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Recapitulation of *Drosophila* Antennal Grooming by Combining Discrete and Rhythmic Movement Primitives

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1 Introduction

Insects are capable of performing highly intricate behaviors; they locomote on uneven terrain, navigate obstacles, and clean their body parts with goal-directed grooming. State-of-the-art robots have yet to match the versatility and dexterity of real animals [1], partly due to our limited understanding of how the animal nervous system integrates information from the environment, musculoskeletal, and the nervous system to generate behavior. The fruit fly, *Drosophila melanogaster*, serves as an ideal model organism for motor control studies because it can generate a large repertoire of complex behaviors with a numerically compact nervous system. Particularly, *Drosophila* antennal grooming is an excellent model for investigating goal-directed reaching movement with a high number of degrees-of-freedom (DOF), an ongoing challenge in robotics.

Computational models have been seminal in motor control research as they allow us to gain a systems-level understanding and test our hypotheses both in vertebrates [2] and invertebrates [3]. In this work, we addressed the question of whether the grooming movements can be explained by the superimposition of simple discrete and rhythmic patterns that are modulated by a limited set of descending signals. To this end, we adapted a dynamical system approach [4] for movement generation where the high-level controller (i.e. brain) defines only the key characteristics of the motion and the low-level controller (i.e. central pattern generators) produces the joint trajectories using motion primitives. Finally, we replayed the resulting kinematics in the neuromechanical simulation of adult *Drosophila* to mimic antennal grooming behavior.

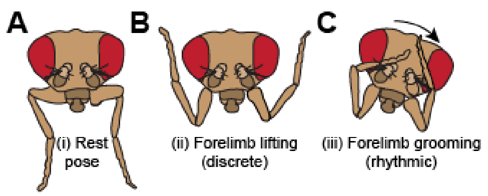

Figure 1: *Drosophila* antennal grooming sequence: From a rest pose **(A)**, the forelegs perform Discrete (i.e. reaching) **(B)** and Rhythmic (i.e. rubbing) movements **(C)** during antennal grooming.

2 Methods

2.1 Antennal grooming behavior in *Drosophila*

The following sequence is typically used for antennal grooming: First, the forelimbs are raised to the antenna, followed by the oscillatory movements of the limbs around that region. By coordinating limb and head movements, debris is removed from the antennae (Fig.1). Here, we focus only on limb movements. To track joint positions in 3D, we used the deep learning-based pose estimator DeepFly3D on the recordings of freely behaving tethered flies [5], which were then processed to compute joint angles [3]. Finally, we obtained the joint angles of each 7 degrees-of-freedom (DOF) per leg, namely thorax-coxa (3), trochanter-femur (2), femur-tibia (1), and tibia-tarsus (1). We used the kinematics of forelimbs (i.e. joint angles) to define the parameters of the CPGs to control each DOF.

2.2 Dynamical system

Discrete and rhythmic movement primitives account for goal-directed reaching and cyclical movements around the antenna, respectively. These movements are superimposed and generated by a single dynamical system, referred to as *Unit Pattern Generator (UPG)* [4], given by

$$\dot{h}_i = 1 - h_i \quad (1)$$
$$\dot{y}_i = v_i \quad (2)$$
$$\dot{v}_i = -\frac{1}{4}B^2 h_i^2 (y_i - \gamma_i) - B h_i v_i \quad (3)$$
$$\dot{m}_i = C(\mu_i - m_i) \quad (4)$$
$$\dot{x}_i = \frac{A}{|\mu_i|}(m_i - r_i^2)(x_i - y_i) - \omega_i z_i \quad (5)$$
$$\dot{z}_i = \frac{A}{|\mu_i|}(m_i - r_i^2) z_i - \omega_i (x_i - y_i) \quad (6)$$

where $r_i = \sqrt{(x_i - y_i)^2 + z_i^2}$, $h_i, y_i, v_i, m_i, x_i, z_i$ are the state variables of the dynamical system, A, B, C are constants adjusting the convergence rate of the solution, and $\mu_i, \omega_i, \gamma_i$ denote the control parameters determining the amplitude, frequency, and the target of the output signal x_i, respectively. The output y_i of the discrete subsystem (Eq. 1-3) is given to the rhythmic subsystem (Eq. 4-6), which as a result, produces oscillatory signal with a time-varying offset. Transition from purely discrete ($\mu_i < 0$) movement to rhythmic

