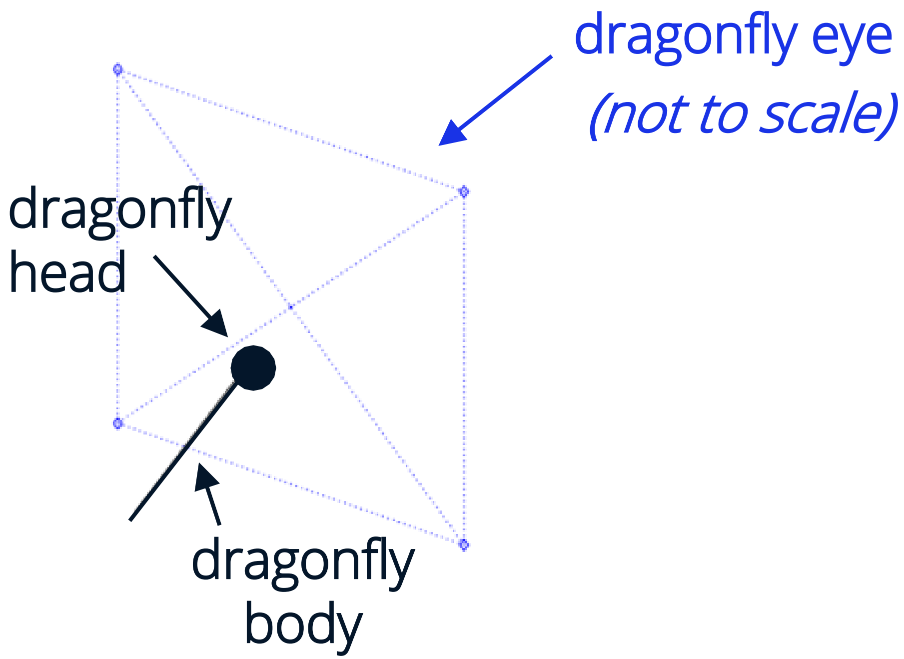
The dragonfly model



We know dragonflies keep the prey-image on a specific location on the eye...

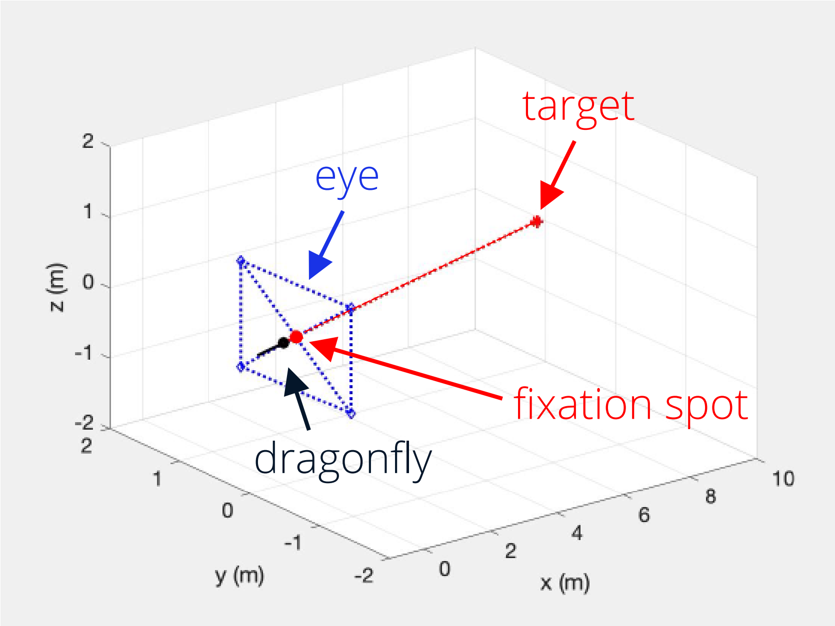
Is dragonfly interception equivalent to holding target-image on a fixation spot?

The dragonfly model



The dragonfly model

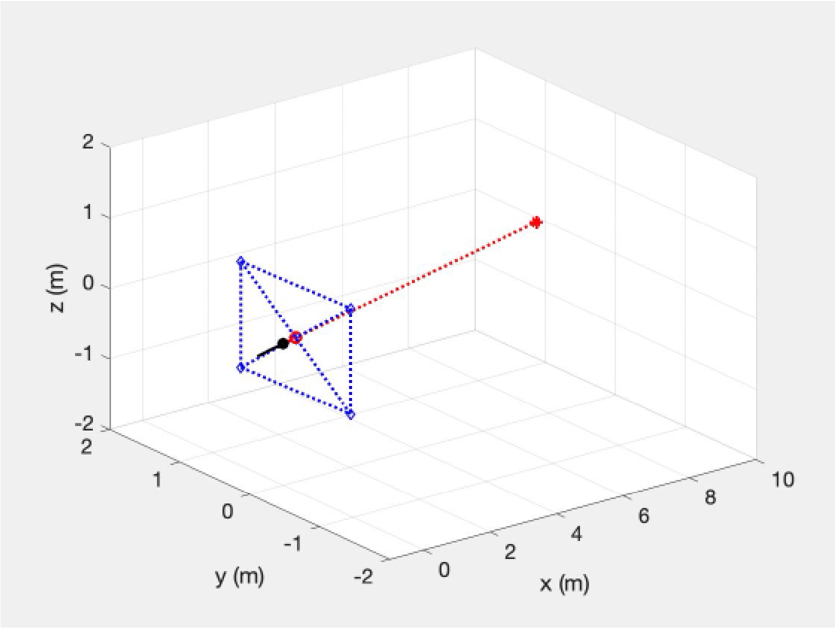
Model dragonfly turns to keep prey-image at fixation spot



