Leveraging Mechanical Instabilities for High-Performance Soft Robots

Jie Yin

Department of Mechanical and Aerospace Engineering
North Carolina State University, Raleigh, NC USA
jyin8@ncsu.edu

Twitter: @JieYinLab Youtube channel: Yin lab@NCSU

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Rigid Machine *vs.* Soft Living Machine

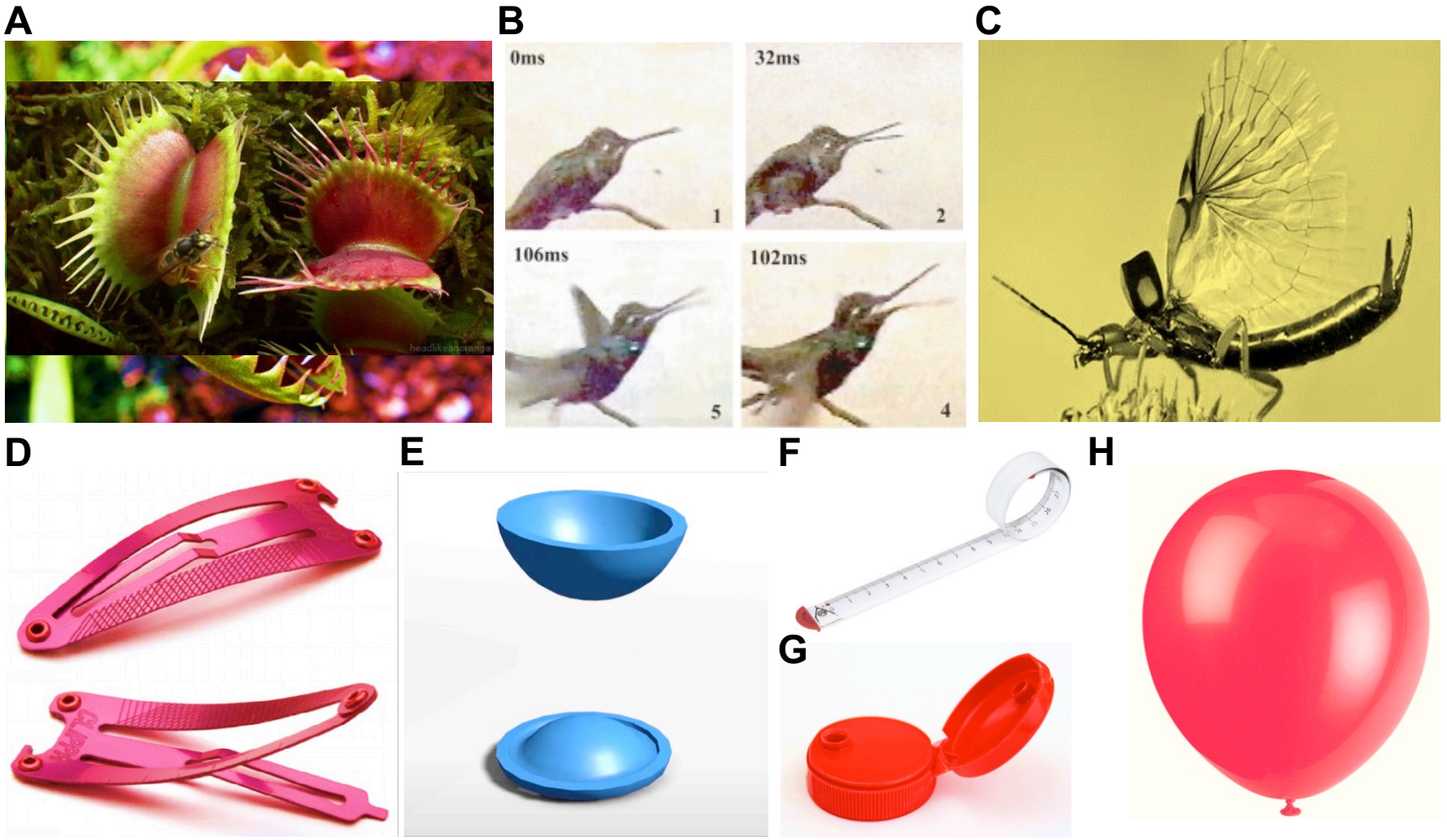
Atlas, Boston Dynamics (from youtube)

(**Precision & powerful**)

Octopus escapes from one-inch hole (from youtube)

(**Adapting to unknown environment**)

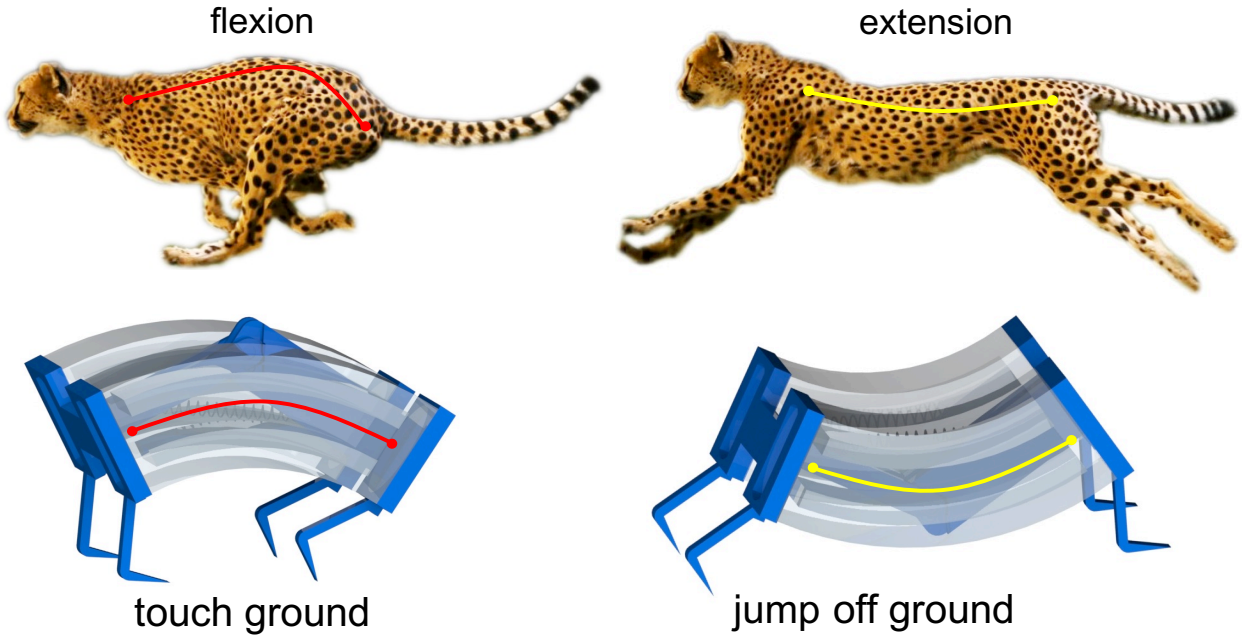
Mechanical Instabilities in Nature and Engineering

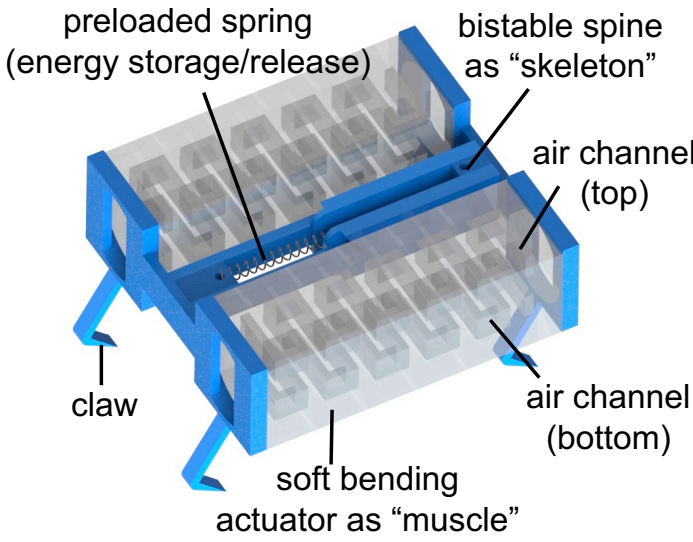


A) Fly-trap leaves. B) Rapid beak closure of hummingbirds. C) Foldable earwig wings. D) Hair clippers. E) Popper jumping toys. F) Tape measures. G) Bottle caps. H) Balloon.

Chi et al., Adv. Mater., 34, 2110384 (2022)

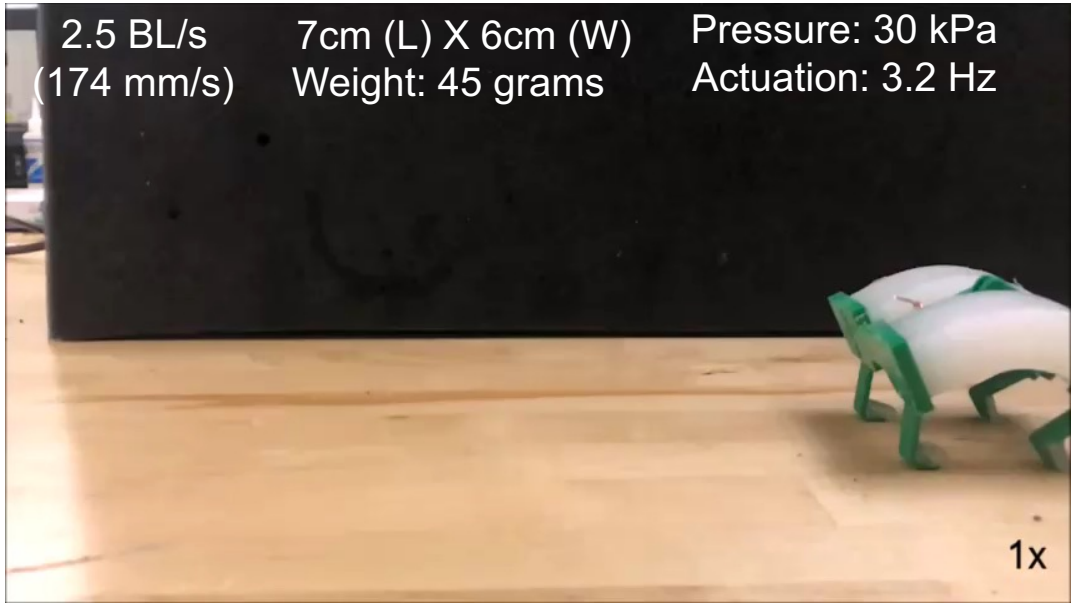
Cheetah-inspired Galloping Bistable Spined Soft Robots

