HexCitations

Team Members:

Andrew Mombay

Helen Primis

Kaya Bruno

Sarah Nguyen

Project Partner:

Jack-William Barotta

01

Introduction

Background & Literature Review

What is Active Matter?

Active Particles -> Active Systems -> Collective Behavior

Active Particles

An active particle is one that moves autonomously by harnessing energy from its environment, and converting it into self-propelled motion.

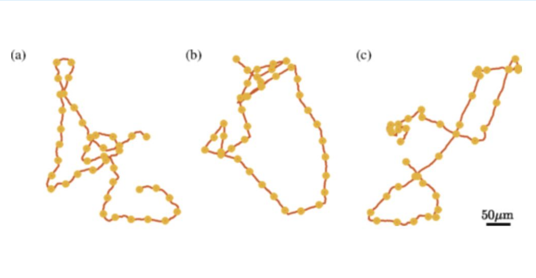
Active Systems

Composed of active particles, active systems are seen across nature—from the microscopic swarming of bacteria colonies, to the macroscopic motion of animal groups such as schools of fish and flocks of birds.

Collective Behavior

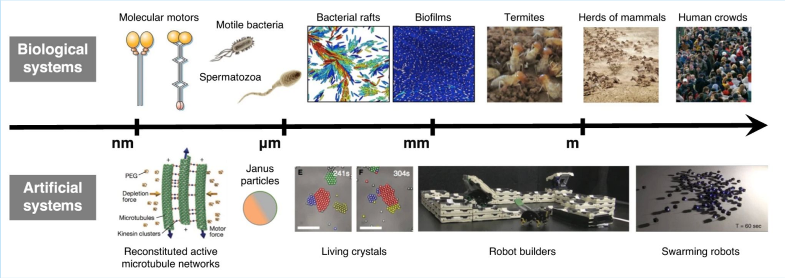
Active particles are inherently out-of-equilibrium, since each self-propelled particle breaks time-reversal symmetry. Therefore, these systems have the capability for complex collective behaviors such as particle aggregation, and synchronization to arise.

Sample trajectories of active Brownian particles corresponding to different mechanisms generating active motion: (a) rotational diffusion dynamics, (b) run-and-tumble dynamics, and (c) Gaussian noise dynamics.



Volpe, G., Bechinger, C. et al. Active particle in complex and and crowded environment (2016).

Examples of active matter systems.



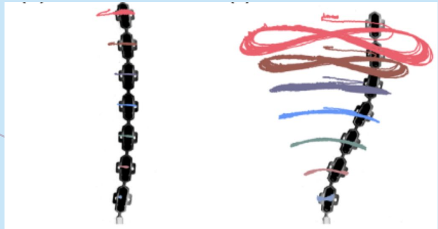
Volpe, G., Bechinger, C., Cichos, F. et al. Active matter in space. npj Microgravity 8, 54 (2022).

How can we model Elastic Active Systems?

Elasticity ->

One topic of particular interest is the interplay of active systems that have elasticity. Such competing effects (activity and elasticity) can lead to synchronous collective motion. By investigating the relative strength of elastic forces to active forces, we gain insight into the driving force behind their collective motion.

Emergence of self-oscillations in elastoactive chains



Zheng et al. *Self-Oscillation and Synchronization Transitions in Elastoactive Structures*, 2023.

Hexbugs ->

Most studies of active motion feature microscopic particles or complex robotic systems, which require advanced technology and setup. To mitigate this, we propose using Hexbugs, small battery powered toys, to serve as a macroscopic version of the often microscopic particles referenced in the relevant literature.

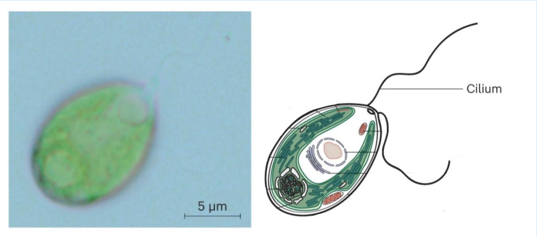
Hexbug Nano Robots

https://www.hexbug.com/nano.html

Biological Models

Considering applications of active particle self-oscillations, biological systems at the microscopic level, such as cilia and flagella, are known to exhibit this type of synchronous motion. By attaching multiple Hexbugs in line through elastic linkages, we model a filament similar to a cilium.

Microscope image of a vegetative C. reinhardtii cell and Illustration highlighting key subcellular compartments



Dupuis, S., Merchant, S.S. *Chlamydomonas reinhardtii: a model for photosynthesis and so much more*, 2023.

Our Goals

- Create an accurate model for an adjustable linked filament to mimic cilia-like behaviors by utilizing Hexbugs, exploring the interplay between the filament elasticity and activity

- Observe and analyze the collective synchronization behavior emergent upon coupling Hexbug active particles with varying bendability

- Investigate two-legged and four-legged gaits, representative of cilia and quadriflagellates by attaching multiple Hexbug filaments to a center pin

02

Experimental Setup

What does our experimental system look like?

