

# Emergence of low-dimensional motor features during sensory guided flight in flies

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# Outline

- **Background**
- Recent progress
- Future plans

# Cognition vs. Motor Control

Logic  
Decision making  
Planning  
Creativity



IBM Deep Blue



1997

DeepMind AlphaGo



2018

ChatGPT



present

Is cognition a solved problem?

Motor planning  
Grasping  
Proprioception  
Visual control



No match

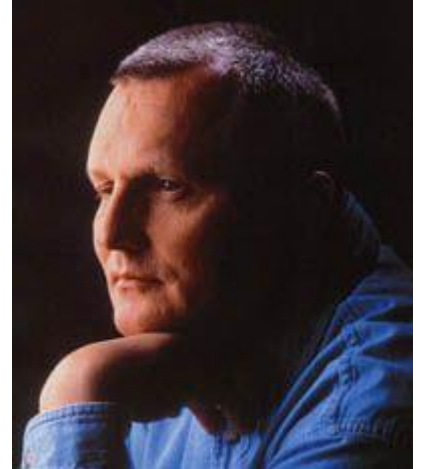


Motor control is  
largely unsolved

# Cognition vs. Motor Control

“Reasoning requires very little computation,  
but **sensorimotor skills require enormous  
computational resources**”

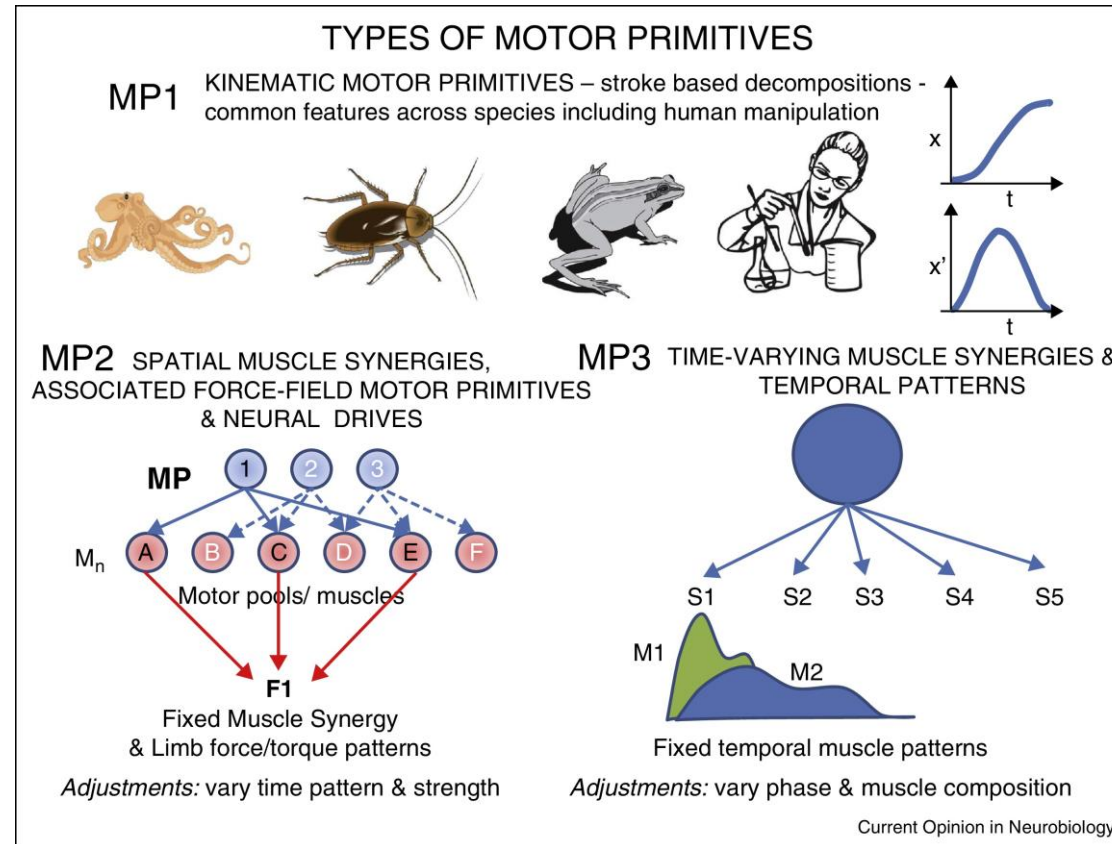
– Hans Moravec

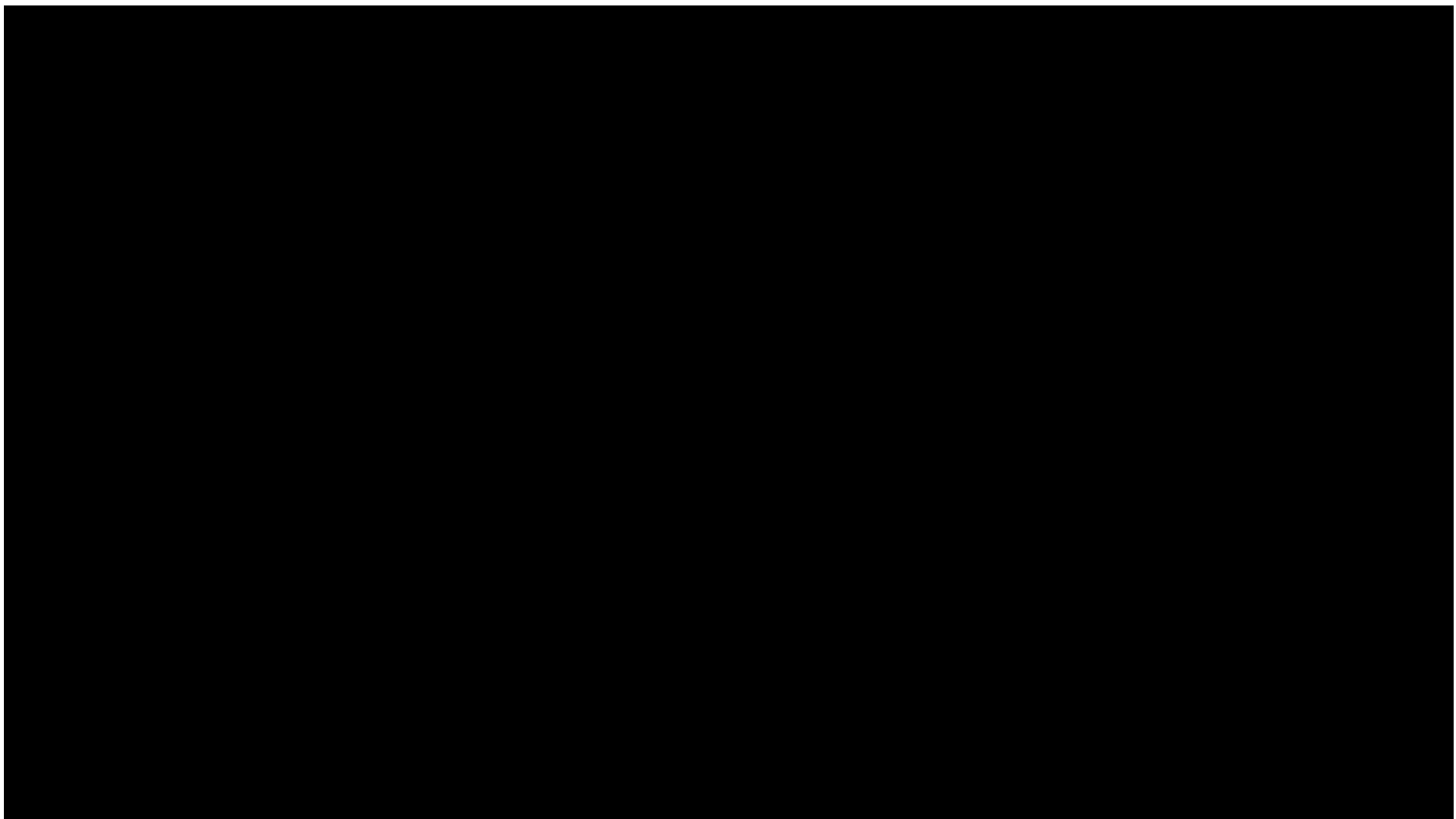


# Why is motor control so hard to solve?

1. Nervous system and body are dynamically coupled
2. Movement is closed-loop
3. Movement is flexible and adaptable
4. Movement is constrained by musculoskeletal system
5. Movement is constrained by neural conduction delays
6. Movement is constrained by physics (Newton's laws)
7. Movement is driven by nested (hierarchical) feedback loops

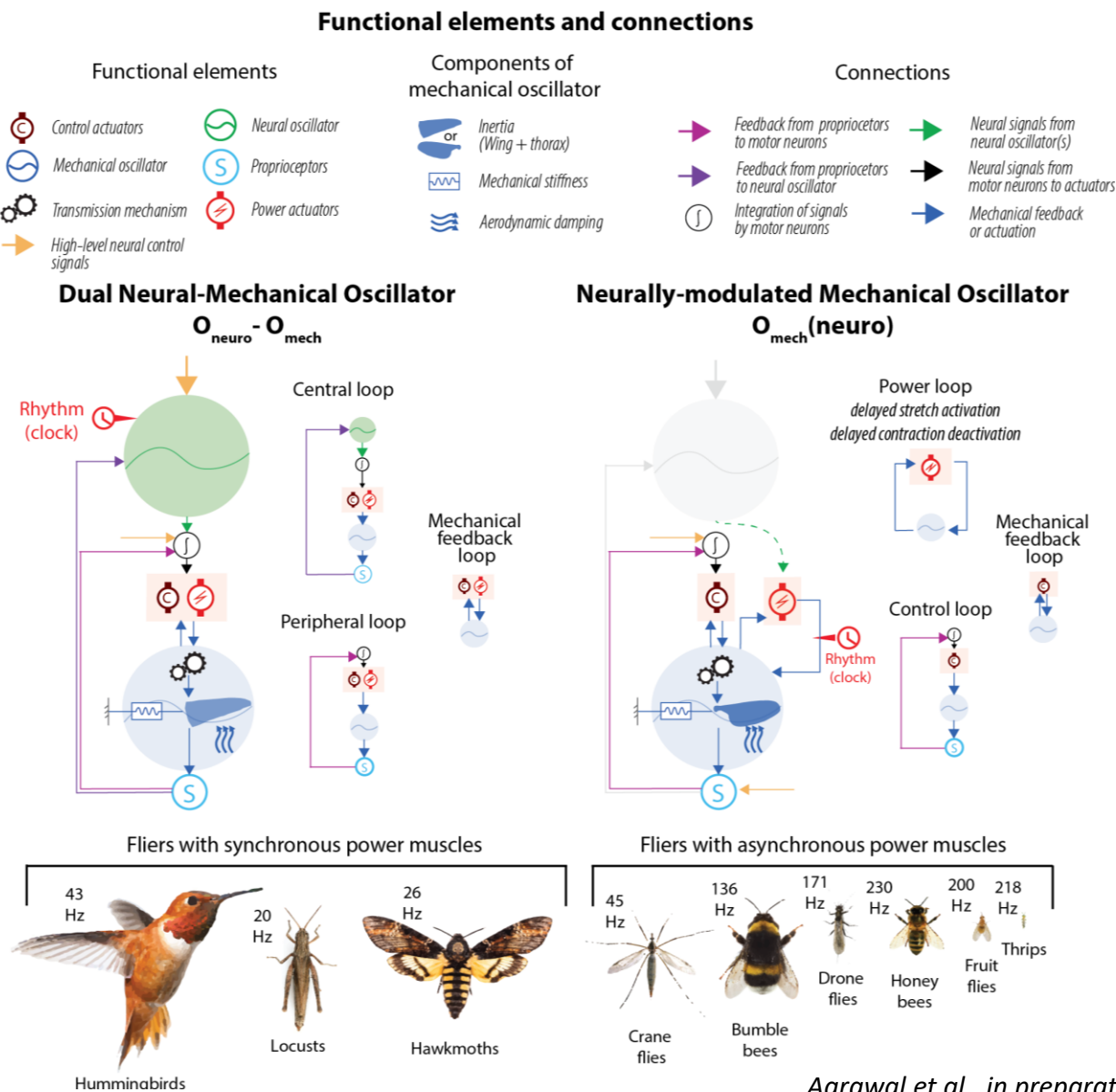
# Motor primitives as a building block of motor control





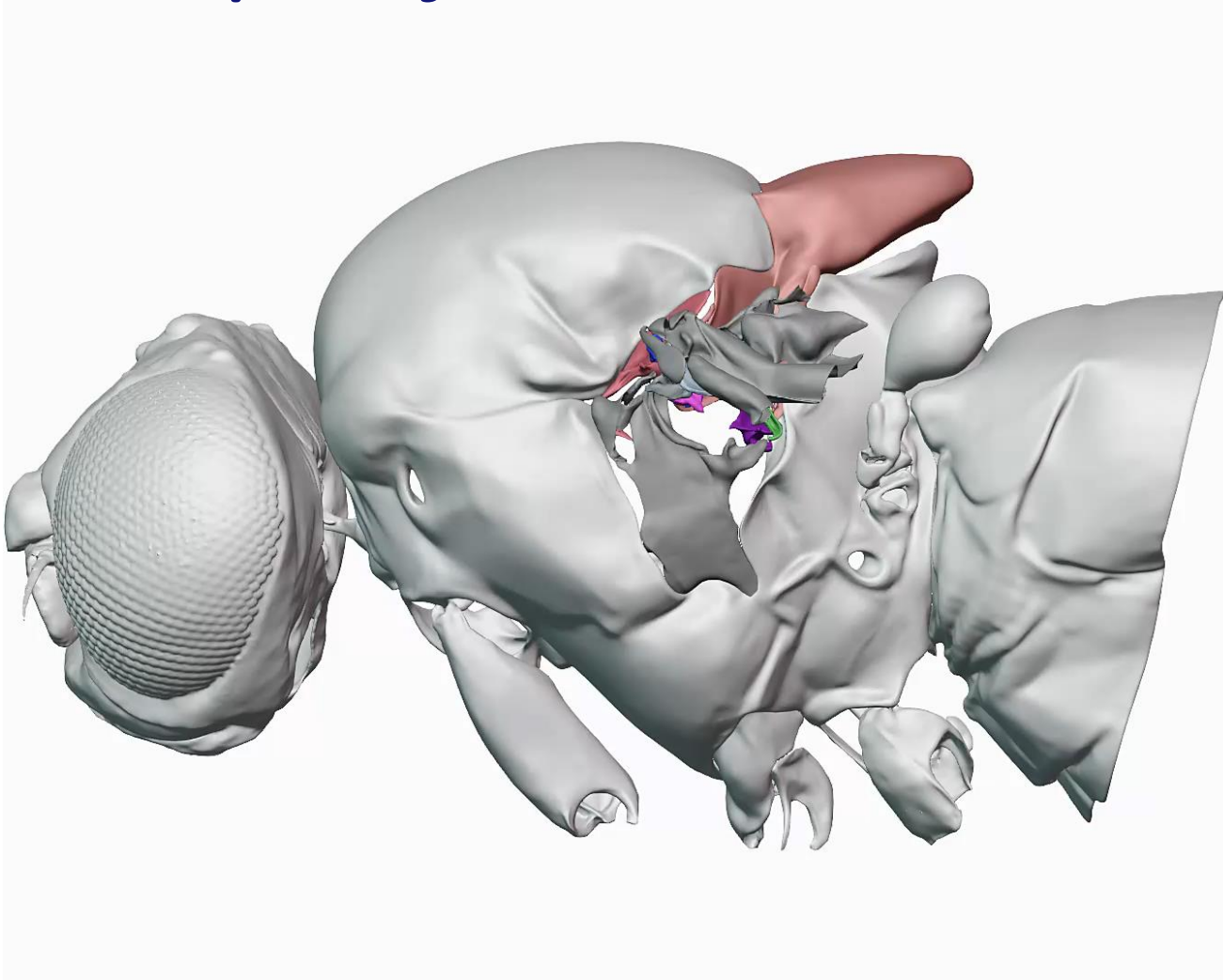
# Fly flight machinery remains poorly understood