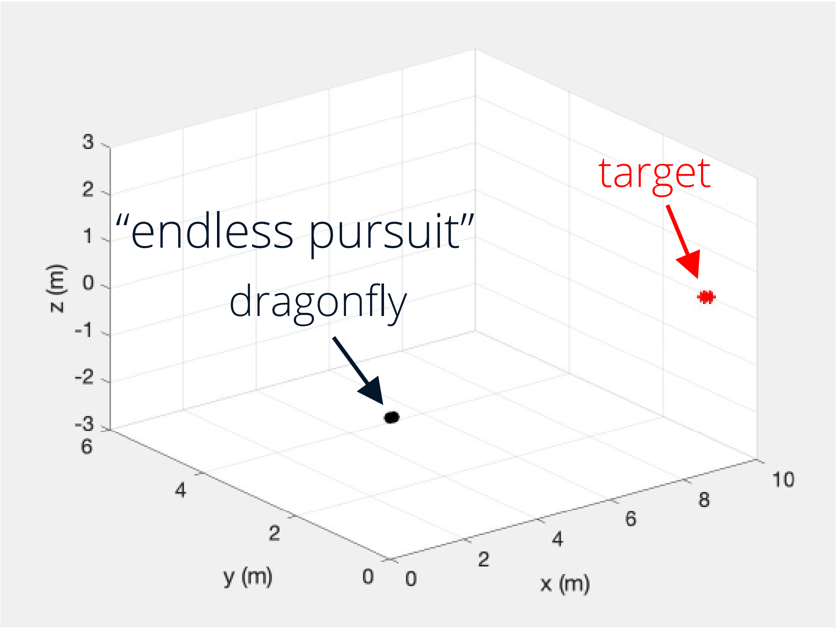
dragonfly-centered reference frame

The dragonfly model

Model dragonfly turns to keep prey-image at eye-center



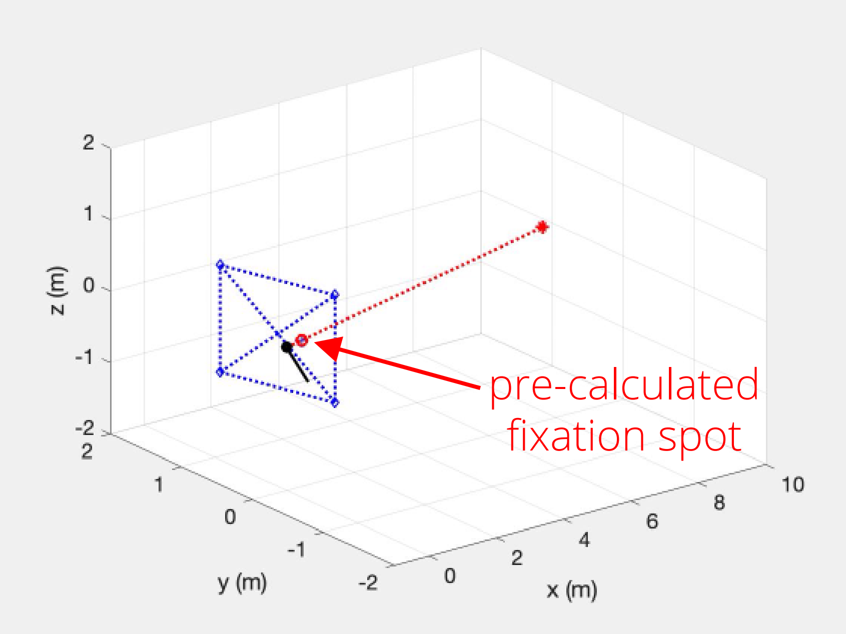
dragonfly-centered reference frame



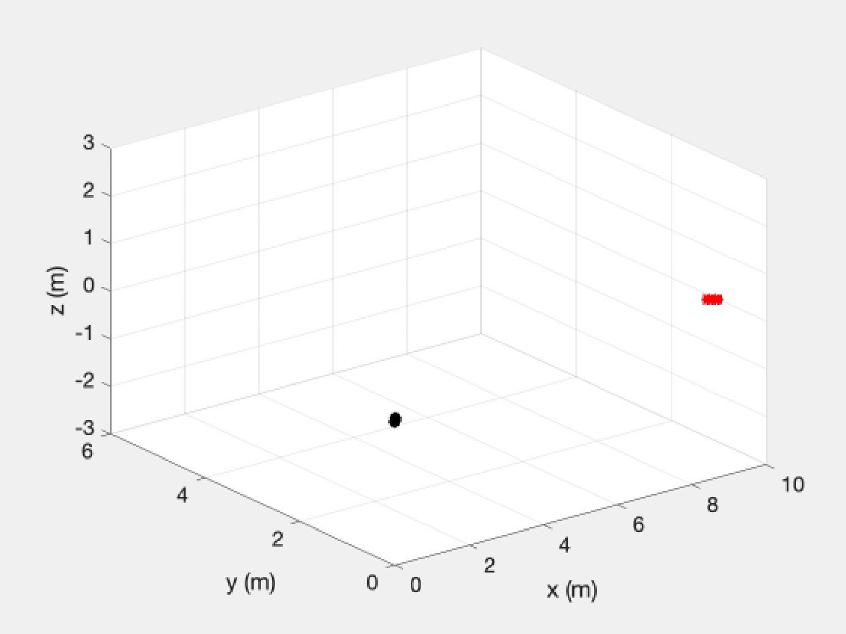
real-world reference frame

The dragonfly model

Parallel navigation (“ideal interception”)



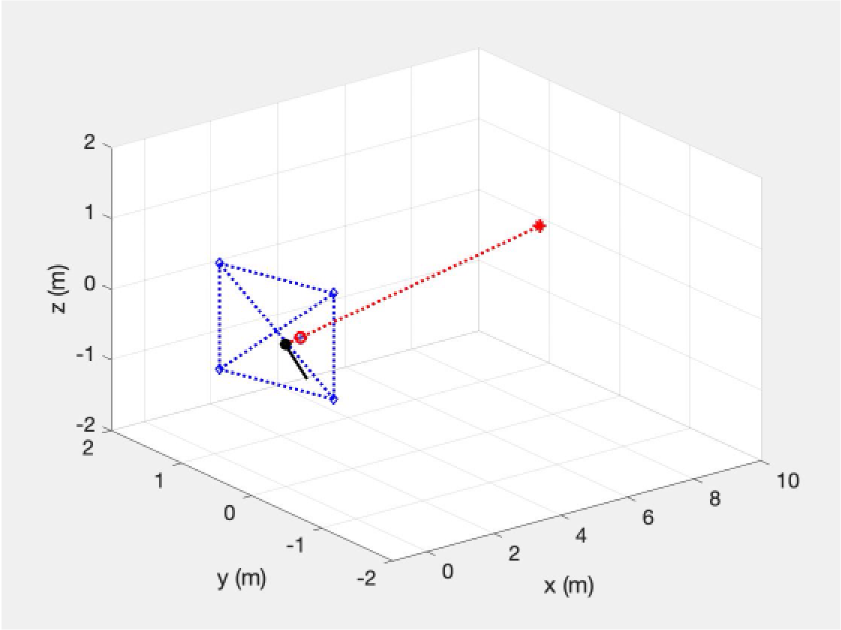
dragonfly-centered reference frame



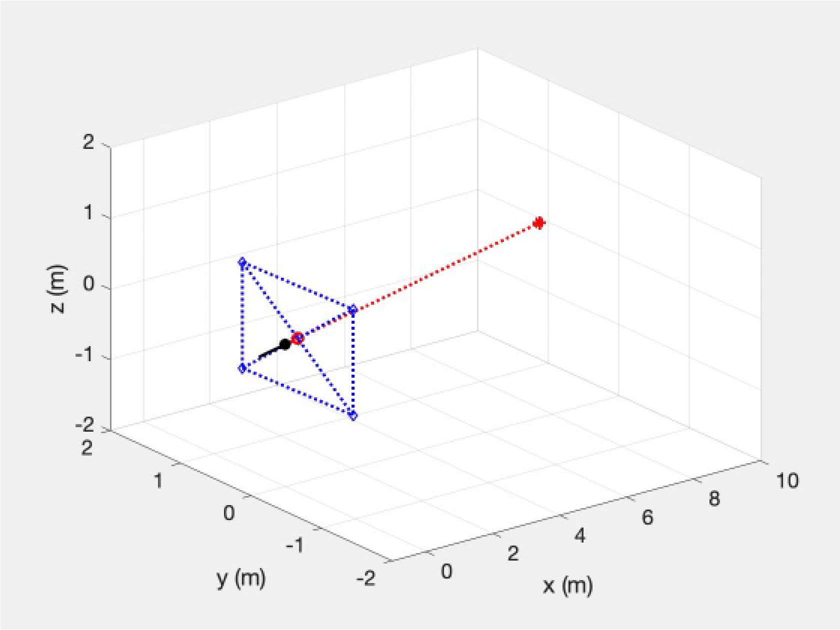
real-world reference frame

The dragonfly model

Comparison with pursuit (from the dragonfly's perspective)



