“NeuroMechFly v2: simulating embodied sensorimotor control in adult *Drosophila*”

Wang-Chen S et al.,
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Agenda

- Background of the paper
- FlyGym
- Leg tip adhesion
- Locomotor controllers
- Fly eyes and smell organ
- Path integration
- Head stabilization
- Hierarchical controller
- Complex odor plume tracking
- Conclusion and Critique

Background: NeuroMechFly (v1)

NeuroMechFly, a neuromechanical model of adult *Drosophila melanogaster*

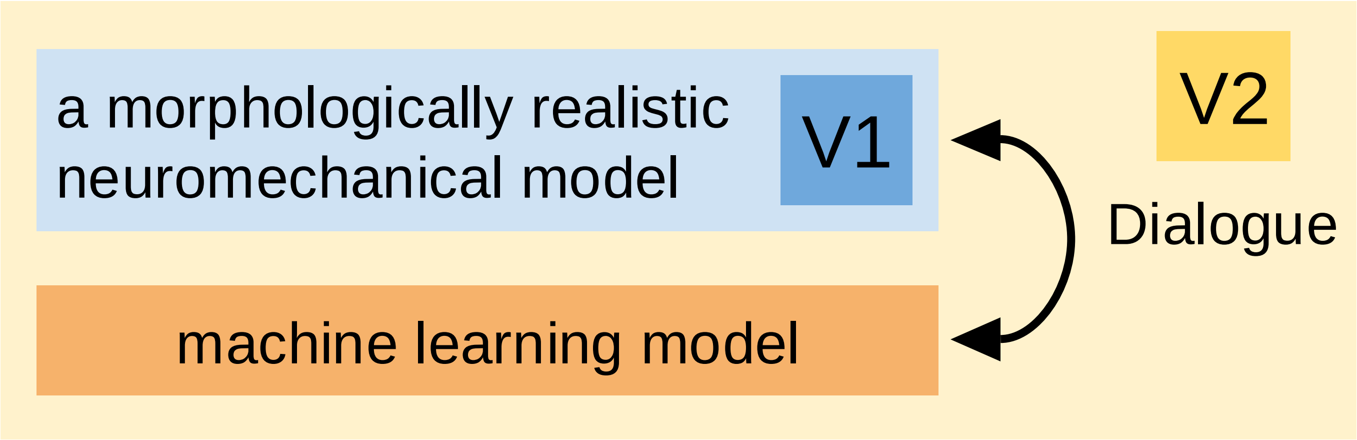
Victor Lobato-Rios[1], Shravan Tata Ramalingasetty[2,3], Pembe Gizem Özdil[1,2,3], Jonathan Arreguit[2], Auke Jan Ijspeert[2] and Pavan Ramdya[1] ✉

Animal behavior emerges from an interaction between neural network dynamics, musculoskeletal properties and the physical environment. Accessing and understanding the interplay between these elements requires the development of integrative and morphologically realistic neuromechanical simulations. Here we present NeuroMechFly, a data-driven model of the widely studied organism, *Drosophila melanogaster*. NeuroMechFly combines four independent computational modules: a physics-based simulation environment, a biomechanical exoskeleton, muscle models and neural network controllers. To enable use cases, we first define the minimum degrees of freedom of the leg from real three-dimensional kinematic measurements during walking and grooming. Then, we show how, by replaying these behaviors in the simulator, one can predict otherwise unmeasured torques and contact forces. Finally, we leverage NeuroMechFly's full neuromechanical capacity to discover neural networks and muscle parameters that drive locomotor gaits optimized for speed and stability. Thus, NeuroMechFly can increase our understanding of how behaviors emerge from interactions between complex neuromechanical systems and their physical surroundings.

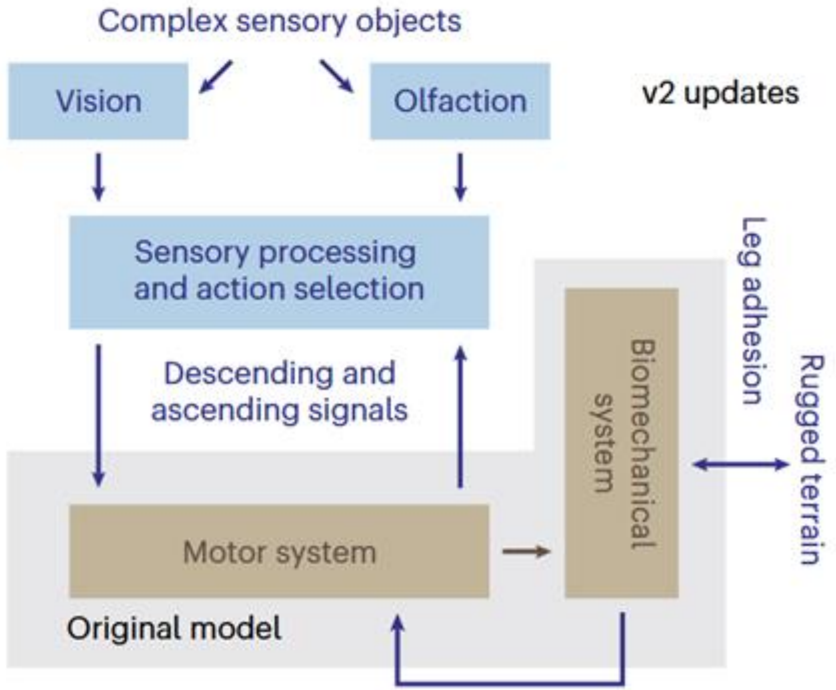
A morphologically realist model of the adult fly.

Background: Why NeuroMechFly v2?

Goal: to discover principles underlying the control of animal behaviors.
Method: to create neuromechanical simulation models that mimic reality to get a better understanding of the animal behaviors.



Background: v2 updates



V2 upgrade:

- Improved morphology
- Better antenna DOF
- More realistic walking
- Leg adhesion
- **Added sensors:**
  - Vision
  - Olfaction
  - Locomotor feedback
- Processing unit
- Path integration
- Head stabilization

Goal of those upgrades:

To have a model capable of doing more complex tasks.

FlyGym Package

Three main changes

Complies with Gym to Facilitate updates to NeuroMechFly

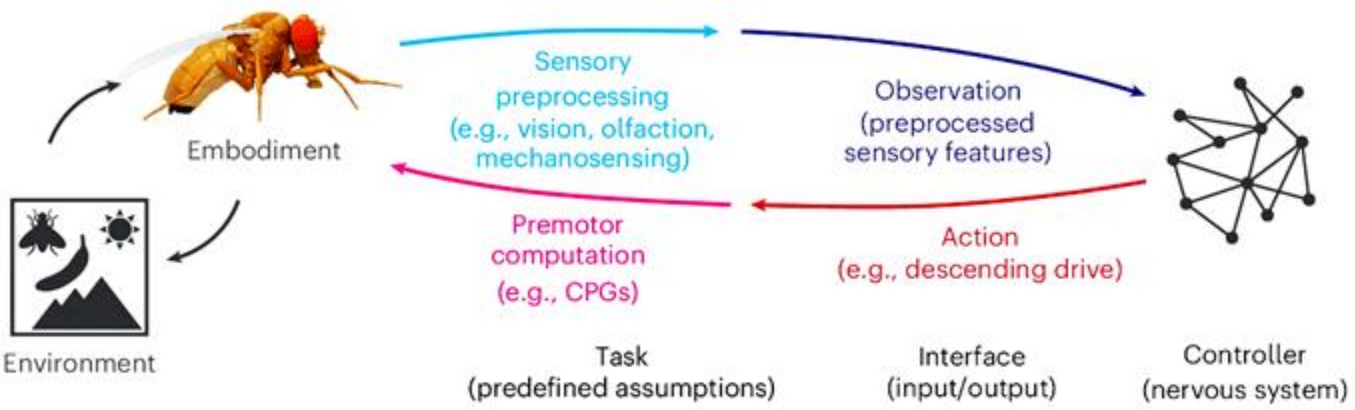
Gym Interface

Three main changes

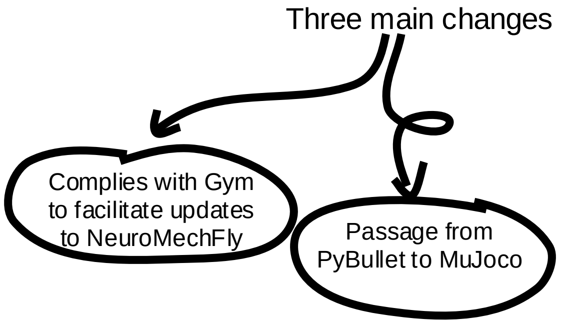
Complies with Gym to facilitate updates to NeuroMechFly