Achieved by mechanical oscillator with rhythm and motion emerging from neuromechanics





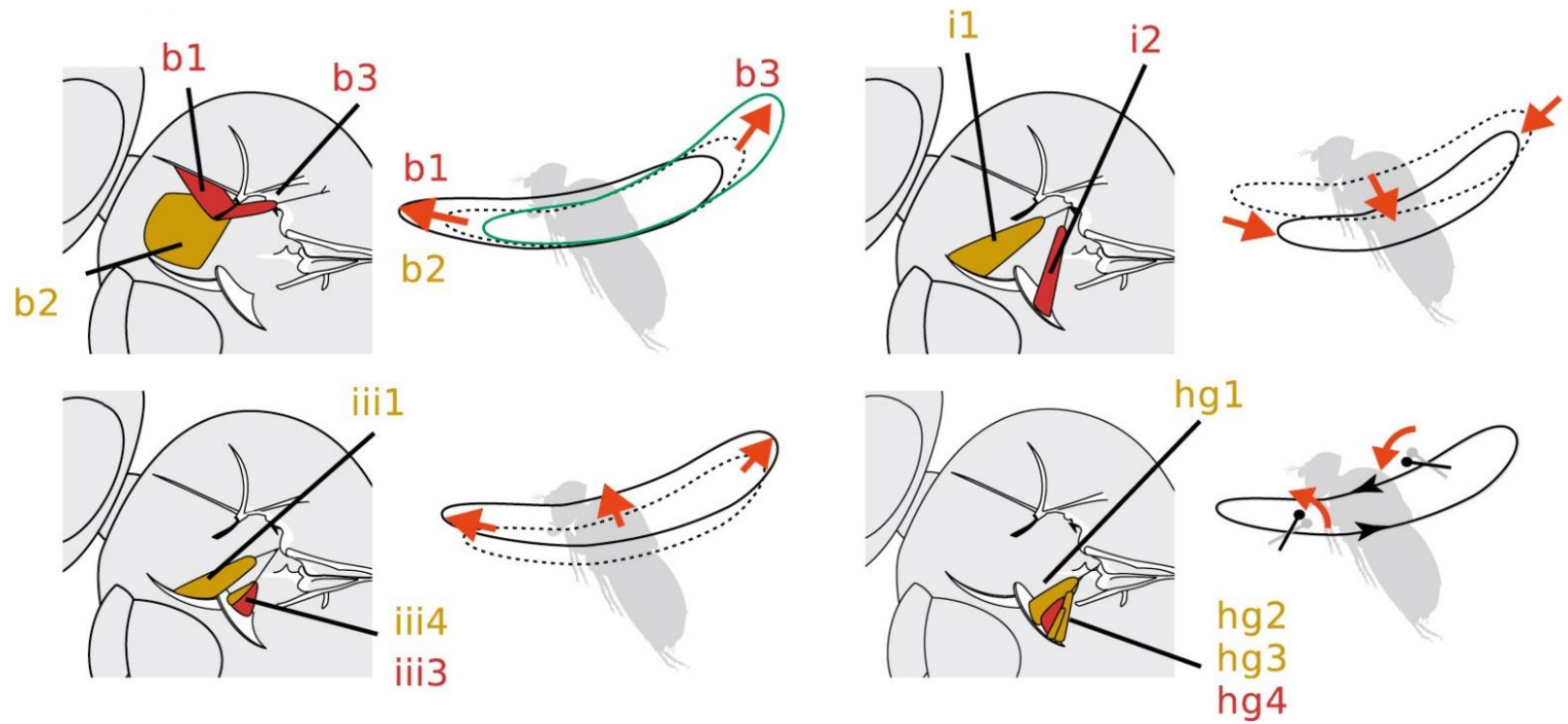
# The wing joint of insects is one of the most complex joint in Nature



**How is the wing joint controlled to initiate complex flight maneuvers?**

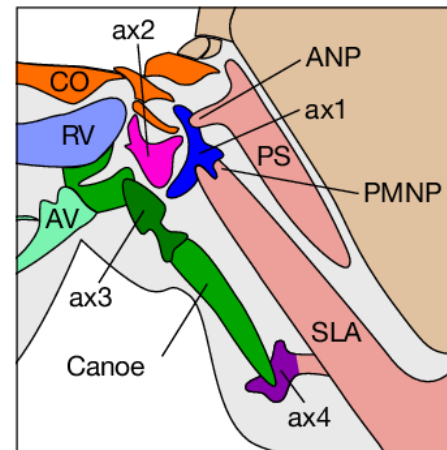
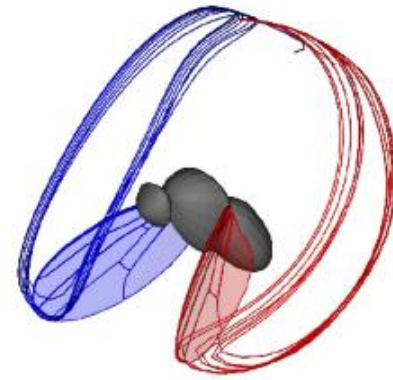
# Steering muscles finely shape wing motion

- 12 synchronous steering muscles attach to the base of the wing
- Grouped according to which sclerite they terminate
  - Basalars
    - b1, b2, b3
  - 1<sup>st</sup> axillary
    - i1, i2
  - 2<sup>nd</sup> axillary
    - iii1, iii3, iii4
  - 3<sup>rd</sup> axillary
    - hg1, hg2, hg3, hg4

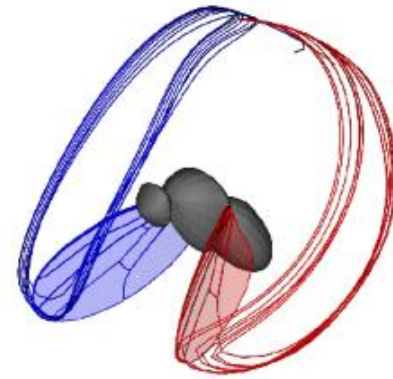


- Tonic (smooth)
- Phasic (saccadic)

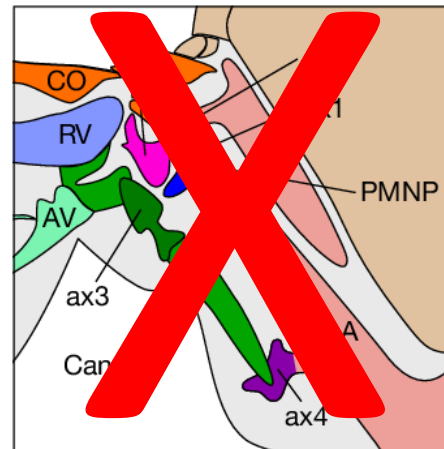
# Combining bottom-up and top-down motor control



# Combining bottom-up and top-down motor control

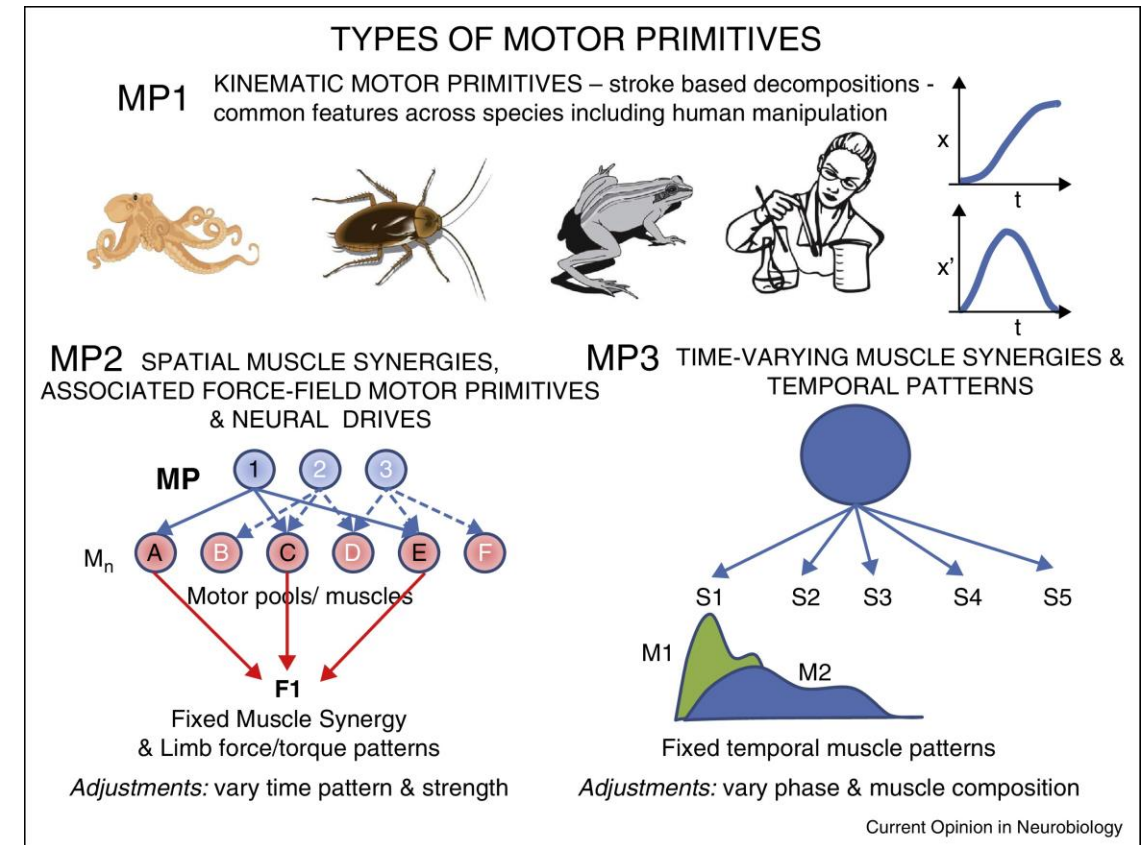


Wing joint torque control



# Wing motor primitives (WMPs) as a building block of complex flight control

- Wing trajectories generated by a finite set of muscles constrained by joint mechanics
- We can define elementary building blocks of limb movement: *motor primitives*



# Hypothesis

**Synergies of steering muscles map to specific WPMs in wing joint torque space, and when combined can synthesize complex wing trajectories**



# Wing motor primitives as a building block of complex flight control

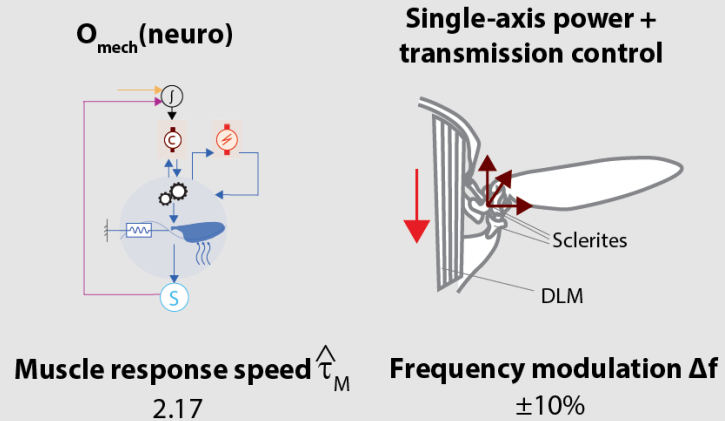
→ Power actuation

→ Control actuation

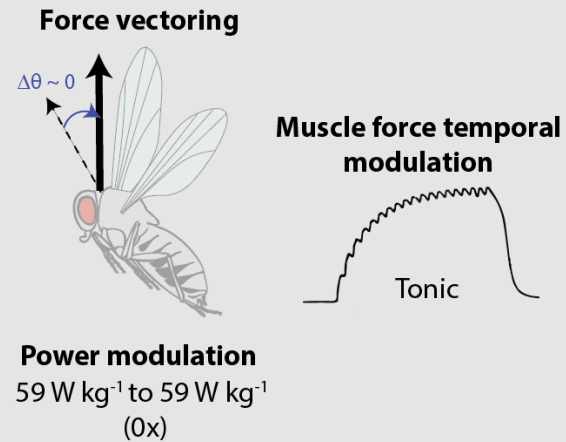
→ Total force

--> Body-axis

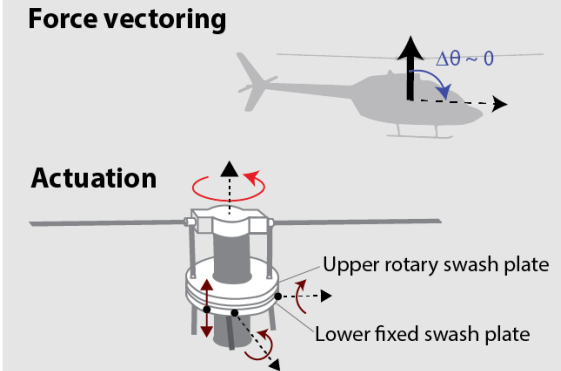
## i) Traits of wing neuromechanical system