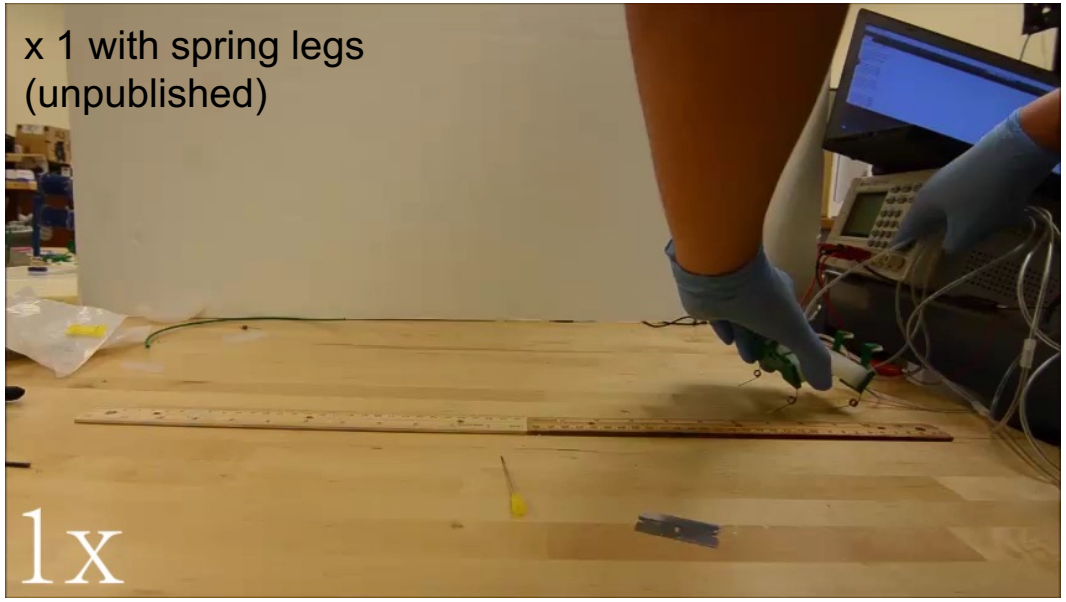


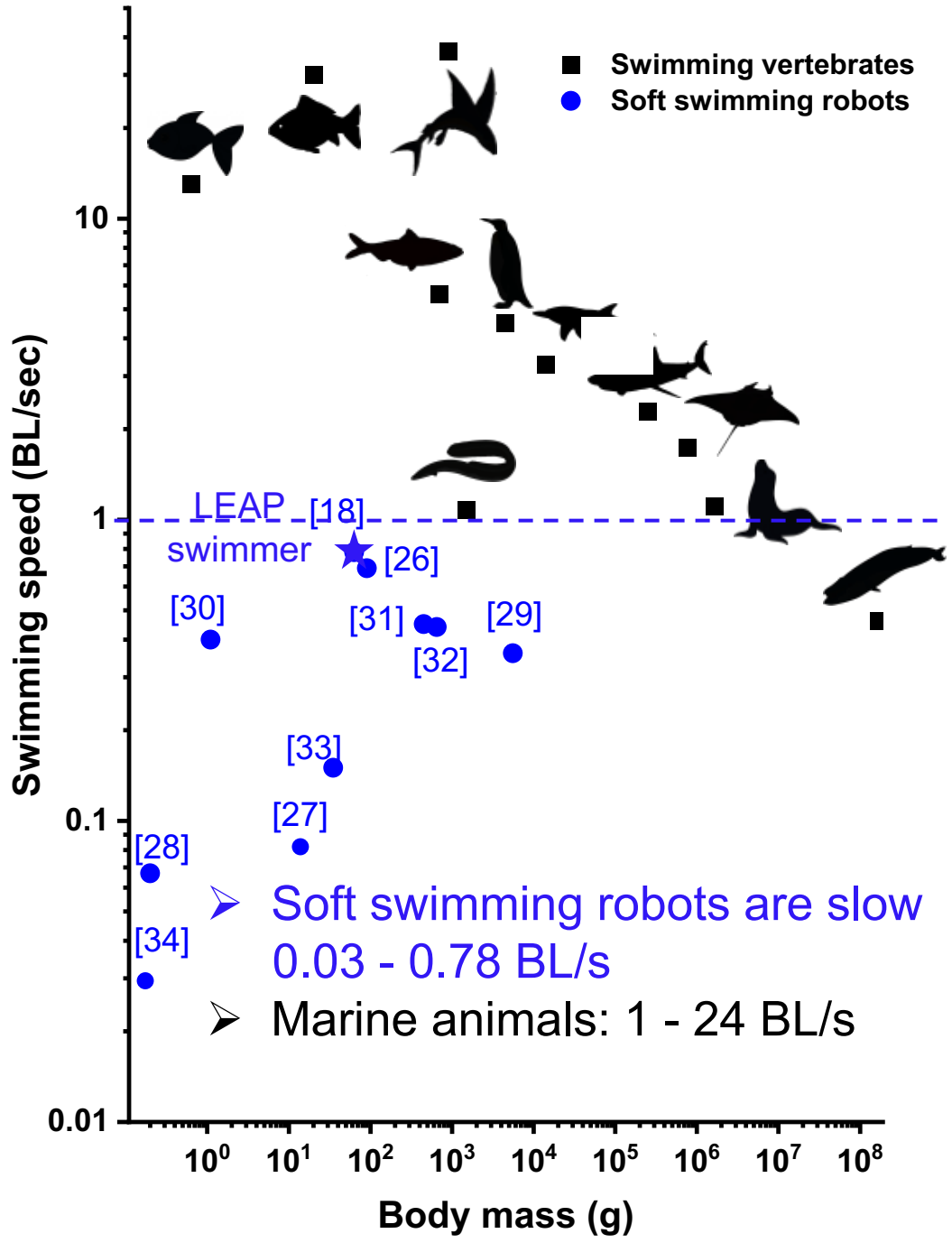


Dr. Yichao Tang
(2014-2018, Temple)

(Y. Tang, et al., Sci. Adv. 6, eaaz6912, 2020)







- Soft swimming robots are slow 0.03 - 0.78 BL/s
- Marine animals: 1 - 24 BL/s

letters to nature

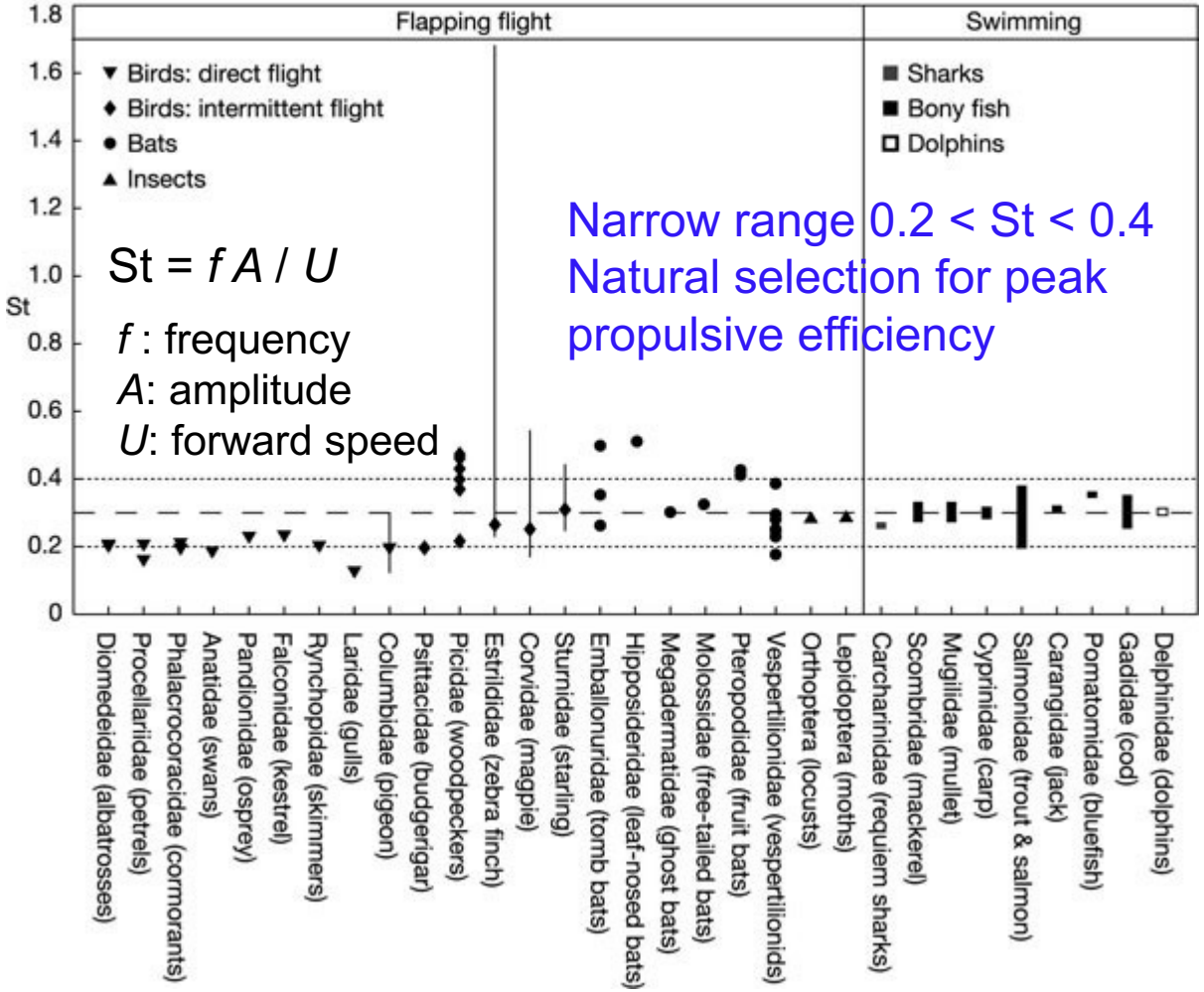
(Taylor, et al., Nature, **425**, 707, 2003)

Flying and swimming animals cruise at a Strouhal number tuned for high power efficiency

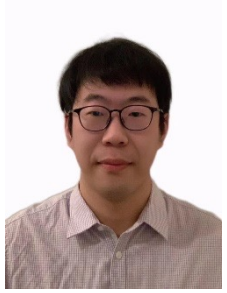
Graham K. Taylor, Robert L. Nudds* & Adrian L. R. Thomas

Zoology Department, University of Oxford, Tinbergen Building, South Parks Road, Oxford OX1 3PS, UK

Can we achieve a high-speed and high-efficient swimming soft robot comparable to marine animals?



