A controller for virtual fly locomotion

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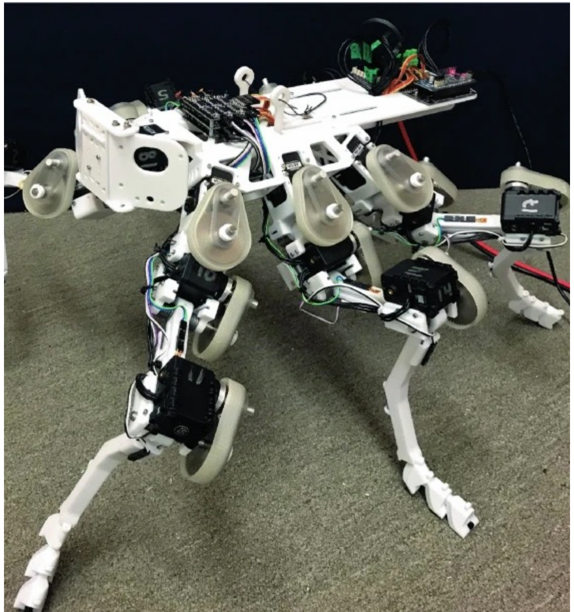
NeuroMechFly model from Lobato-Rios et al.

Introduction

Introduction

Understanding animal behavior is crucial in fields of **NEUROENGINEERING** and **ROBOTICS**


Drosophibot from Goldsmith et al.

- Extract information from simulation fails
- "Deconstruct" and artificially modulate behaviors
- Investigate biological underlying mechanisms
- Develop bio inspired robots

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Rule-based controller

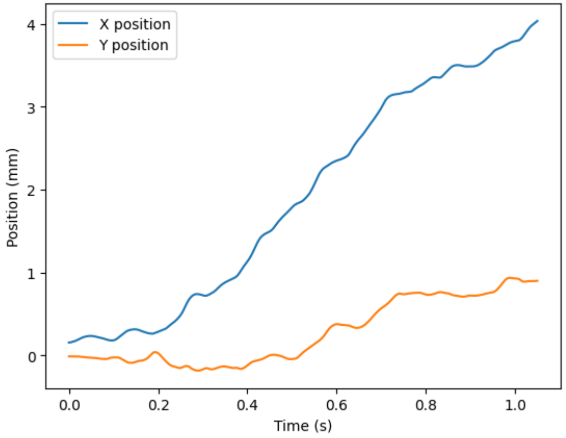
- Decentralized controller based on simple rules
- Results
- Possible improvements

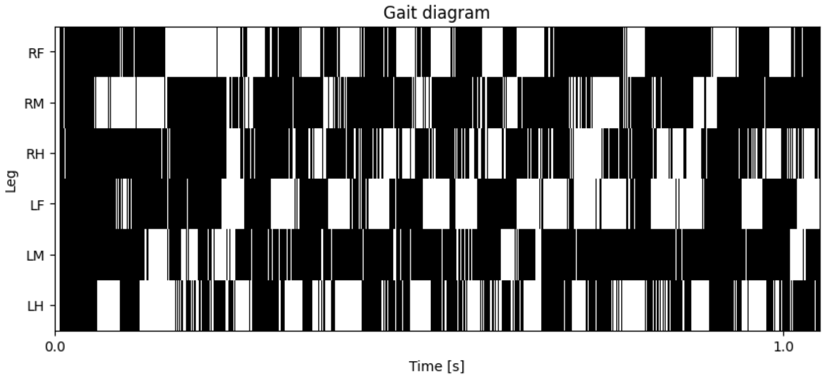
Decentralized controller based on simple rules

- Walking pattern controlled by rules presented in the Cruse et al.
  - 1st rule “suppress lift-off”
  - 2d rule “facilitate early protraction”
  - 3rd rule “enforce late protraction”
  - 5th rule “distribute propulsive force”

- New rule: "leg gap extraction"

Results - Flat terrain





- Forward motion
- Irregular gait pattern with unbalanced swing and stance phases

Results - Blocks terrain

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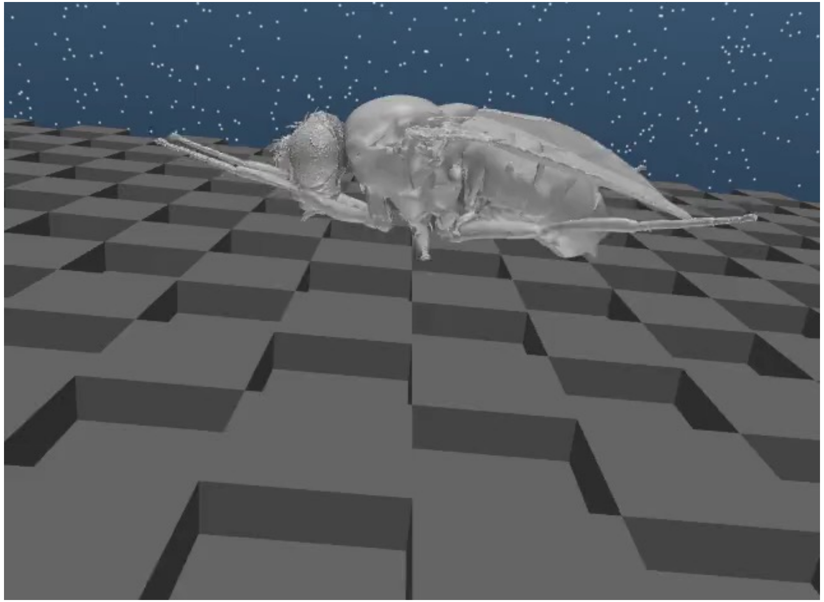
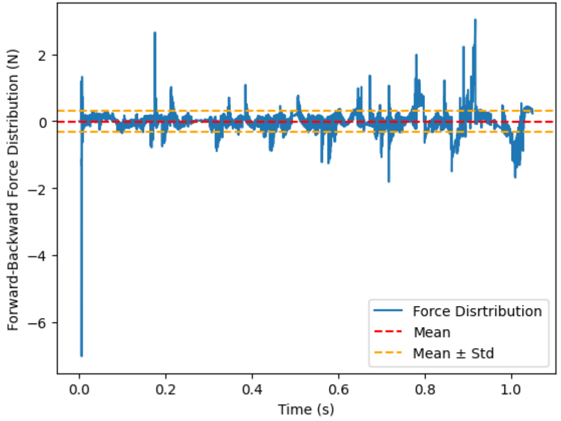
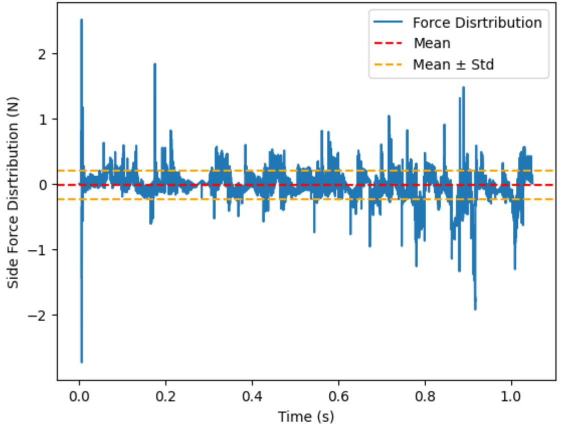
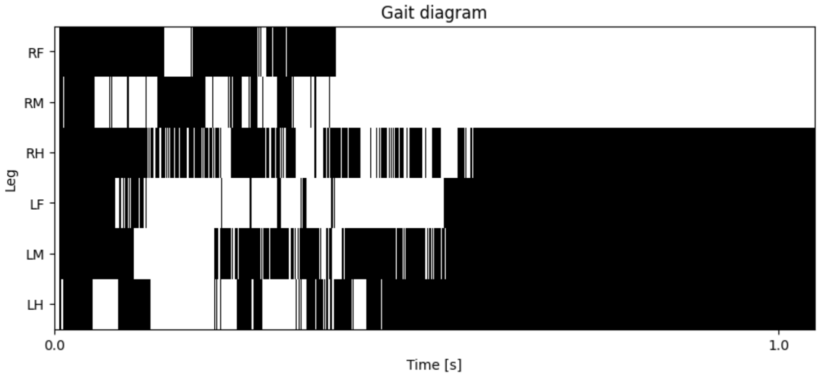