Experimental Setup

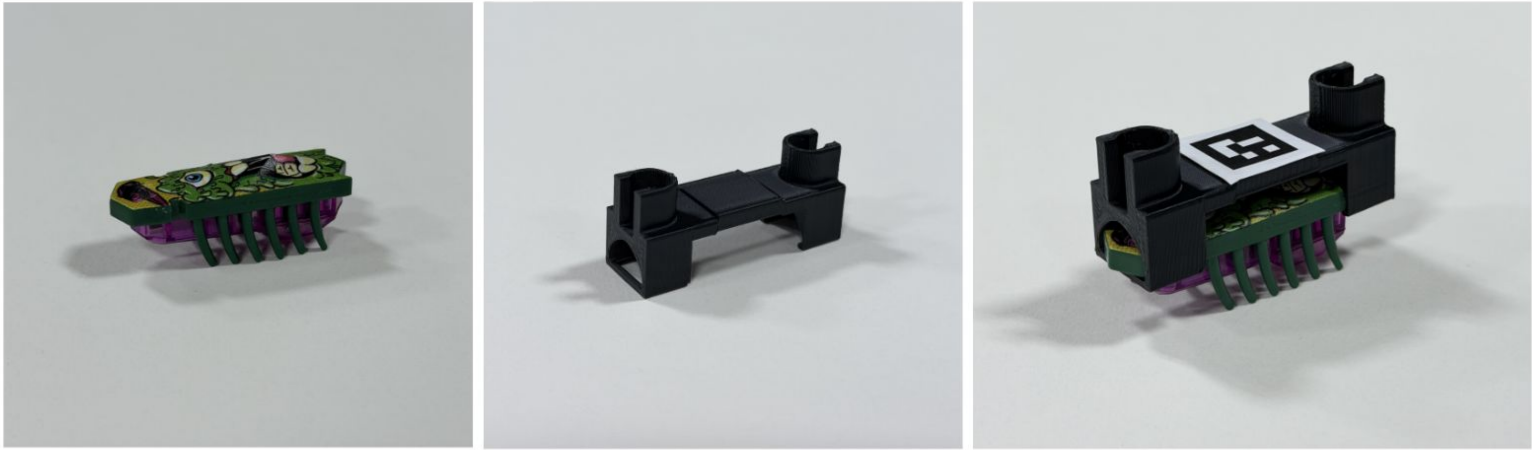


Figure 1: (a) Singular Hexbug, (b) 3D Printed Hexbug Cage, (c) Hexbug Mounted with Cage and QR tracking code

Experimental Setup

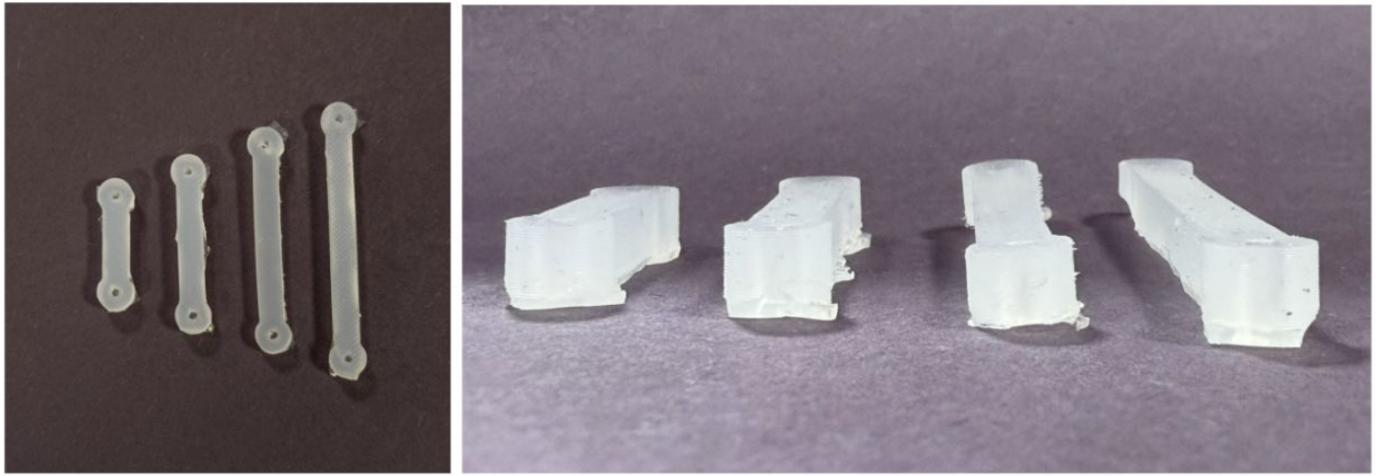


Figure 2: (a) Silicone Linkages Plane View, (b) Silicone Linkages Cross Sectional View