## ii) Contributors to maneuverability

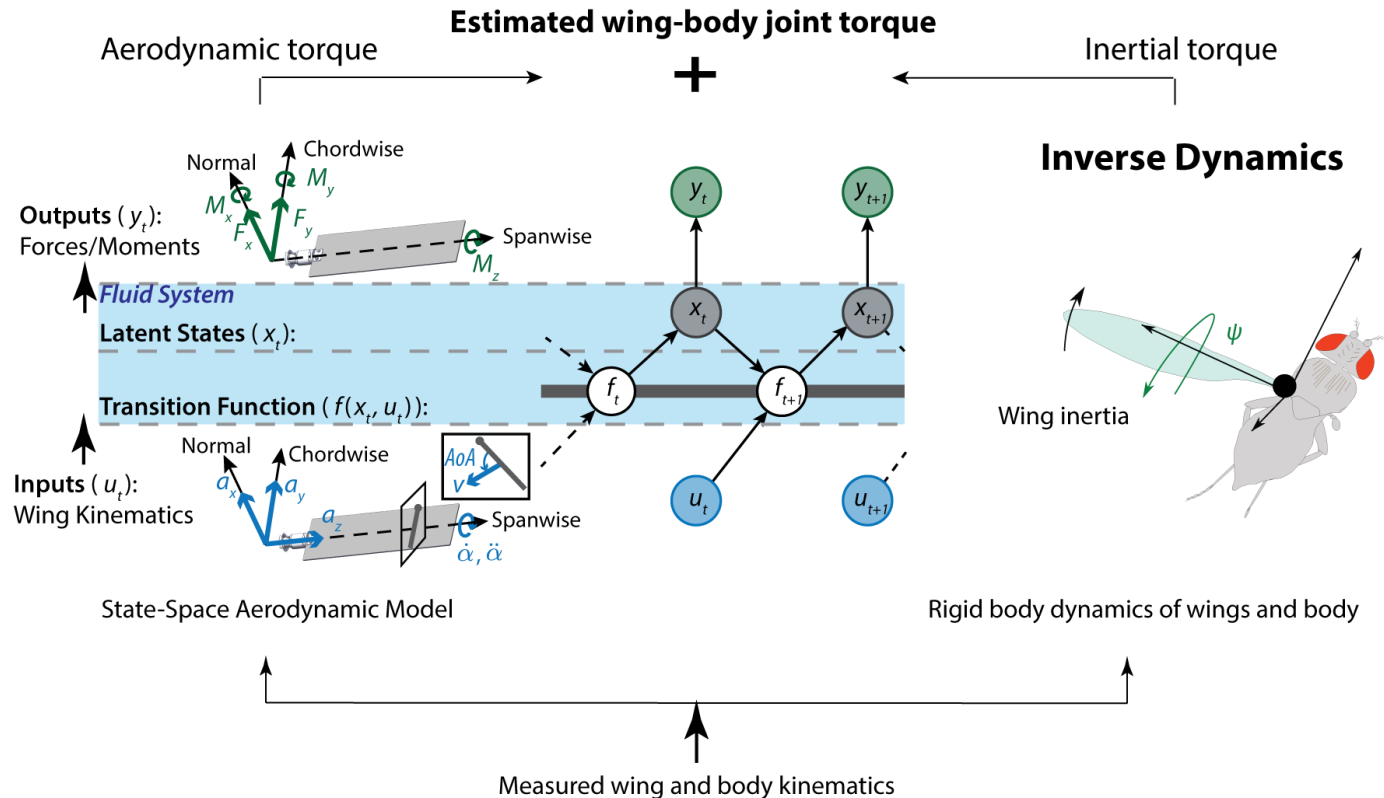


## iii) Helicopter analogy



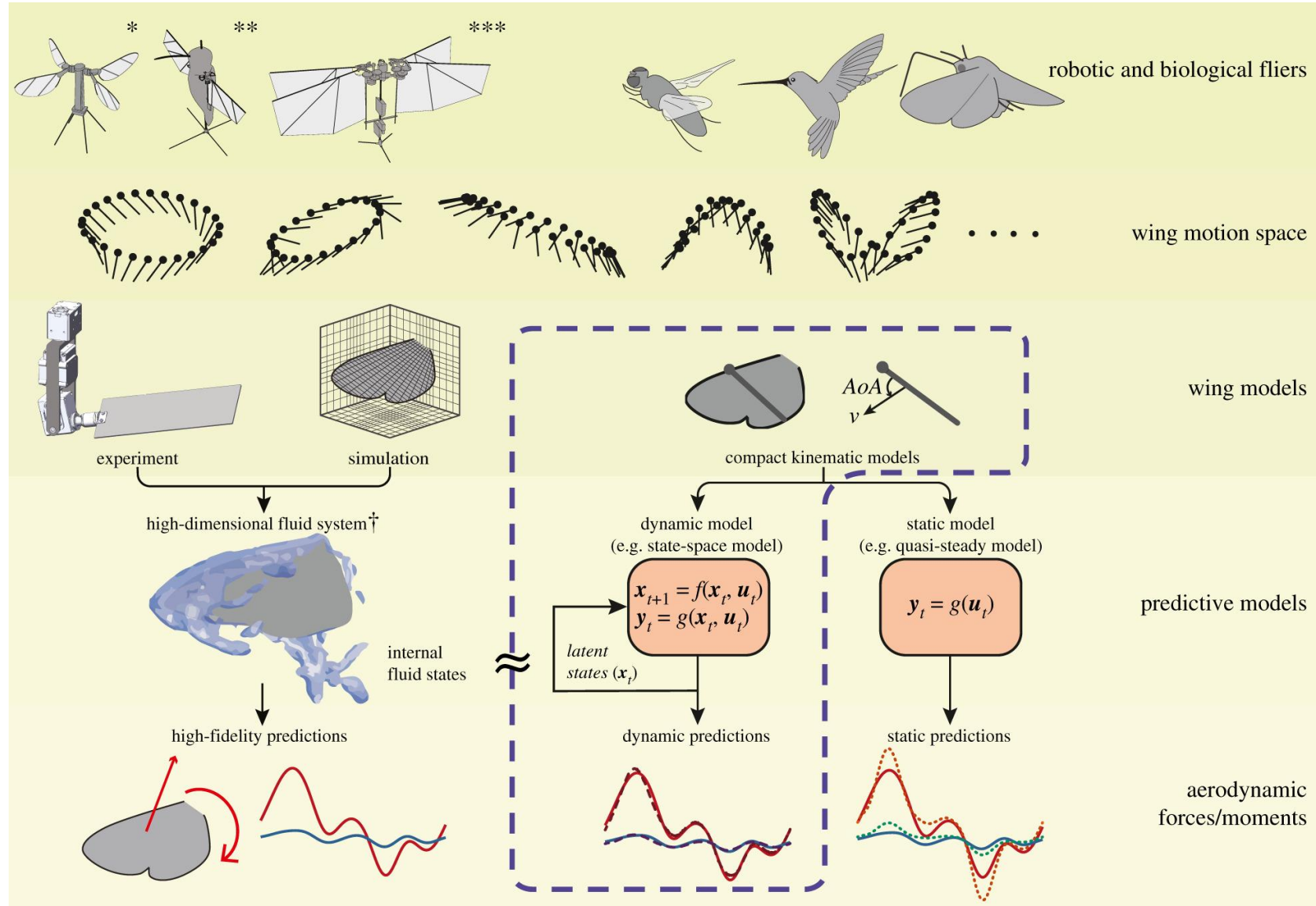
# WMPs defined in *wing joint torque space*

- Apply dimensionality reduction to wing joint torque, which is more fundamental and links closely to the wing muscle torque and passive mechanics of the joint
- We can now reliably predict aerodynamics forces/torques, including unsteady and nonlinear fluid effects

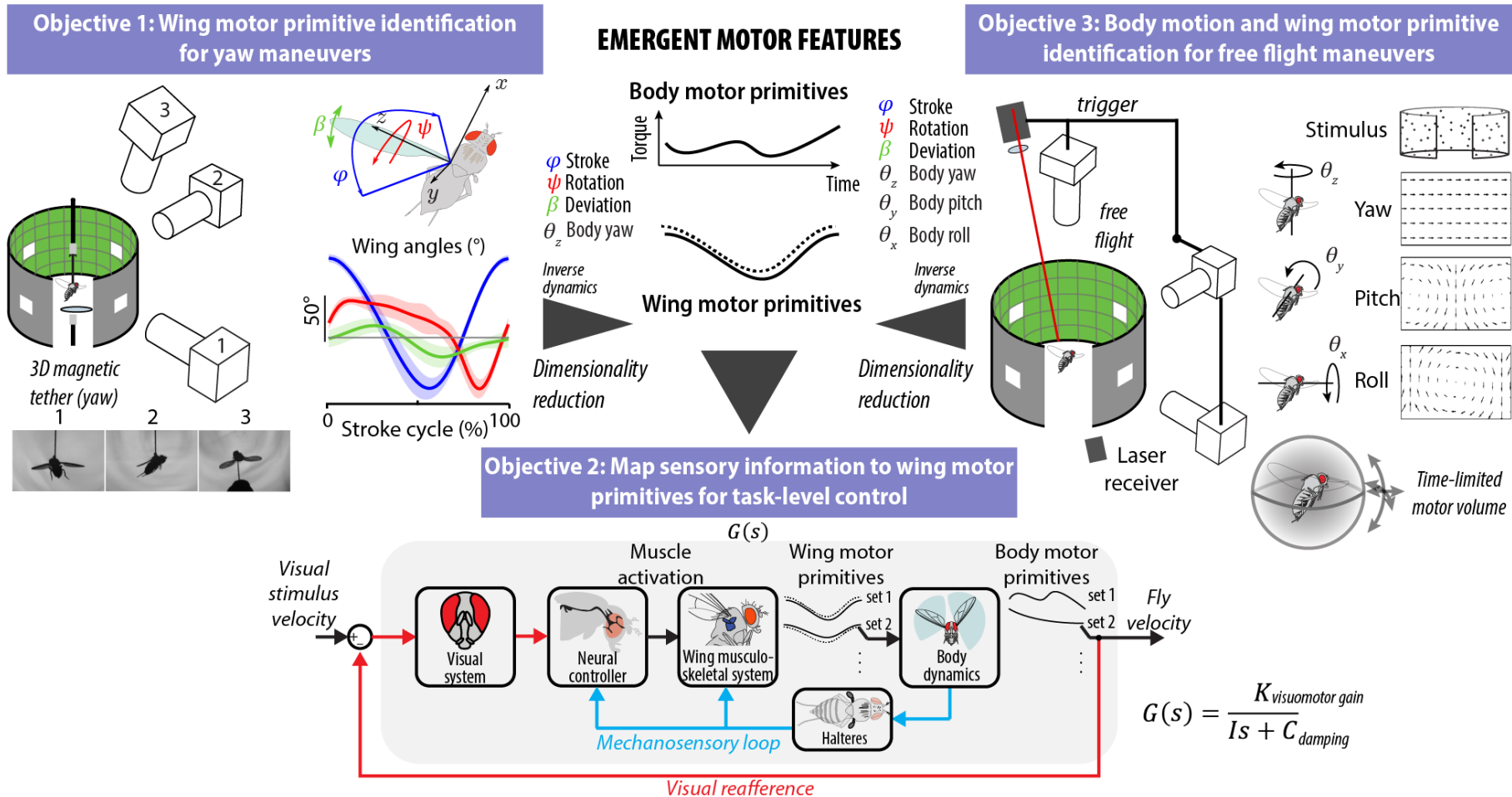




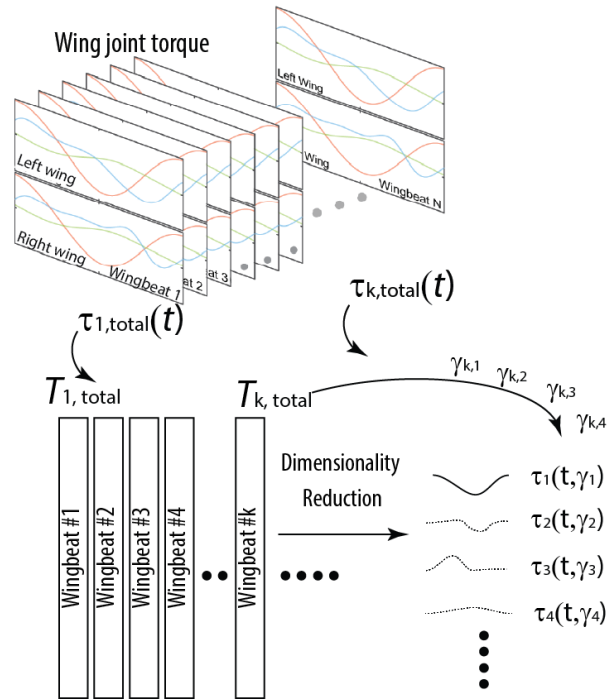
# State space aerodynamic model surpasses quasi-steady model



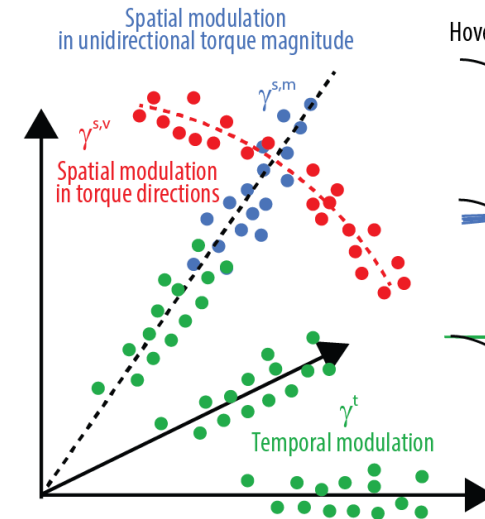
# Wing Motor Primitives (WMPs) as a building block of complex flight control



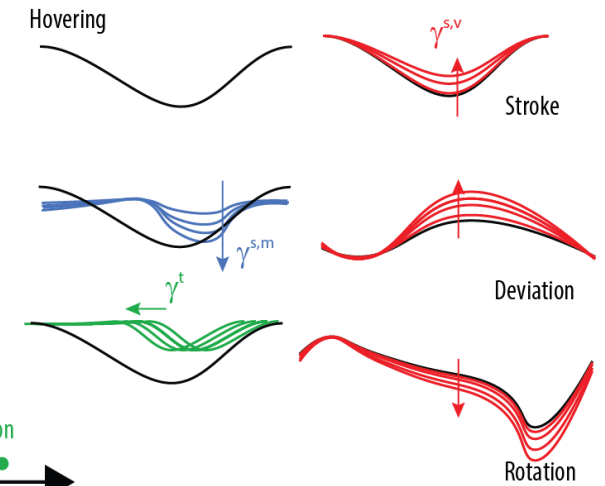
# Dimensionality reduction to extract WMPs



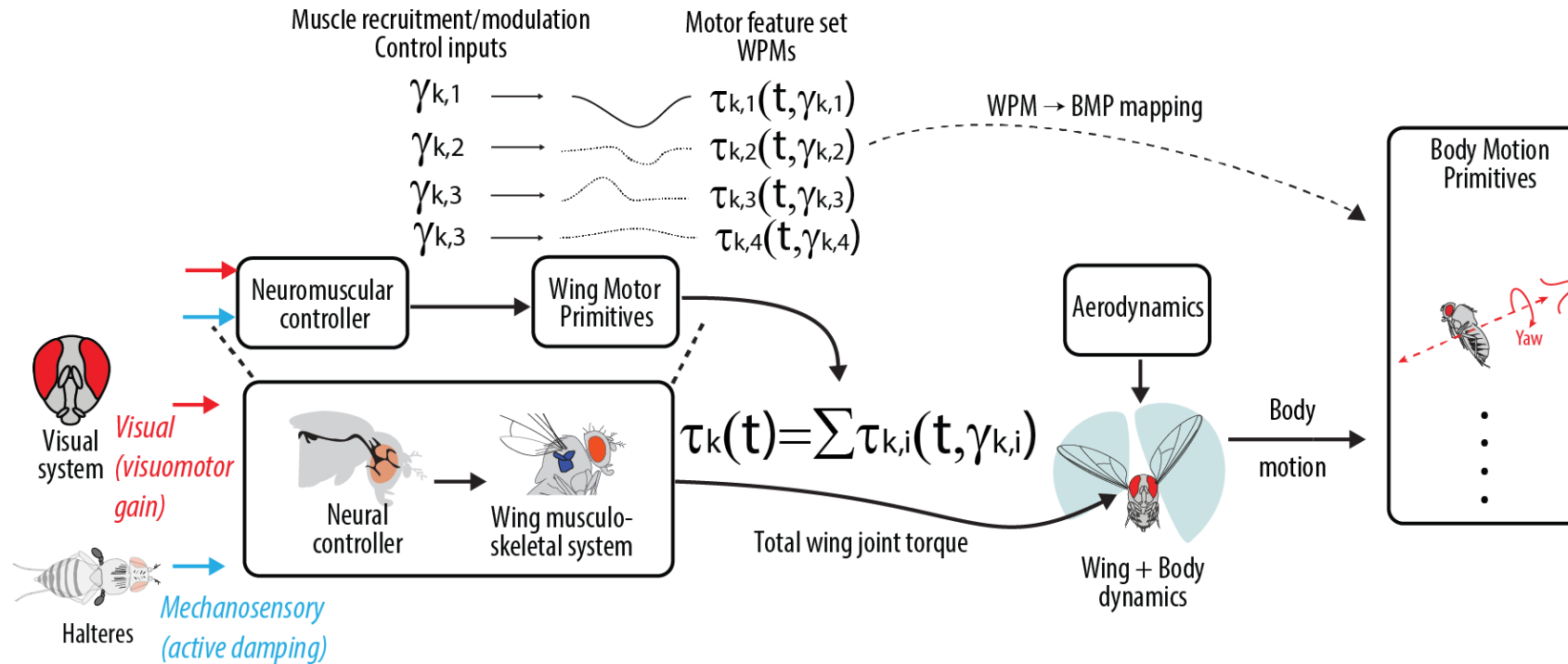
Conceptualized  $\mathbf{T}_{\text{total}}$  hyperspace and three hypothesized modulation of WMPs