- **Open-source** library
- Various built-in environments

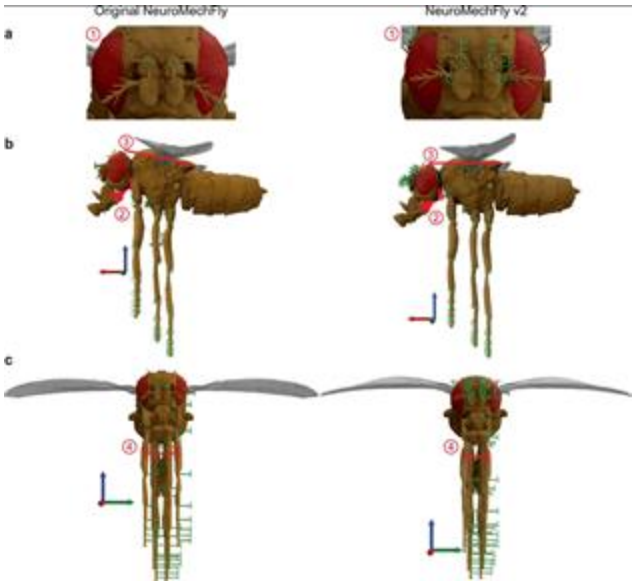
- Supported by most training librairies
  - **Fully complies** with FlyGym package
- Controller-environment interactions in robotics and RL



MuJoco Framework



- Physical representation of the Fly
  - **Flexible parameter** depending on the task
- New physics dynamics implementation
- Better stability and performance
- Wider range of actuators (leg adhesion)
- Sizes adapted to obtain observable measurements

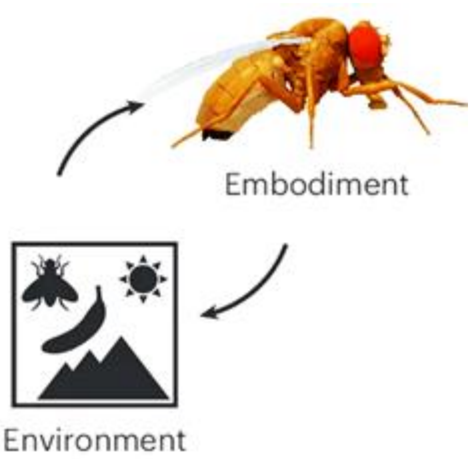


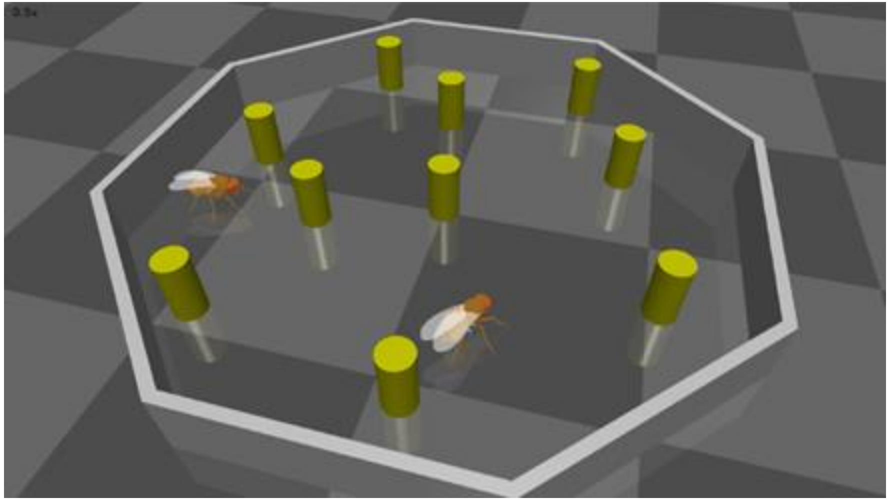
Embodiment

Custom environment

Three main changes

- Complies with Gym to facilitate updates to NeuroMechFly
- Passage from PyBullet to MuJoco
- Custom environmental features