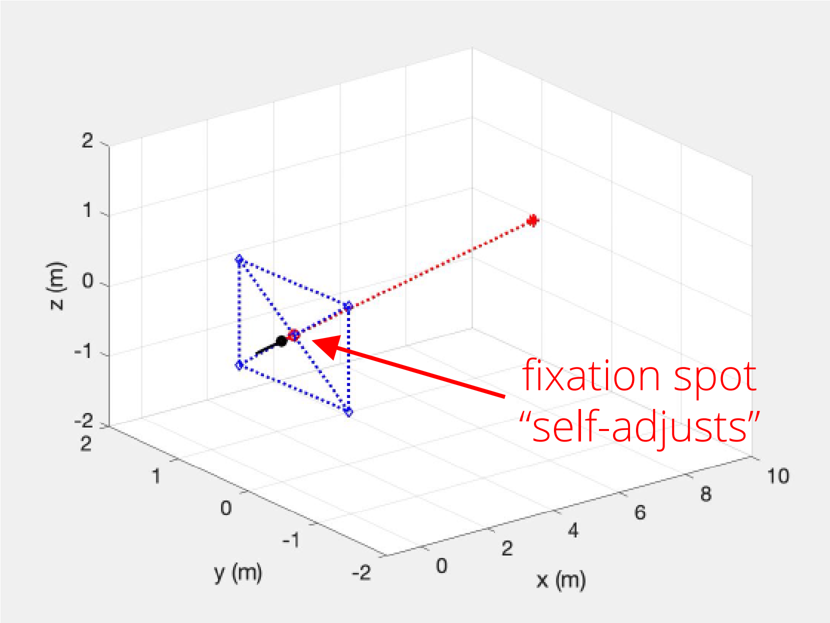
parallel navigation



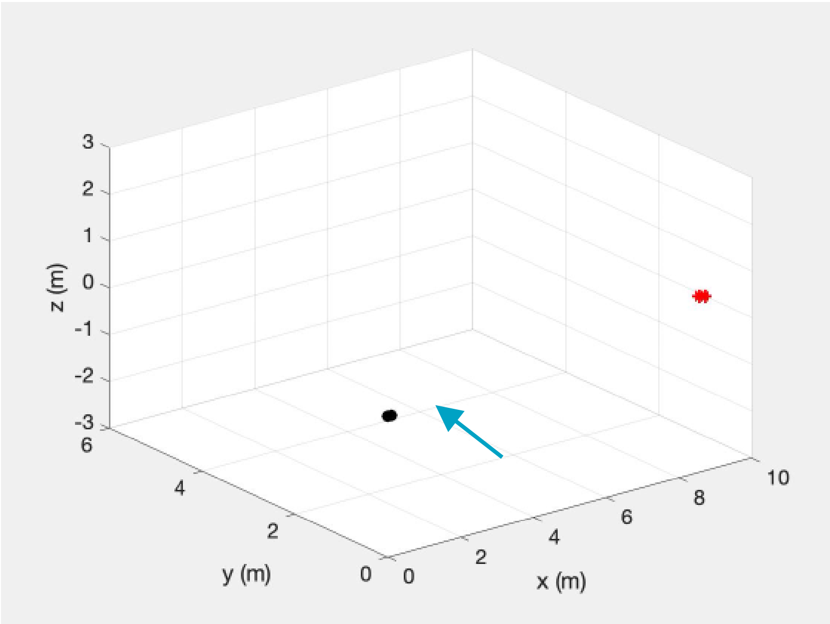
fixation spot at eye-center

The dragonfly model
(with turning as an error signal)

Dragonfly turning provides “error” signal
(initial condition: fixation spot at eye-center with dragonfly flying straight at target)