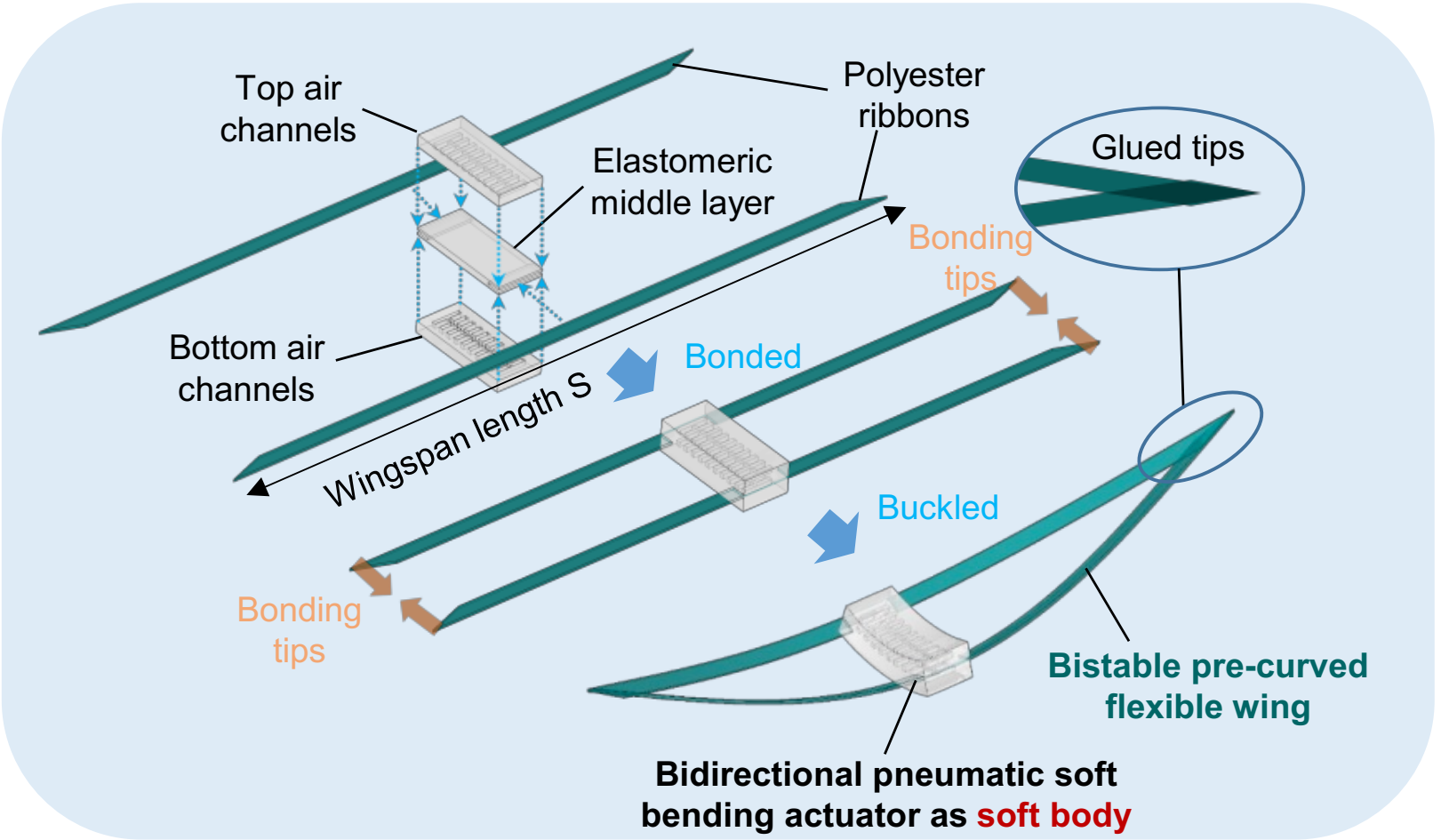
Bistable Soft Flapping Actuator: Soft Body + Bistable Wings



Dr. Yinding Chi
(2018 – 2022, NCSU)

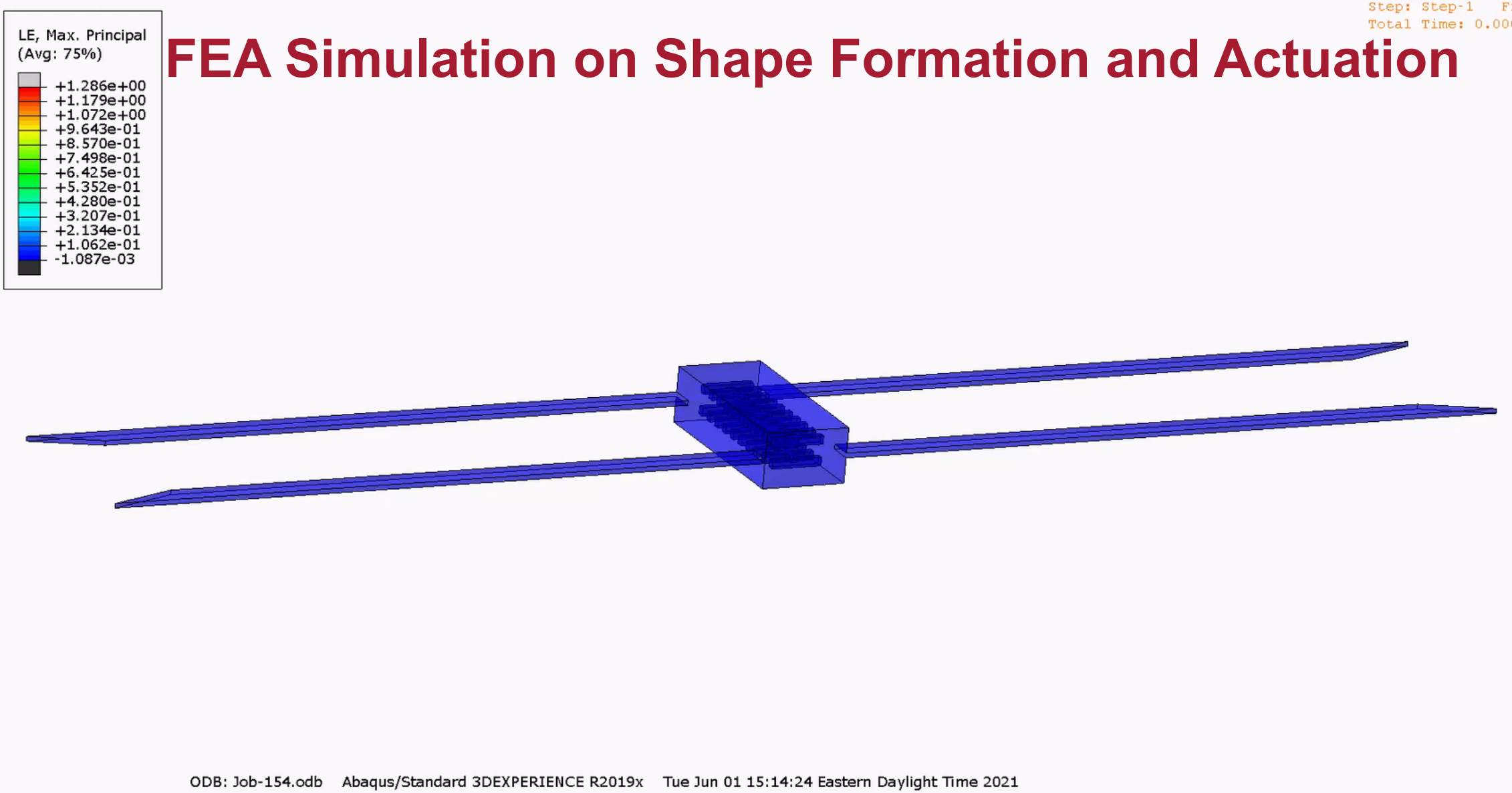
Hair clips

Schematics of fabrication

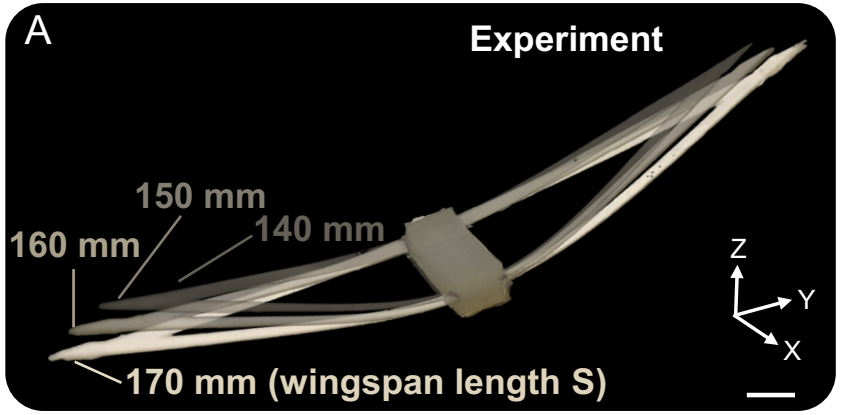


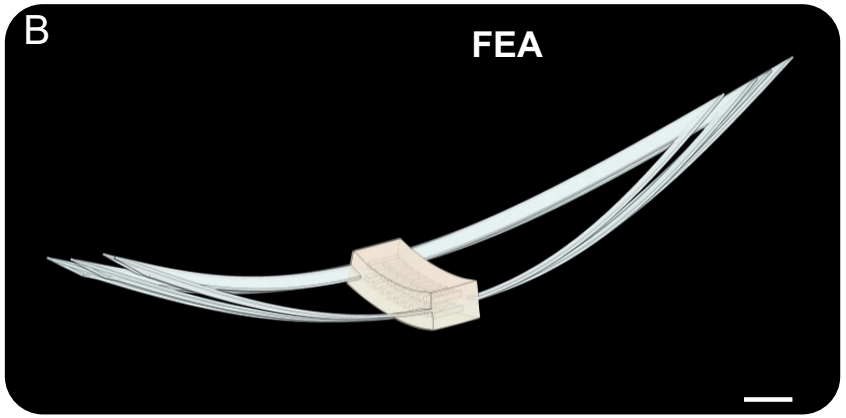
(Chi et al., Sci. Adv., in press, 2022, arXiv:2204.05987)

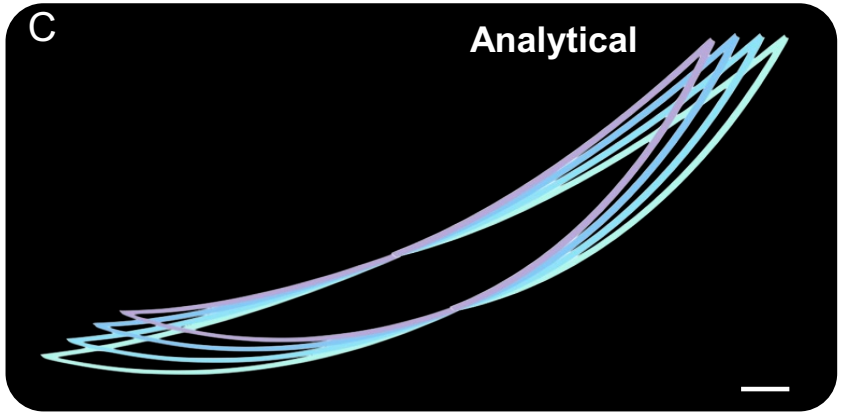
FEA Simulation on Shape Formation and Actuation