Conceptualized WMPs or  $\tau_i(t)$  and three hypothesized modulation of WMPs



# Mapping task-level control to WMPs and BMPs



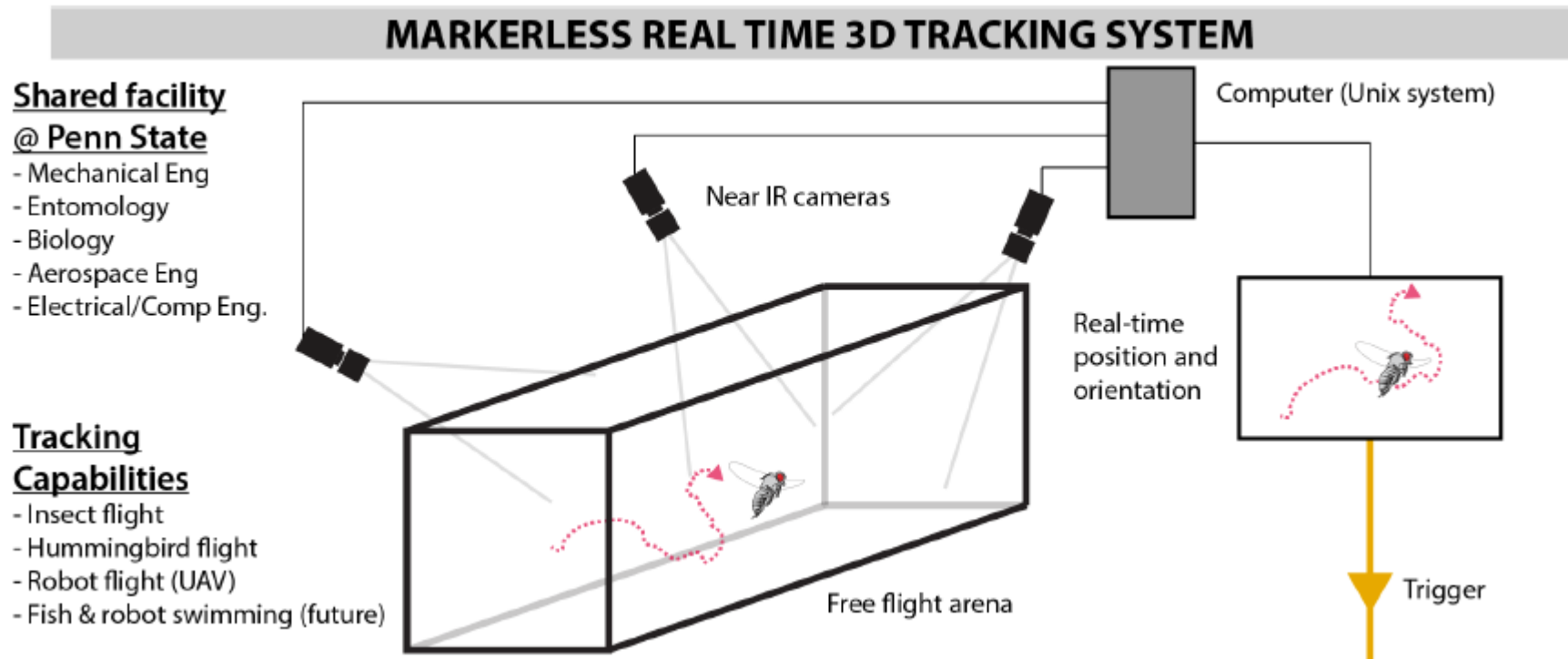
# Expected Outcomes

- By taking top-down approach, it will reveal insights into the logic of the wing machinery
- Extend lexicographic description of flight control to sensory guided flight with natural physics
- Comprehensive library of motor features for closed-loop flight
- Mathematical framework will be applicable to study insect and bird flight
- Approach can inspire robotic fliers with rich flight repertoires and enhanced flight autonomy

# Outline

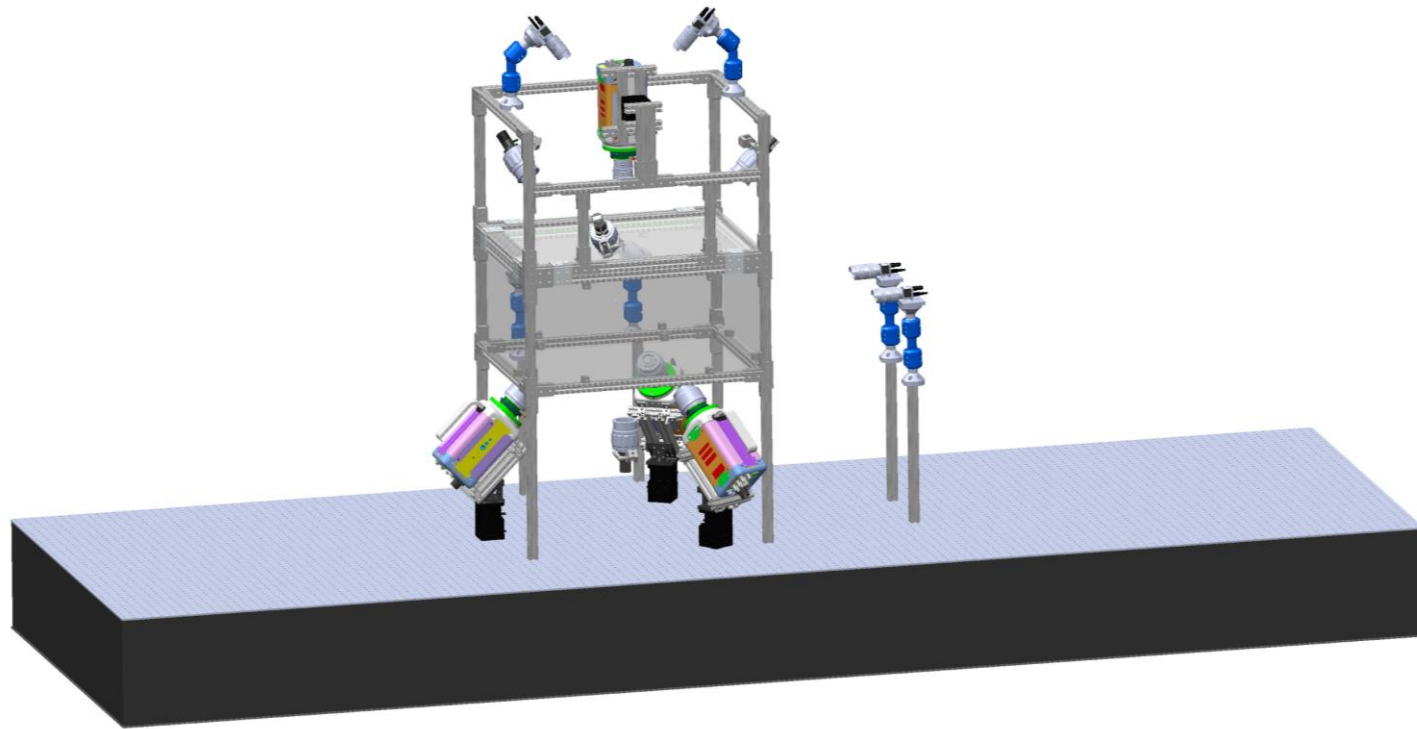
- Background
- **Recent progress**
- Future plans

# Developing a free flight arena



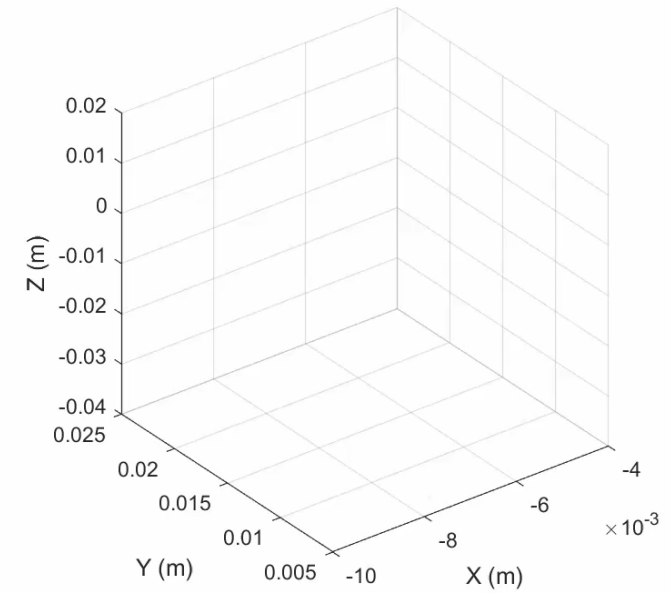
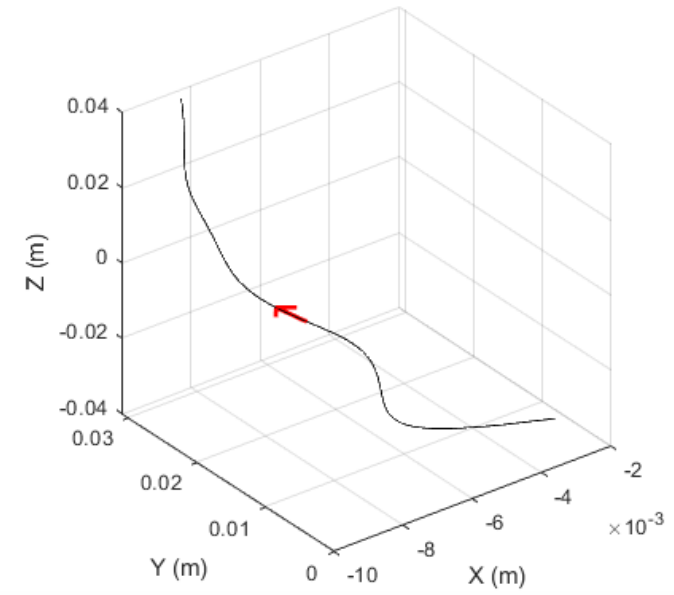
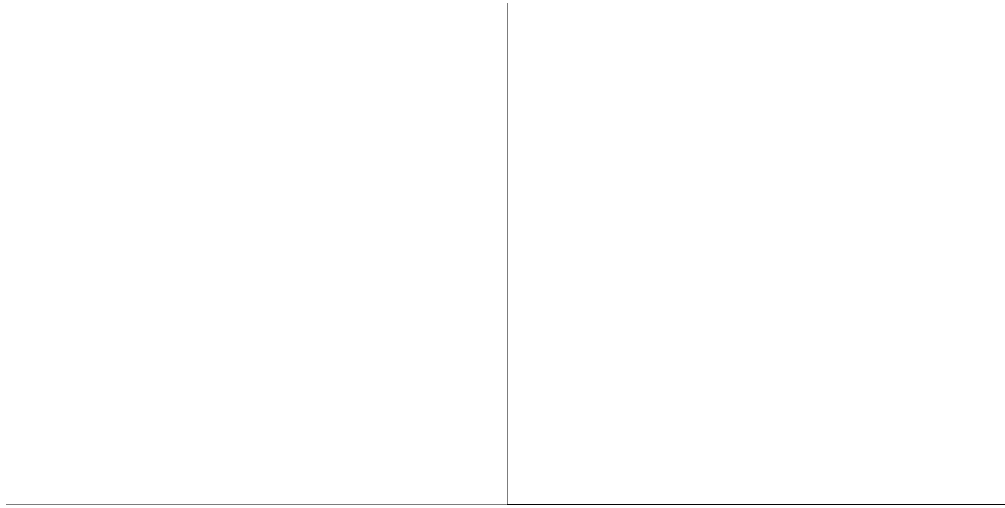