Experimental Setup

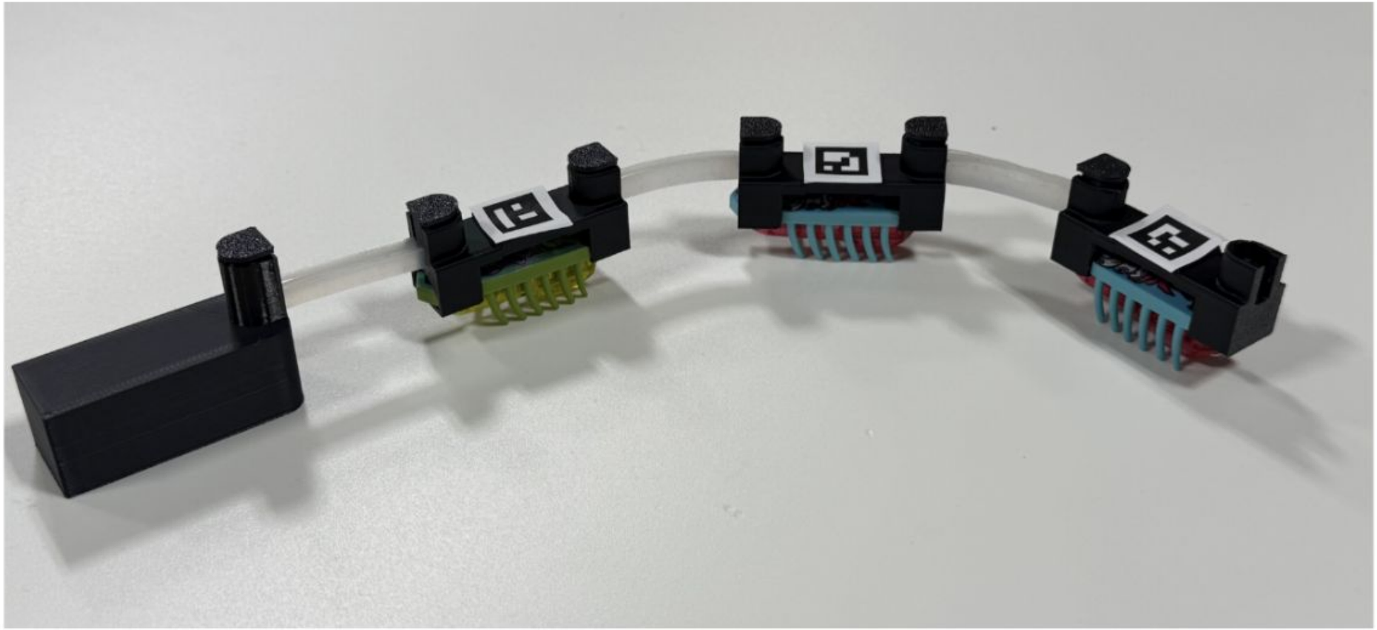


Figure 3: Hexbug Filament with Three Hexbugs

Experimental Setup

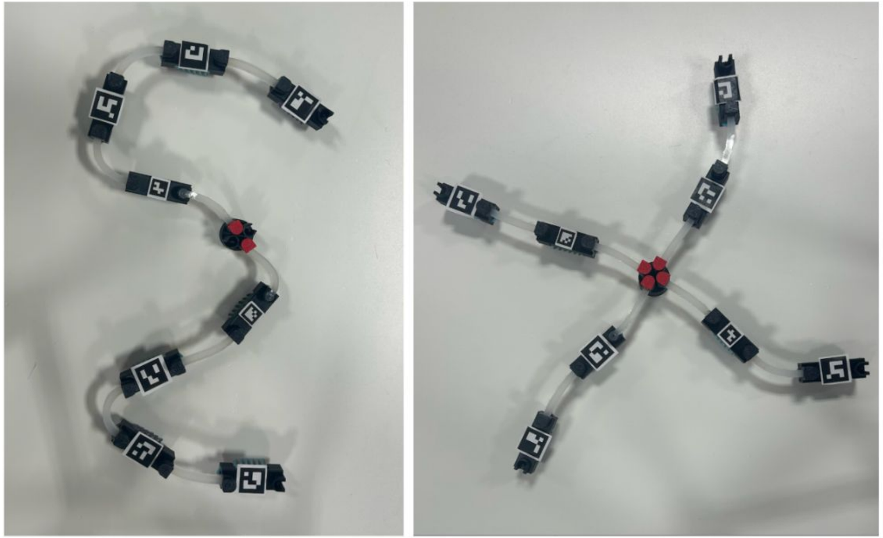


Figure 4: (a) Two Hexbug Filaments Connected to Central Body, (b) Four Hexbug Filaments Connected to Central Body

03

Quantifying System

Parameter Estimation

Parameter Estimation

Spring Constant: $k = \frac{F}{\delta}$

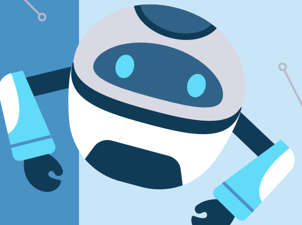
Young Modulus: $E = \frac{FL}{Ax}$

Torsional Stiffness: $C = \frac{EJ}{L}$

Sigma: $\sigma = \frac{F_a L}{C}$

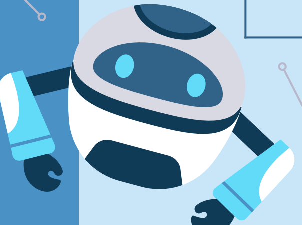
Tau: $\tau = \frac{\psi l^2}{C}$

k: Spring Constant
E: Young's Modulus
F: Applied Force from Mass
x: Displacement
L: Length of Silicone
A: Cross Sectional Area of Silicone
J: Torsion Constant
C: Torsional Stiffness
F_a: Forcing of Hexbug
ψ: Isotropic Viscosity (damping)
l: Length of Pendulum
σ: Elastoactive Parameter
τ: Characteristic Timescale



Parameter Estimation

Linkage	1	2	3	4
Length L (mm)	27.3	37.3	47.3	57.3
Spring Constant k (N/mm)	0.1312	0.0745	0.0903	0.057
Young's Modulus E (MPa)	0.132			
Torsional Stiffness C (Nm/rad)	9.45E-4	5.21E-4	3.60E-4	2.74E-4
Elastoactive Parameter σ	1.0071	1.8800	3.0232	4.4366
Characteristic Timescale τ (s)	1.1032	2.8139	5.7381	10.2011



04

Model

Mathematical Motivation

Mathematical Motivation

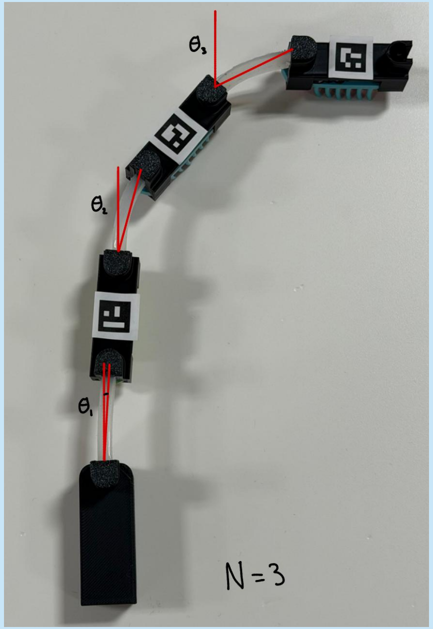
The model that governs our experiment is an energy balance. Using the three equations below that characterize Bug 1, Bug 2 through Bug N-1, and Bug N, we are able to create a set of differential algebraic equations that can be solved in MATLAB using readily available solvers such as ODE45 to solve for the time derivative of the angle.

$$\textit{For Bug 1:}\ 0 = 2\theta_1 - \theta_2 - \sigma\sum_{j=i}^{N} \sin(\theta_1 - \theta_j) + \tau\left(N\dot{\theta}_i + \sum_{j=2}^{N}(N - j + 1)\dot{\theta}_j\cos(\theta_j - \theta_i)\right)$$

$$\textit{For Bug 2} - \textit{Bug N} - 1\textit{:}\ 0 = 2\theta_i - \theta_{i+1} - \theta_{i-1} - \sigma\sum_{j=i}^{N} \sin(\theta_i - \theta_j) +$$

$$\tau\left[(N - i + 1)\sum_{j=1}^{i}\dot{\theta}_j\cos(\theta_i - \theta_j) + \sum_{j=i+1}^{N}(N - j + 1)\,\dot{\theta}_j\cos(\theta_j - \theta_i)\right]$$

$$\textit{For Bug N:}\ 0 = \theta_N - \theta_{N-1} + \tau\sum_{j=1}^{N}\dot{\theta}_j\cos(\theta_N - \theta_j)$$

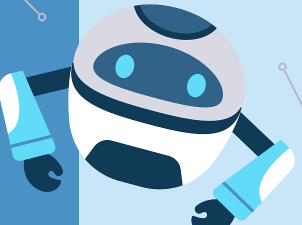


05

Comparison

Between Experiment and Model

Demo!
Live Tracking!