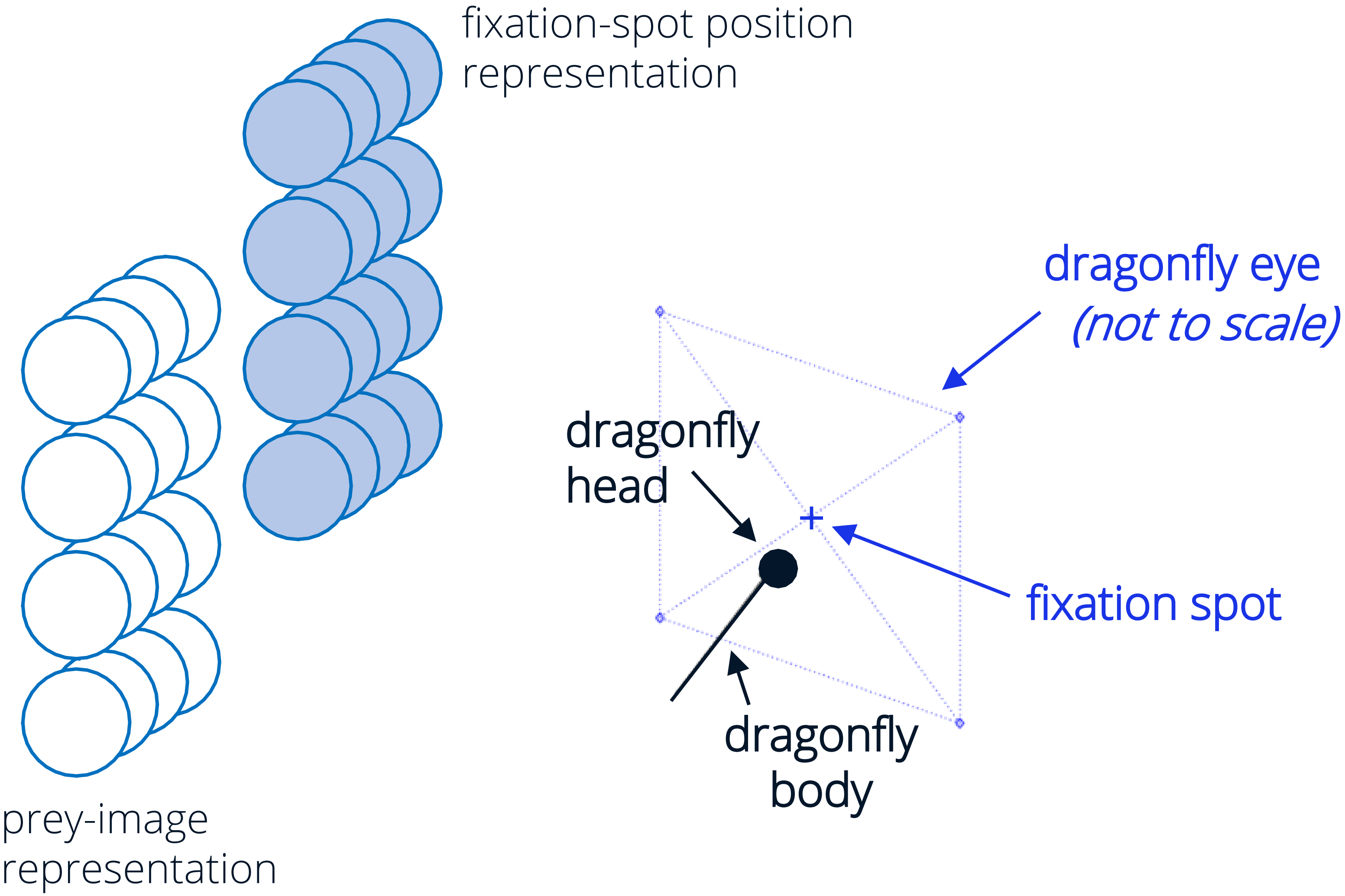


dragonfly-centered reference frame

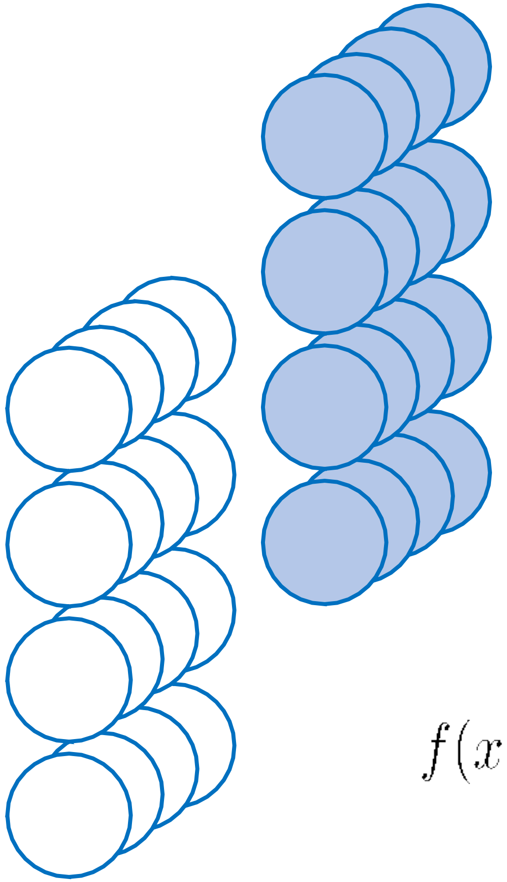


physical-space reference frame

Dragonfly neural network model

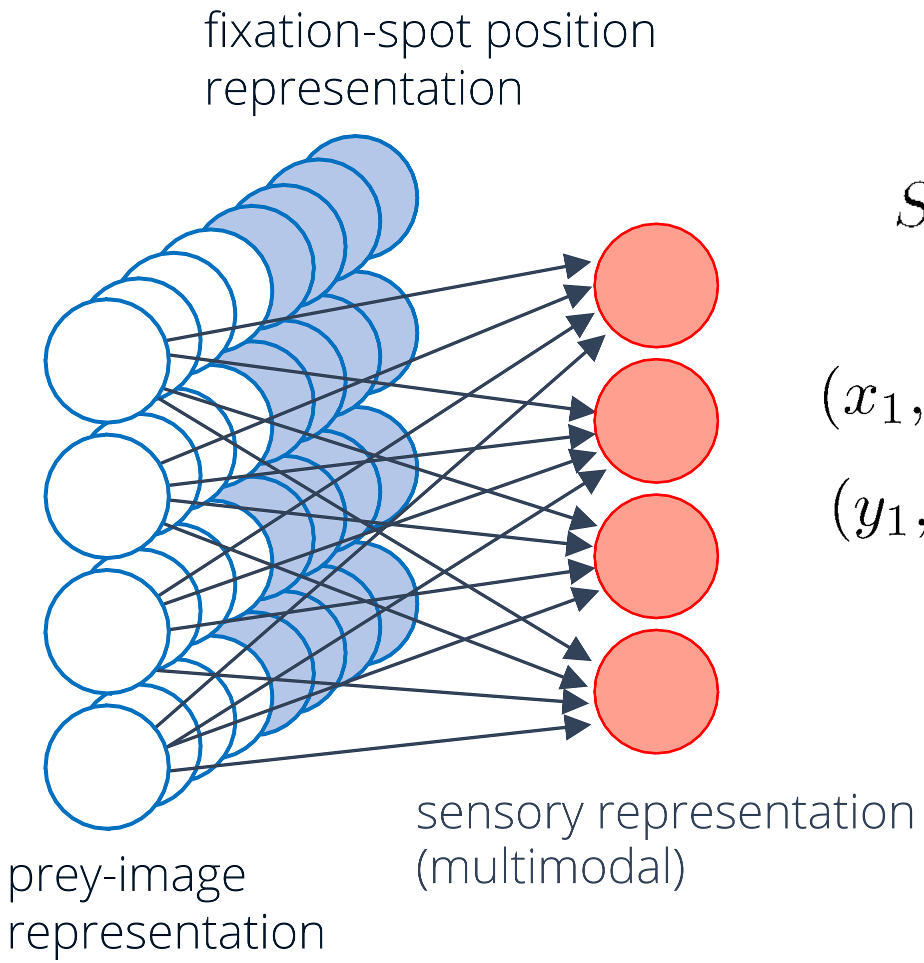


Dragonfly neural network model



$$f(x_1, x_2) = \exp\left(-\frac{(\mathrm{a}_1 - \mathrm{x}_1)^2 + (\mathrm{a}_2 - \mathrm{x}_2)^2)}{2\sigma_{\mathrm{r}}^2}\right)$$

Dragonfly neural network model



$$S_{ij} = f_i(x_1, x_2)g_j(y_1, y_2)$$

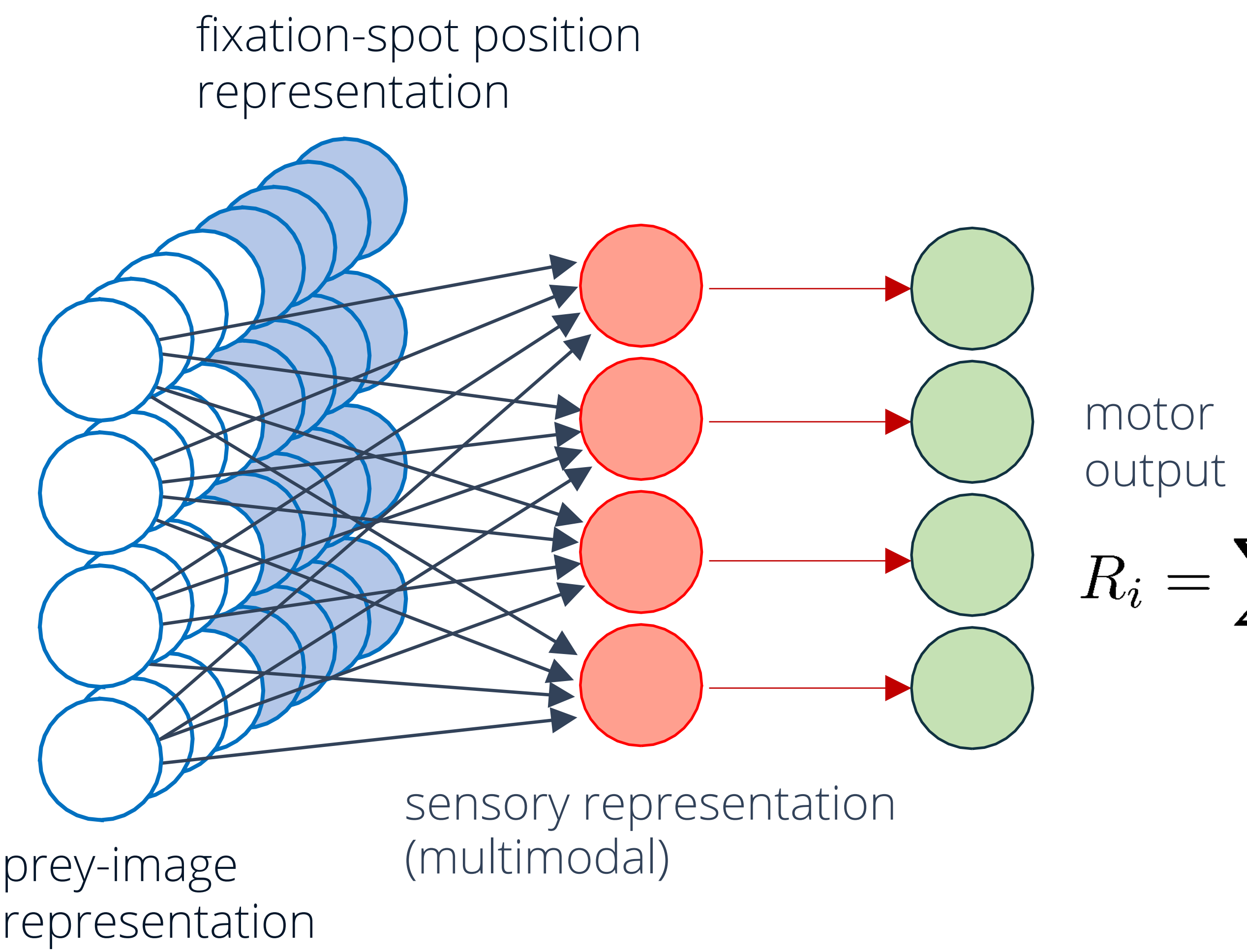
(x_1, x_2) = position of target image on eye