# Progress on assembly

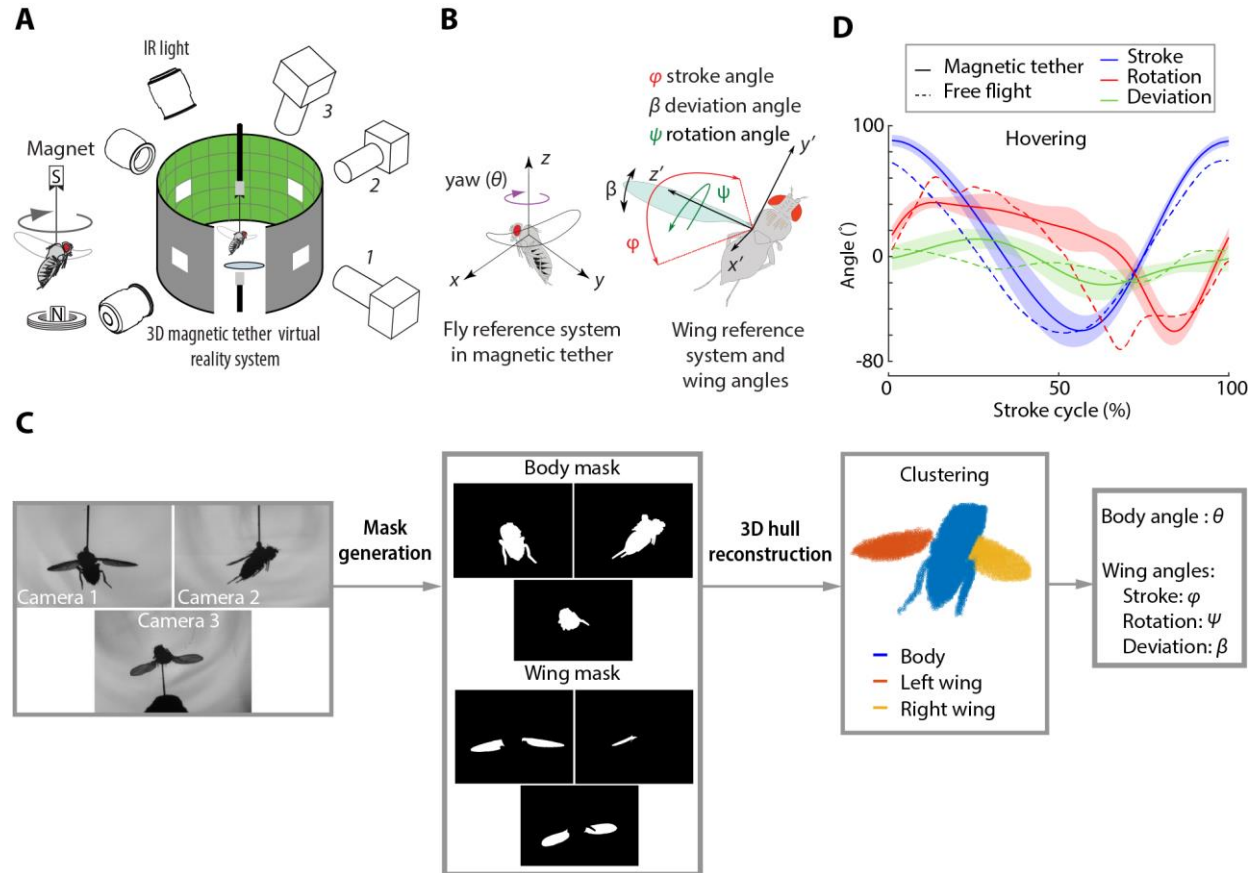




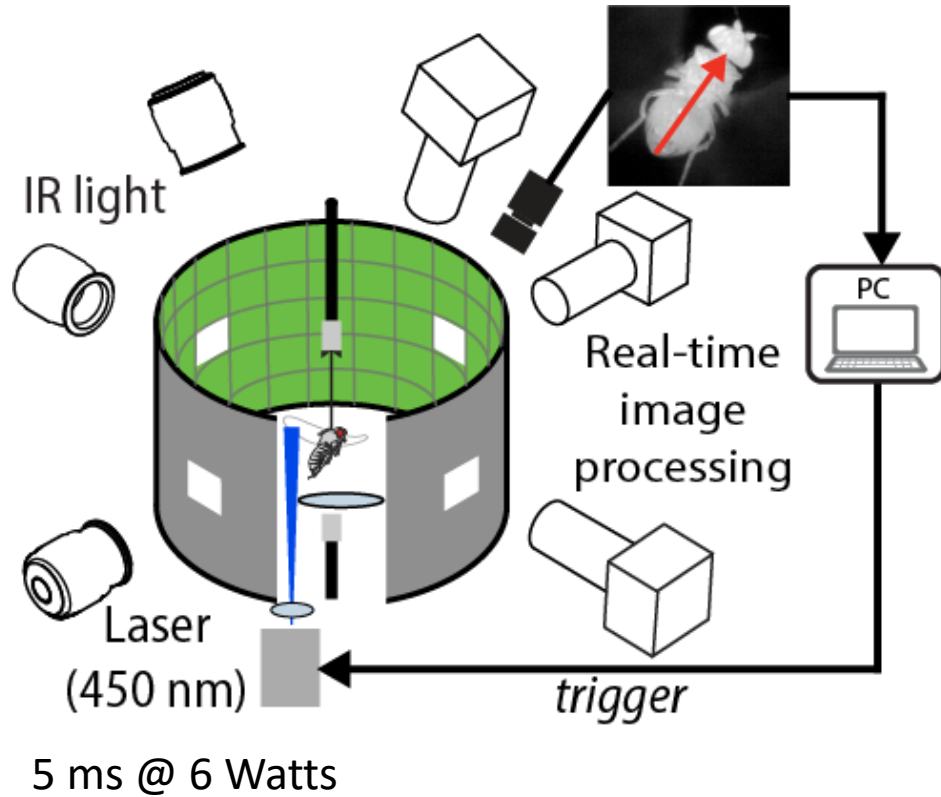
# 3D flight trajectory



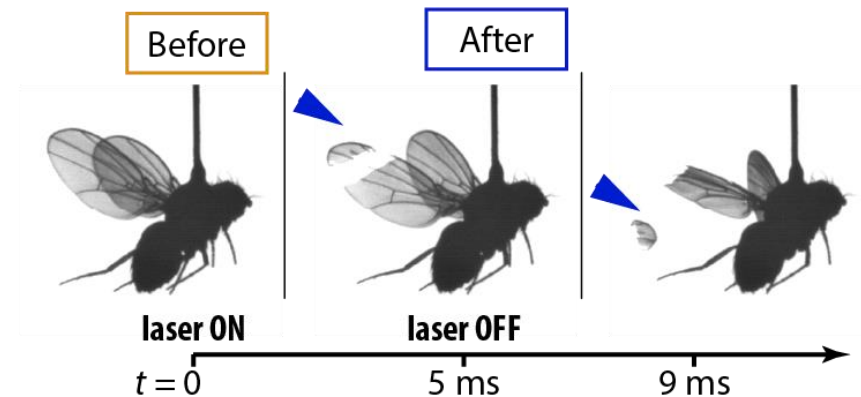
# Automated 3D wing reconstruction



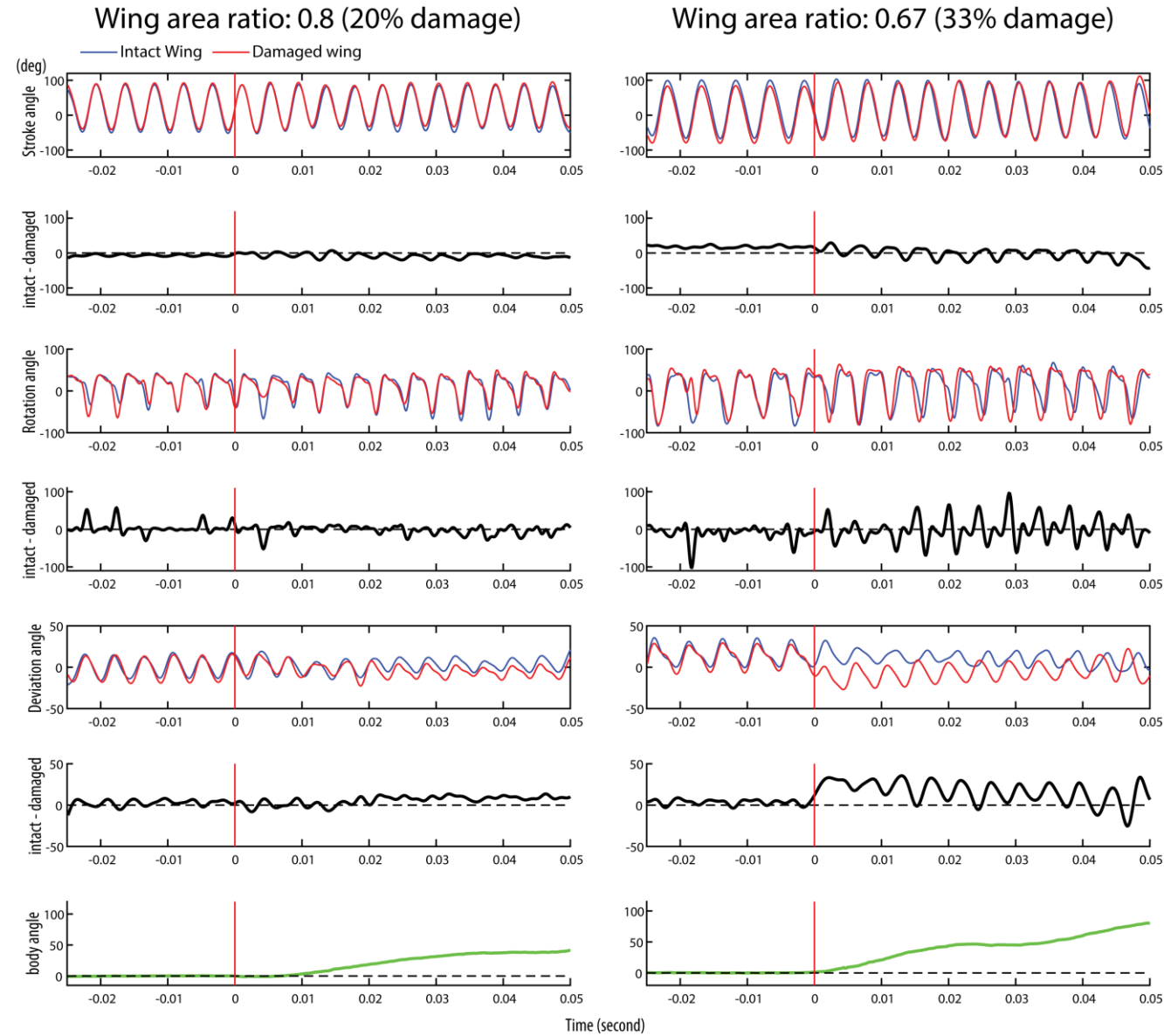
# Studying *real-time* adaptation to wing damage



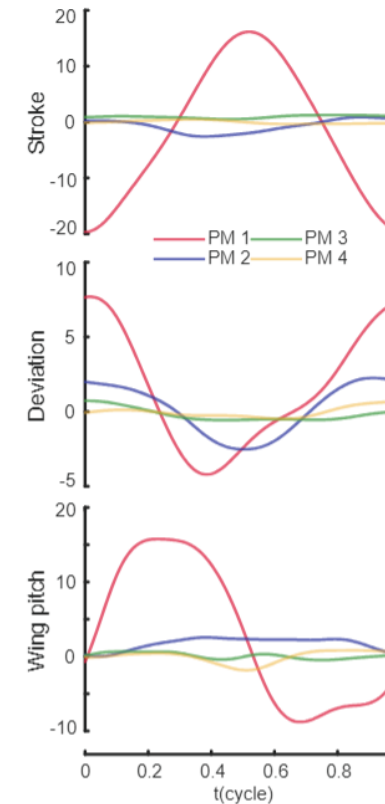
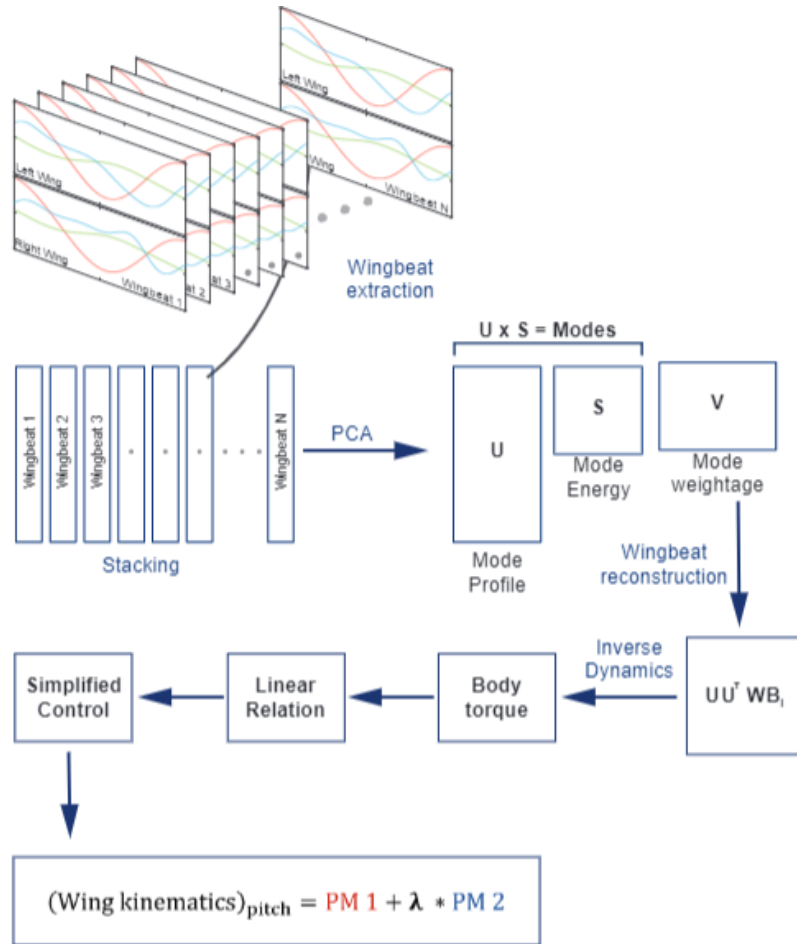
Slowed 260X



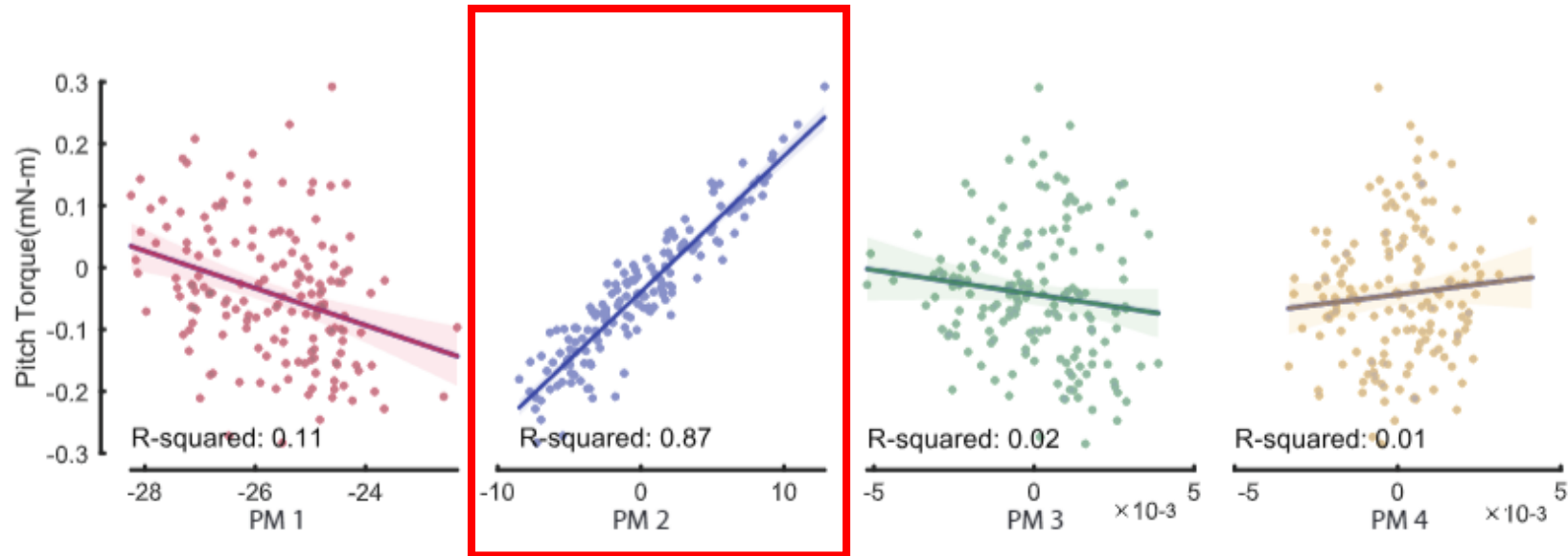
# 3D wing kinematics instantaneously change after damage and are sensitive to amount of damage



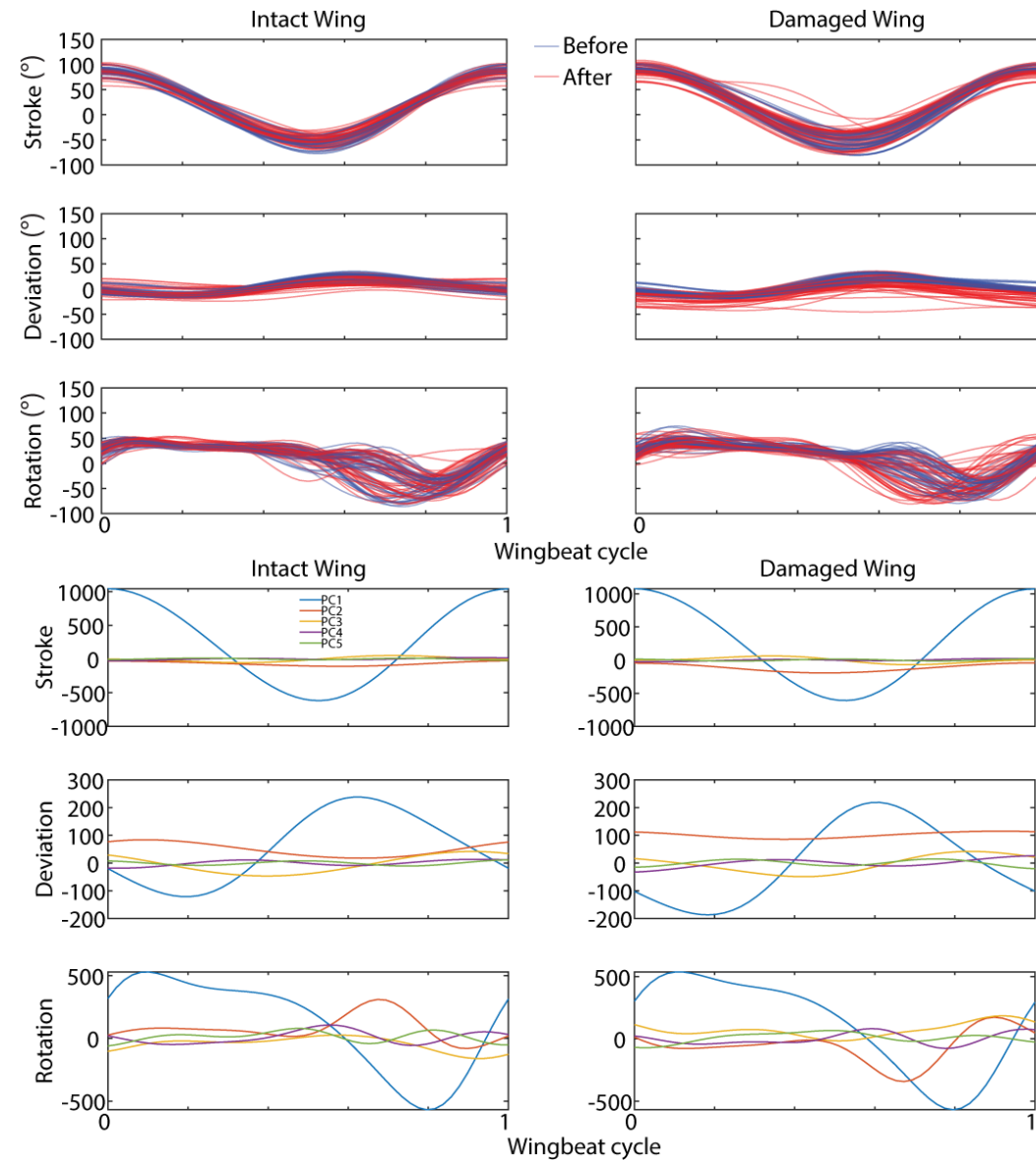
# PCA to decompose complex wing motion into Principal Modes (PM)