Outline

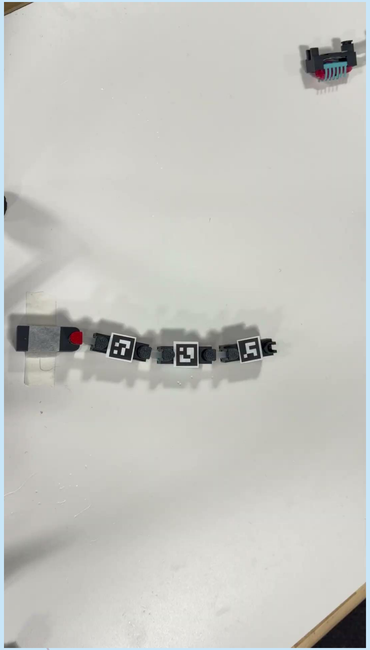
σ: elastoactive parameter that changes based on the length of the linkage between Hexbugs in the filament

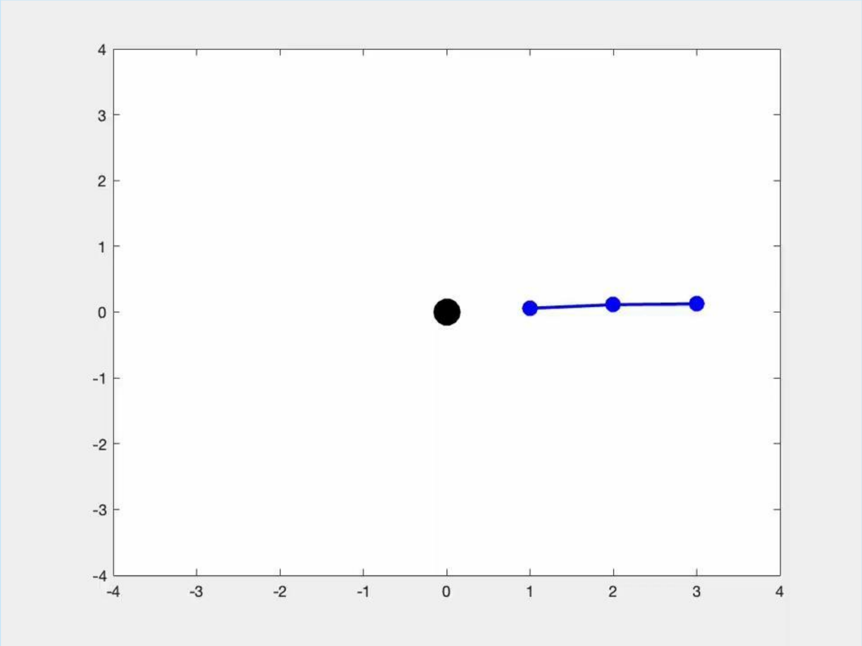
N: number of Hexbugs in the filament

Trial #1 (σ = 1.0071, N = 3)
Trial #2 (σ = 1.0071, N = 4)
Trial #3 (σ = 1.8800, N = 3)
Trial #4 (σ = 3.0232, N = 3)
Trial #5 (σ = 4.4366, N = 3)

For each trial we compare experimental and theoretical reference frames as well as plots for xy trajectory, mean curvature vs time, and mean curvature vs mean polarization (phase space).

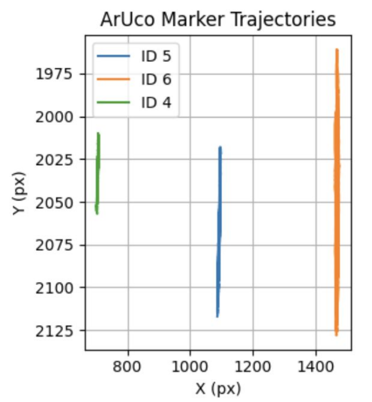
Trial #1 (σ = 1.0071, N = 3)

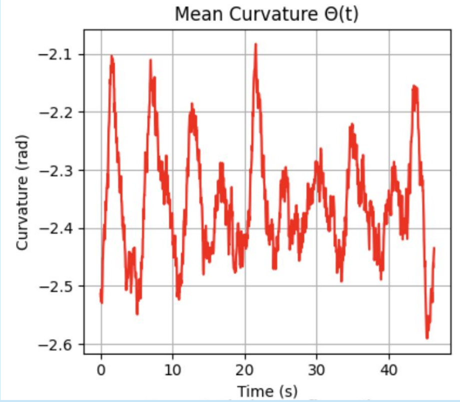


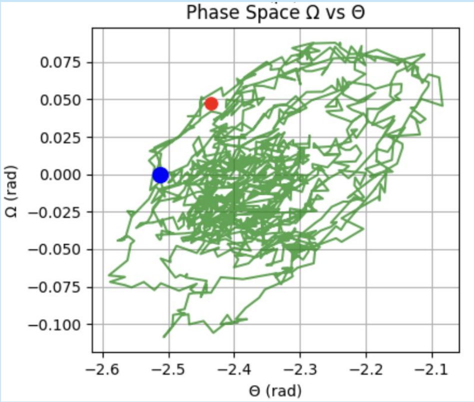


Trial #1 (σ = 1.0071, N = 3)