Results - Gapped terrain



- Despite the additional rule the fly get stuck
- Find a rules which can extract the fly when multiple legs are trapped

Possible improvements

- Essential to tune the different rules weight with Reinforcement Learning
- Implement specific swing and stance movements
- Improve force signal detected by sensors
- Implement new experimental rules

CPG-based controller

- Introduction
- From open-loop to closed-loop
- Tripod gait VS Caterpillar gait
- Results

Introduction

- **CPG-based controllers** have been extensively described in **literature**;
- One of the **main limitations** of the standard formulation of **CPG** is that it is **open-loop**;
- CPGs are well suited for **rapid**, **cyclical movements** that do not heavily rely on sensory feedback;
- We decided to employ **six CPGs**, one per leg.

From open-loop to closed loop

- **CPG-based controllers** have been extensively described in **literature**;
- One of the **main limitations** of the standard formulation of CPG is that it is **open-loop**:

$$\dot{\theta}_i = 2\pi\nu_i + \sum_j (r_j w_{ij} \sin(\theta_j - \theta_i - \phi_{ij}))$$

ν_i → Frequency of the i-th oscillator;
r_i → Amplitude of the i-th oscillator;
w_{ij} → Coupling strength between the i-th and the j-th oscillators;
θ_i → Phase of the i-th oscillator;
ϕ_{ij} → Phase bias between the i-th and the j-th oscillators;

From open-loop to closed-loop

- We therefore decided to introduce **sensory feedback** in different ways;
- **Strategy 1**: Adding a term related to the **force** in the **differential equation**:

$$\dot{\theta}_i = 2\pi\nu_i + \sum_j (r_j w_{ij} \sin(\theta_j - \theta_i - \phi_{ij})) - c(F_{i,t} - F_{i,t-1})$$

ν_i → Frequency of the i-th oscillator;
r_i → Amplitude of the i-th oscillator;
w_{ij} → Coupling strength between the i-th and the j-th oscillators;
θ_i → Phase of the i-th oscillator;
ϕ_{ij} → Phase bias between the i-th and the j-th oscillators;
$F_{i,t}$ → Force experienced by the i-th end effector at time step t;
$F_{i,t-1}$ → Force experienced by the i-th end effector at time step t – 1.

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From open-loop to closed-loop

- We therefore decided to introduce **sensory feedback** in different ways;
- **Strategy 2**: **Scaling the frequencies** of the oscillators based on the **contact forces** experienced by the end effectors:

$$F_{max} \rightarrow c_{\max F} < 1$$

$$F_{min} \rightarrow c_{\min F} > 1$$

$$\Delta_F = F_{\max} - F_{\min}$$

$$S_i = c_{\max F} + (c_{\min F} - c_{\max F}) * \frac{F_i - F_{\min}}{\Delta_F}$$

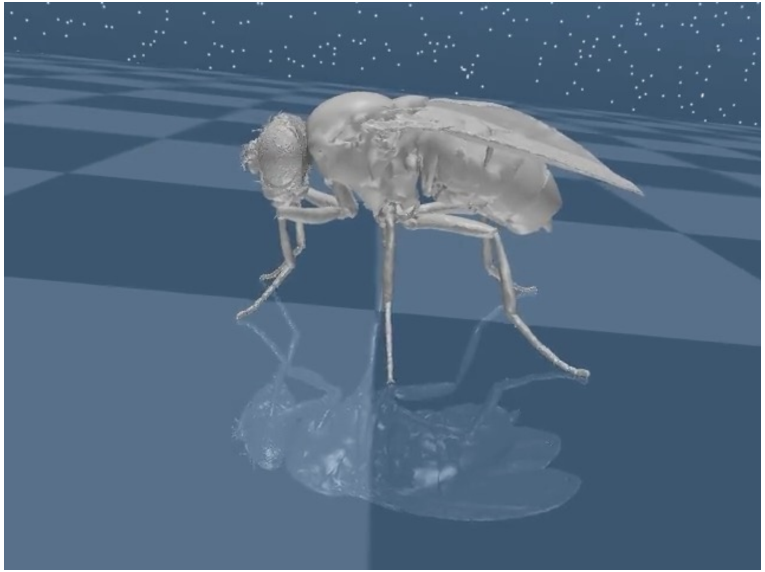
Linear interpolation approach

From open-loop to closed-loop

- We therefore decided to introduce **sensory feedback** in different ways;
- **Strategy 3**: **Freezing a leg** (keeping the phase and amplitude of the oscillator constant) if the experienced **force** is **above a threshold**.

Tripod gait VS Caterpillar gait

- One of the gait types described more in detail in literature is the **tripod gait**:
  - **Three legs move simultaneously**, the others keep contact with the ground;
  - Good compromise between **speed** and **stability**.



$$\phi_{ij} = \begin{bmatrix} 0 & 0.5 & 1.0 & 0.5 & 0 & 0 \\ 0.5 & 0 & 0.5 & 0 & 0.5 & 0 \\ 1.0 & 0.5 & 0 & 0 & 0 & 0.5 \\ 0.5 & 0 & 0 & 0 & 0.5 & 1.0 \\ 0 & 0.5 & 0 & 0.5 & 0 & 0.5 \\ 0 & 0 & 0.5 & 1.0 & 0.5 & 0 \end{bmatrix}$$

Phase bias matrix for the tripod gait

Tripod gait VS Caterpillar gait

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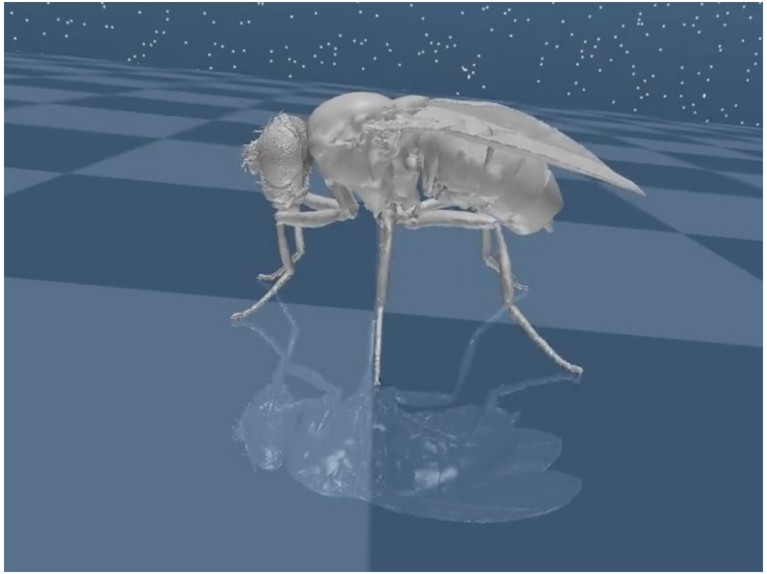
Tripod gait VS Caterpillar gait

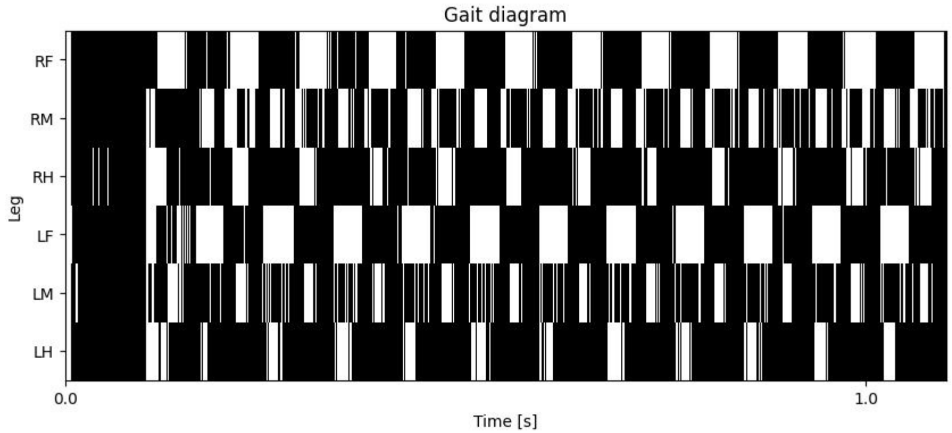
- We investigated a different type of gait, the **caterpillar gait**:
  - **Wave motion**, **two** front/mid/back **legs** are in the swing phase at the same time while the other four are in the stance phase;
  - **Very stable** motion without sacrificing speed.