Tunable Bistable Wing Shapes by Wingspan Length S

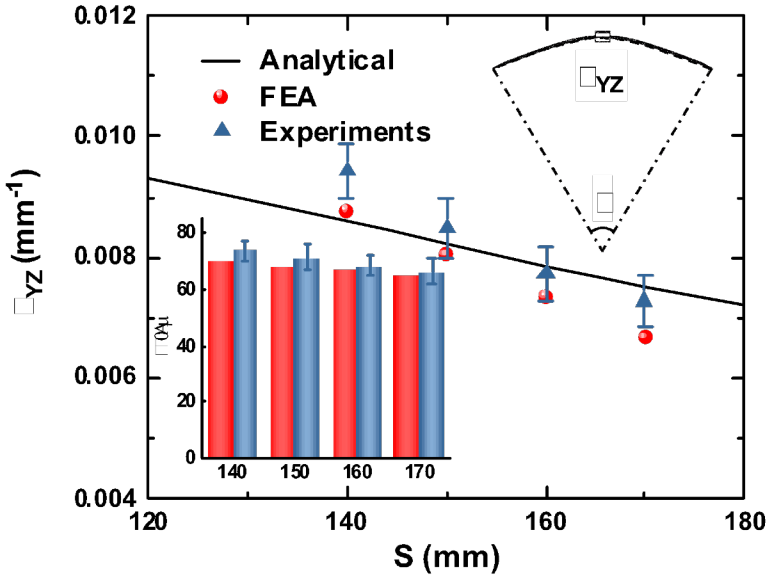




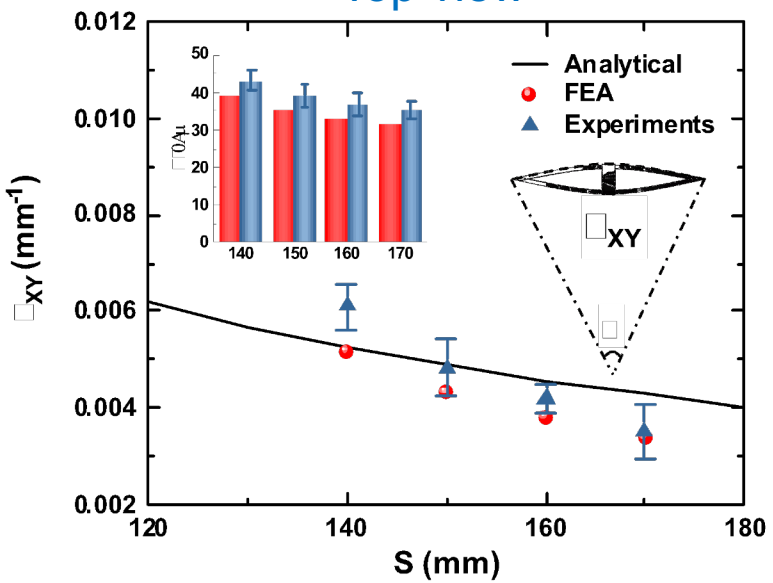


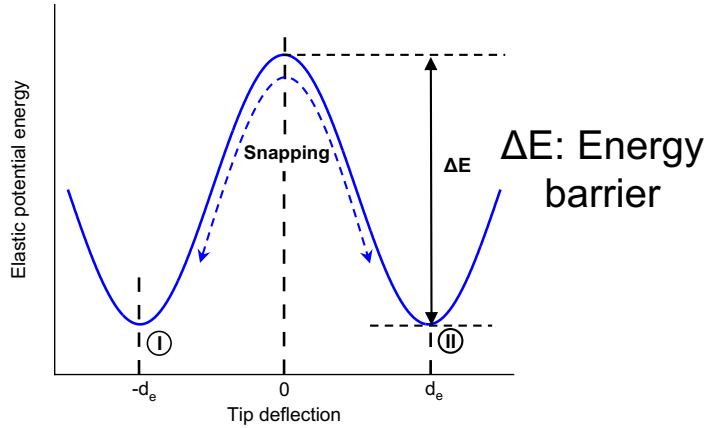
$$U = a\,\kappa_{XY}^{\,2} + b\,\kappa_{YZ}^{\,2} + (1+c)\,\tau^2$$

Front view



Top view



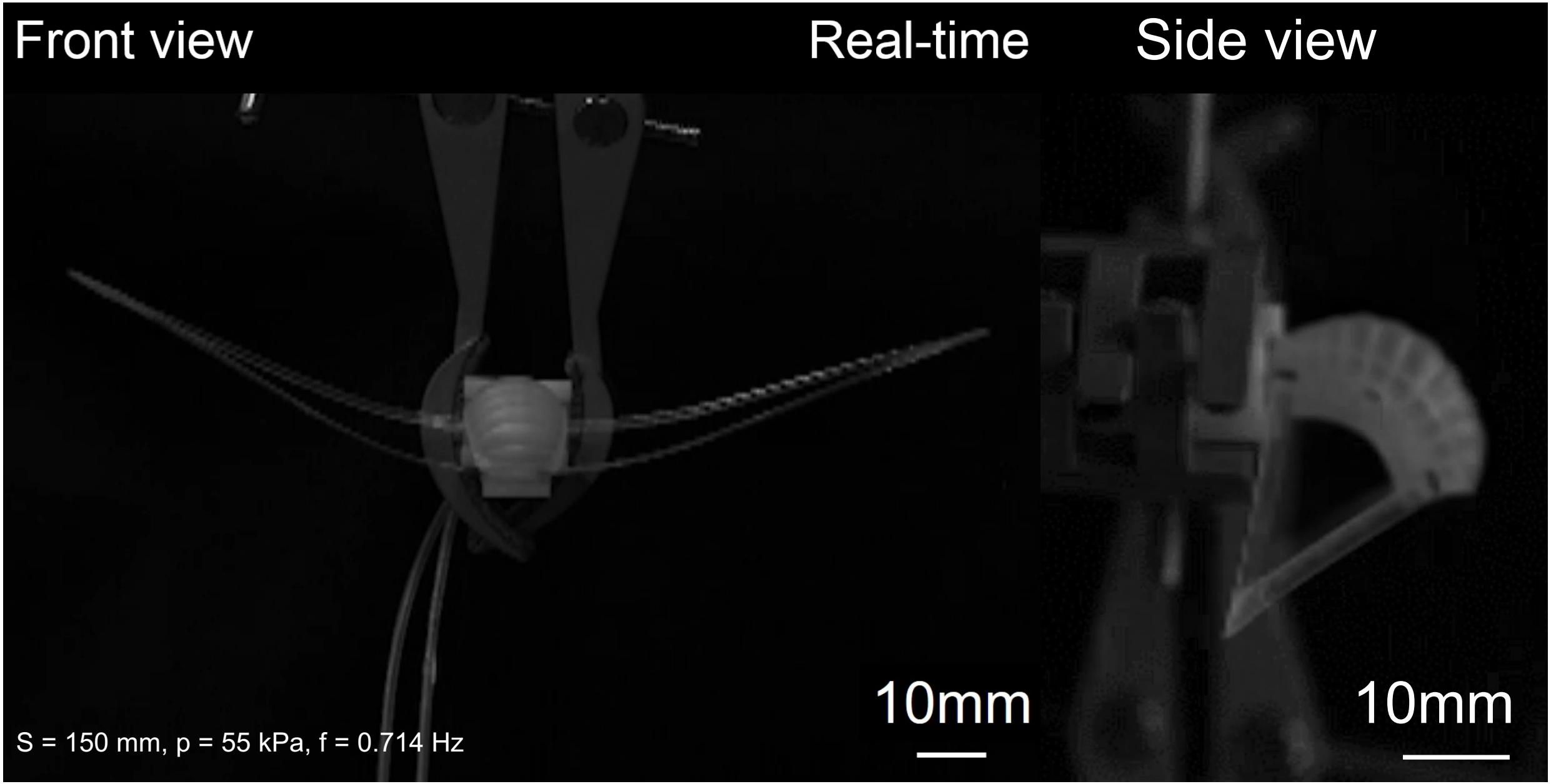


ΔE: Energy barrier

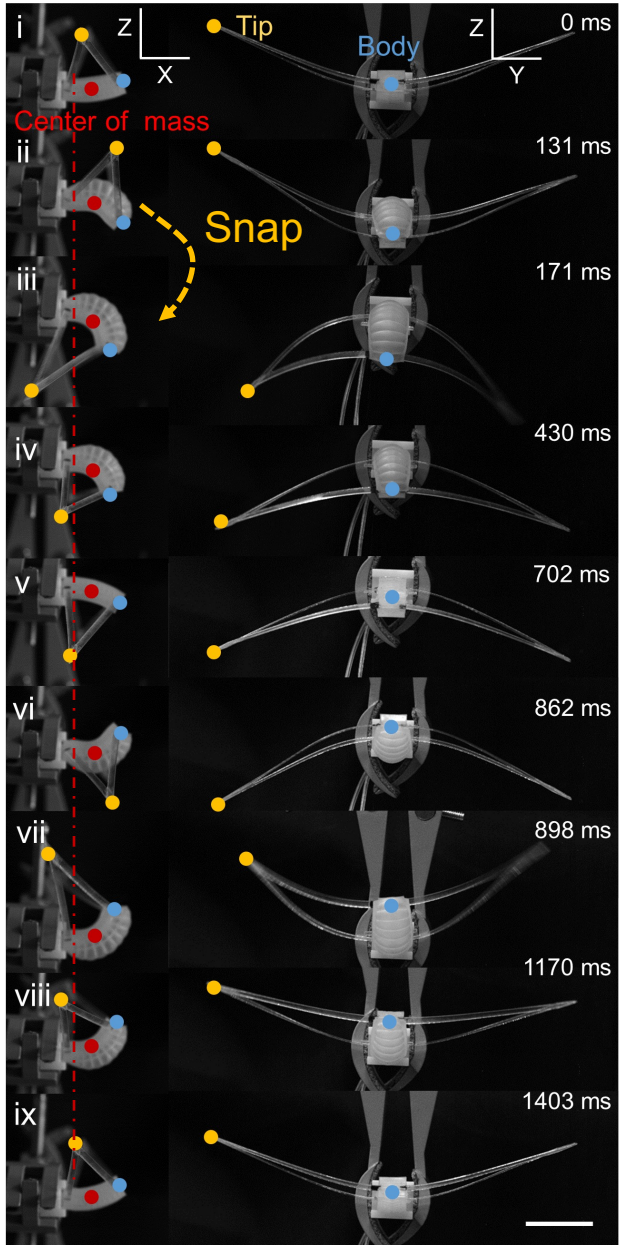
- Tip bonding induces both bending and torsion of the wings
- The smaller the S, the larger the κ and ΔE

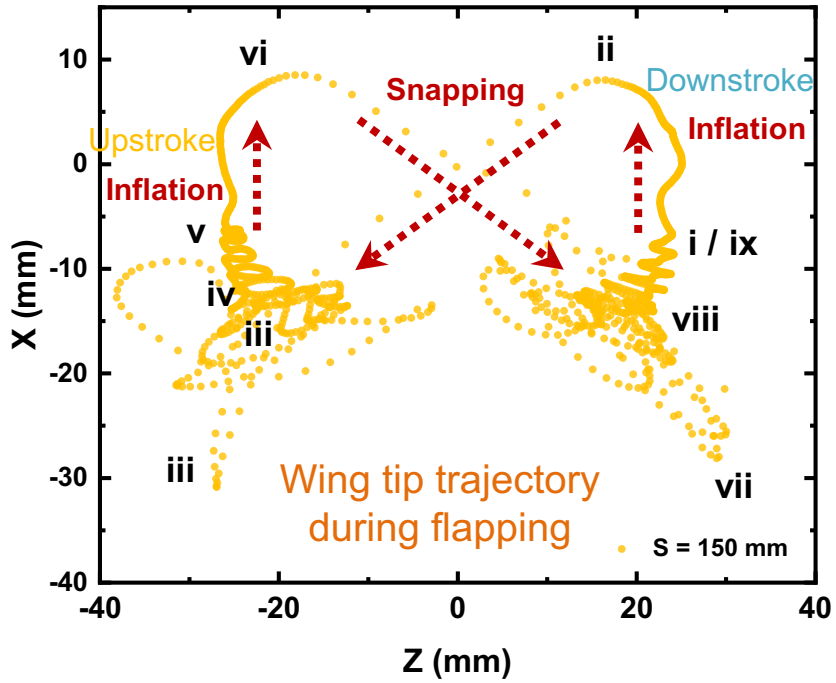
(Chi et al., Sci. Adv., in press, 2022, arXiv:2204.05987)