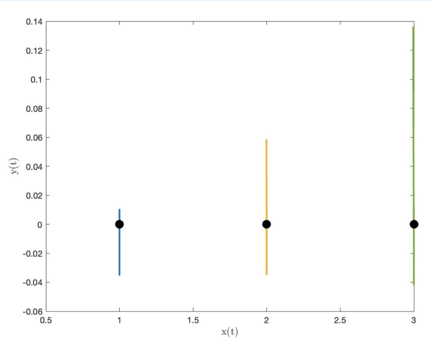
Experimental

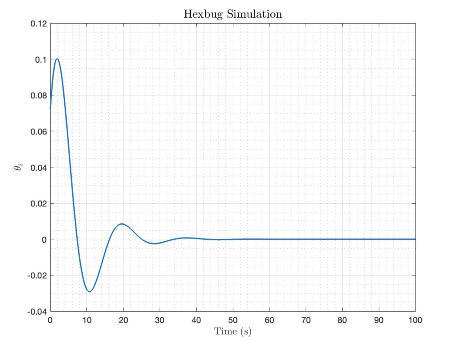


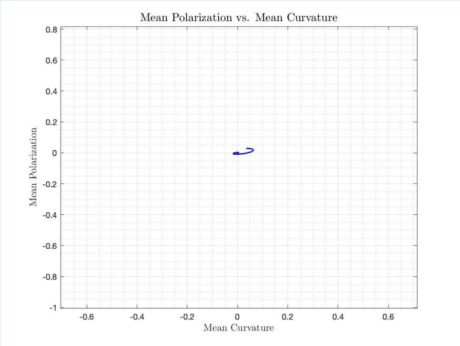




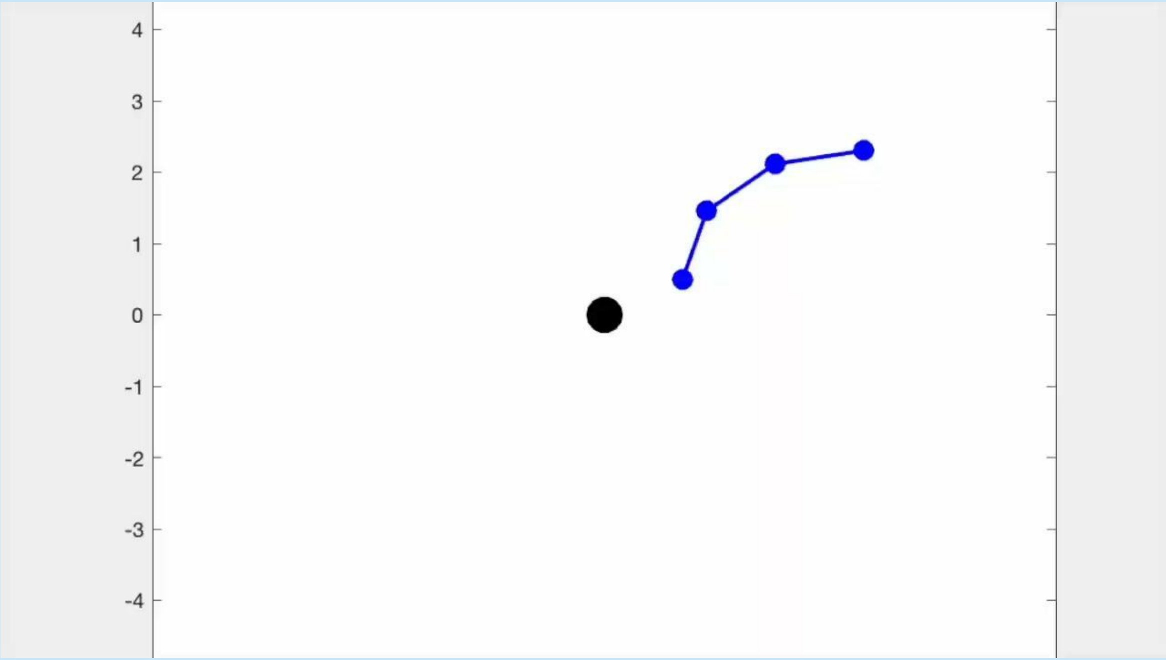
Simulation





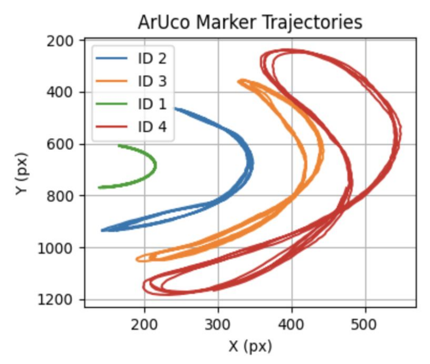


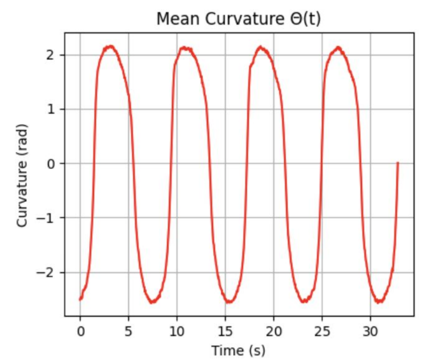
Trial #2 (σ = 1.0071, N = 4)

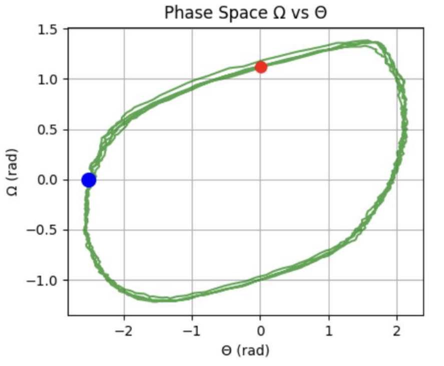


Trial #2 (σ = 1.0071, N = 4)