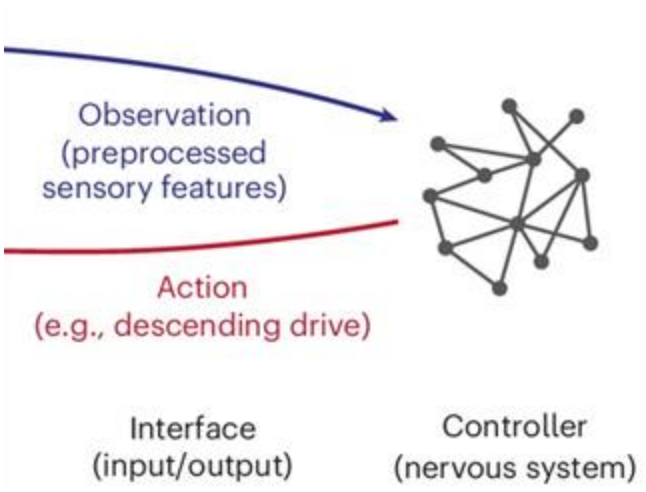




EPFL

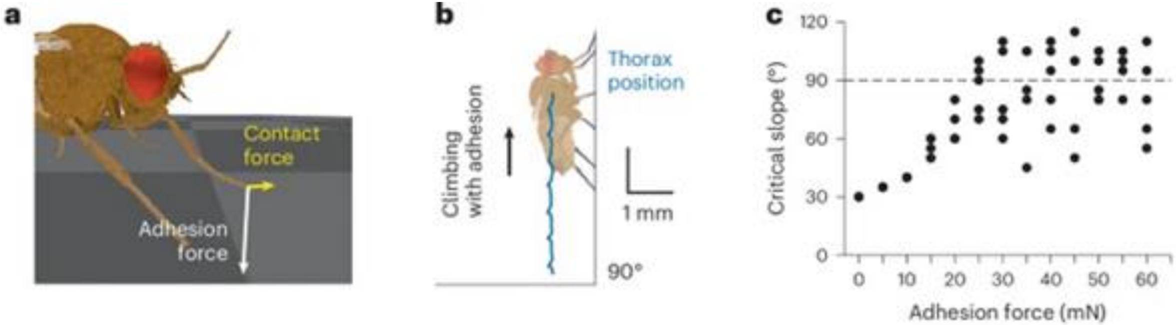
FlyGym : Reinforcement learning

Partially Observable Markov Decision Process (**POMDP**) implementation

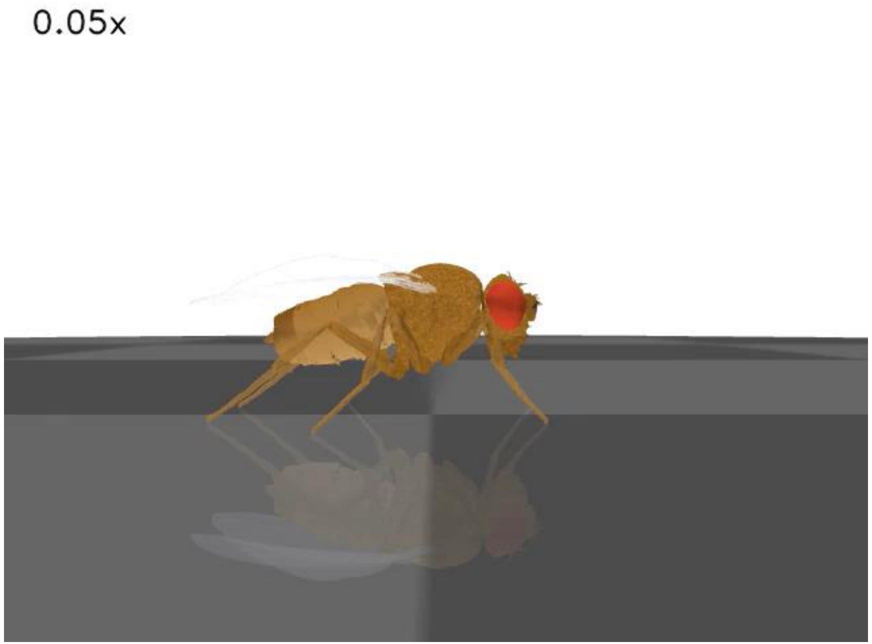


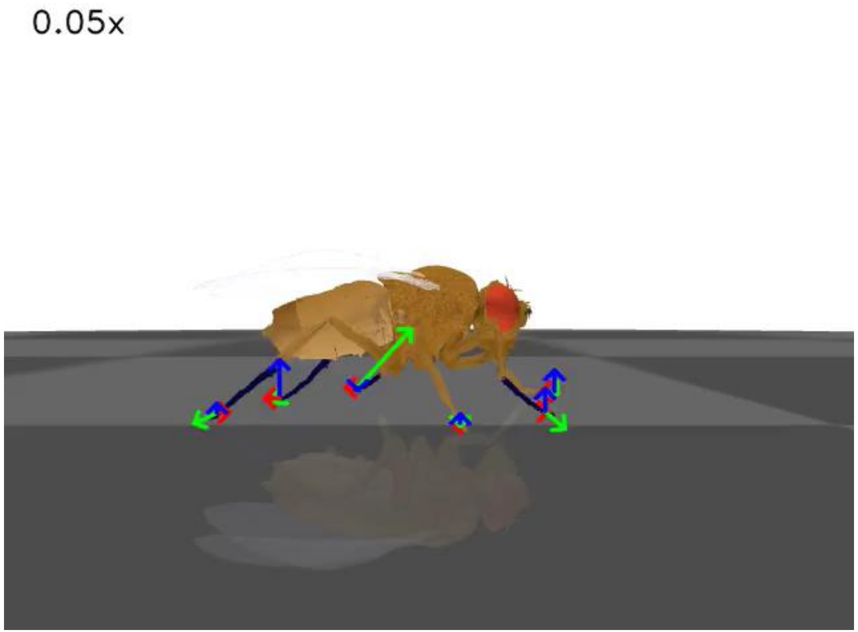
New feature : Leg tip adhesion

- Not easy to model the physics of real adhesion
    - Modeled the adhesion as an **additional normal force**
- Liftoff mechanism abstracted for the *Drosophila*
    - Adhesion force **off** during **swing phase**
- Without adhesion : **30°** / With adhesion : **> 90°**