(y_1, y_2) = fixation spot location on eye

f = response of prey-image neuron

g = response of fixation-spot neuron

Dragonfly neural network model

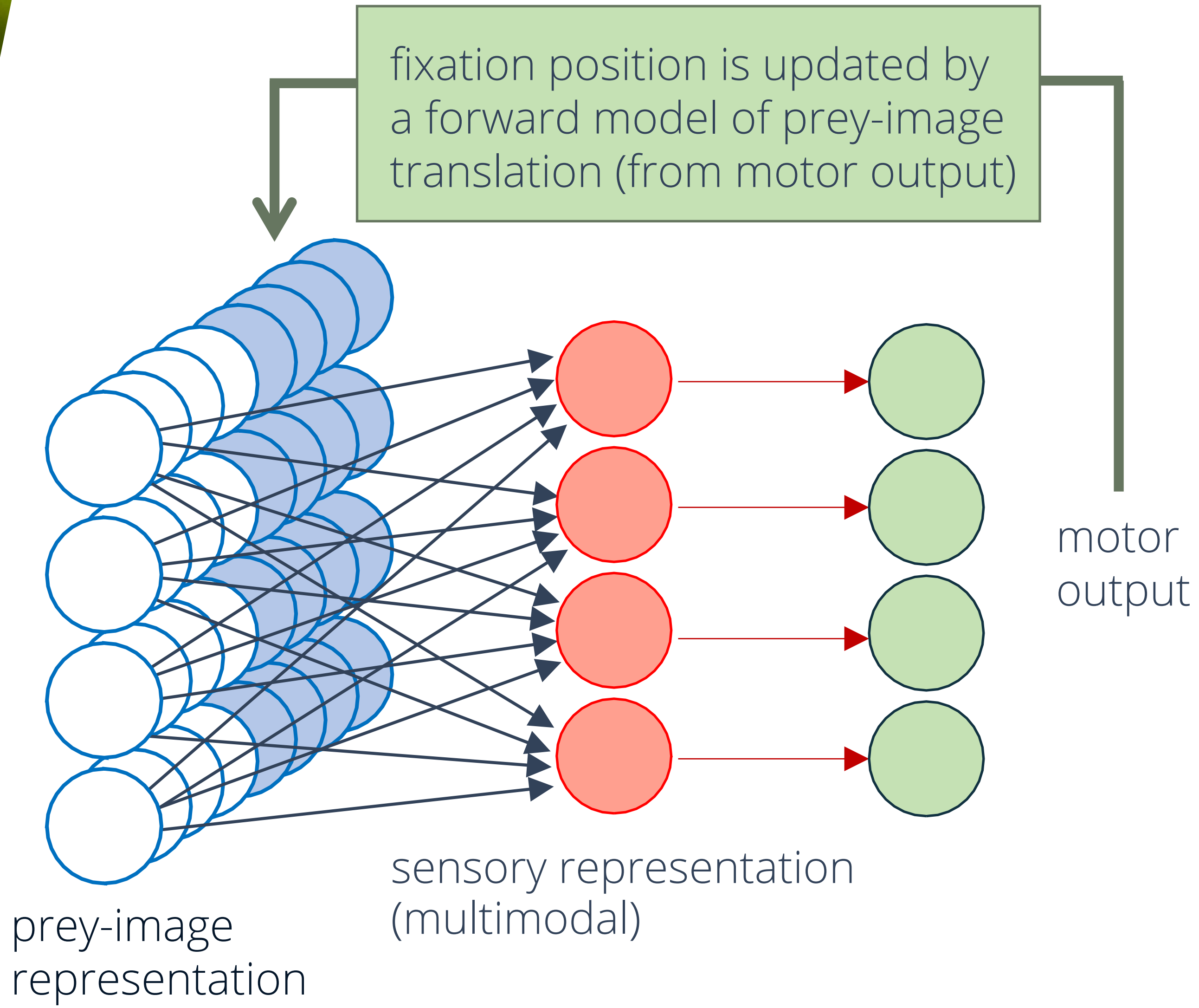


$$R_i = \sum_j W_{ij} S_j$$

see Chance, International Conference on Neuromorphic Systems (ICONS) 2020

neural network receives no training - weights are calculated
(see Zipser & Andersen, 1988; Salinas & Abbott, 1995)