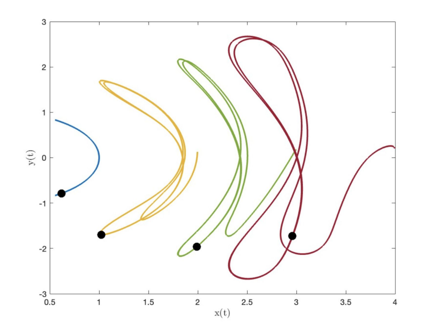
Experimental

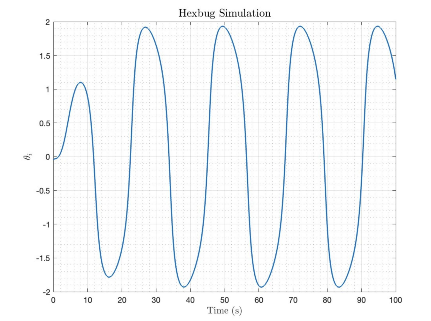


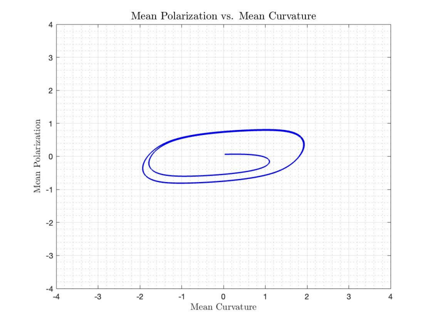




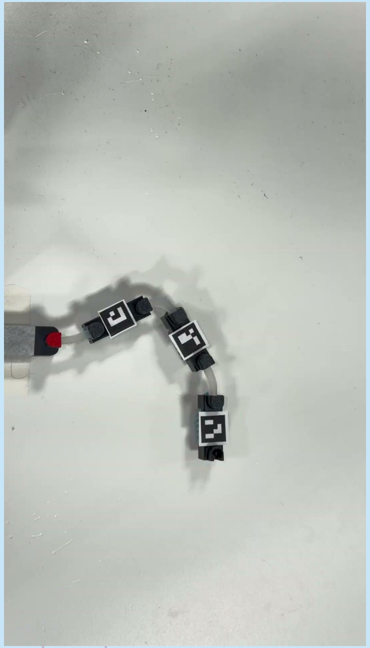
Simulation

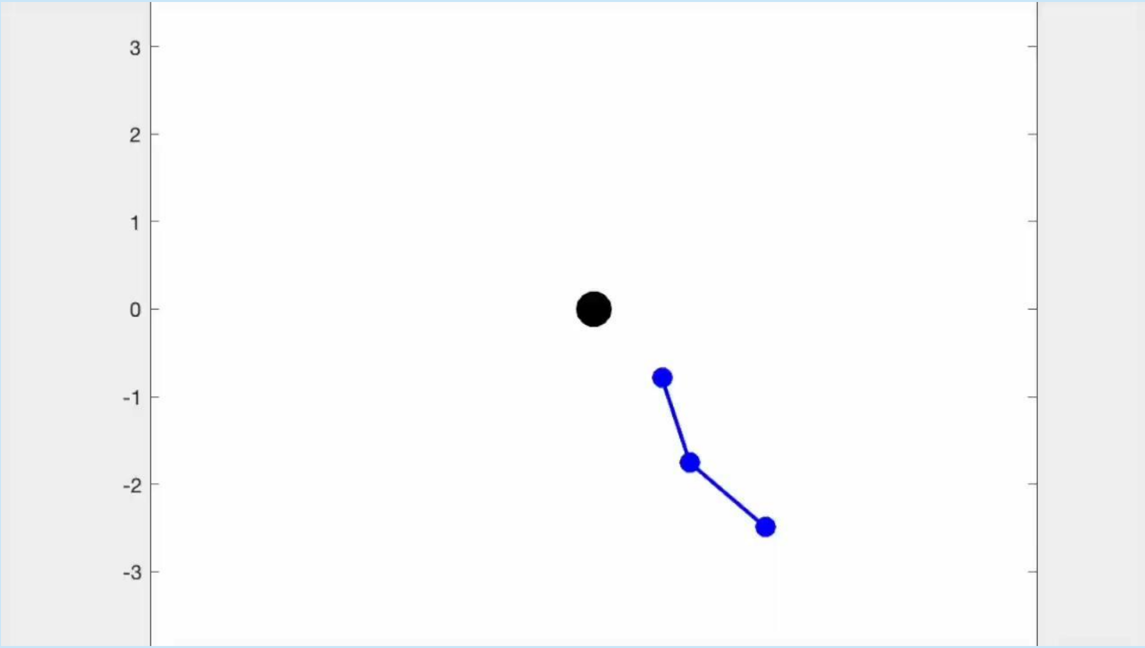






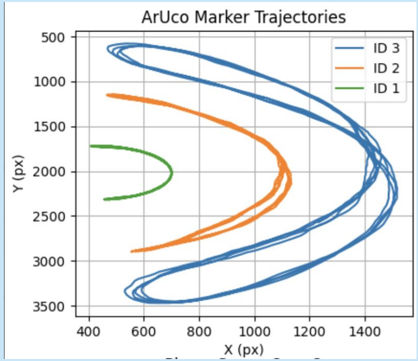
Trial #3 ($\sigma = 1.8800$, $N = 3$)

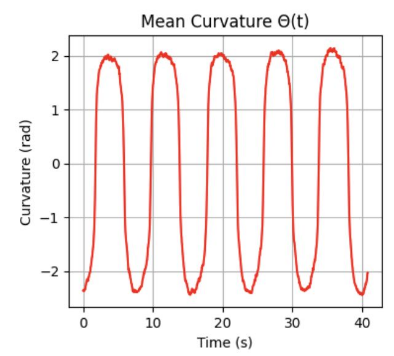


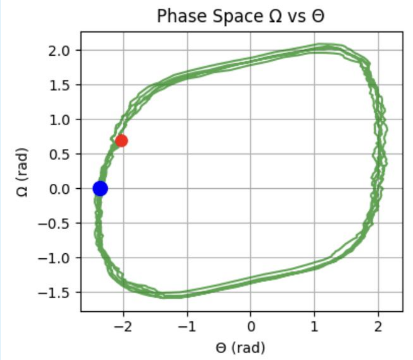


Trial #3 (σ = 1.8800, N = 3)