Pneumatic Actuated Body Induced Snapping and Flapping Wings



Bird-like Figure-of-eight Wing Flapping Mode

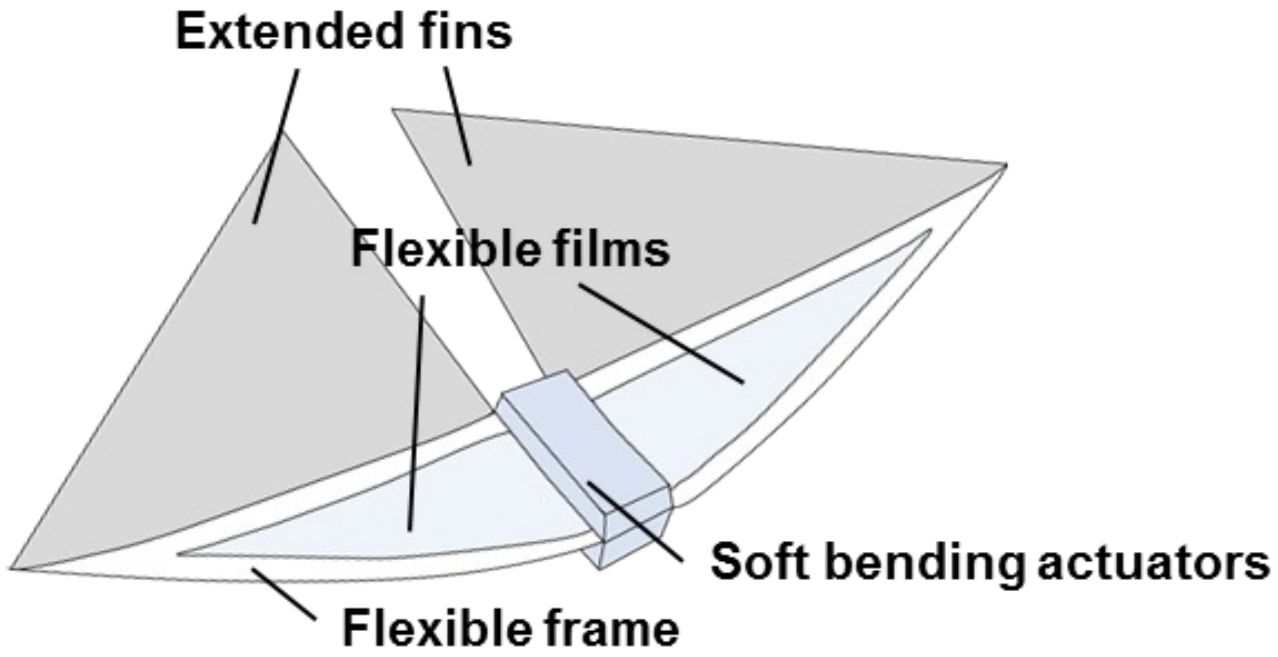




- Snapping time: ~ 40 ms, snapping speed: ~ 10 m/s, snapping acceleration: ~ 2,550 m/s^2, large flapping angle (– 38^o, + 38^o)
- The wing tip undergoes simultaneous large deflection and 360^o clockwise rotation during one flapping cycle
- The bistable flapping actuator can achieve the similar figure-8 flapping mode to birds and bees

(Chi et al., Sci. Adv., in press, 2022, arXiv:2204.05987)

Fast-Speed Bistable Soft Flapping Swimmer



150mm

Real-time 1Hz

Soft body: 22.8 × 10 × 6.55 (mm), Total mass: 2.8 gram
Wingspan length S = 150 mm, p = 55 kPa

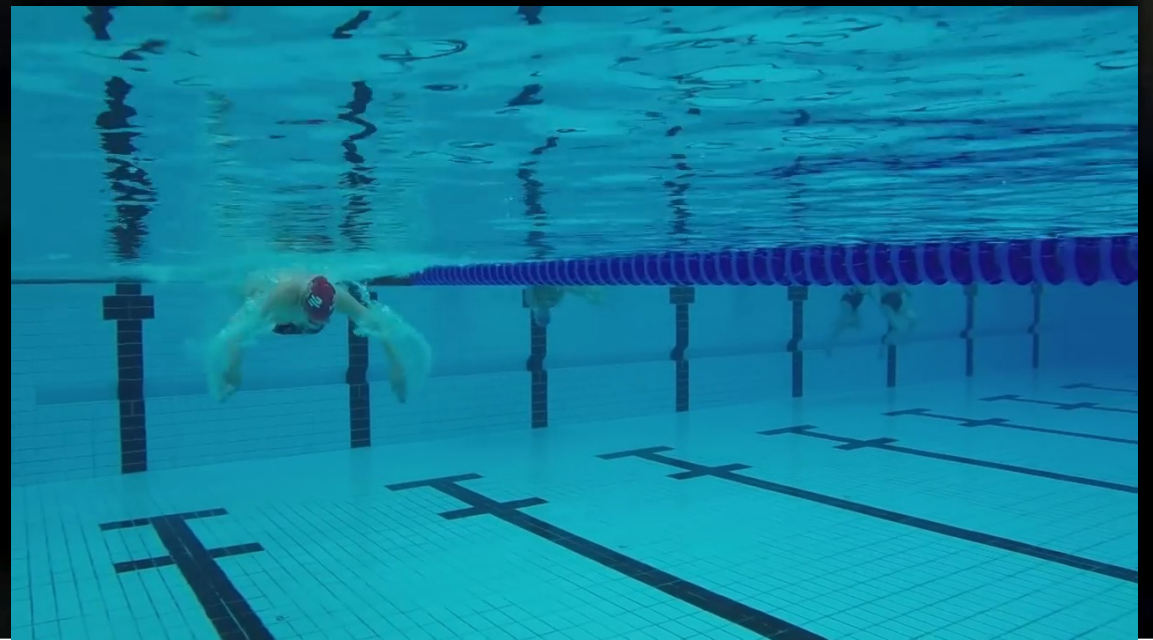
20 mm


150mm
1/10 X
0.4Hz
20mm

150mm

Butterfly Swimming-like Soft Flapping Swimmer

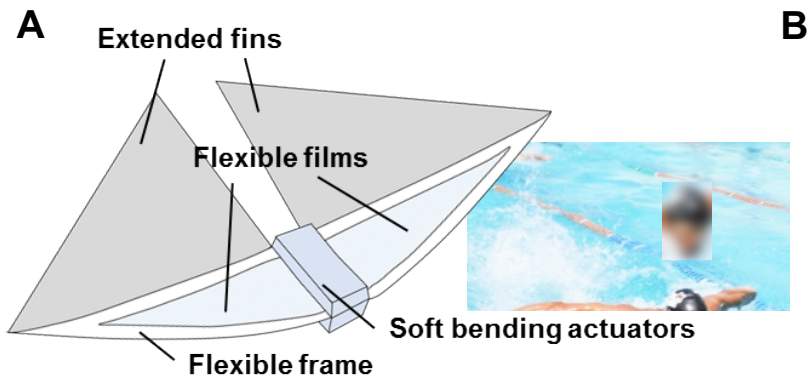
1/10 X
0.4Hz

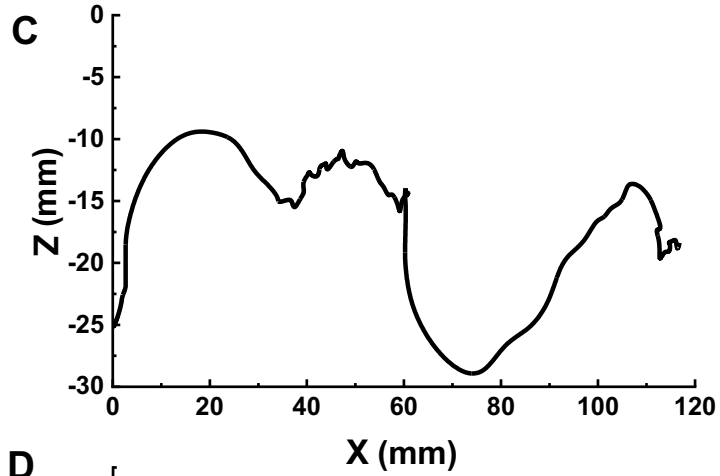


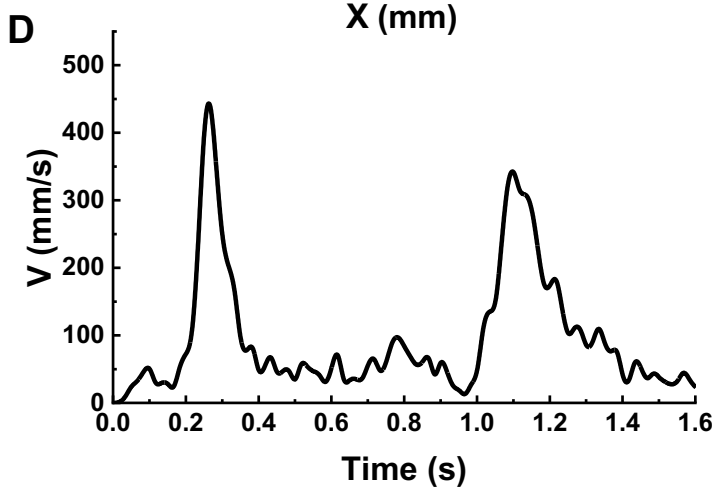
20mm

Undulating body motion

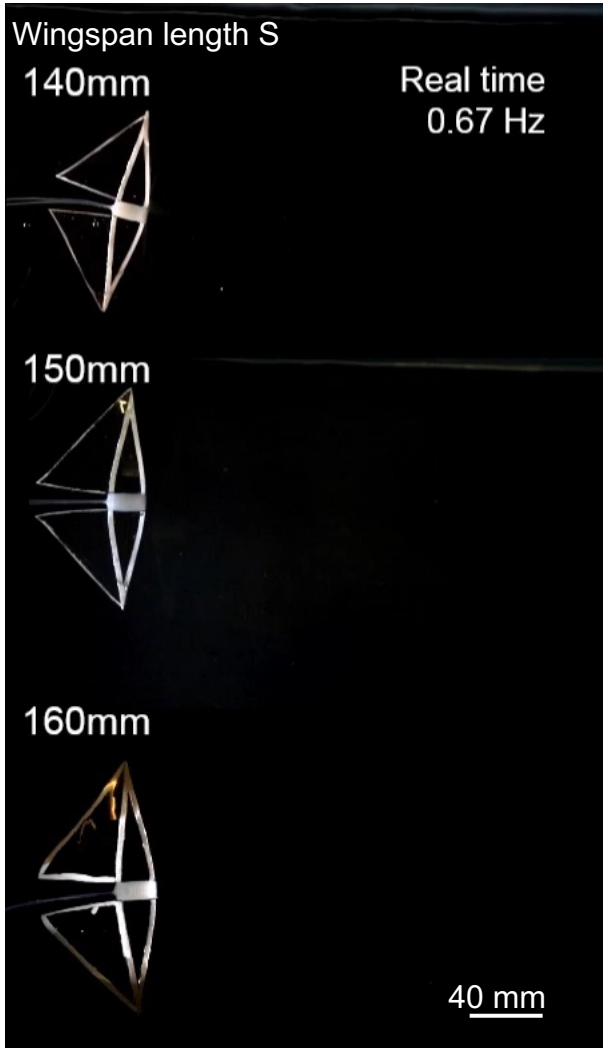
Burst-and-coast swimming style for higher thrust force at a low frequency