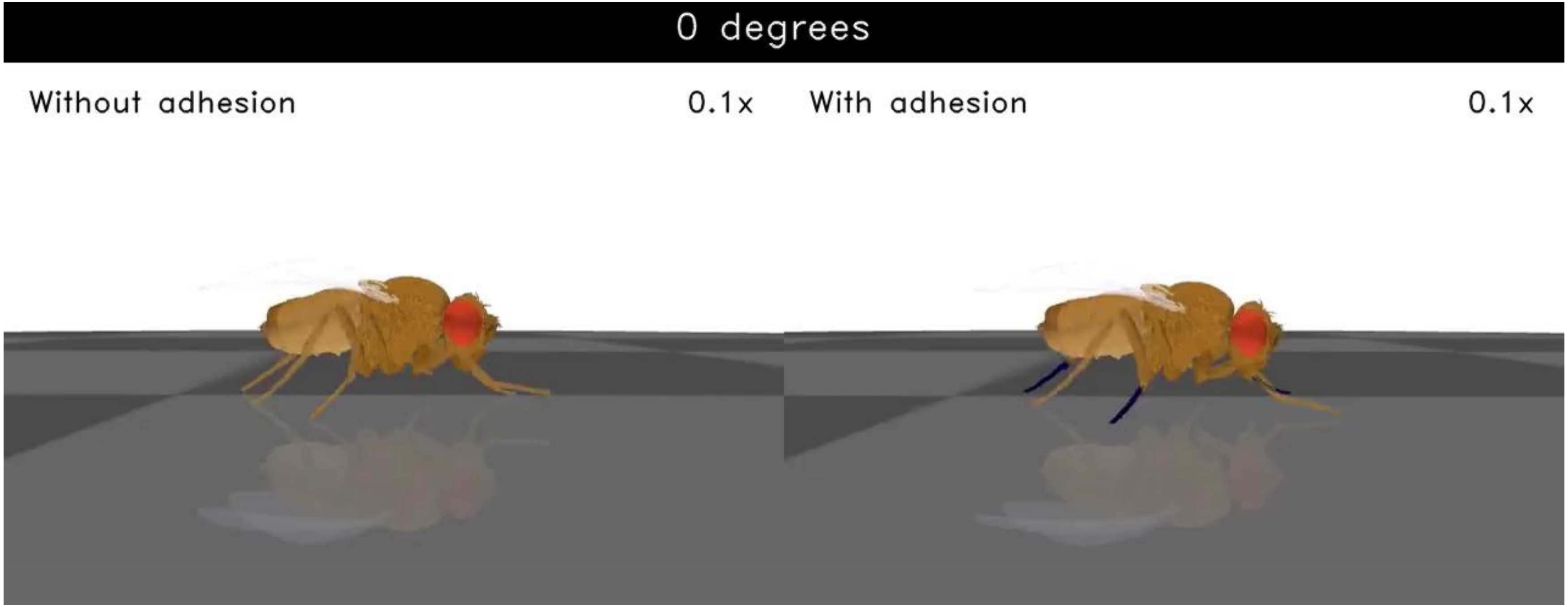


Adhesion efficiency





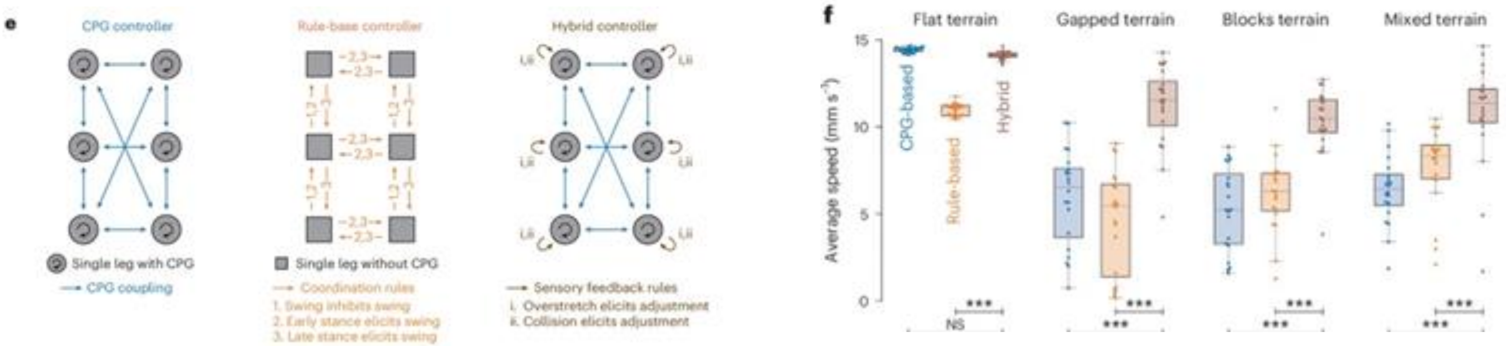
Walking on slopes



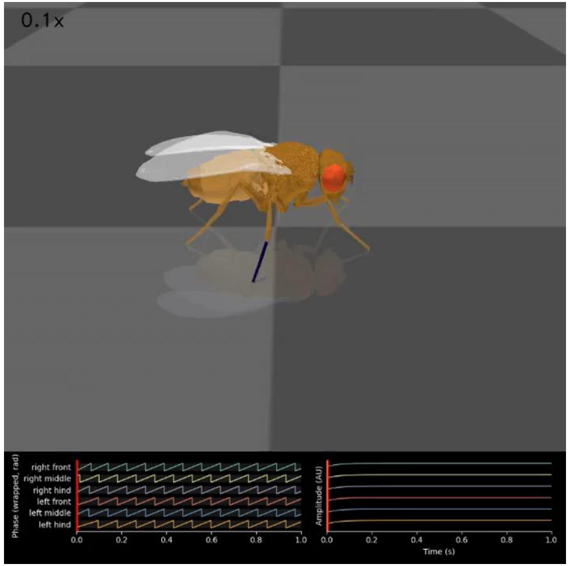
Locomotor controllers

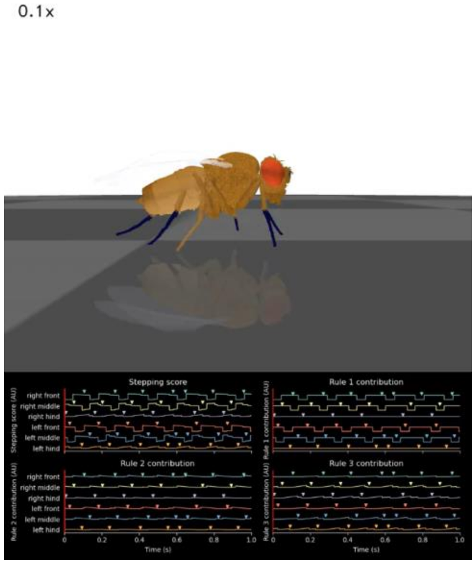
- Three kind of controllers :

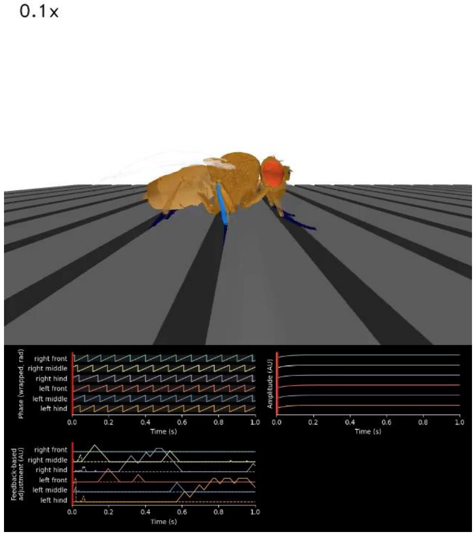
CPG	Rule-based	Hybrid
• Rhythmic motor output without rhythmic input • Fast on flat terrain, but slow on others	• Predefined rules + sensory feedback from the env. • Slow on all all terrains	• Combination of the two previous • Fast on all terrains



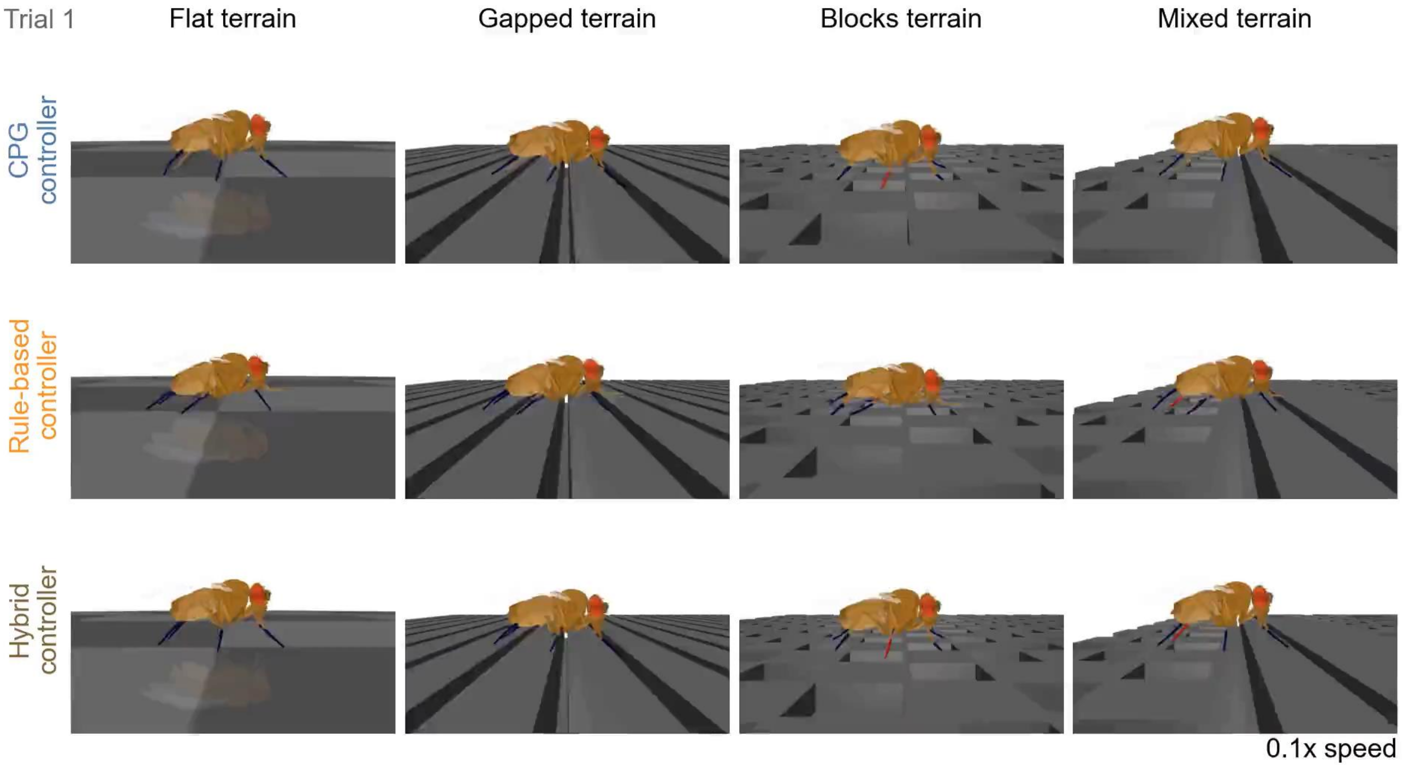
Locomotor controllers







Locomotor controllers



Fly eyes

	Fly retina	Human eyes
Similarities :	Function of vision; Photoreceptors; Processing of visual information	
Differences :	compounded eyes made up of ommatidia	single lens structure with a retina
	field of view of ~270°	field of view of ~180°
	color sensitivity : Ultraviolet, blue, green	color sensitivity: red, green, blue
	low resolution	high resolution