Dragonfly neural network model

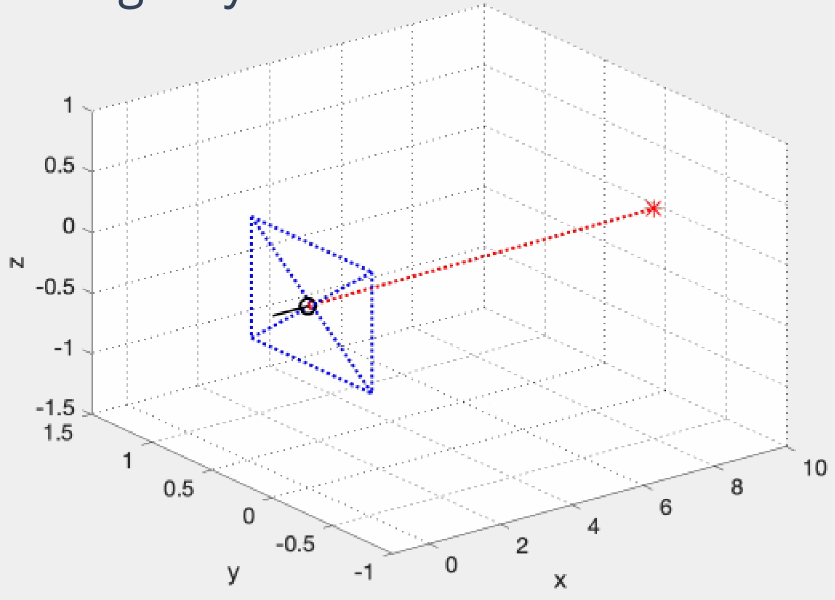


see Chance, International Conference on Neuromorphic Systems (ICONS) 2020

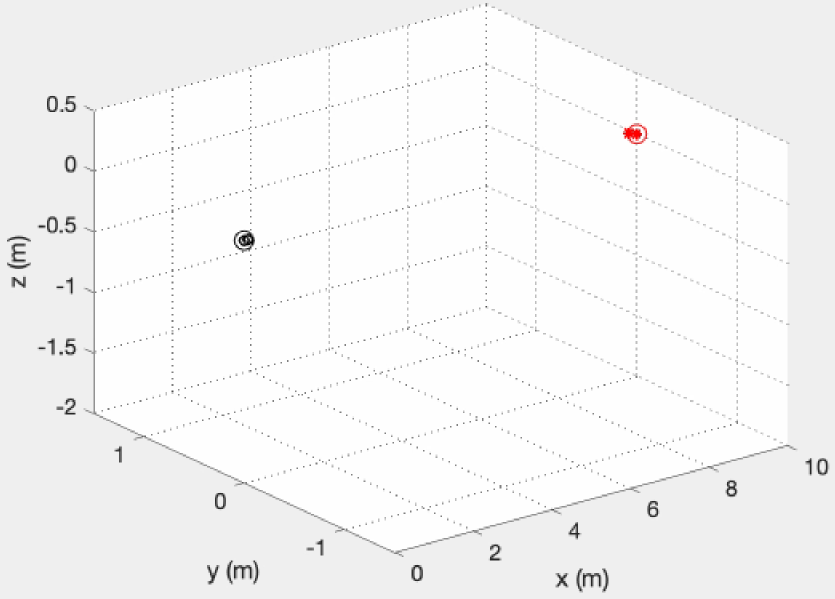
neural network receives no training - weights are calculated
(see Zipser & Andersen, 1988; Salinas & Abbott, 1995)

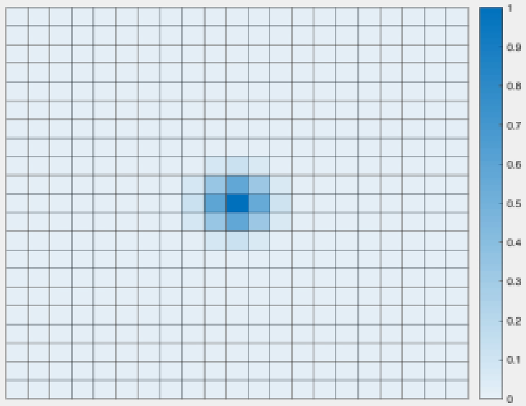
Neural network model of dragonfly prey-interception

dragonfly-centered reference frame

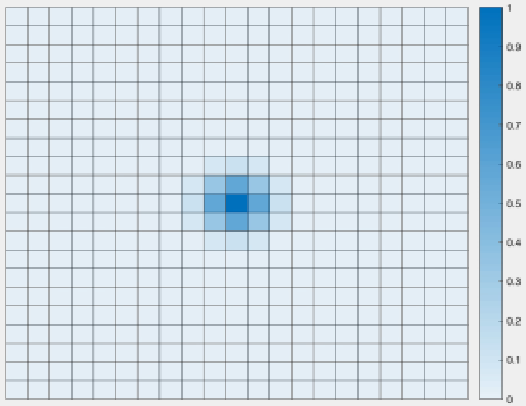


real-world reference frame

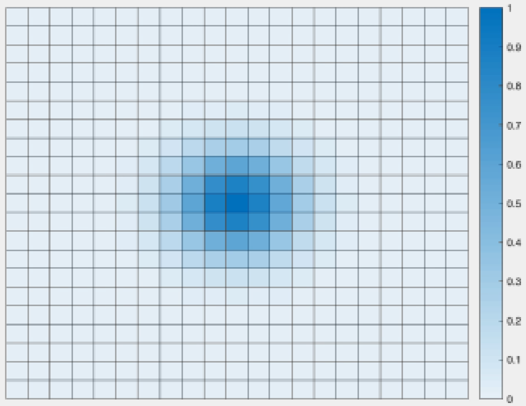




target image

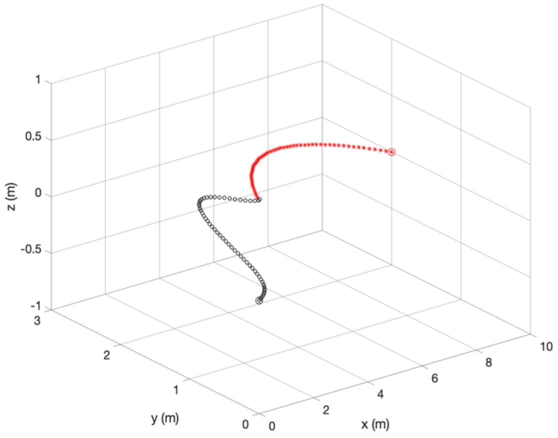


fixation position

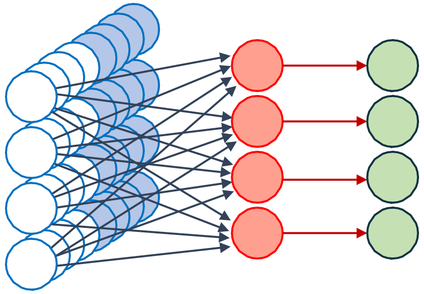


motor output

Lessons from the dragonfly brain



Brain Algorithms



Neural Network Models

Back to the dragonfly…

motion-sensitive neurons

neck/gimbal

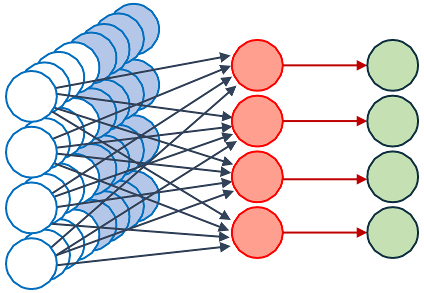
What are the biological analogs of the different layers in the neural network

What is the neural basis of these computations?

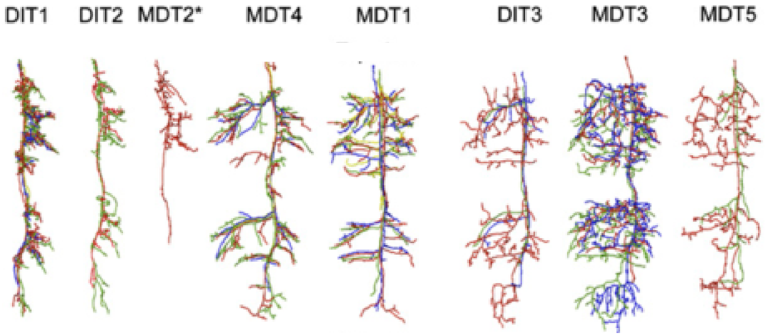
Lessons from the dragonfly brain

Advantages of an invertebrate system

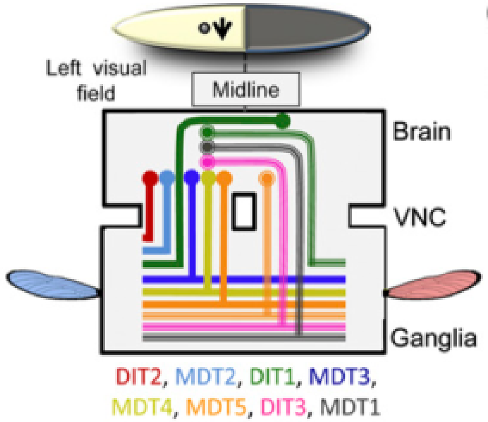
- the neural circuit is 'light'
- the individual components are identifiable
- access to computation at the cellular level