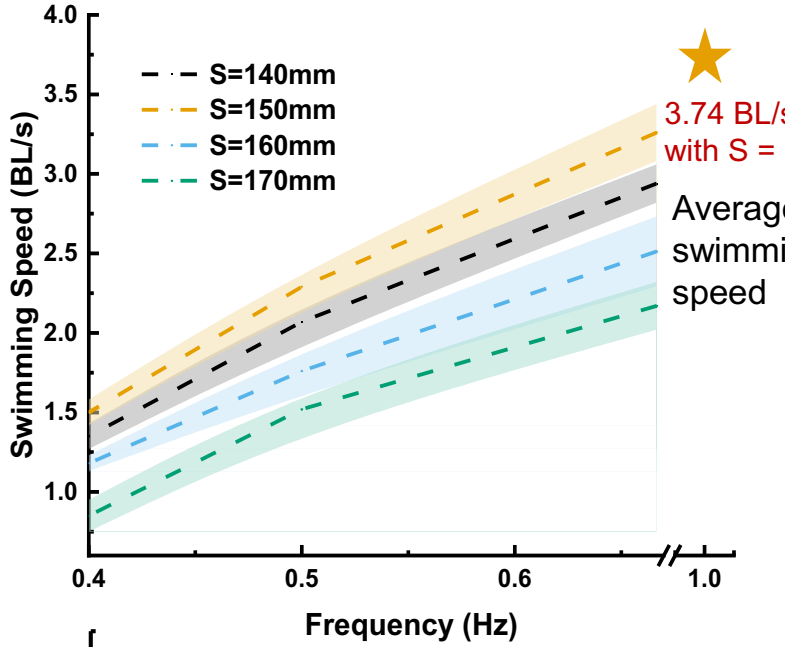


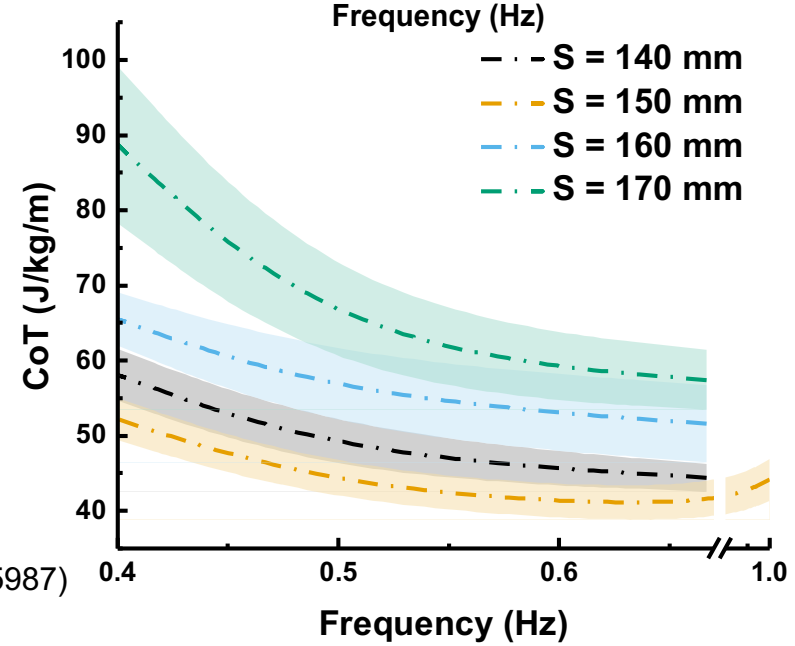




Moderate S Achieves the Fastest Speed at the Lowest CoT





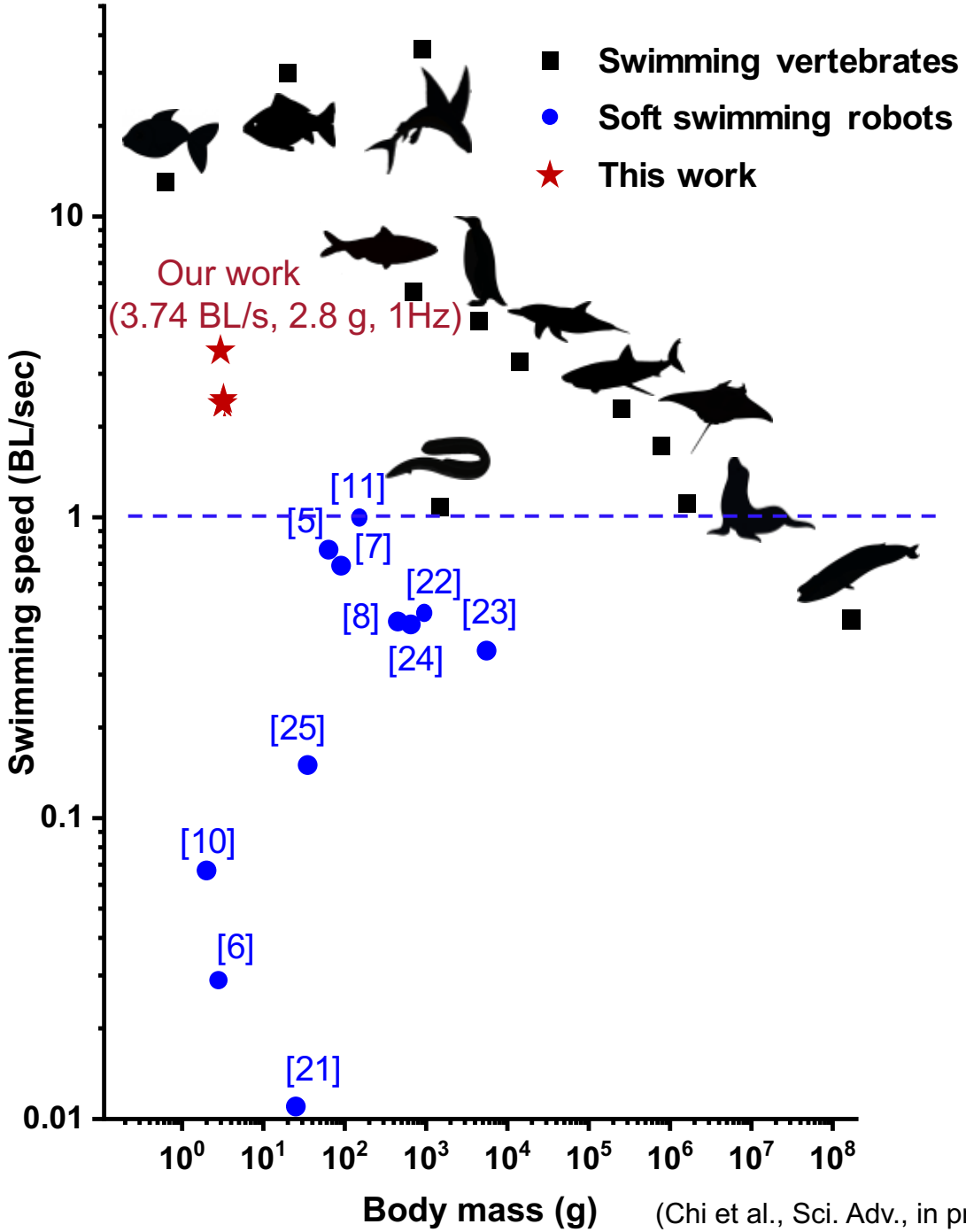


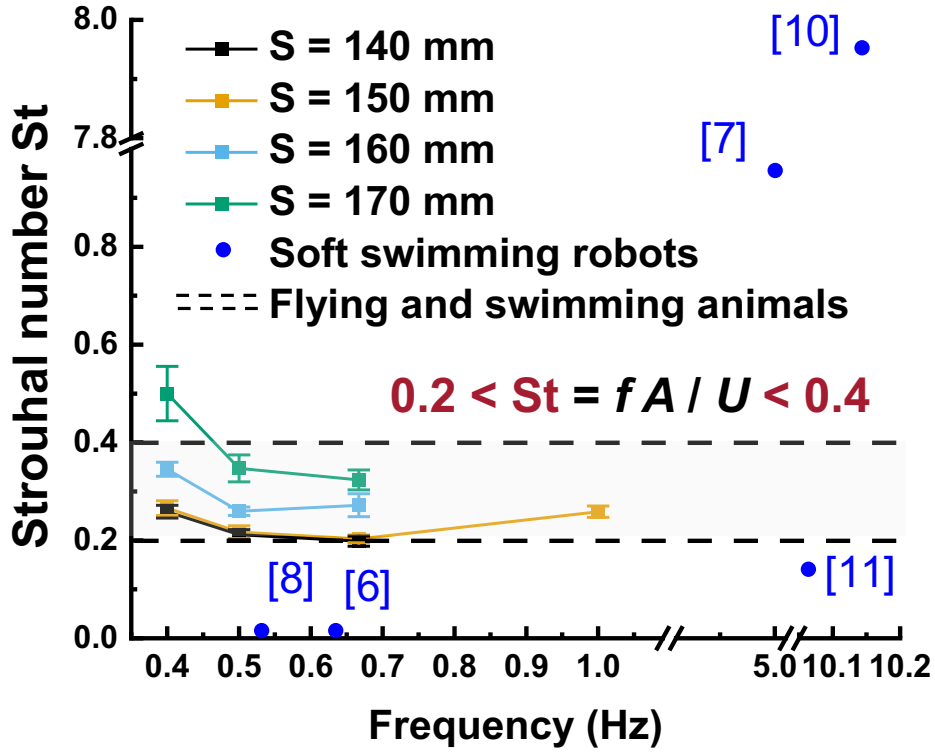
- Smaller S → Higher snapping-induced dynamic block force
- Smaller S → Smaller solid-fluid interaction surface area

Cost of Transport (CoT)

$$\mathrm{CoT} = \frac{E}{(m \times g \times d)}$$

(Chi et al., Sci. Adv., in press, 2022, arXiv:2204.05987)