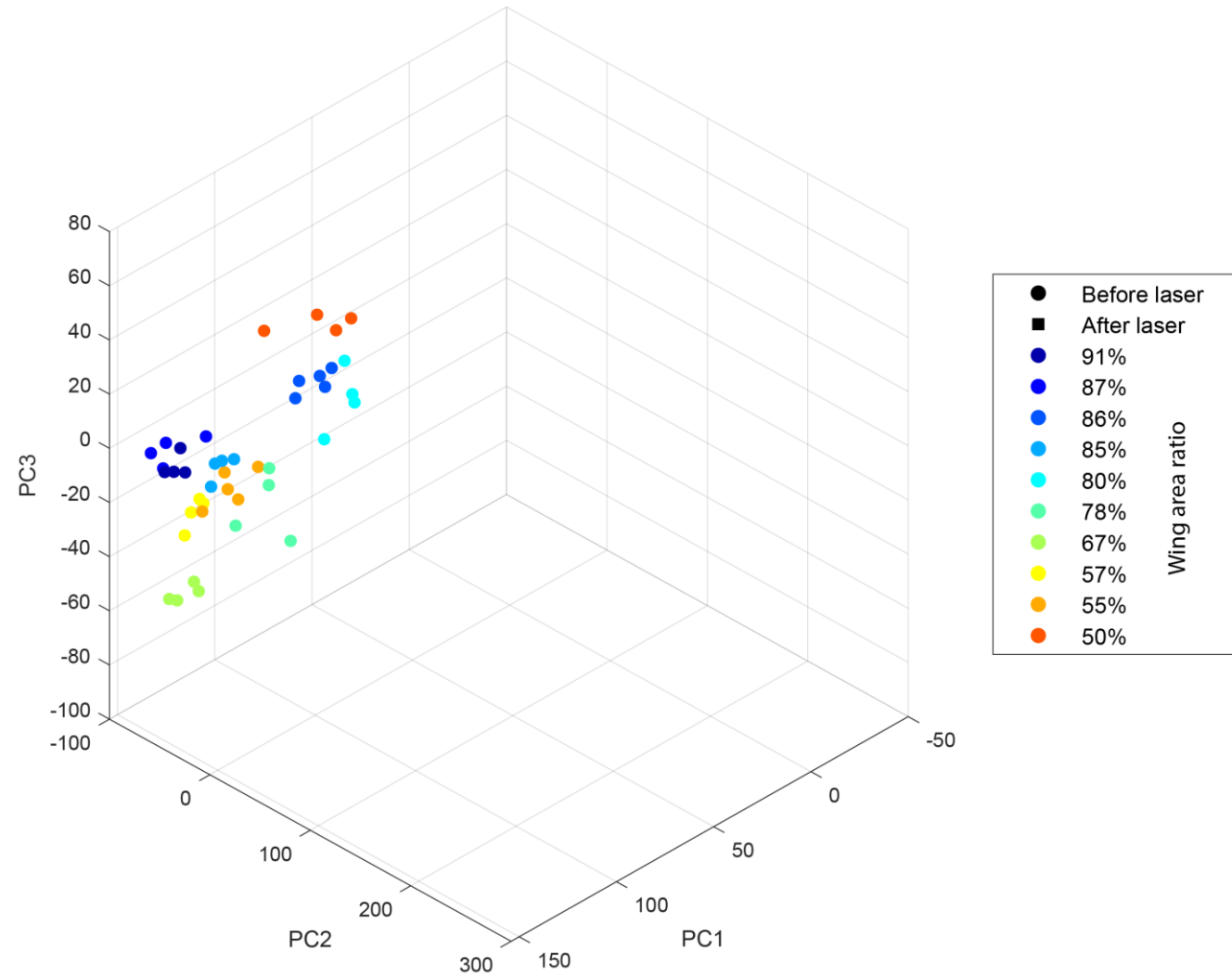
# Principal Mode correlates linearly with pitch torque



# PCA to reveal motor variability after damage

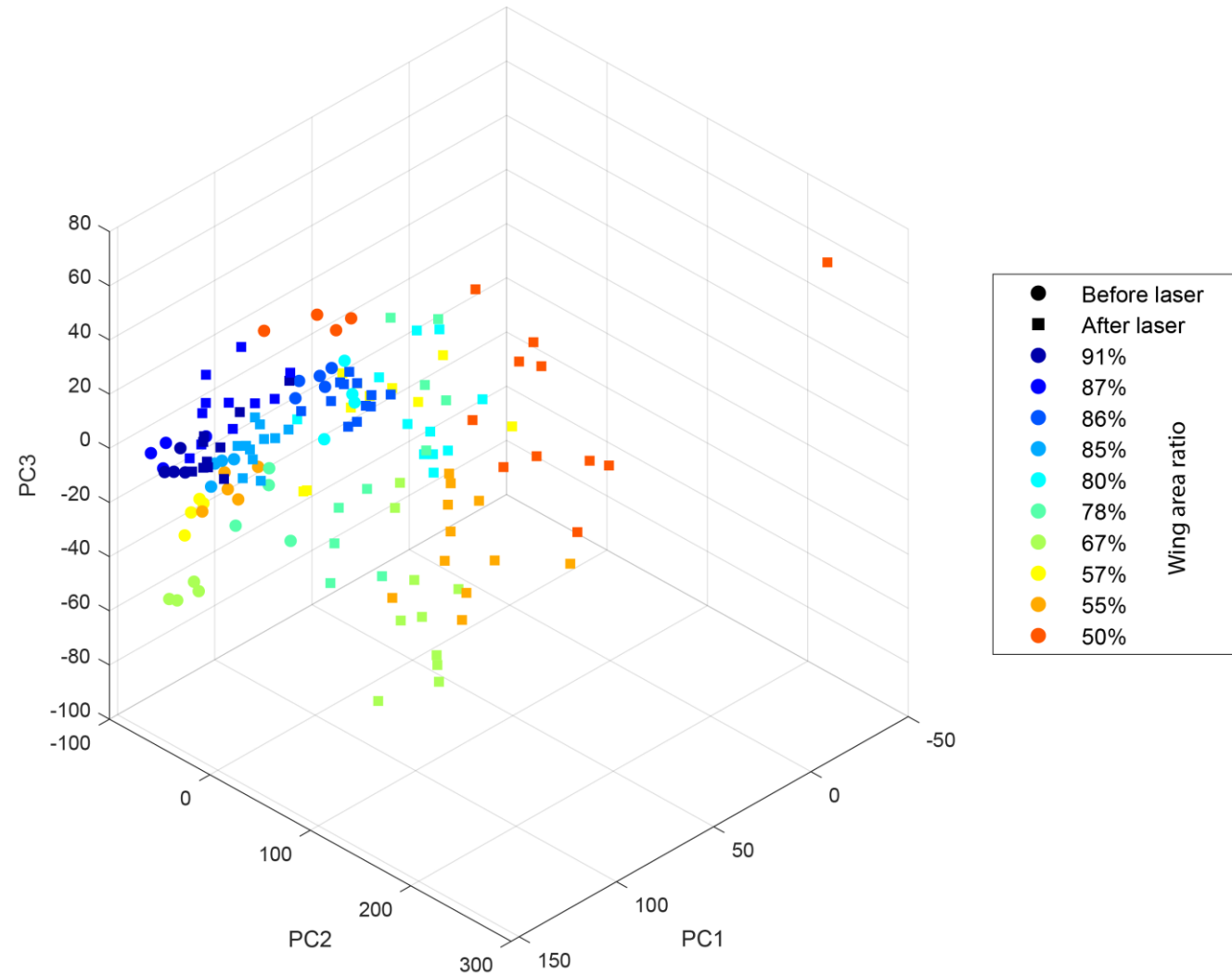


# Flies cluster before wing damage

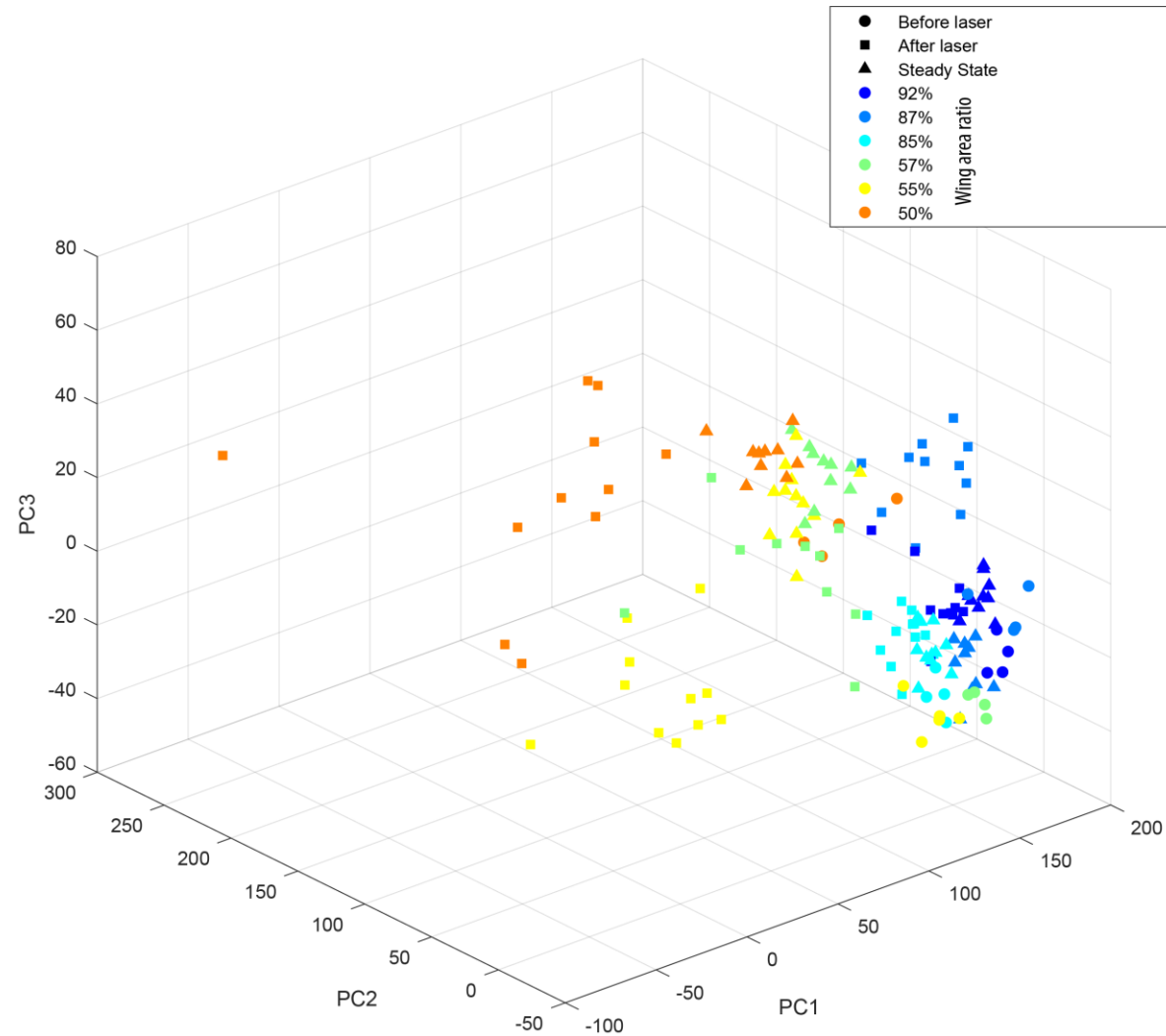




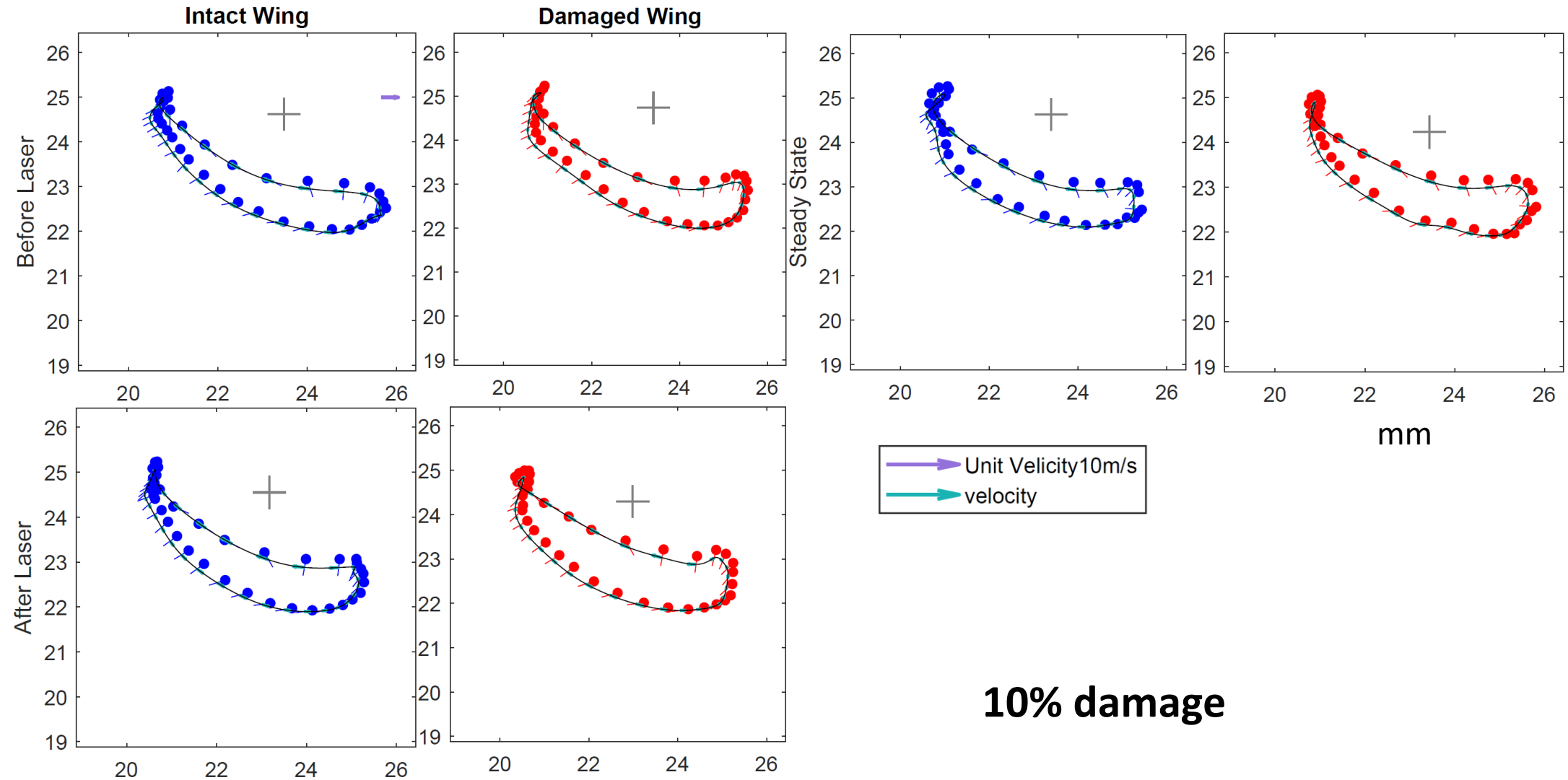
# Wing damage increases motor variability