Neural Network Models



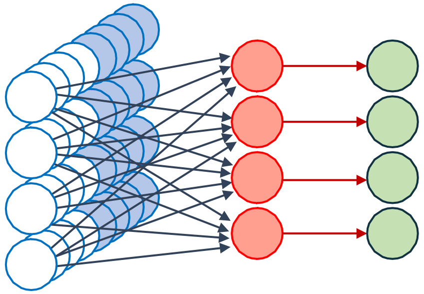
from Gonzalez-Bellido et al (2013) PNAS 110: 696



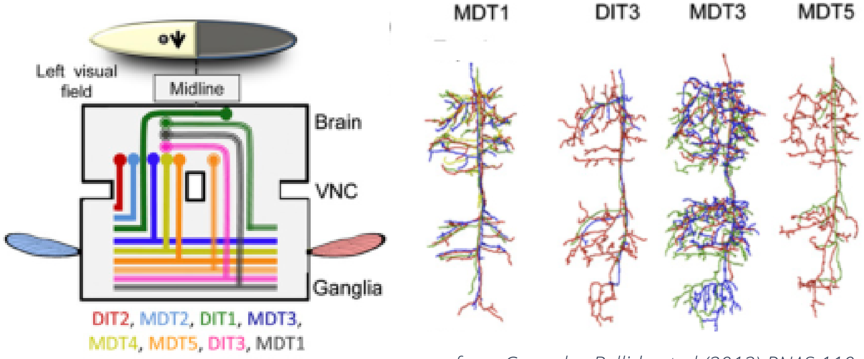
Dr. Paloma Gonzalez-Bellido

University of Minnesota

Lessons from the dragonfly brain
… for neuromorphic computing



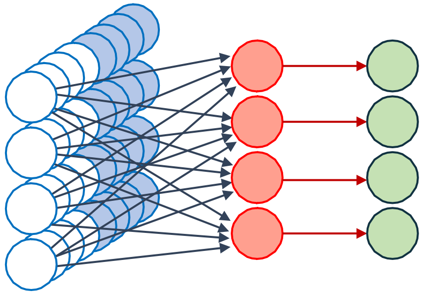
Neural Network Models



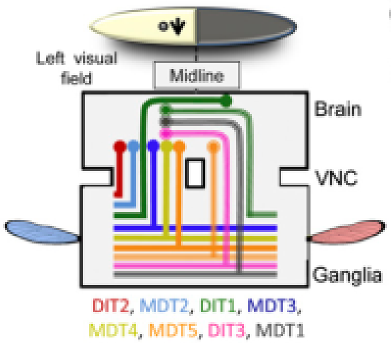
from Gonzalez-Bellido et al (2013) PNAS 110: 696

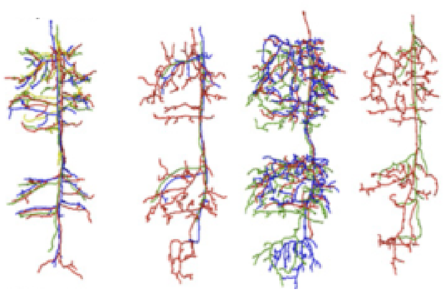
Models in Neuromorphic Hardware

Lessons from the dragonfly brain
… for neuromorphic computing

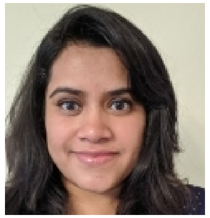


Neural Network Models





from Gonzalez-Bellido et al (2013) PNAS 110: 696

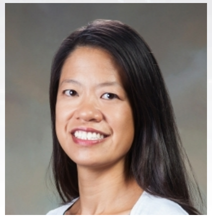


Dr. Suma Cardwell
Sandia National Laboratories

Dr. Scott Koziol
Baylor University

The End

Questions? Email fschanc@sandia.gov



Dr. Frances Chance
Sandia National Laboratories

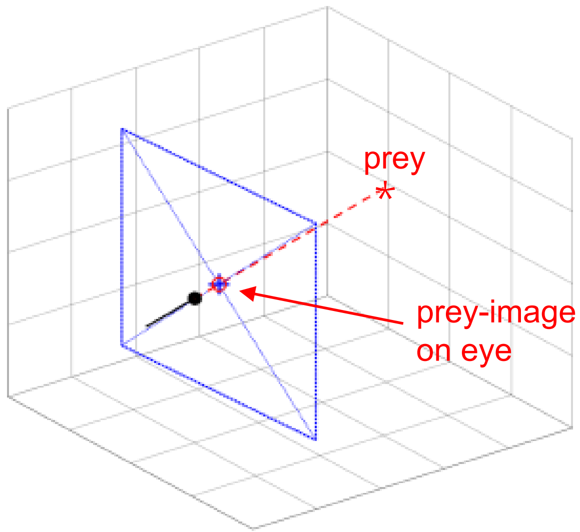
The End

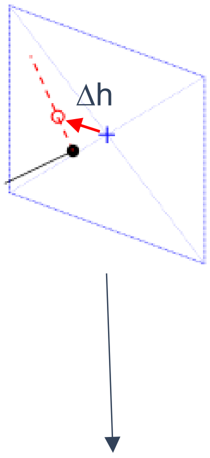
Questions? Email fschanc@sandia.gov

Dr. Frances Chance
Sandia National Laboratories

Backup slides…

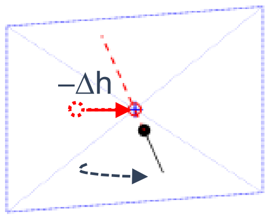
Building a dragonfly model





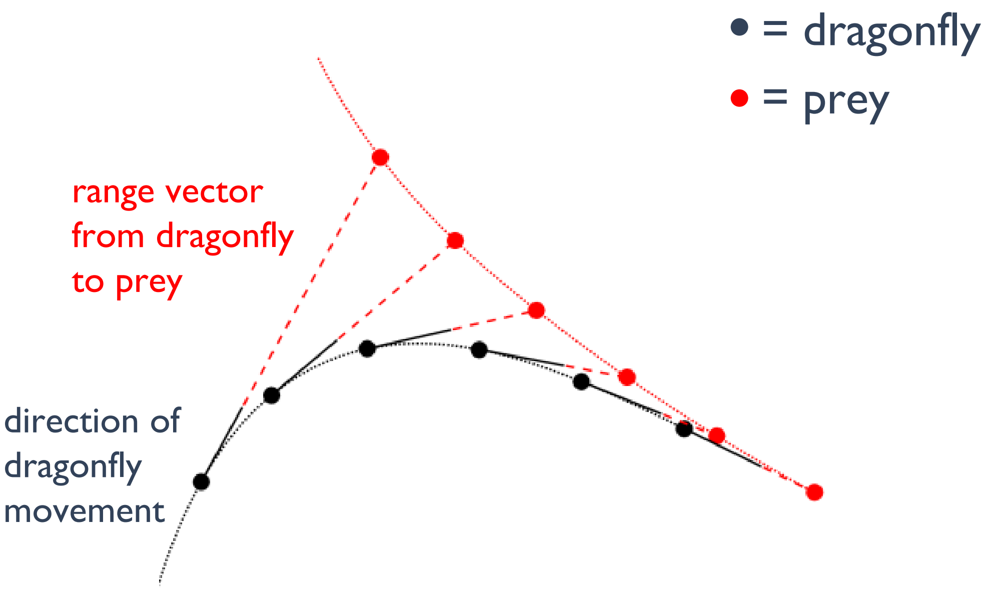
As the prey moves, prey image slips by Δh