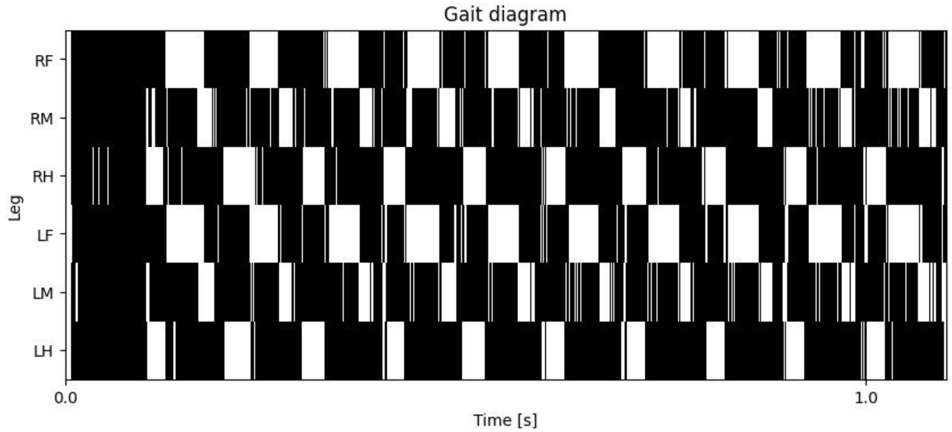
$$\phi_{ij} = \begin{bmatrix} 0 & \frac{2}{3} & \frac{1}{3} & 0 & \frac{2}{3} & \frac{1}{3} \\ \frac{1}{3} & 0 & \frac{2}{3} & \frac{1}{3} & 0 & \frac{2}{3} \\ \frac{2}{3} & \frac{1}{3} & 0 & \frac{2}{3} & \frac{1}{3} & 0 \\ 0 & \frac{2}{3} & \frac{1}{3} & 0 & \frac{2}{3} & \frac{1}{3} \\ \frac{1}{3} & 0 & \frac{2}{3} & \frac{1}{3} & 0 & \frac{2}{3} \\ \frac{2}{3} & \frac{1}{3} & 0 & \frac{2}{3} & \frac{1}{3} & 0 \end{bmatrix}$$

Phase bias matrix for the caterpillar gait

Tripod gait VS Caterpillar gait

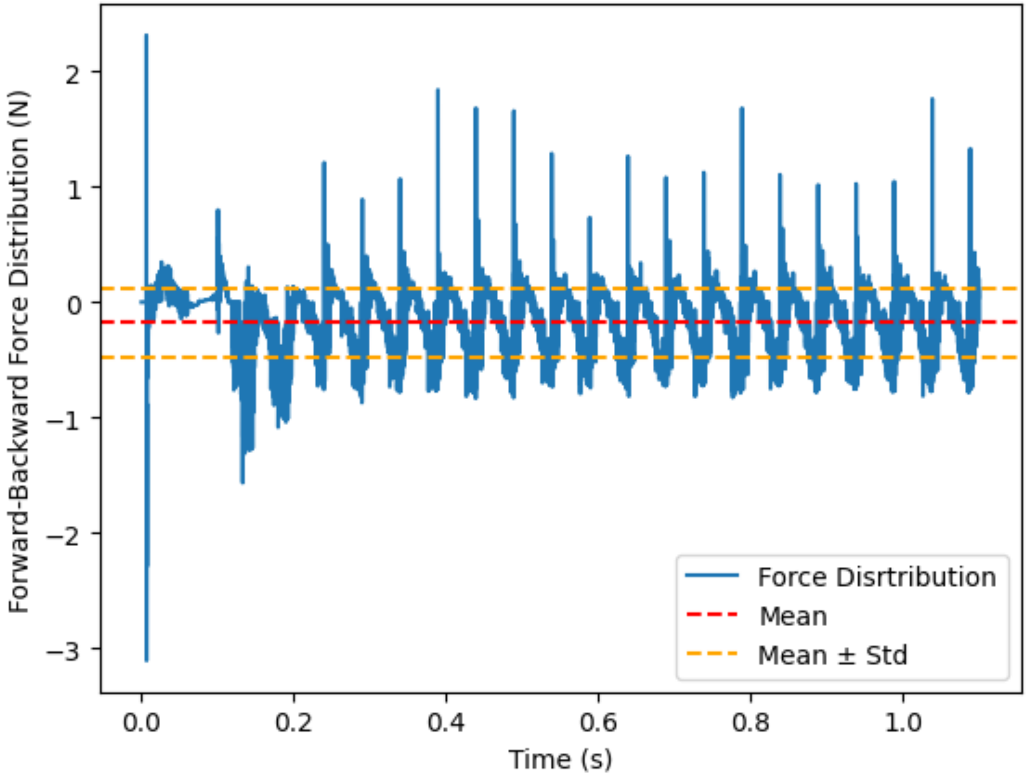


Tripod gait



Caterpillar gait

Tripod gait VS Caterpillar gait

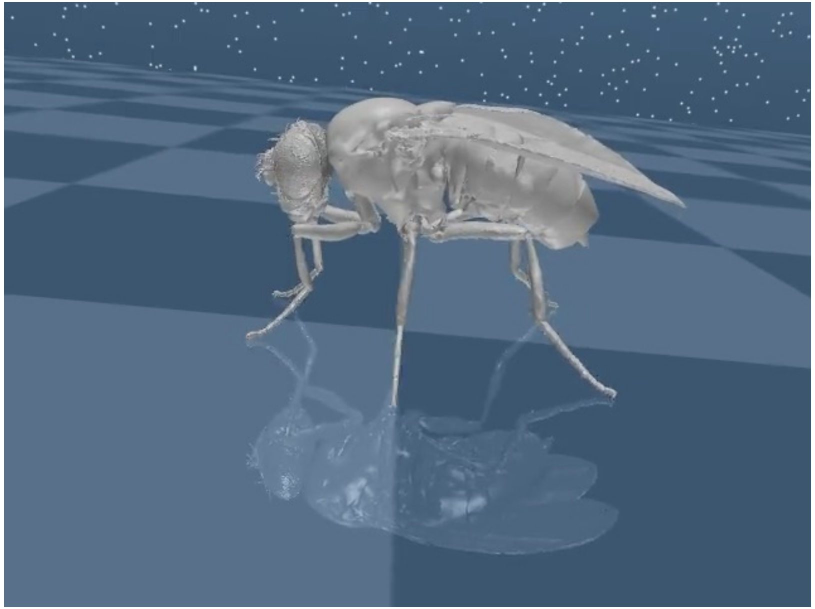


Forward-backward force distribution for the caterpillar gait on flat terrain

Results – Flat terrain

- The **fly** is quite **fast** and **stable**, the distance travelled with the caterpillar gait is larger than the one travelled with the tripod gait;
- The **terrain** is **easy** to be traversed.