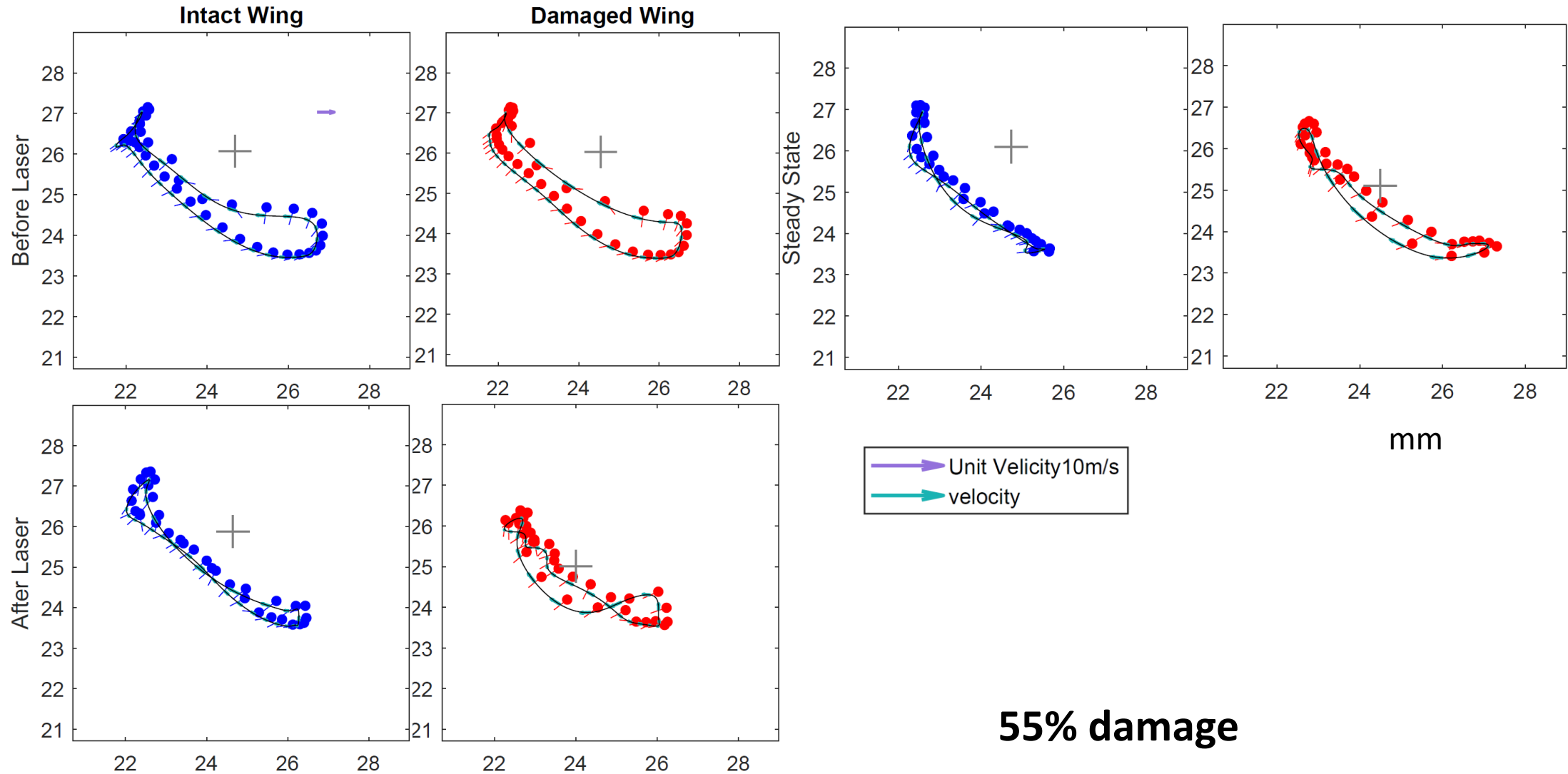
# Motor variability gone within 500 ms (steady state)



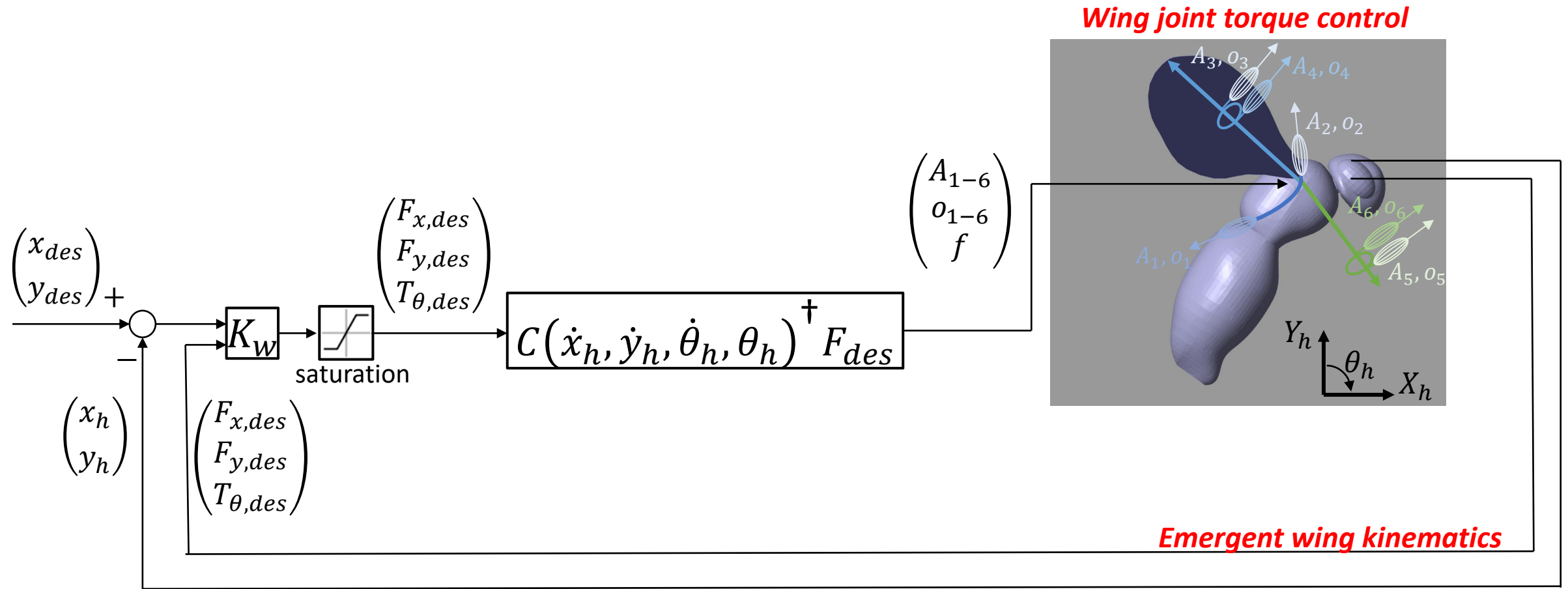
# Wing trajectories consistent with dimensionality reduction



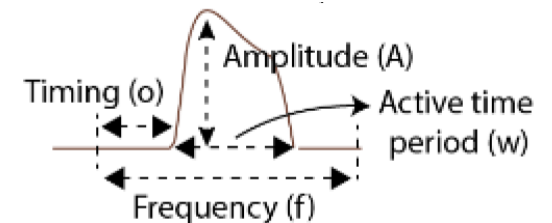
# Wing trajectories consistent with dimensionality reduction



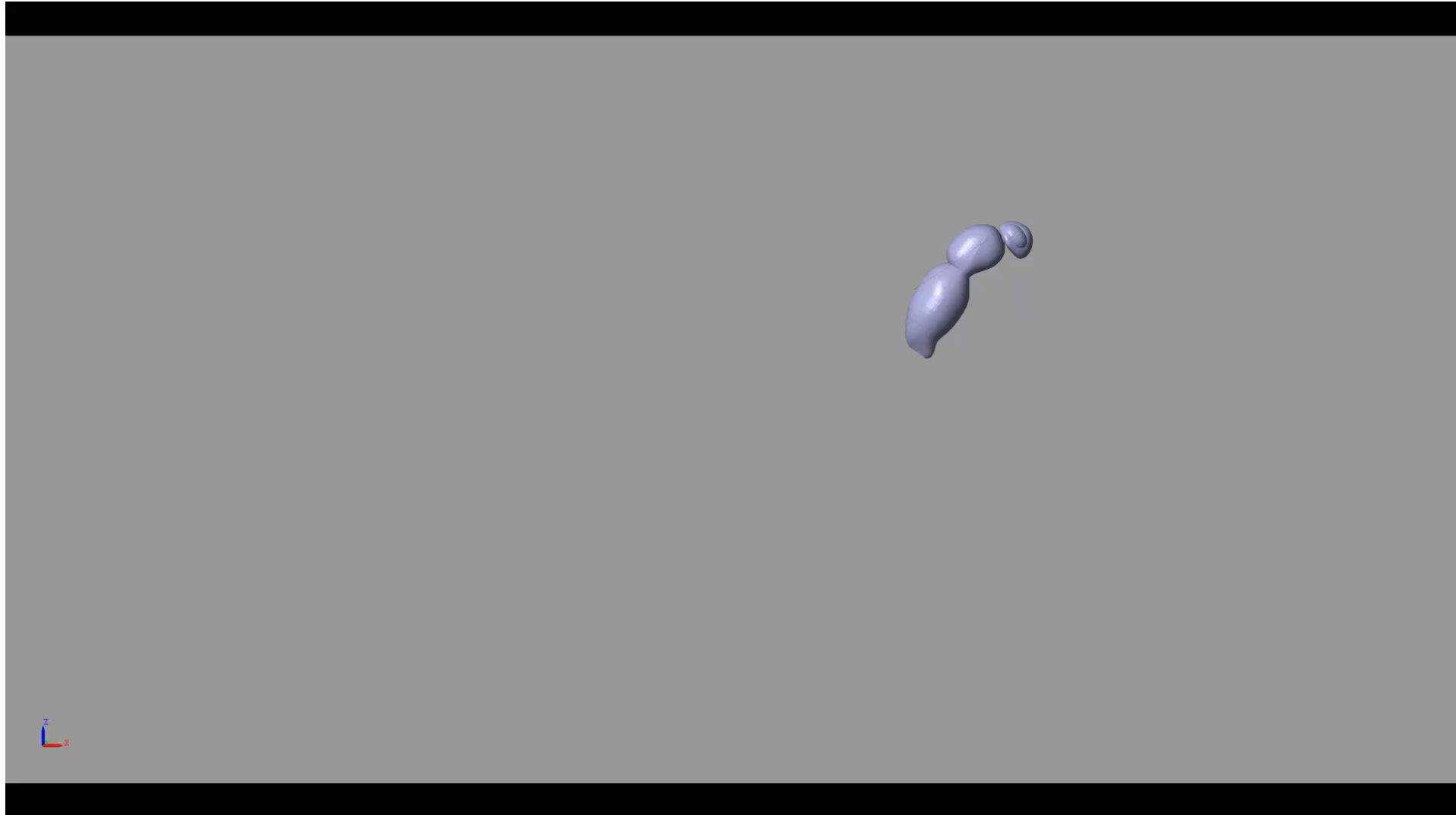
# Physics-based neuromechanical model of fly flight



$A_{1-6}$ : Amplitude in CPG profile from muscle one to six  
 $o_{1-6}$ : Onset timing in CPG profile from muscle one to six  
 $f$ : Frequency