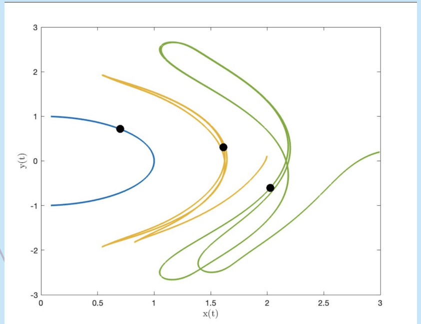
Experimental

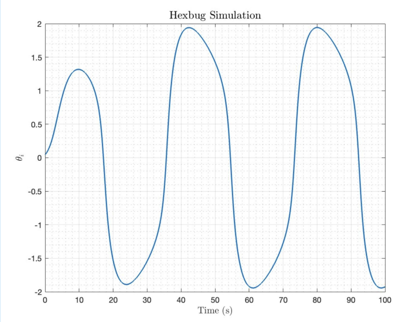


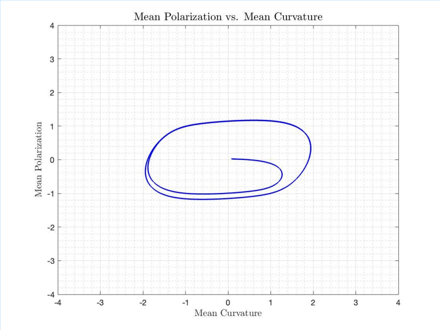




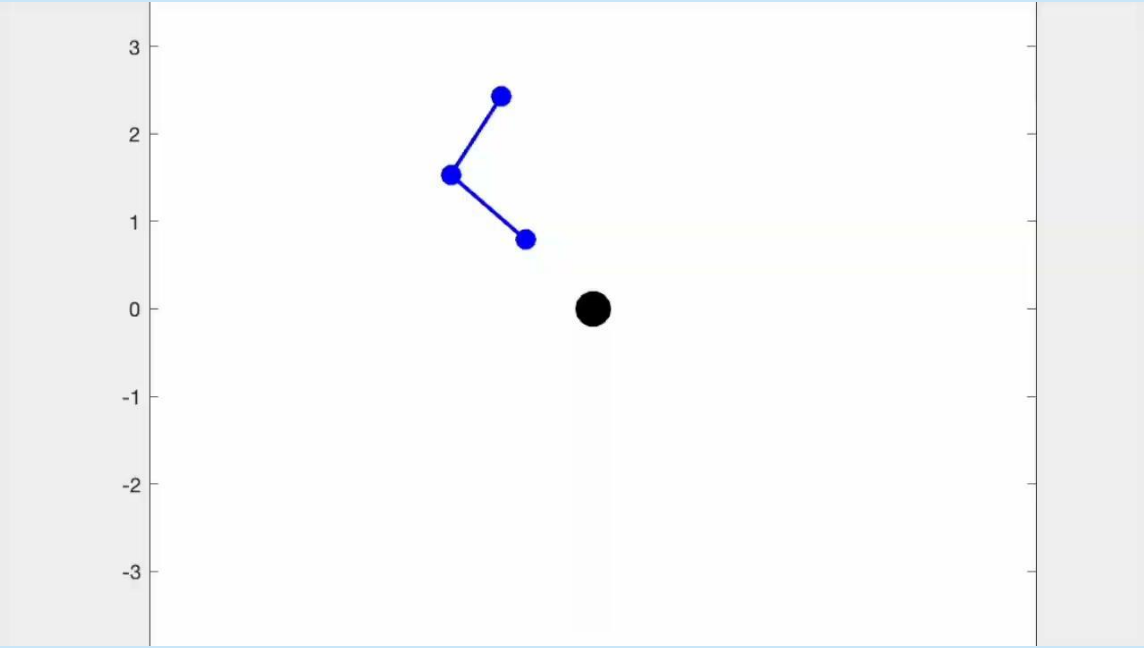
Simulation





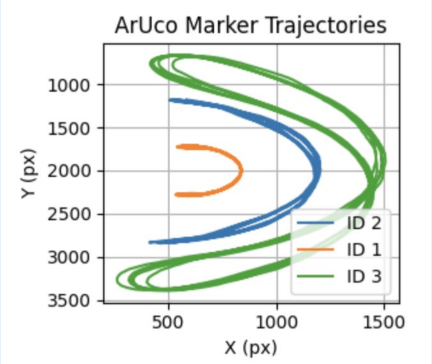


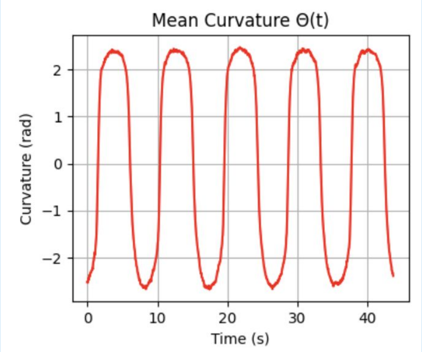
Trial #4 ($\sigma = 3.0232$, $N = 3$)

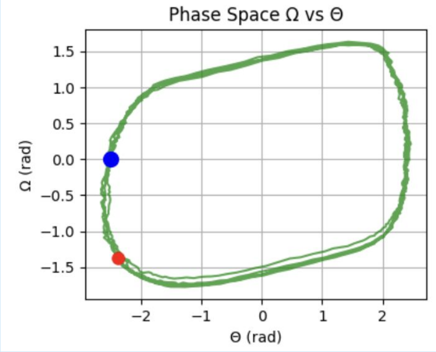


Trial #4 (σ = 3.0232, N = 3)