Terrain	Final X distance	Final Y distance
Flat	**18.65 mm**	**1.71 mm**
Blocks	3.47 mm	0.65 mm
Gapped	4.55 mm	0.16 mm



Results – Blocks terrain

- The **controller has trouble keeping stability** in all situations, but the **caterpillar gait** seems to be **beneficial** in this regard;
- Sometimes, the fly tips over.

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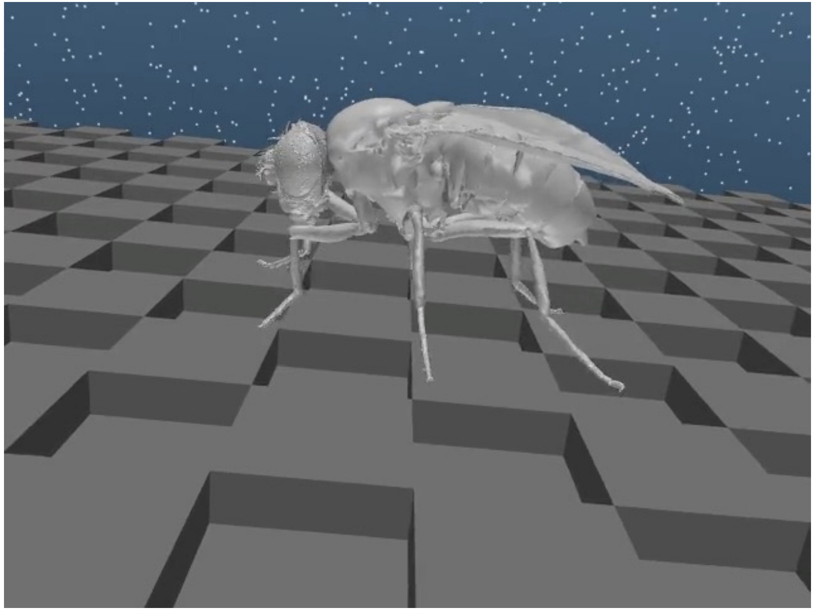

Results – Gapped terrain

- The **fly can free the legs** from the gaps most of the time;
- The **caterpillar gait seems beneficial**, but sometimes two legs get stuck at the same time.

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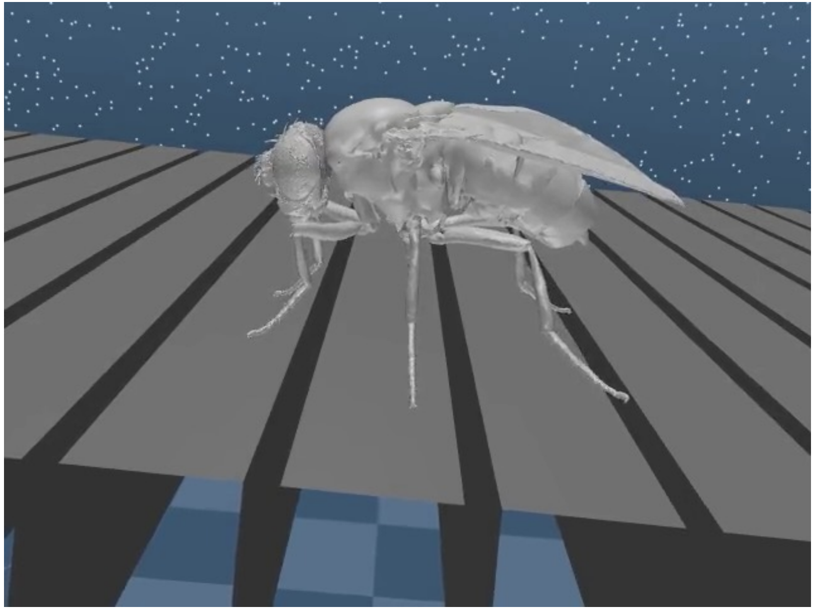

Results – Gapped terrain

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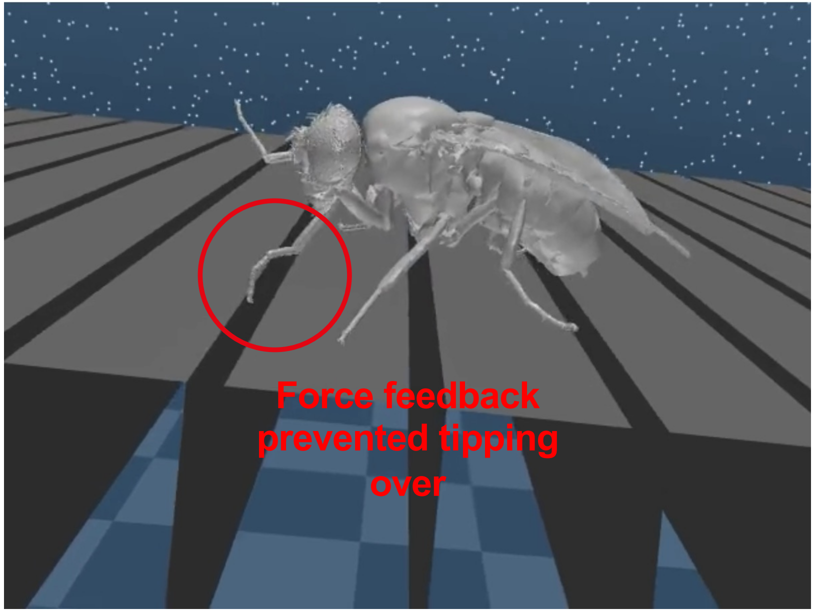

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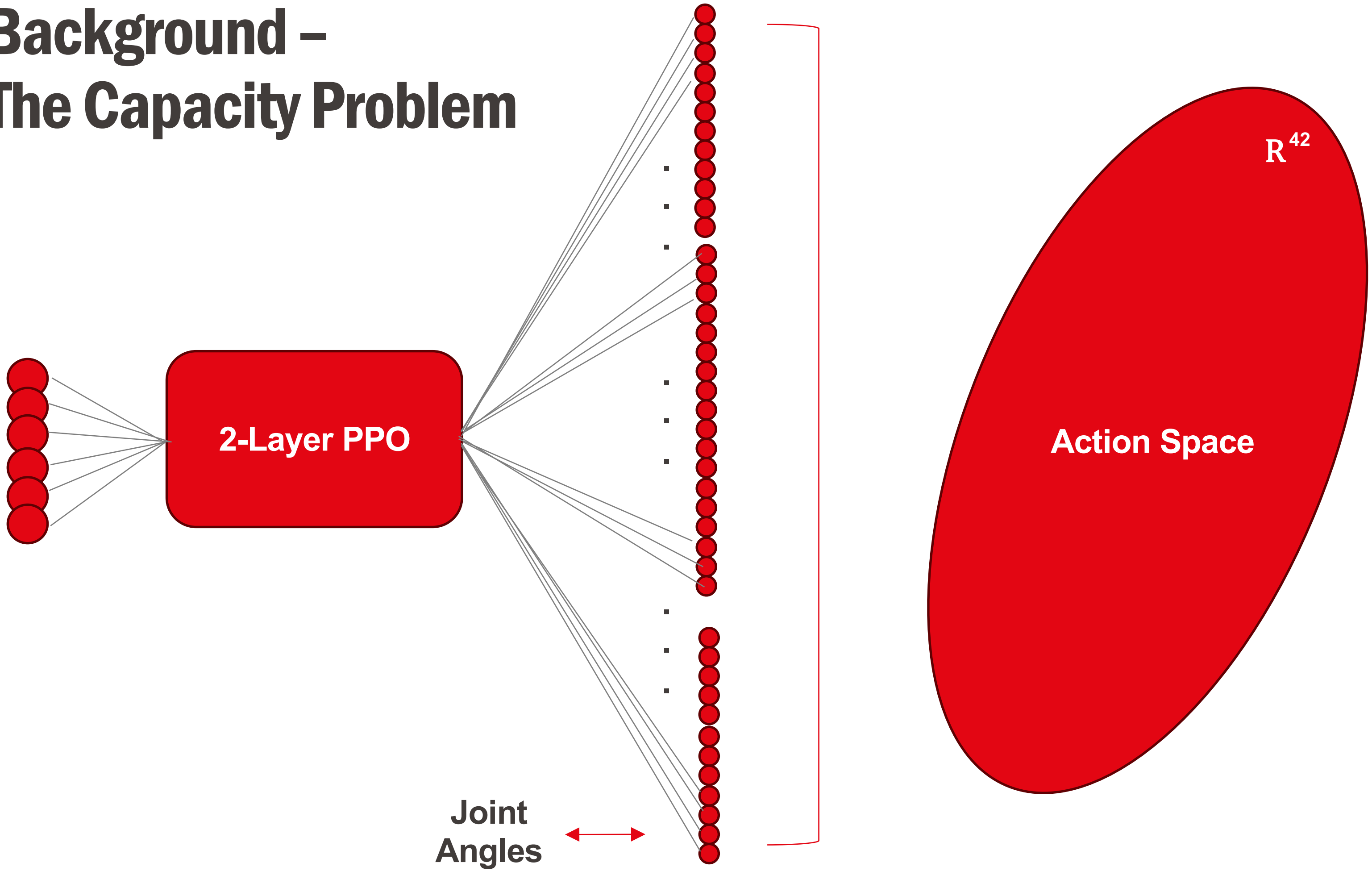
Rule-Based Reinforcement Learning Hybrid controller