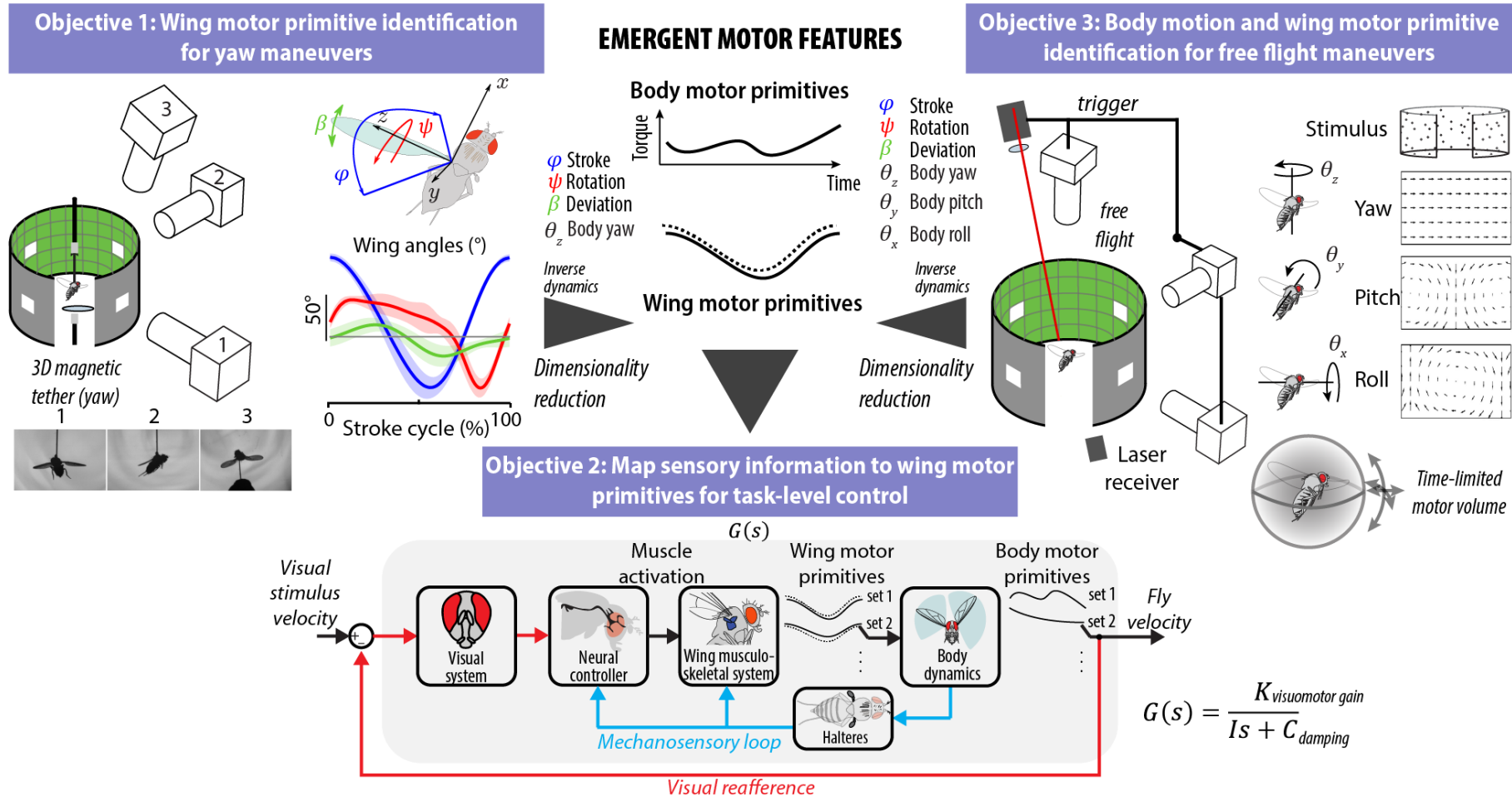
# Fly Simulation



# Outline

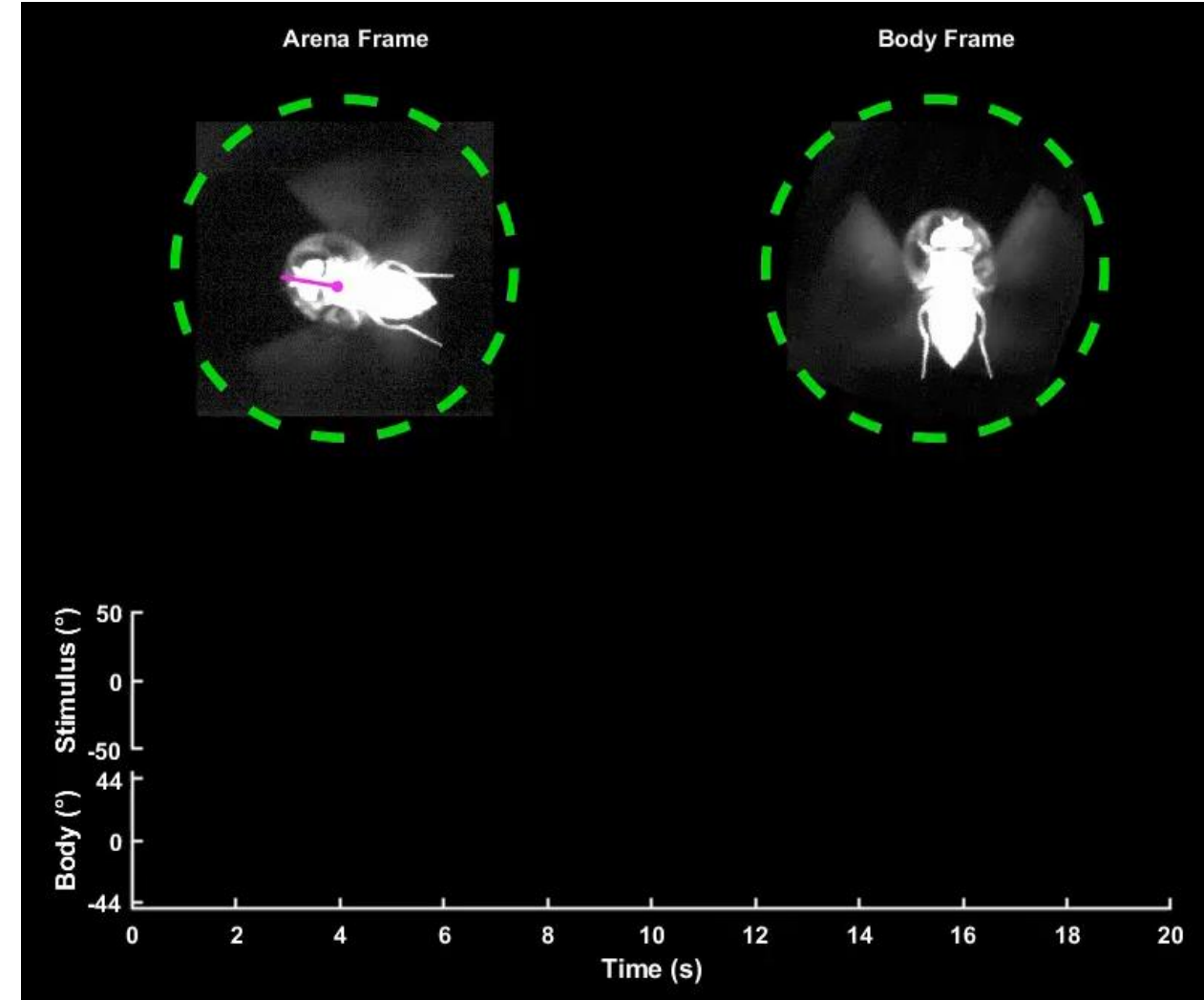
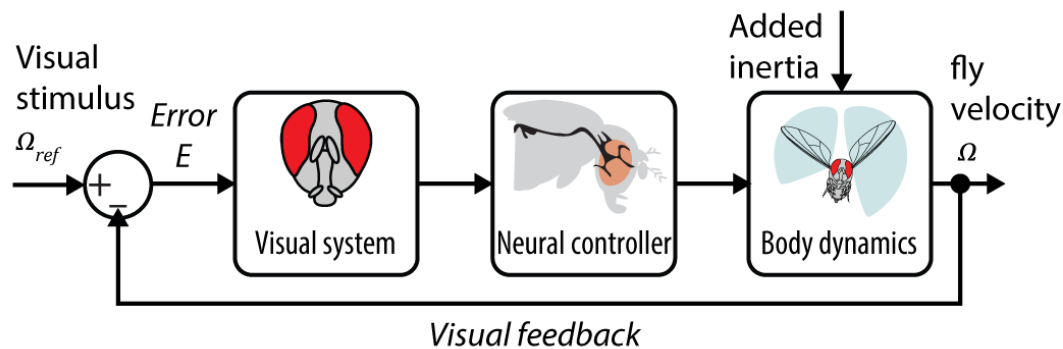
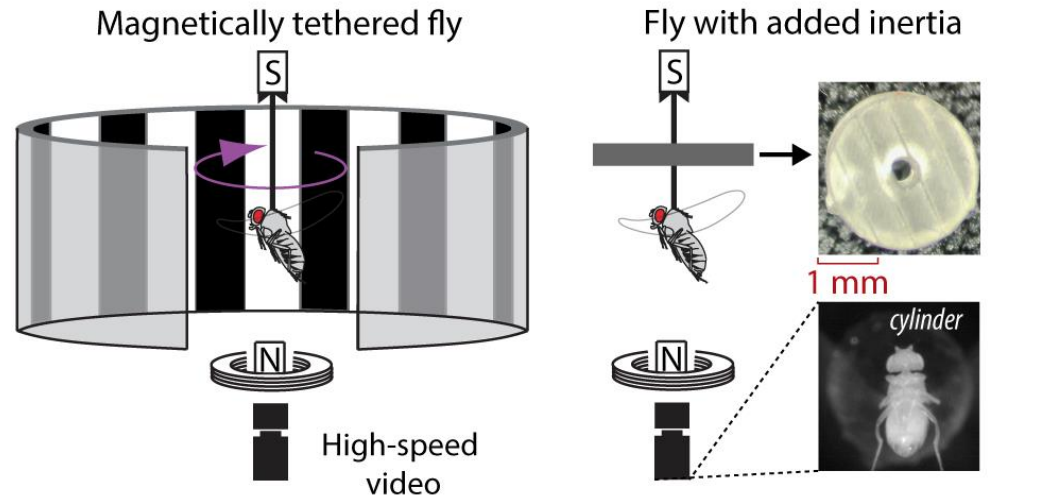
- Background
- Recent progress
- **Future plans**

# Generate a comprehensive library of motor features by extracting WMPs & BMPs

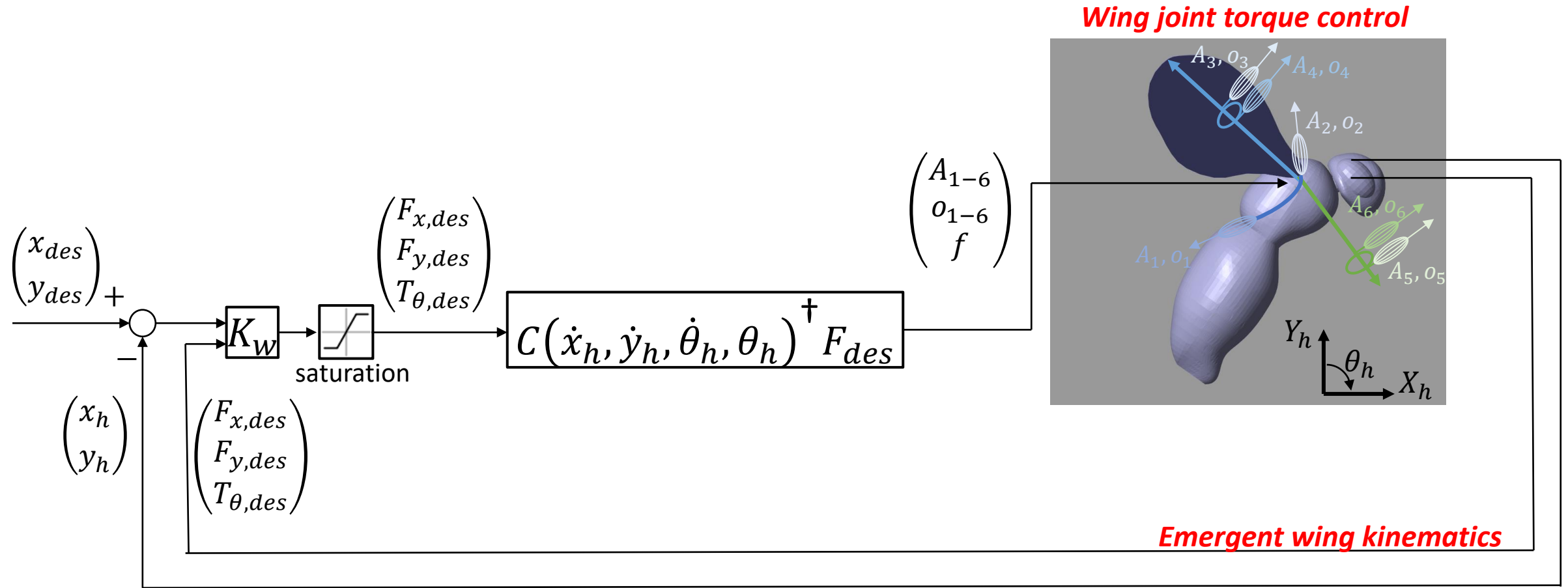




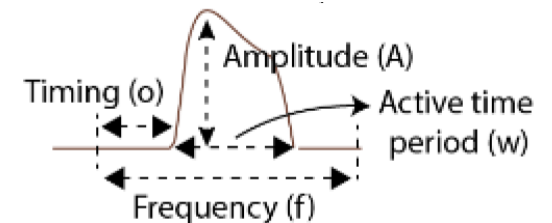
# Inertia increased to study sensory influence on WMPs



# Model to validate WMPs



$A_{1-6}$ : Amplitude in CPG profile from muscle one to six  
 $o_{1-6}$ : Onset timing in CPG profile from muscle one to six  
 $f$ : Frequency





# Emergence of low-dimensional motor features during sensory guided flight in flies

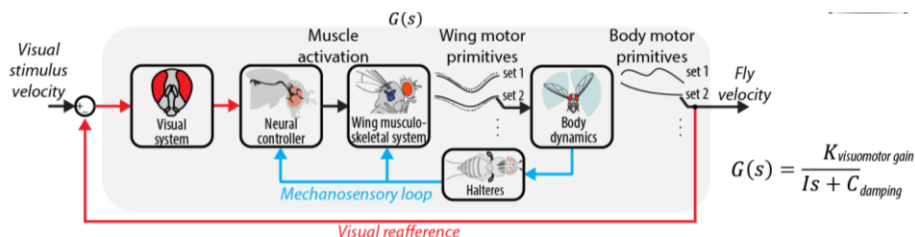
Jean-Michel Mongeau, Dept. of Mechanical Engineering, Penn State

Bo Cheng, Dept. of Mechanical Engineering, Penn State



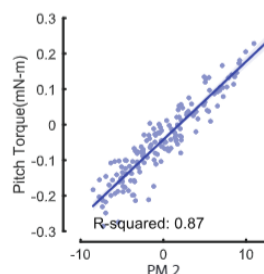
## Objectives:

- 1) Implement a data- and model-driven exploration of Wing Motor Primitives (WMPs) during yaw turns
- 2) Reveal how sensory information maps to WMP recruitment for task-level flight control
- 3) Identify how flight WMPs and Body Motor Primitives (BMPs) emerge in free flight maneuvers



## Accomplishments:

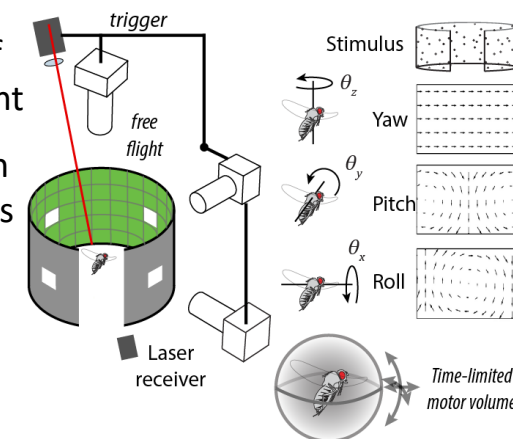
- Discovered how flies compensate for sudden wing damage using laser-based ablation of a single wing
- Identified kinematic-based WMPs using Principal Component Analysis before and after wing damage
- Revealed how WMPs relate to pitch torque, demonstrating that simple motor features can linearly map to control of complex aerial maneuvers



Mongeau et al., ICB, 2024  
3 manuscripts in preparation

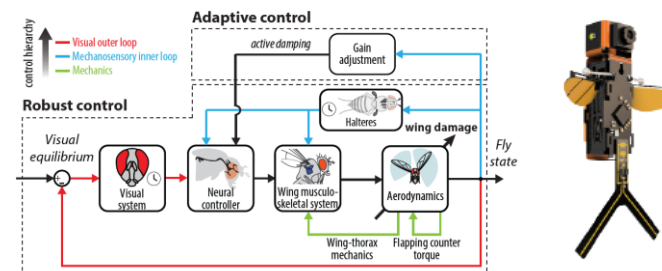
## Technical Approach:

- Use machine vision to generate a rich set of 3D wing kinematics in tethered and free flight
- Train a state-space aerodynamic model with robophysical model and use inverse dynamics to obtain wing joint actuation torque
- Apply dimensionality-reduction analytics (Singular Value Decomposition) to generate WMPs and BMPs
- Determine how visuomotor gain and damping correlate with the recruitment of WMPs



**DoD Benefit:** This work will generate novel bio-inspired algorithms for flight control and lay the groundwork for the development of autonomous aerial systems capable of flexible control and rich flight repertoires, thereby enhancing flight autonomy

**AF2030: Complexity, unpredictability, and mass**



# Accomplishments associated with project

- 1 invited review paper
  - Mongeau et al., 2024, *Integrative and Comparative Biology*
- Conference abstracts associated with project
  - Society of Integrative & Comparative Biology SICB (2)
- Manuscripts associated with project
  - 3 manuscripts under review and in preparation

Salem, W., Zhu, Y., Meng, L., Cheng, B., Mongeau, J-M. Response to sudden wing damage in flying flies reveals the robustness of flapping-wing flight (To be submitted).

Agrawal, S., Zhou, Z, Rahn, C. Mongeau, J-M., Cheng B., SimHummer: Biomechanical flight model of hummingbird generates hovering and translational maneuvers with reduced head vibrations (under preparation)

Anwar, Z., Mongeau, J-M., Cheng B., Wing motion primitives in hummingbird maneuvers and stabilization (under preparation)

- 2 Ph.D. students supported
  - Yue Zhu, Zafar Anwar