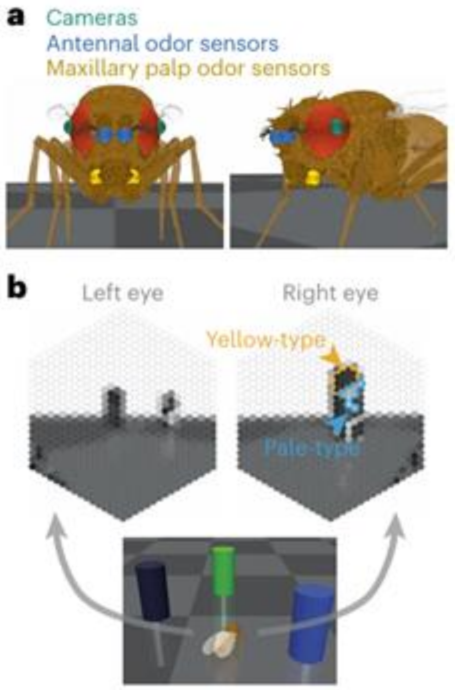
Fly eyes simulation

Goal : avoid obstacles, reach a target

Simulation :

- Compounded eyes
  - Color camera to each compounded eyes

- Yellow and pale type ommatidia

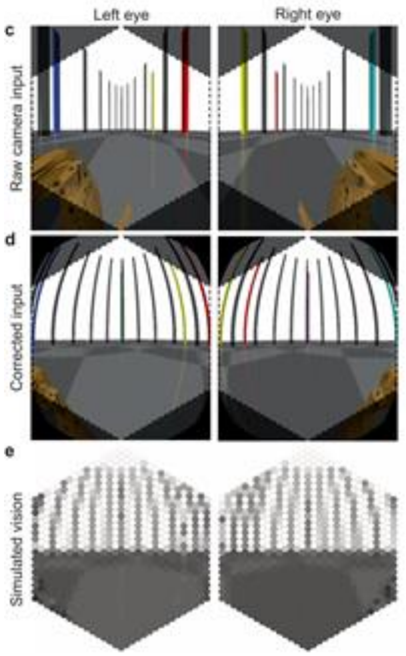


Fly eyes simulation

Goal : avoid obstacles, reach a target

Simulation :

- Compounded eyes
  - Arranged in hexagonal pattern
  - Fisheye effect
  - Transformed into 721 bins on a hexagonal grid

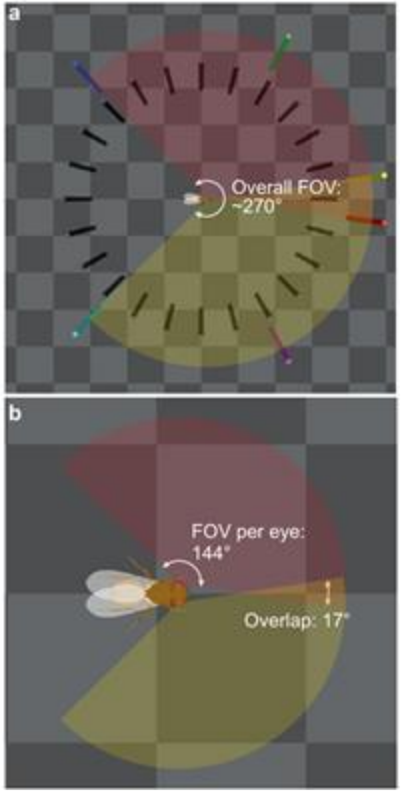


Fly eyes simulation

Goal : avoid obstacles, reach a target

Simulation :

- 270° of FOV with a ~17° binocular overlap

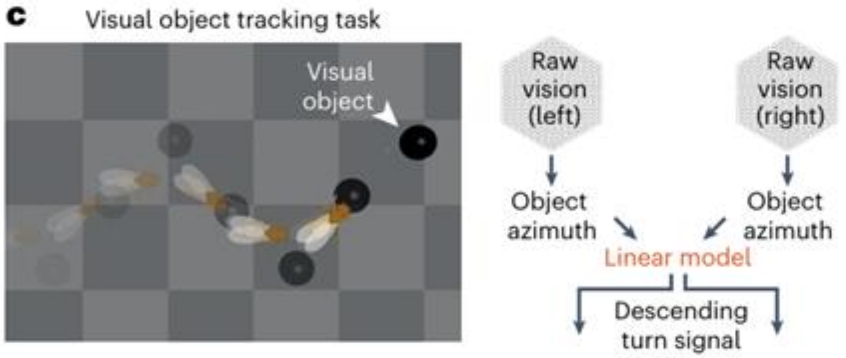


Use of fly eyes in locomotion

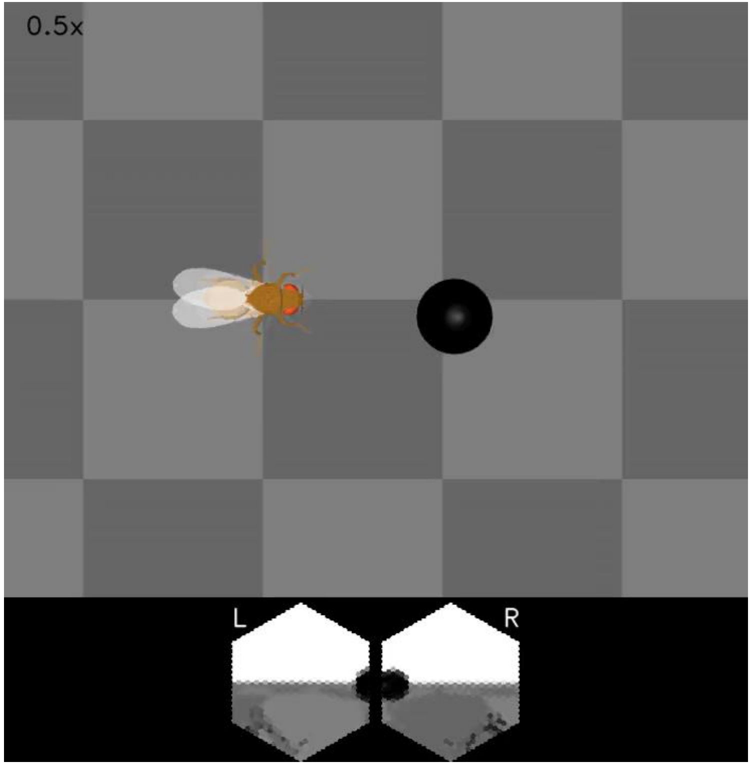
Task: Visually track and follow a black sphere

How:

- Threshold to detect the object
- Extract object azimuth
- Linear transformation
- descending signal transformed into a turning bias



Visual object tracking task



EPFL

Fly smell organ

Fly antenna | Human nose

Similarities :

- Olfactory function
- Sensory neurons
- Signal processing

Differences :

Fly antenna:

- Antenna and maxillary palps
- Detect odor gradients across left and right
- detect specific odors

Human nose:

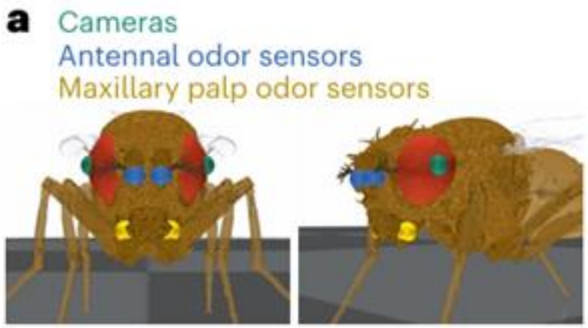
- Nasal cavity
- airflow through the nasal cavity
- Broad scent discrimination

Fly smell organ simulation

goal : reach attractive odor, avoid repulsive odor

Simulation :

- olfactory receptors in the antenna and maxillary palps
- Virtual odor intensities sensors



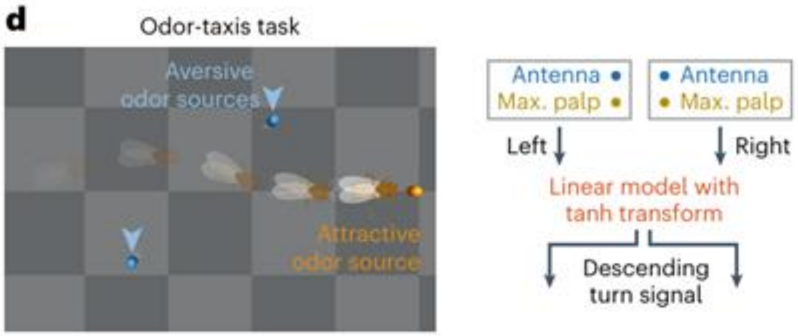
EPFL

Use of fly smell organ in locomotion

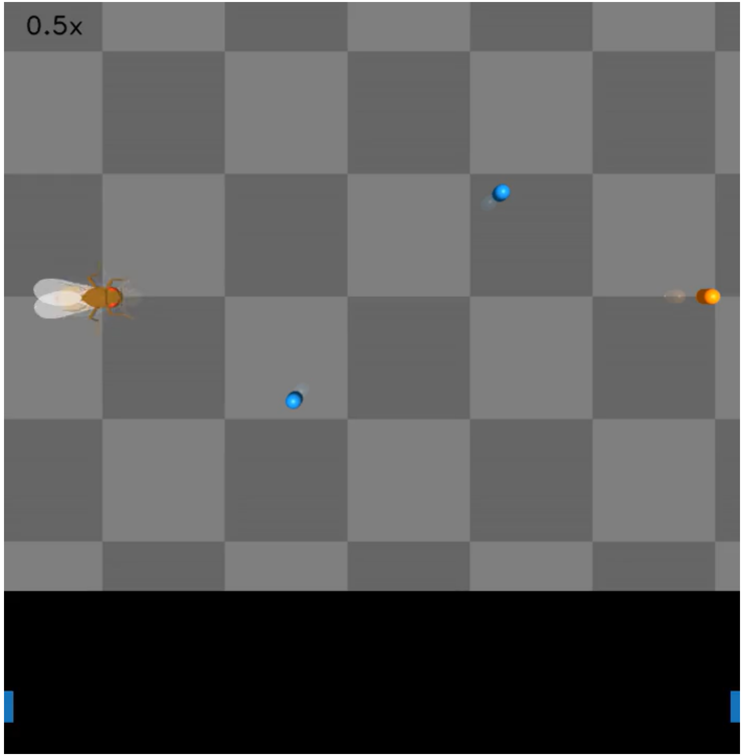
Task: reach an attractive odor while avoiding to aversive odor

How:

- Compare of intensities of attractive and aversive odor
- Weight of opposite sign for attractive and aversive odor
- Descending signal transformed into a turning bias



Olfactory chemotaxis task



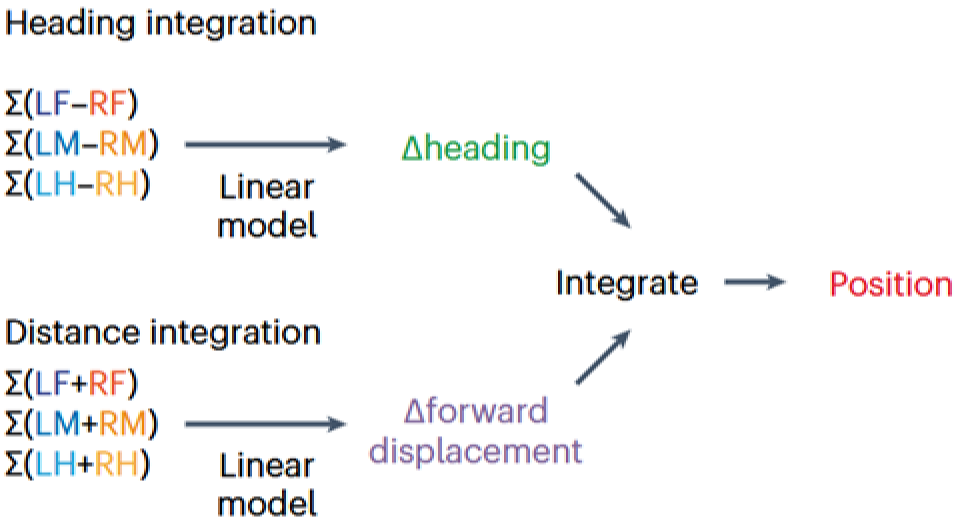
Path integration

Two variables integrated per leg:

- Leg **proprioception**
- **Tactile** signals

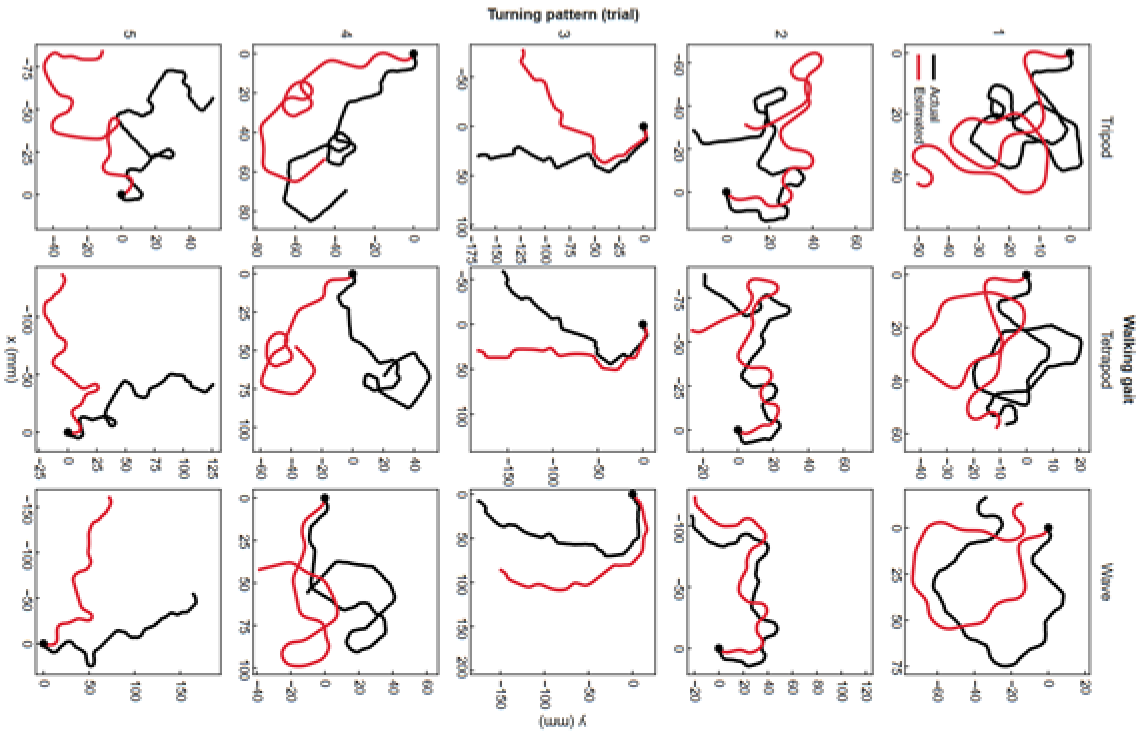
→ **Stride length** per leg

The **position** is **deduced** from the **stride lengths** of the **differents legs**:



Path integration

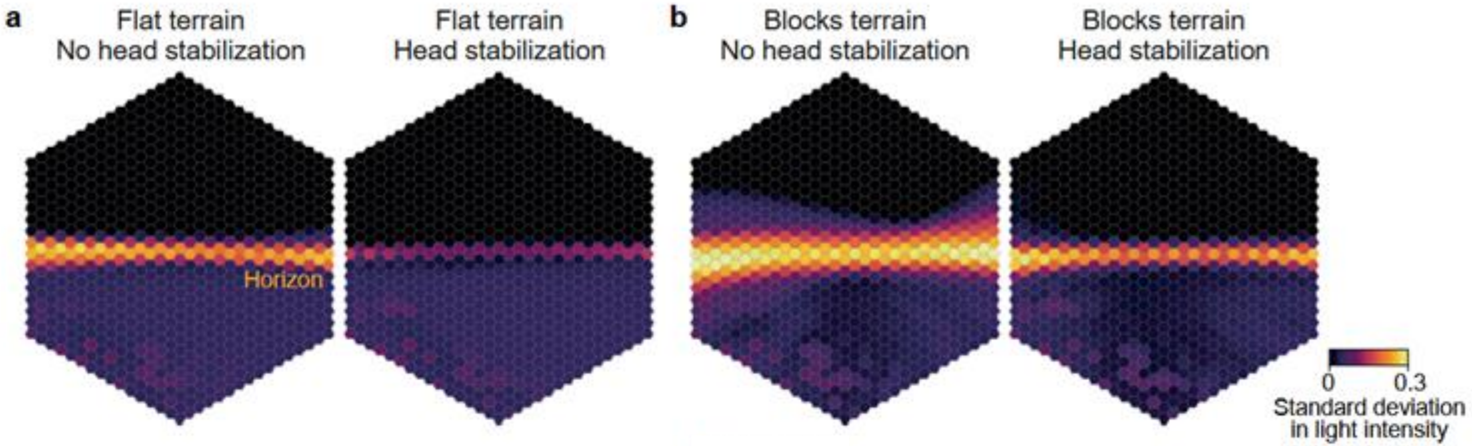
Results:



Some estimations are way off, a **real fly** probably use some **additional sensors** to calibrate its position.

Head stabilization

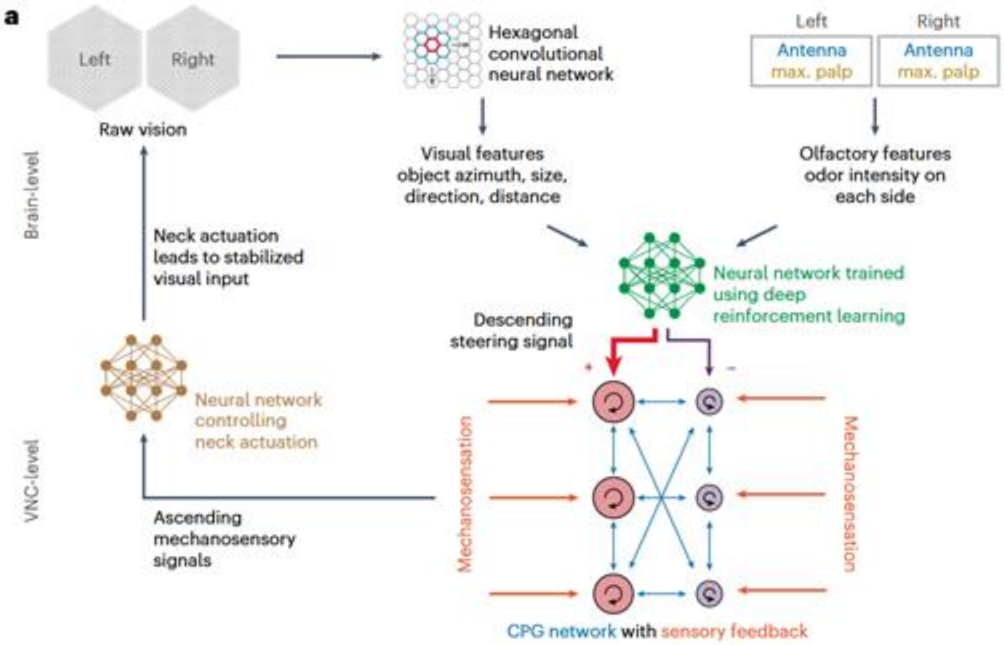
Purpose: To get better visibility inputs.

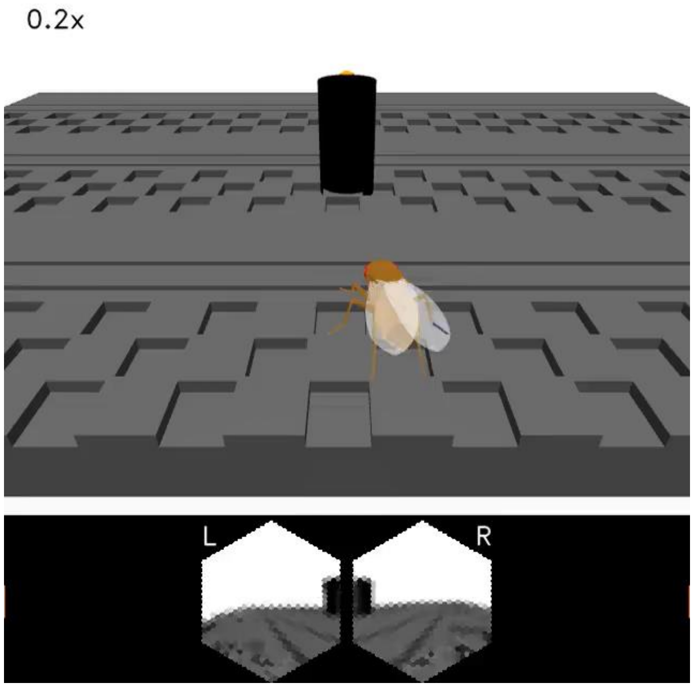


Needed for tasks that required visual tracking.

Hierarchical controller

Realisation of a **complex task** using **hierarchical controller** trained with **Reinforcement Learning** (RL).