Background

- The team trying to fine-tune Cruse rules.
- The team trying to fine-tune CPGs.
- The team trying to learn a 42-DoF continuous output using a 2-layer PPO Policy Network.

Background – The Capacity Problem



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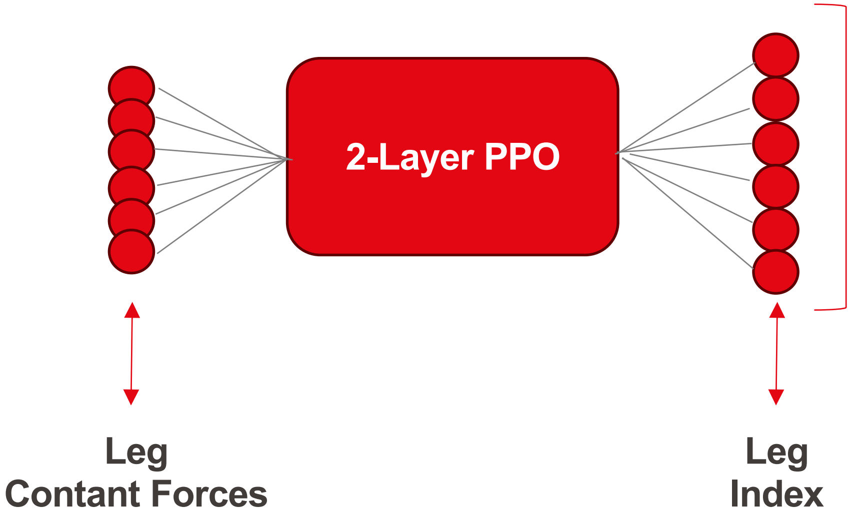
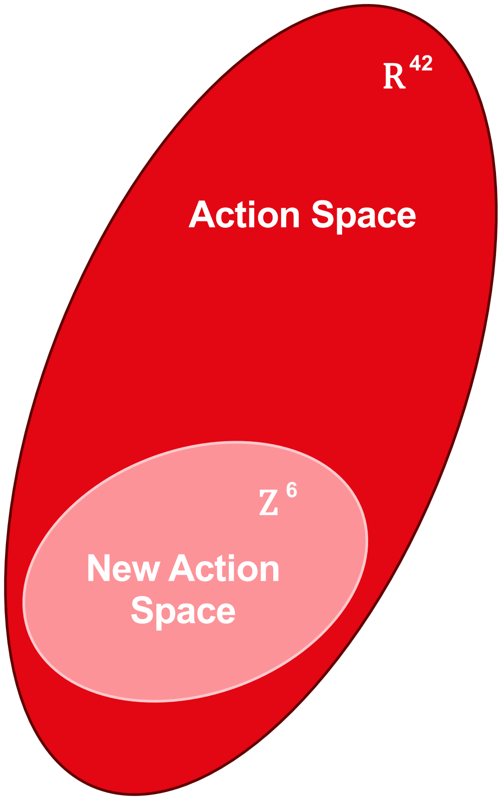
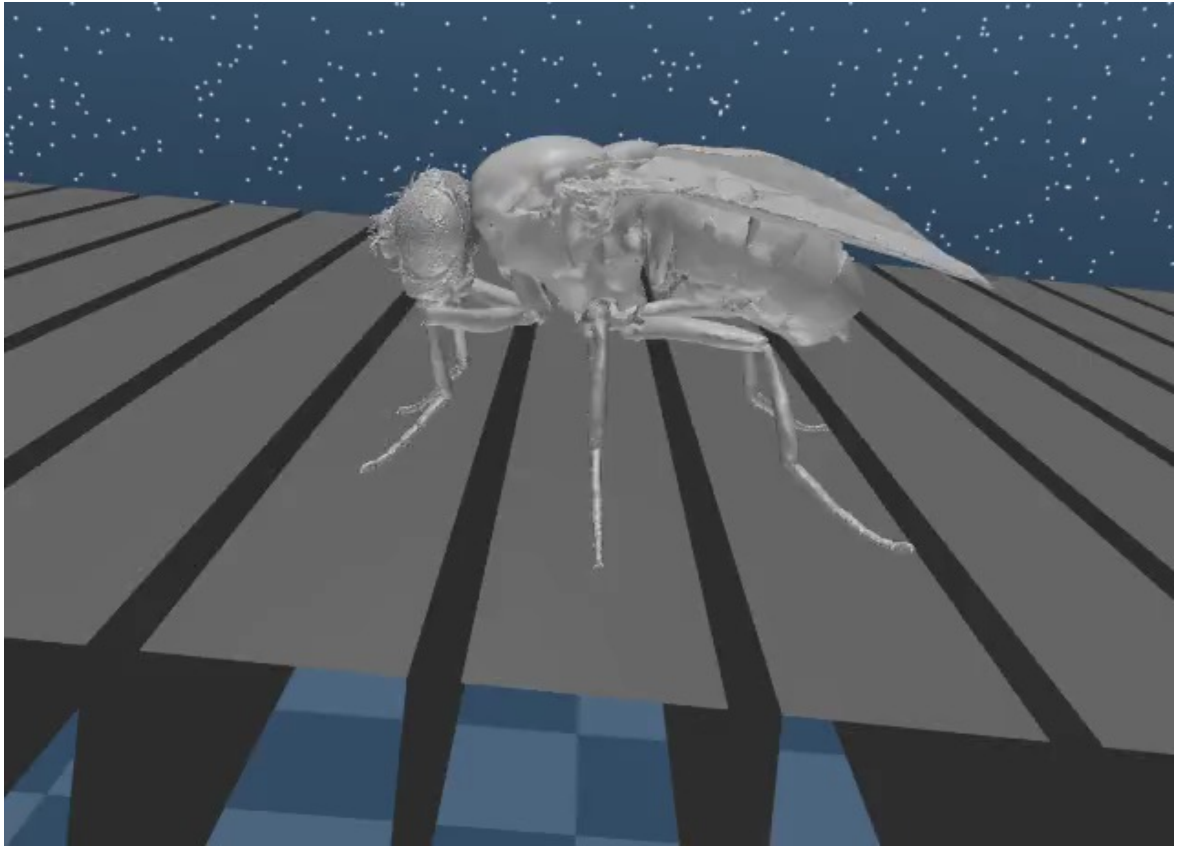
Background – Matching Capacities