Dragonfly turns to re-align prey image with fixation spot



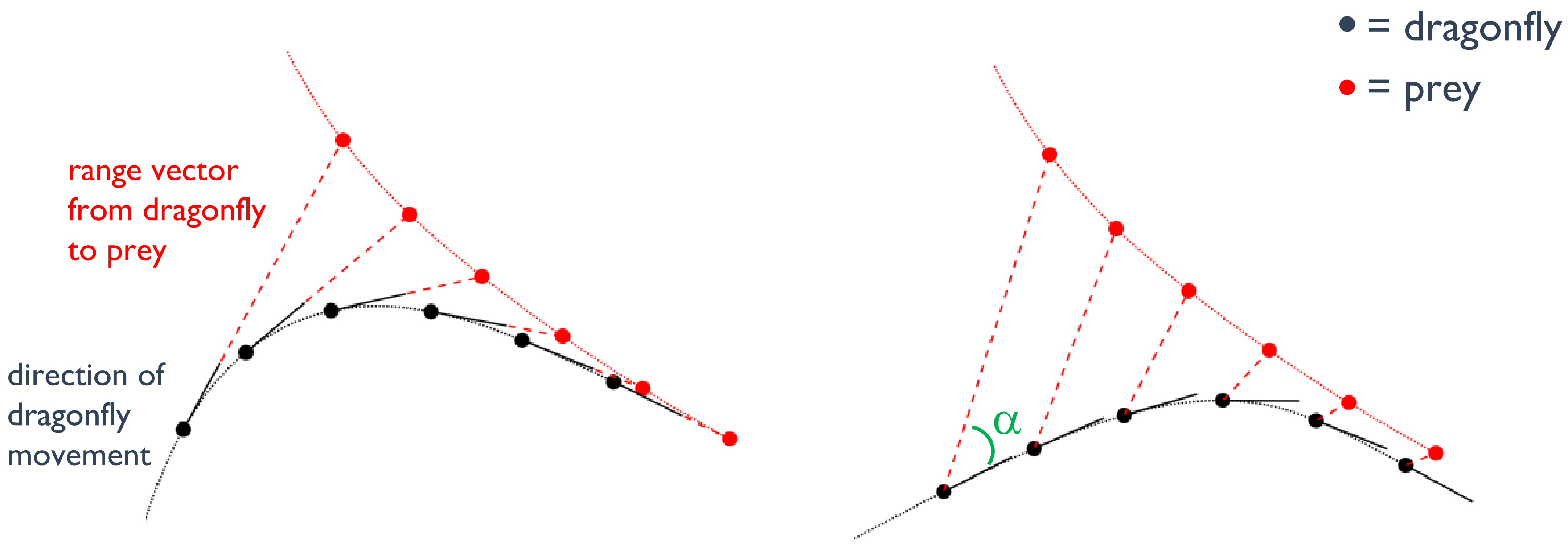
Prey image translation = -Δh

What is pursuit?



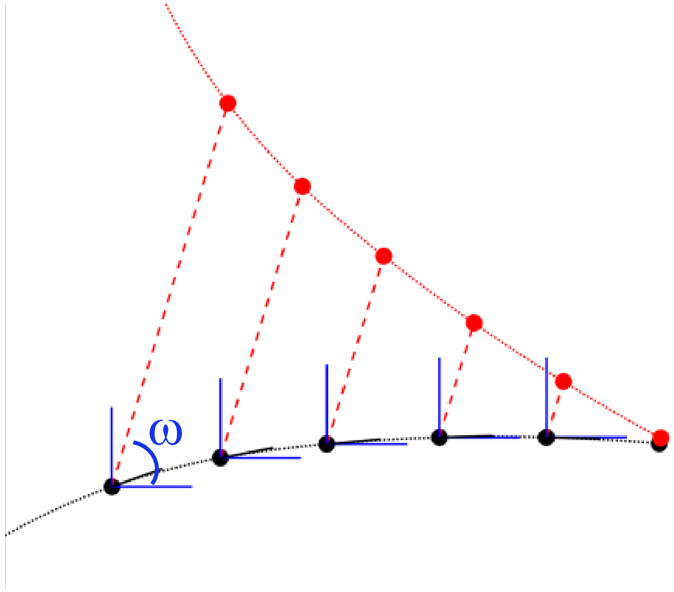
Classical pursuit
direction of movement = range vector

What is pursuit?



Deviated pursuit
constant angle between range
vector and direction of movement

What is parallel navigation



Parallel navigation

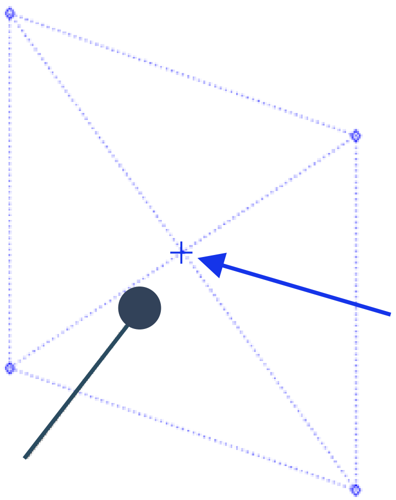
aka constant-bearing decreasing-range

maintain a constant line-of-sight angle (relative to external reference frame)

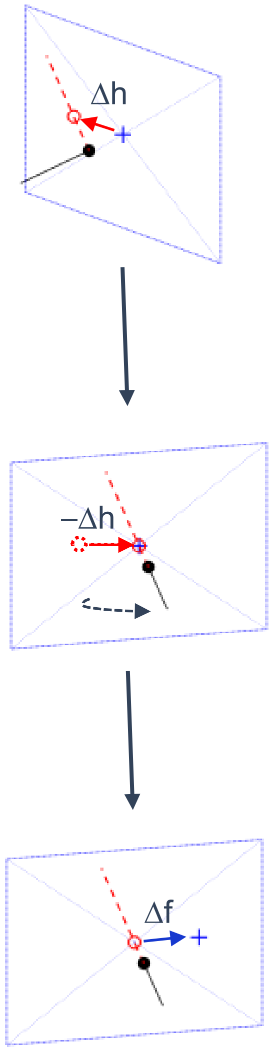
will produce the geometrically shortest path to interception if the prey is moving in a straight line

evidence that the dragonfly follows parallel navigation during final approach (Mischiati et al, 2015)

Parallel navigation in the dragonfly model



fixation spot location
“self-adjusts” depending
on turn history



As the prey moves, prey image slips by Δh

Dragonfly turns to re-align prey image with fixation spot

Prey image translation = -Δh

fixation spot is repositioned by
Δf = QΔh