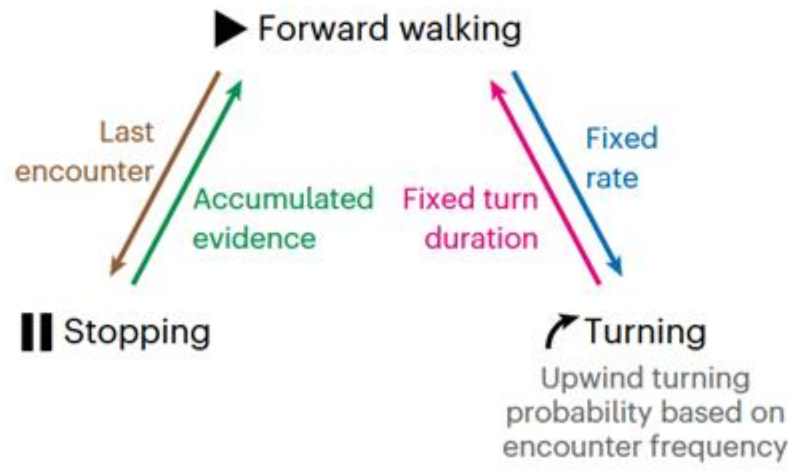


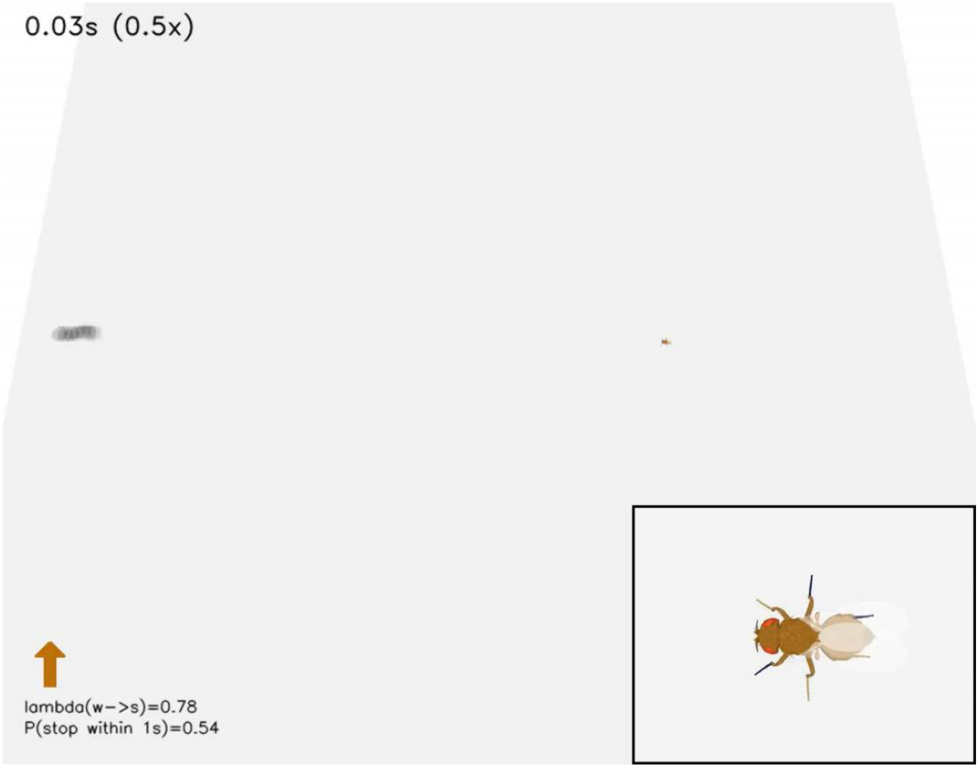


Complex odor plume tracking

Complex odor plume simulated using PhiFlow.

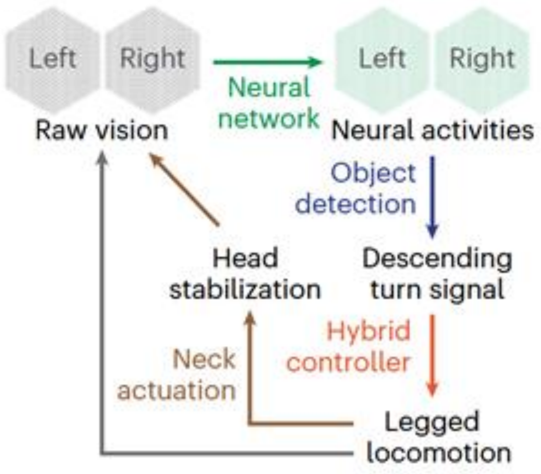
Tracking algorithm used to control **locomotion**:

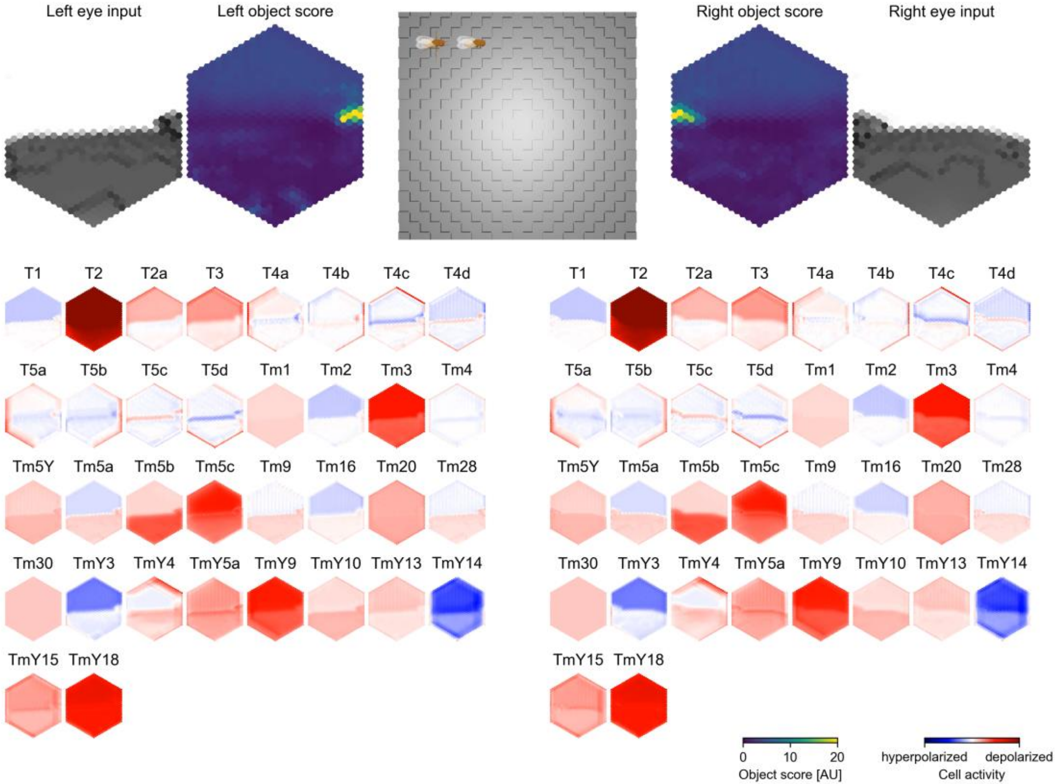




Fly following another fly

Algorithm, with **neural network for vision** used to control the fly:





Conclusions

Hybrid controller better than CPG or rule-based controller

Addition of sensors helps in navigation

Simulation of complex behavior

- Improvement of the simulation
- More representative of the reality

Discussion

- Some parts of the model rely on undefined biological mechanisms
  - Adhesion mechanism abstracted, muscoskeletal system
- Larger model training for even more relevant results
- Using vision for the path integration would be a good alternative to the one cited before
- Some improvements can be done on the behaviour of fly involving control of wings, abdomen, etc… But supported within the framework !
- Possibility to perform experiments with connectome-constrained neural networks
  - Investigate biologically-relevant behaviors
  - Better physical simulations -> training for larger models
  - Better analysis of the fly's muscoskeletal system

Thank you!

Any questions?

Sources

- Prof. Pavan Ramdya - **Controlling behavior in animals and robots** course - EPFL - 2025
- https://www.nature.com/articles/s41592-024-02497-y
- https://www.nature.com/articles/s41592-022-01466-7
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