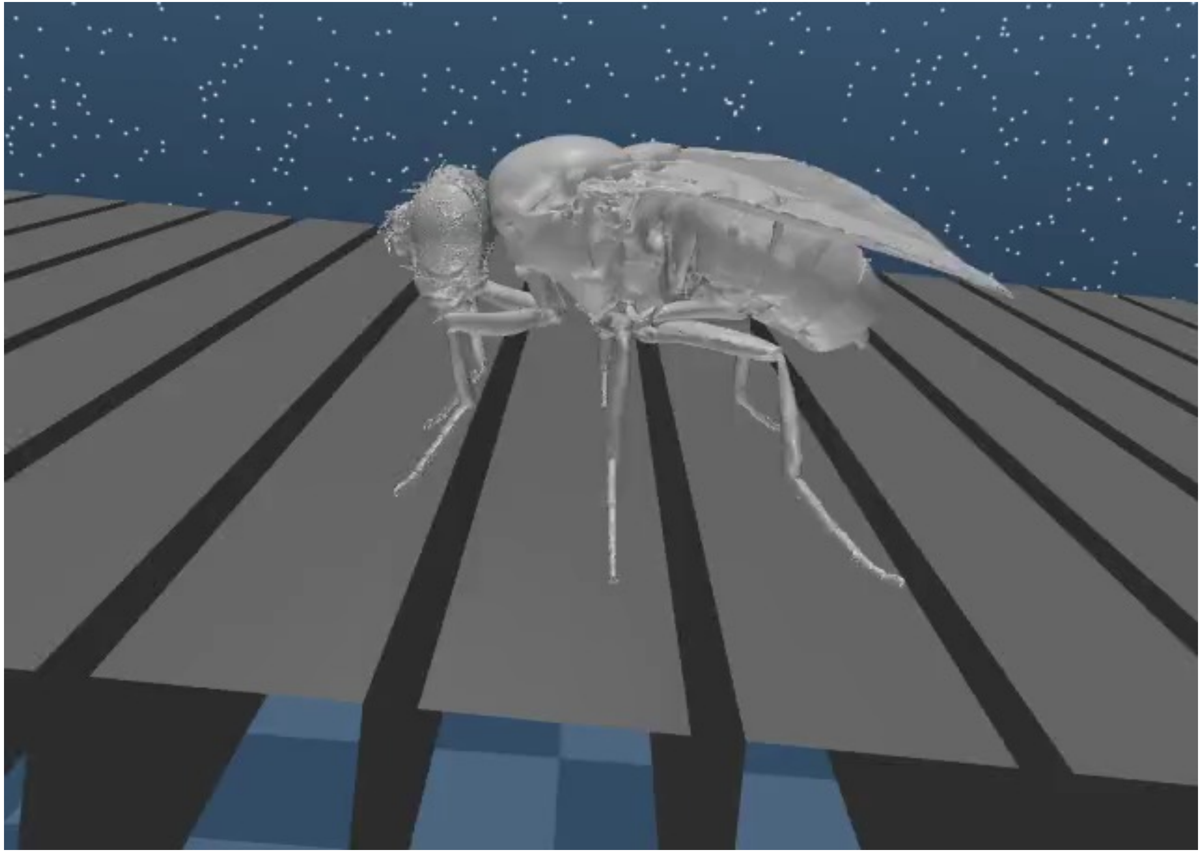


Results



Terrain	Final X	Final Y
Gapped	~16 mm	-

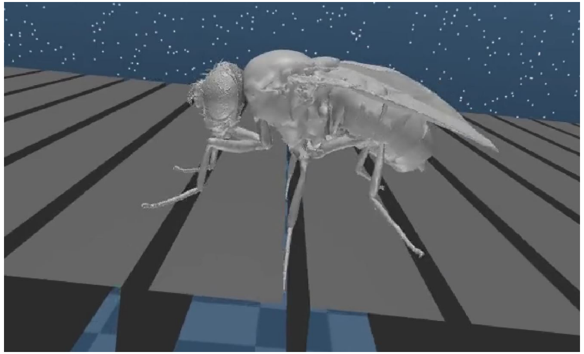
Results



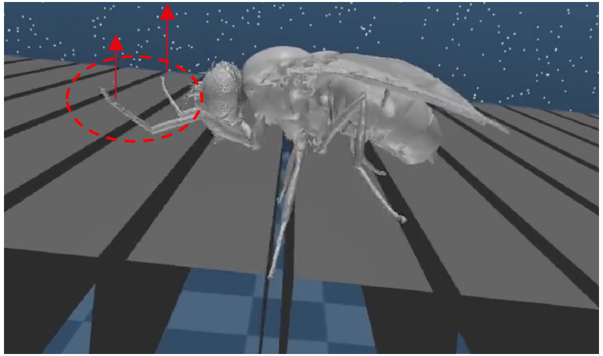
Terrain	Final X	Final Y
Gapped	10 mm	~ -5 mm