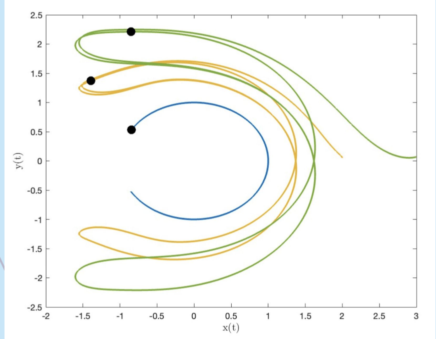
Experimental

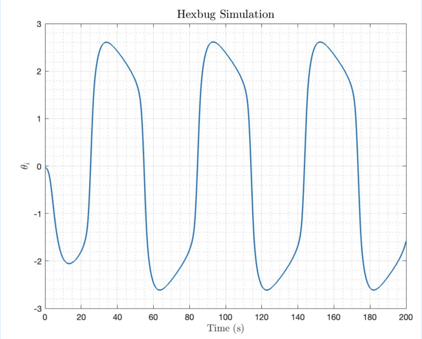


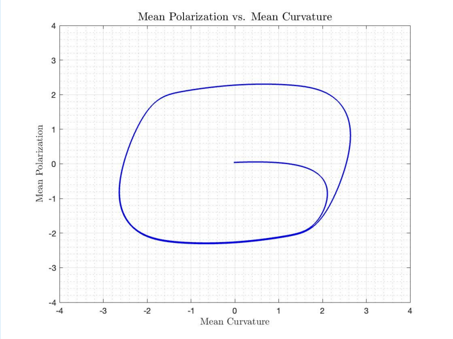




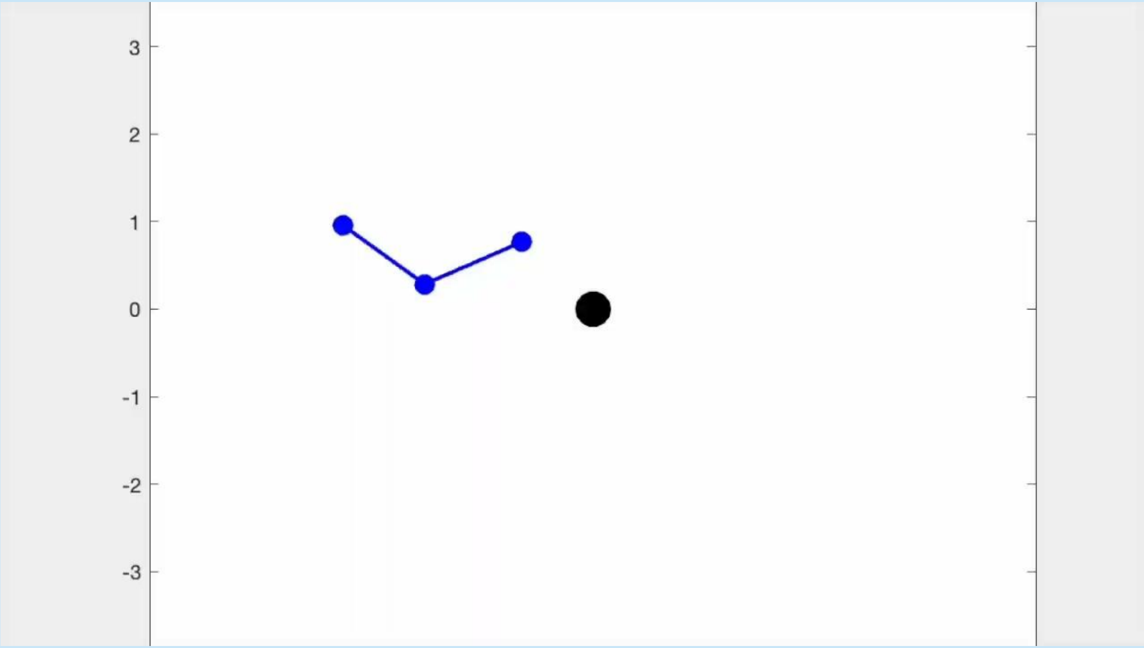
Simulation





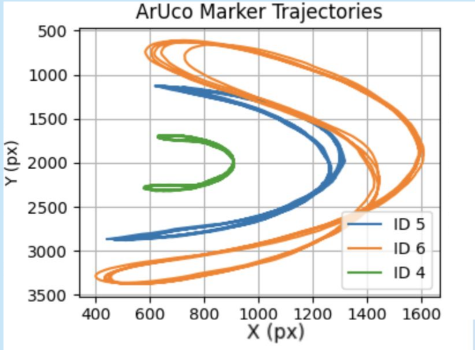


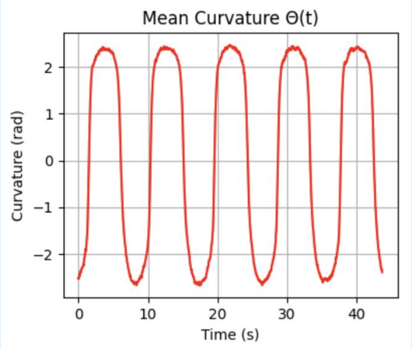
Trial #5 (σ = 4.4366, N = 3)

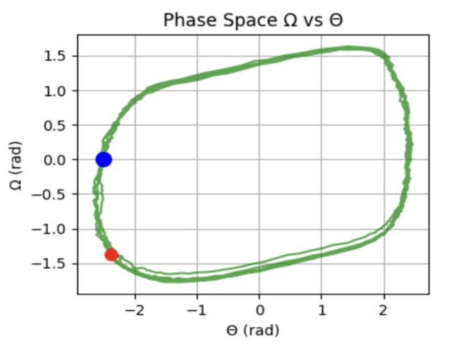


Trial #5 (σ = 4.4366, N = 3)

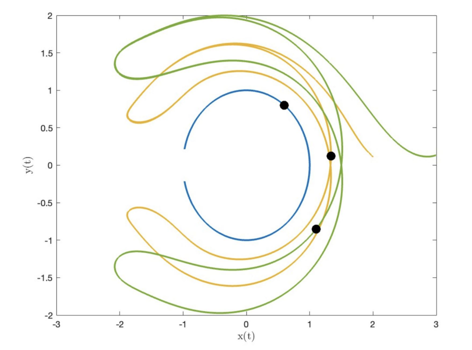
Experimental

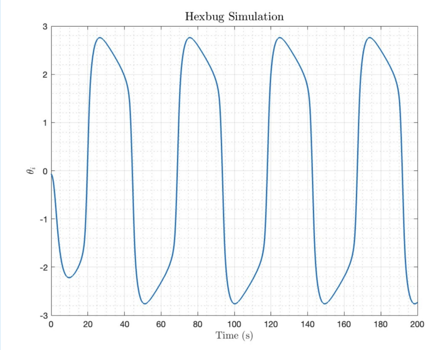


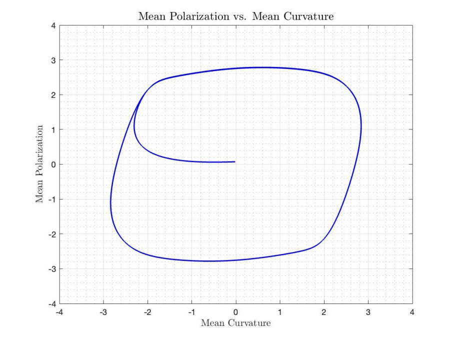




Simulation





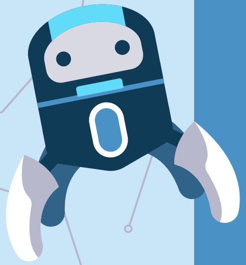


06

Multifilament System

Qualitative Analysis

Demo!



Qualitative Analysis

2 Filament System (rotation)

2 Filament System (fixed)

4 Filament System (fixed)

07

Conclusion

Lessons, Questions & Next Steps

Takeaways, Questions & Next Steps

Takeaways

- ★ For the one filament system, the model and experiment show agreement in terms of trajectory, mean polarization, and mean curvature
- ★ We are able to see instances of synchronization in the two and four filiamnet system but need to quantify further

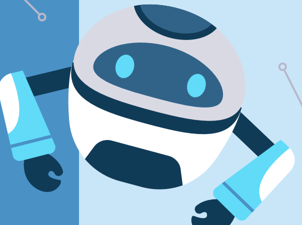
---

Questions

- ★ How can we create a DV-powered homemade model to better simulate collective behavior?
- ★ How can we more robustly track the orientation and positioning of our hexbugs beyond QR code tracking?
- ★ How can we elicit multi-filament synchronization in hexbug behavior?

Next Steps

- ★ Revise physical model
- ★ Improve tracking software
- ★ Explore multi-filament synchronization



Thank you!