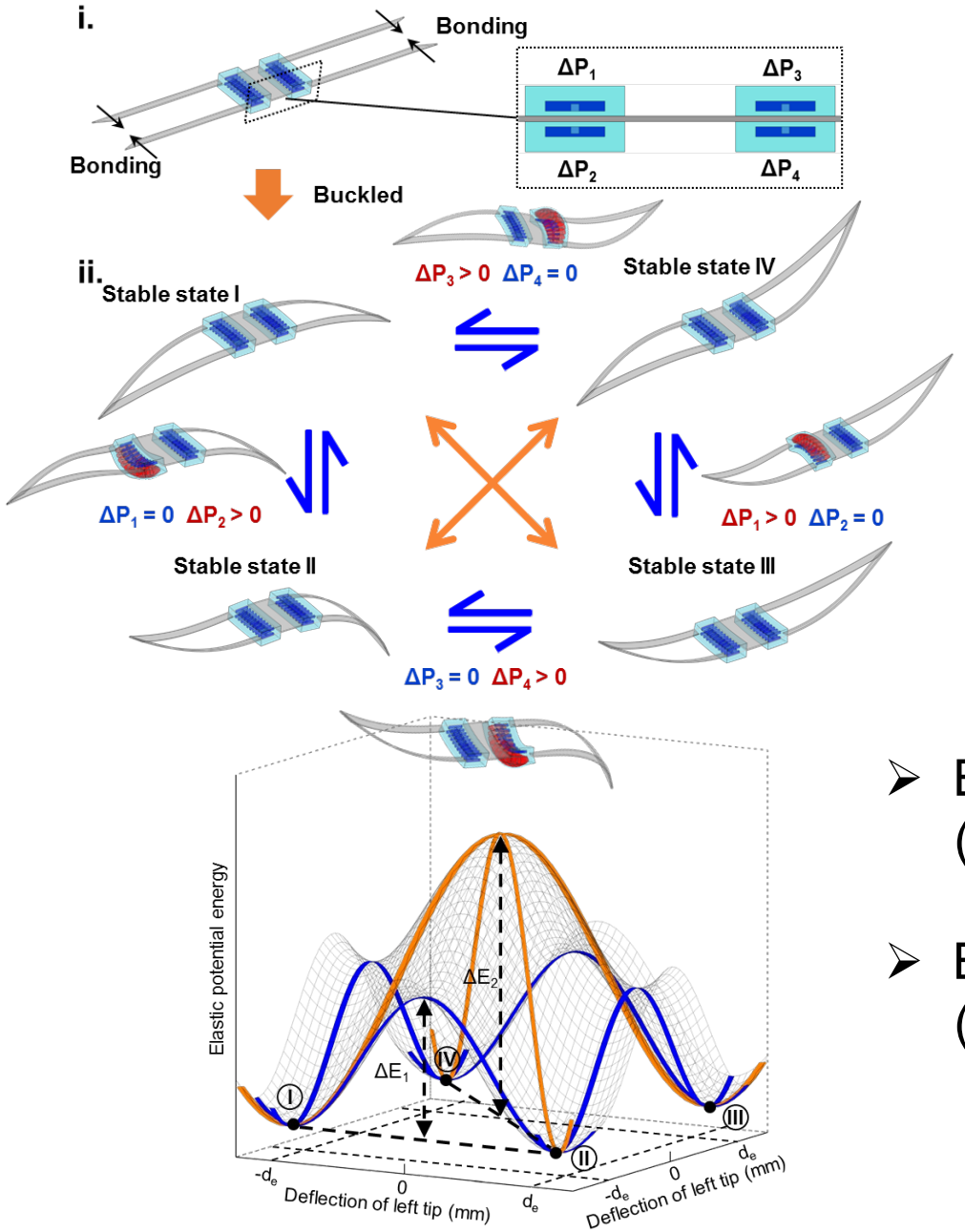


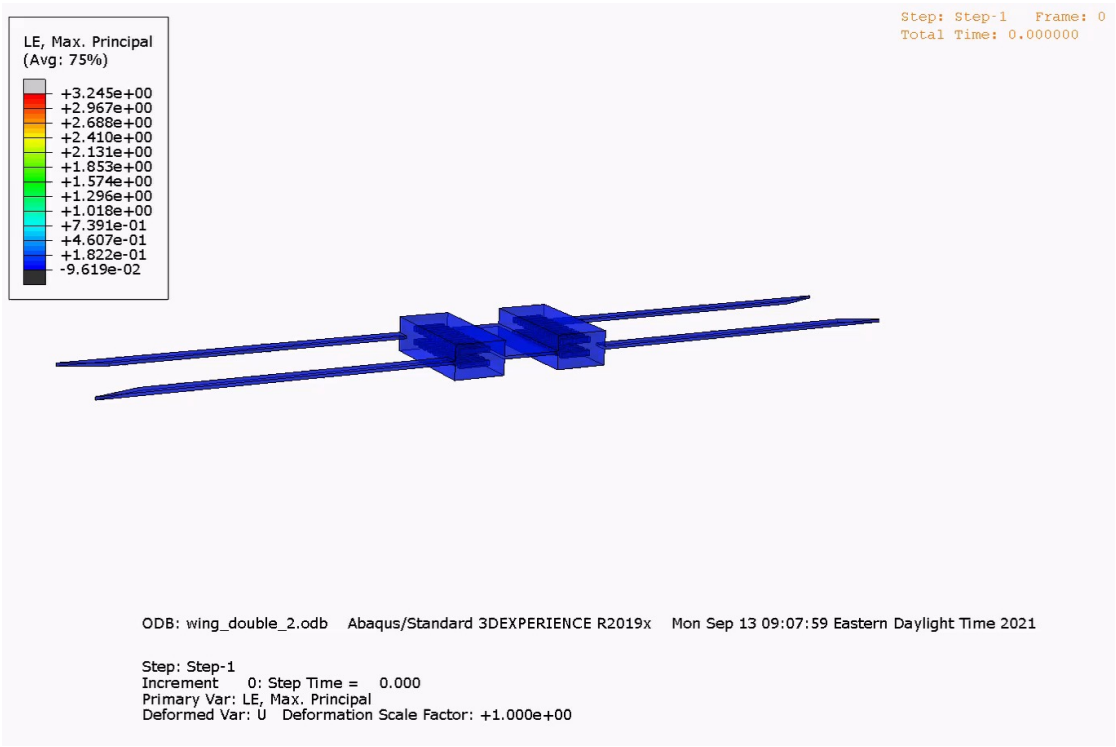


Our flapping robot achieves high speed & high energy efficiency comparable to animals!

(Chi et al., Sci. Adv., in press, 2022, arXiv:2204.05987)

Multistable Soft Flapping Actuator





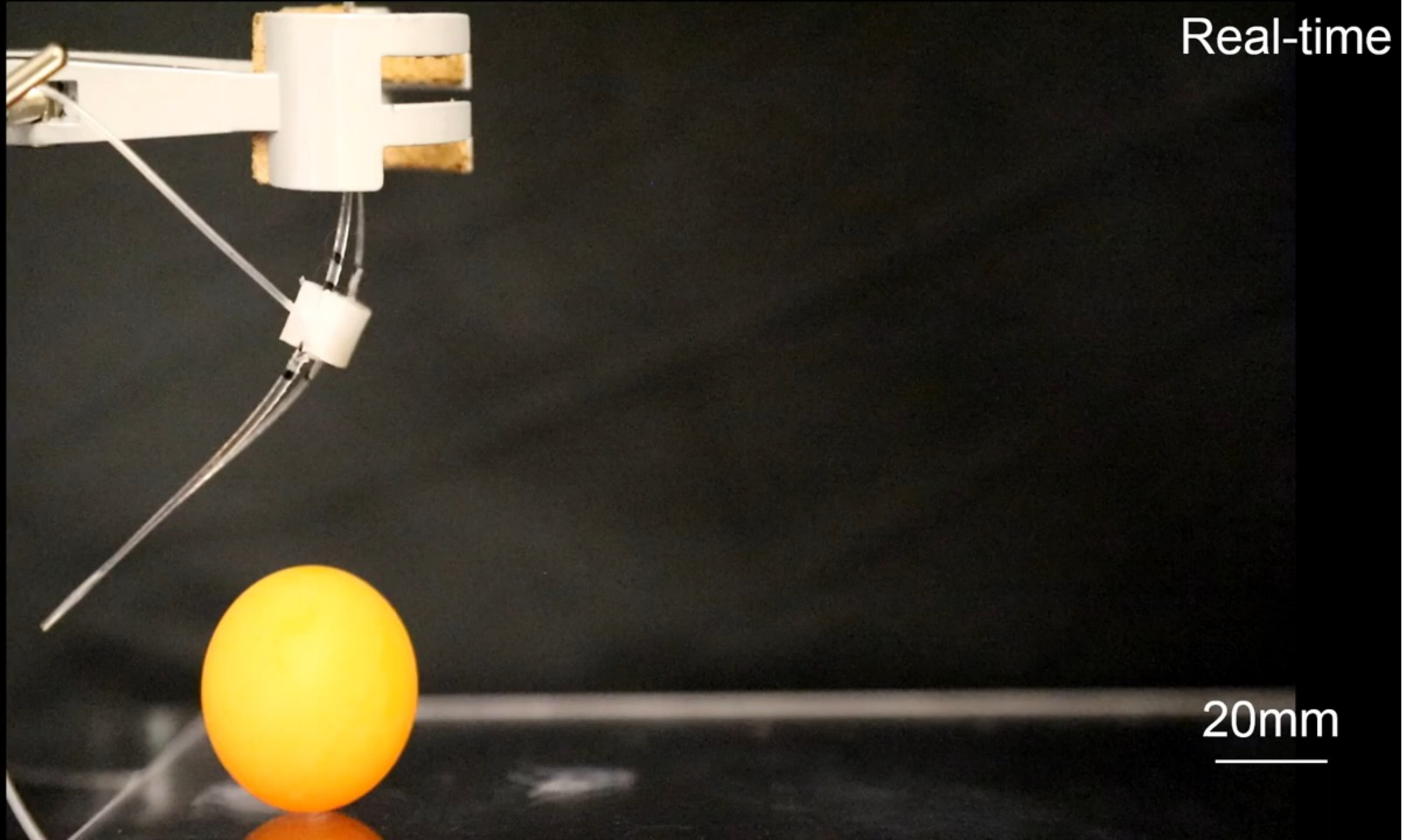
- Either wing can be actuated independently (mono-actuation for breaking symmetry: steering)
- Both wings can be actuated simultaneously (double actuations for flipping: directional propulsion)

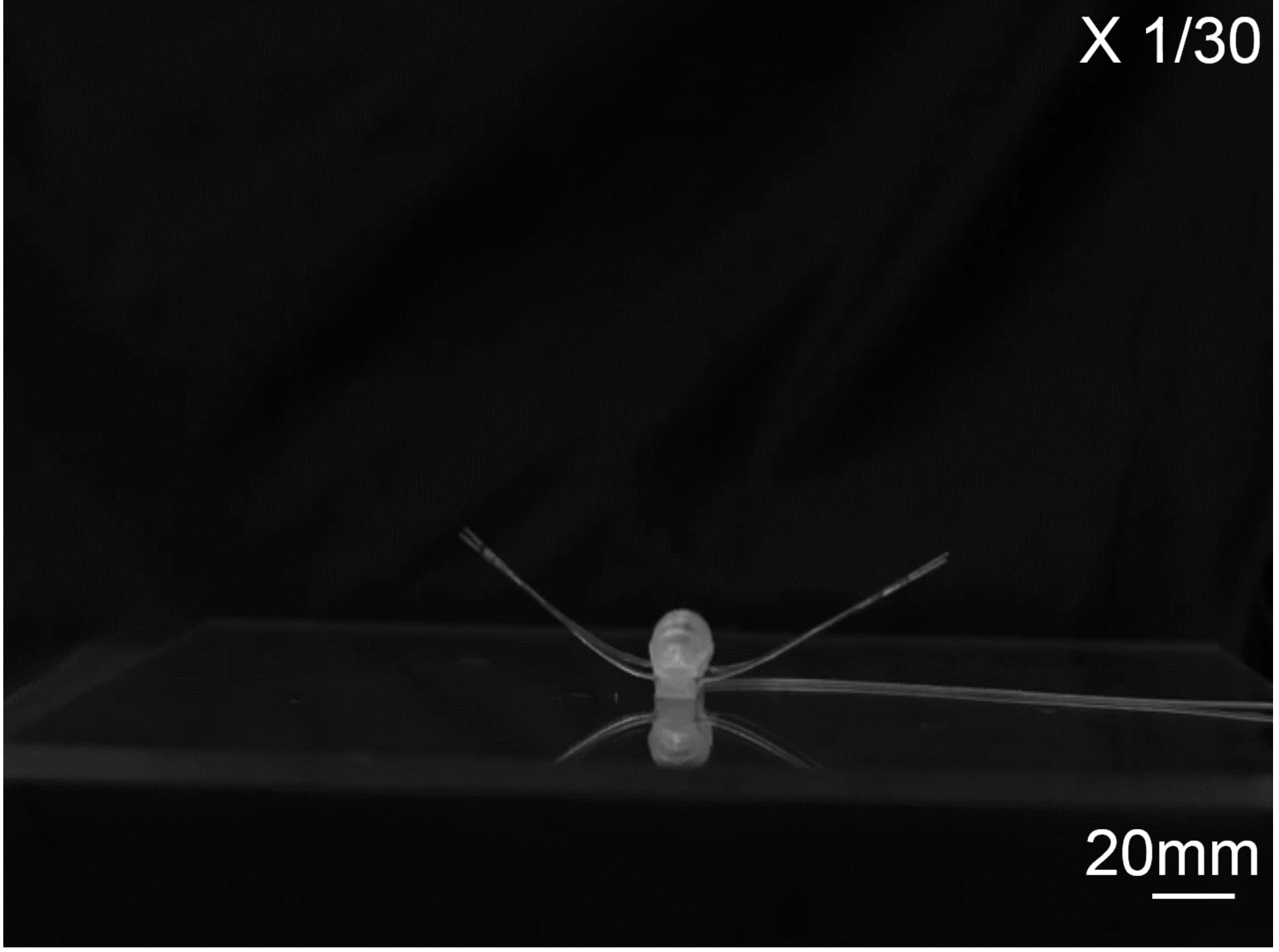
Multistable Maneuverable Soft Flapping Swimmer