Results

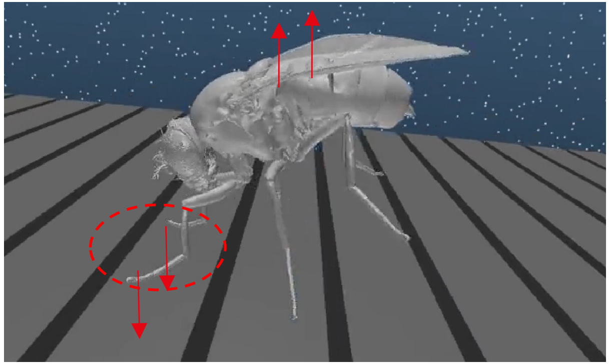
1 Gets Stuck



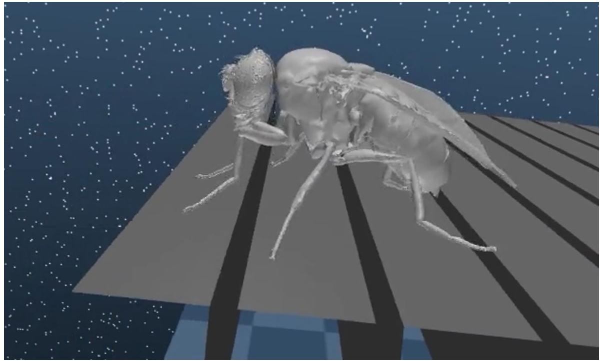
2 Thrusts with Front Legs



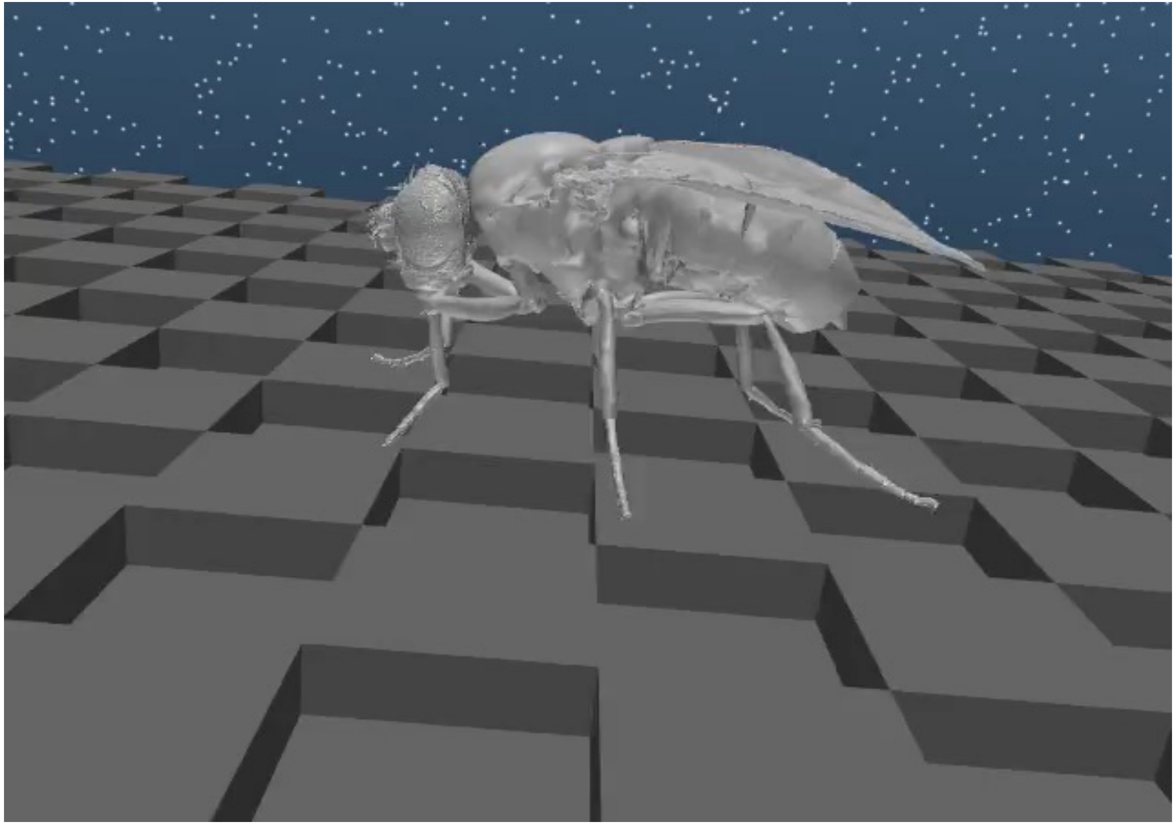
3 Pulls Itself Up



4 Locomotes to the Edge of the World



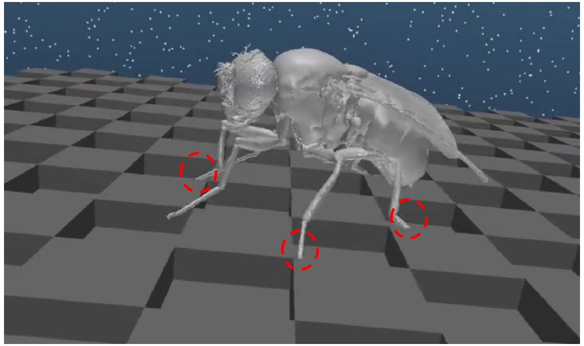
Results



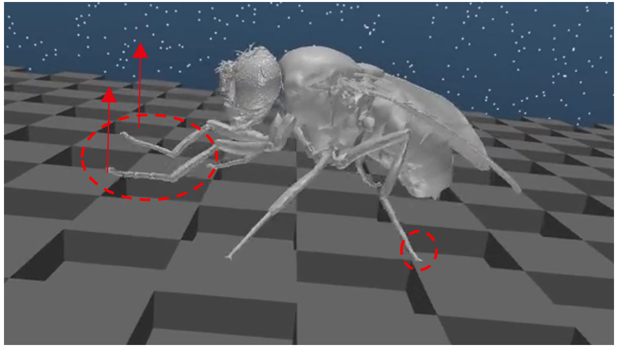
Terrain	Final X	Final Y
Blocks	7 mm	~2 mm

Results

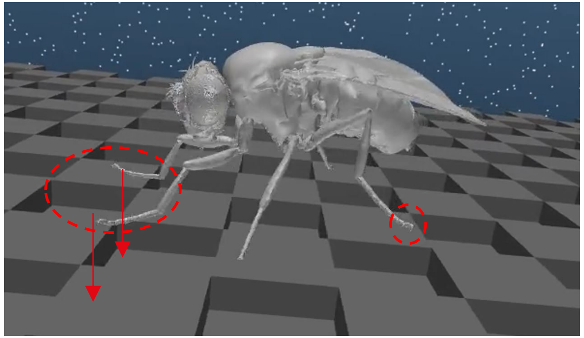
1 Legs in Cavities



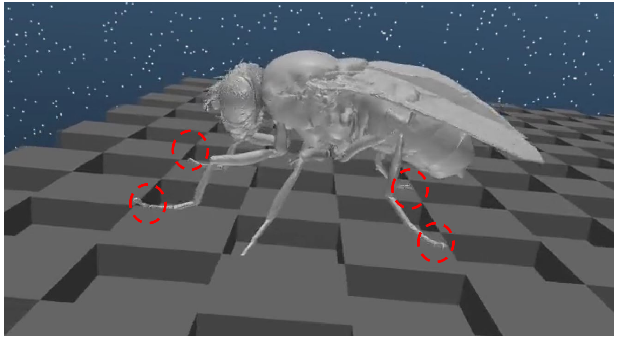
2 Swings Front Legs – Supports with Hind Legs



3 Pulls Itself Up



4 Good Placement



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Results

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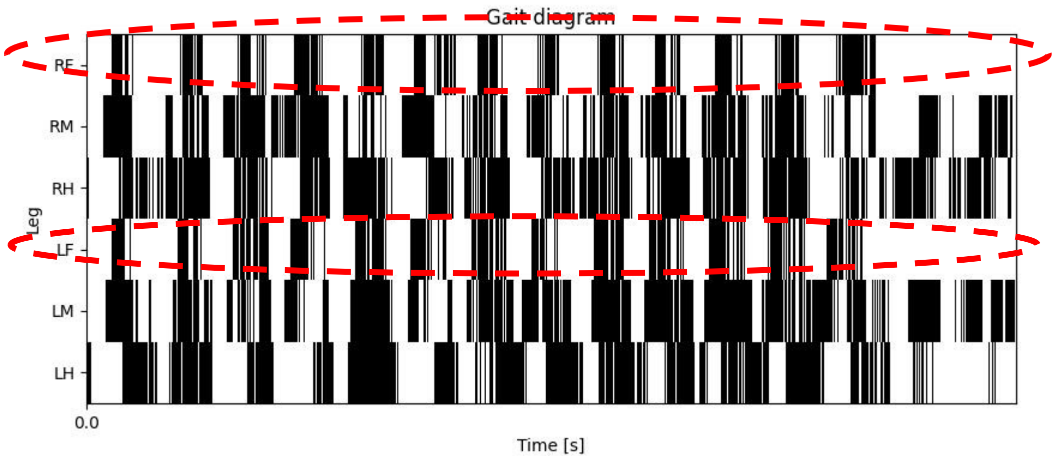
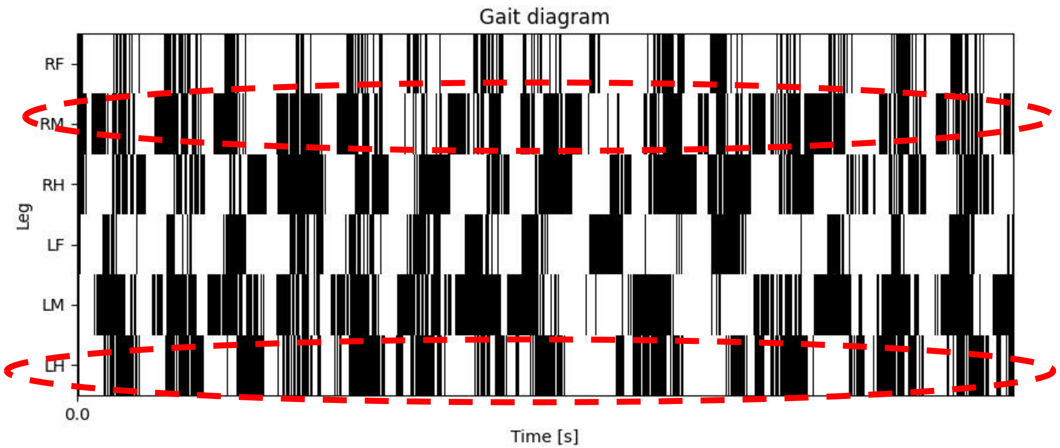
LF & RF exhibit a shorter stance phase:

- ❑ More reactive
- ❑ Contribute less to stabilization
- ❑ Contribute more to locomoting

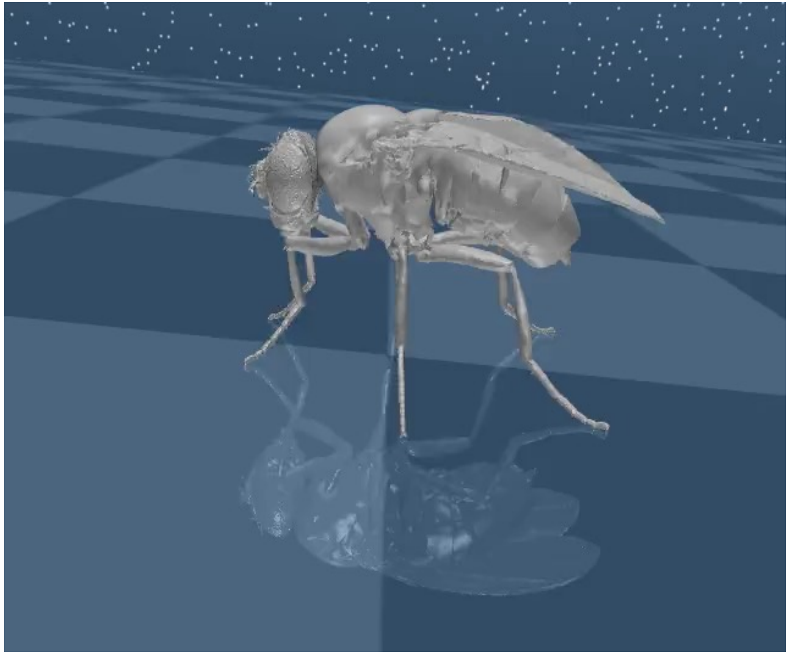


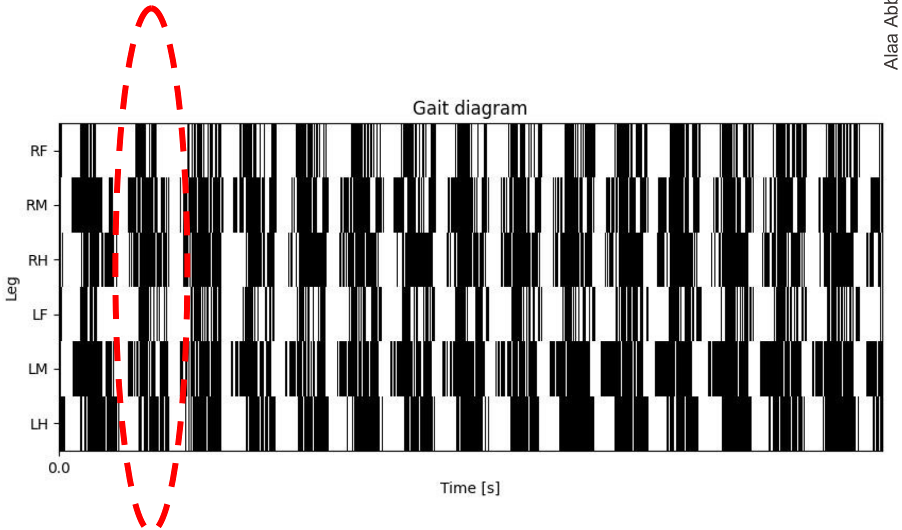
Middle & Hind Legs exhibit a Longer stance phase:

- ❑ Contribute more to stabilization



Results





Terrain	Final X	Final Y
Flat	13 mm	~ 1 mm

Near-Synchronized Gait:

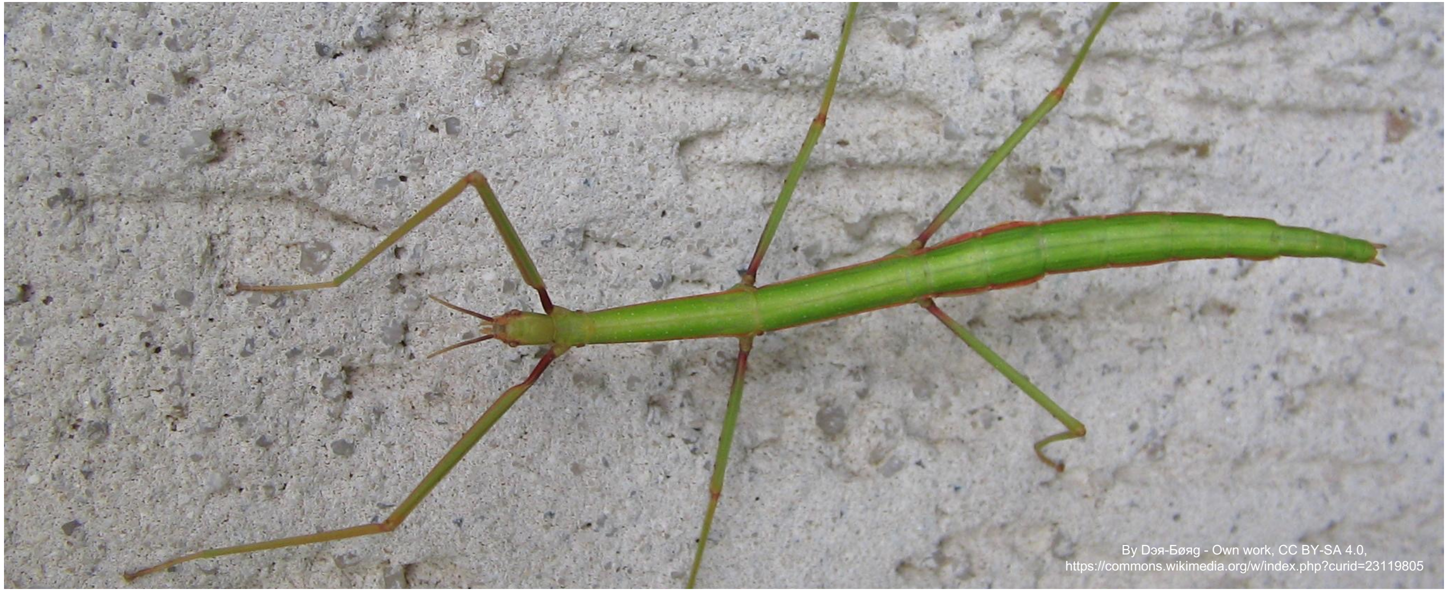
- ❑ Hop-like locomotion

Summary

- Summary – Rule-based controller
- Summary – CPG-based controller
- Summary – RL-based controller

Summary – Rule-based controller

- Rule-based controller shows some unsatisfactory results, but some improvements could be done to increase its robustness.



Summary – CPG-based controller

- Controllers purely based on CPG are very effective on flat terrain, while sensory feedback is needed to improve performance on complex terrain;
- Even with force feedback, GPG-based controllers are not entirely robust on complex terrains.

Summary – RL-based controller

- Pure RL lacks capacity to learn a 42-DOF continuous action space;
- Rule-based RL allows for a narrow action space and a more efficient optimization process, adapting well to all 3 terrains.

Critique

Critique

- We were given a single dataset for the fly step, having more data could have allowed for more variability in the stepping pattern;
- The mechanical model of the fly seemed quite realistic and well realized;
- Integrating vision and olfaction could be valuable to realize a more robust controller.

Critique

- These three controller could be merged:

1. Rule-based as a baseline → simplicity
2. CPG-based for enhancement → regularity
3. Reinforcement learning for fine-tuning → optimization

EPFL

Critique

- We obtained some non-realistic gait patterns with some controllers;
- Combine neurophysiological experiments with controller development to get more biologically relevant gait patterns.

Thanks for your attention!