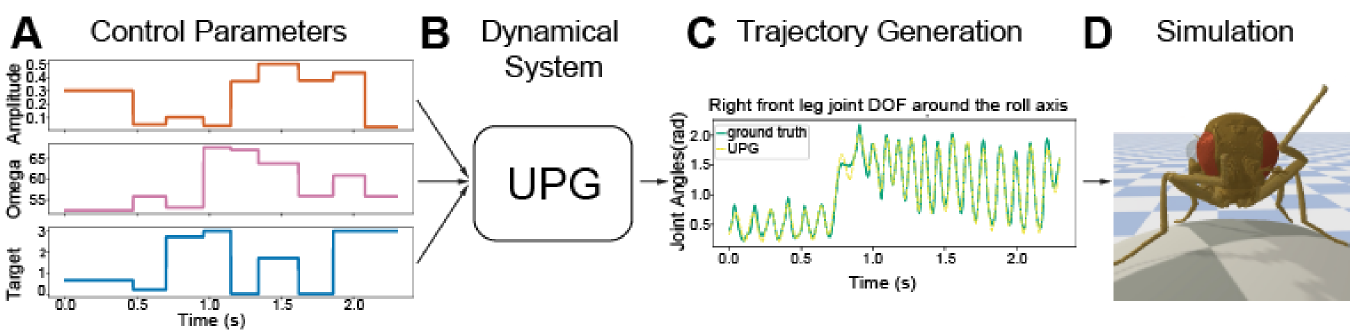

Figure 2: Workflow of the control system. **(A)** Control parameters are given to **(B)** the UPG, **(C)** based on the key features of the movement, the UPG generates the motor primitives, **(D)** the resulting joint angles are replayed in the physics-based simulation environment. `https://www.dropbox.com/s/npwbhtdckqkel6q/Optimization_Result_UPG.mp4?dl=0`

one ($\mu_i > 0$) occurs via Hopf bifurcation. Finally, the output signals x_i, i.e. joint angles, are used to actuate the individual leg joint DOFs of the biomechanical model.

2.3 Optimization

We used Adaptive Memory Programming for Constrained Global Optimization [6] method to find the optimal control parameters (i.e. μ, ω, and γ) that will match the UPG's output to the fly kinematics. To do so, we formulated the loss function as the mean squared error between the desired trajectory and the UPG's output. For each DOF, we ran the optimization on the entire joint trajectory with small-time windows ($\simeq 100ms$). We empirically set the coefficient values to guarantee a fast convergence (i.e. $A, B, C \in [1, 15]$).

3 Results and Discussion

The proposed control framework was able to generate the *Drosophila* limb kinematics to a large extent. To quantify the similarity between the UPG results and the computed joint angles, we replayed these kinematics in the neuromechanical simulation of *Drosophila* in the physics simulation environment PyBullet (Fig.2) [3]. PyBullet provides the collisions between antenna and forelimb segments, allowing us to draw a collision diagram between these body parts. We noted striking similarities between the experimental and the actual results during antennal grooming behavior. However, we did not achieve the same precision for the forelimb grooming, largely because synchronization of two moving body parts to effectively rub against each other is more challenging than a moving body part touching a stationary goal.

Our work's contribution is two-fold: First, we showed that a cyclical motion of forelimbs can be described as a superimposition of discrete and rhythmic movement primitives described by three simple control parameters (i.e. the amplitude, frequency, and target). The control parameters used in this framework resemble the command-like descending neurons in *Drosophila*. Such neurons are suggested to modify different modes of the movements that they initiate (e.g. speed). However, the underlying control mechanism is still unexplored [7]. This correspondence can be further tested with detailed modeling of the control system and behavioral experiments. Second, to the best of our knowledge, the existence of CPG circuits in the VNC of adult *Drosophila* has not been reported yet. Despite requiring more evidence, the sufficiency of UPGs to generate cyclical trajectories of forelimbs in an articulated body might suggest that this behavior can be executed via CPG-like mechanisms in *Drosophila* nervous system. Extending this approach with more biologically grounded controllers can be used for testing specific hypotheses regarding the pattern generator circuits in the VNC.

4 Conclusions

This study adapted a dynamical system approach combining discrete and movement primitives to control *Drosophila* forelimbs using three simple control parameters in a neuromechanical simulation. The proposed method allowed us to generate leg kinematics that closely follows the joint angles captured from a real fly, suggesting the adequacy of discrete and rhythmic movement primitives to generate the antennal grooming behavior. Future work will include expanding this control system by incorporating muscle models in the neuromechanical model and enhancing the controller using neuron-based CPG models.

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References

[1] A. J. Ijspeert. Biorobotics: Using robots to emulate and investigate agile locomotion. *Science*, 346(6206):196–203, 2014.

[2] A. J. Ijspeert, A. Crespi, D. Ryczko, and J.-M. Cabelguen. From Swimming to Walking with a Salamander Robot Driven by a Spinal Cord Model. *Science*, 315(5817):1416–1420, 2007.

[3] Victor Lobato-Rios, Pembe Gizem Özdil, Shravan Tata Ramalingasetty, Jonathan Arreguit, Auke Jan Ijspeert, and Pavan Ramdya. Neuromechfly, a neuromechanical model of adult *Drosophila melanogaster*. *bioRxiv*, 2021.

[4] S. Degallier, L. Righetti, S. Gay, and A. Ijspeert. Toward simple control for complex, autonomous robotic applications: combining discrete and rhythmic motor primitives. *Autonomous Robots*, 31(2):155–181, 2011.

[5] S. Günel, H. Rhodin, D. Morales, J. Campagnolo, P. Ramdya, and P. Fua. DeepFly3D, a deep learning-based approach for 3D limb and appendage tracking in tethered, adult *Drosophila*. *eLife*, 8:e48571, 2019.

[6] L. Lasdon, A. Duarte, F. Glover, M. Laguna, and R. Martí. Adaptive memory programming for constrained global optimization. *Computers Operations Research*, 37(8):1500–1509, 2010.

[7] S. Hampel, C. E. McKellar, J. H. Simpson, and A. M. Seeds. Simultaneous activation of parallel sensory pathways promotes a grooming sequence in *Drosophila*. *eLife*, 6:e28804, 2017.