Real time

Turn right → Directional → Turn left → Directional → Speeding up

20 mm


Real-time
20mm

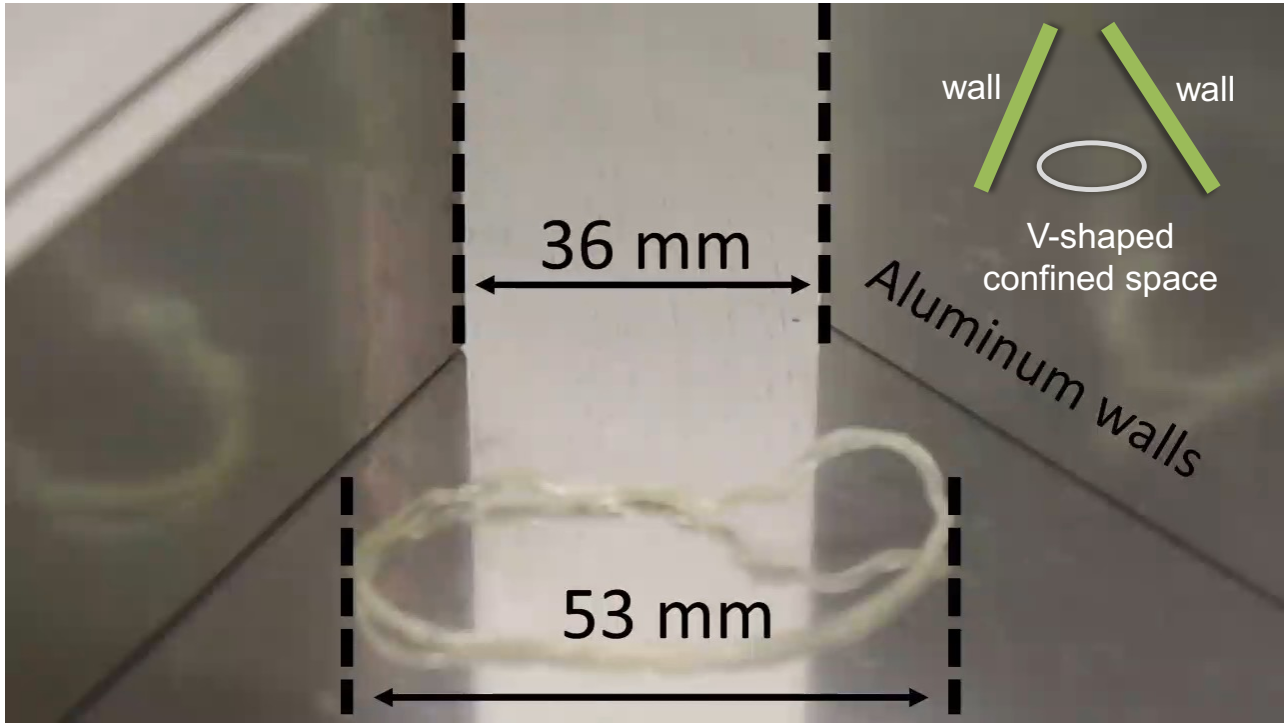

X 1/30
20mm

Conclusion

Structure Intelligence (SI)

- Leveraging rational designs of advanced structures (e.g., bistability and multistability) can achieve high performance in soft robotics (e.g., fast and efficient locomotion, multimodal locomotion etc.,)

Acknowledgement

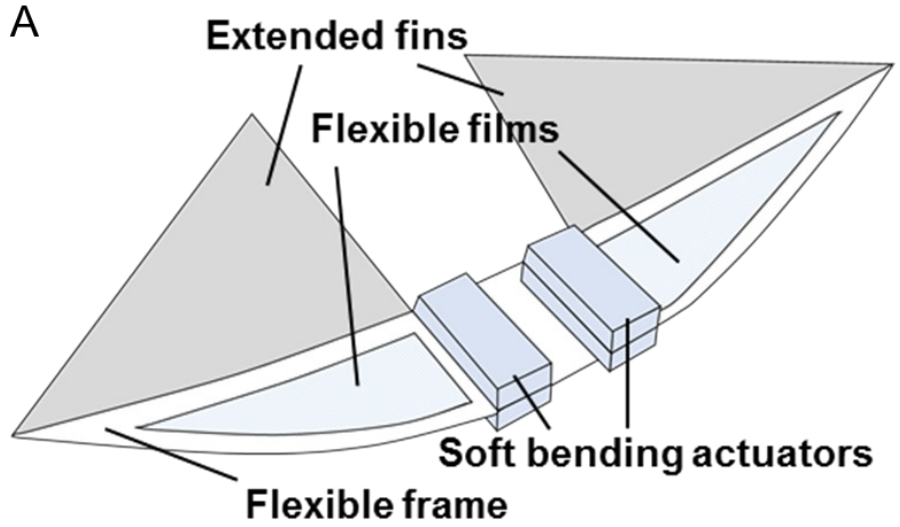


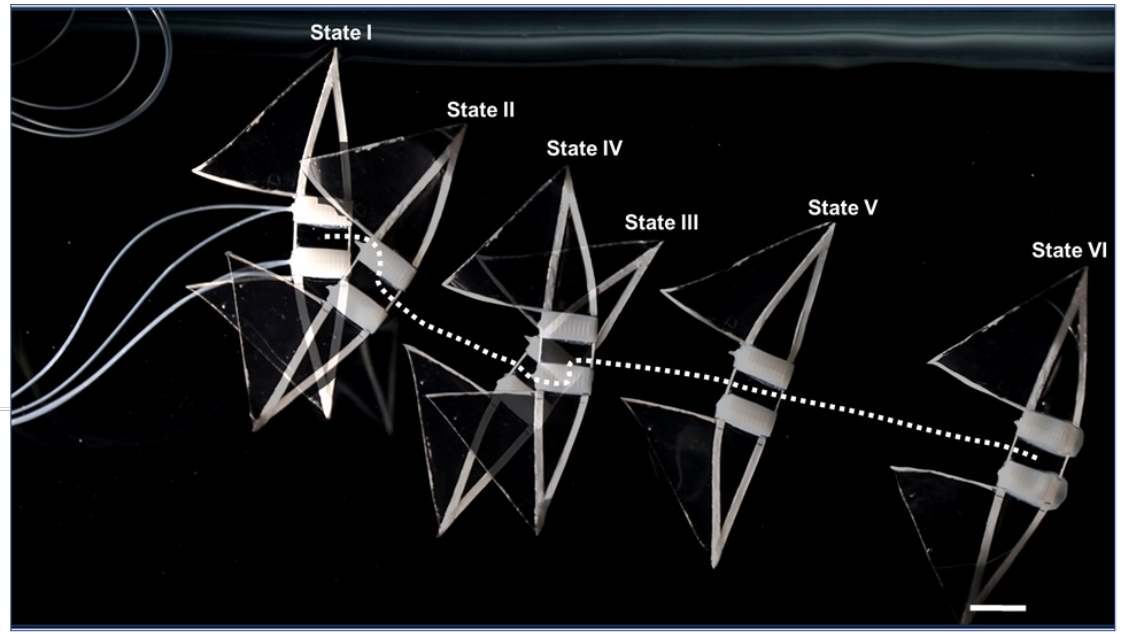
(Zhao, et al., Adv. Mater., 35, 2207372, 2023)

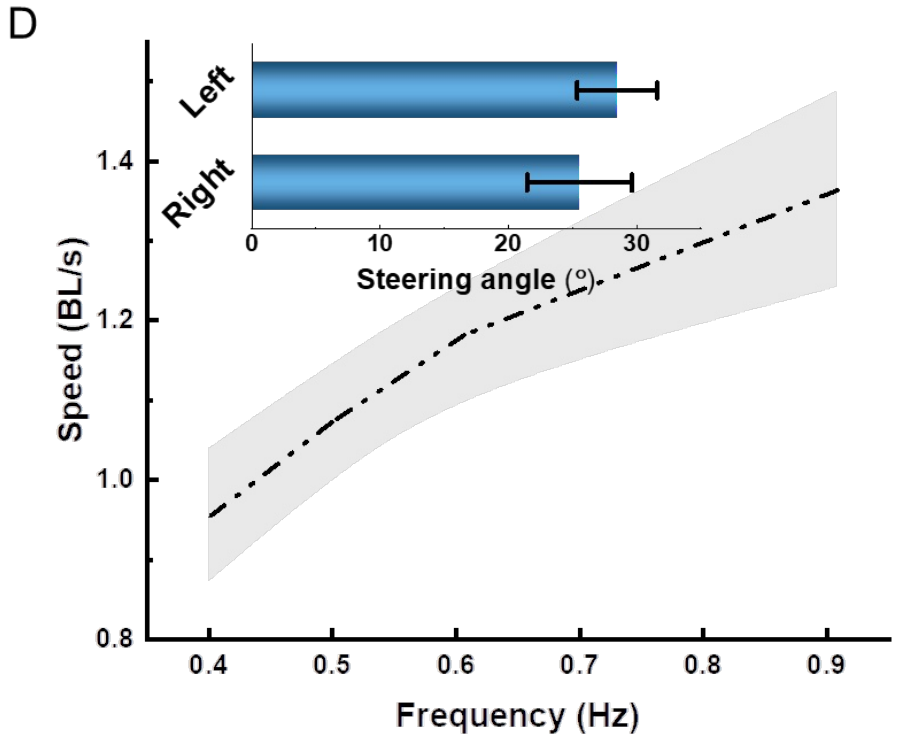
(2126072, 2010717)

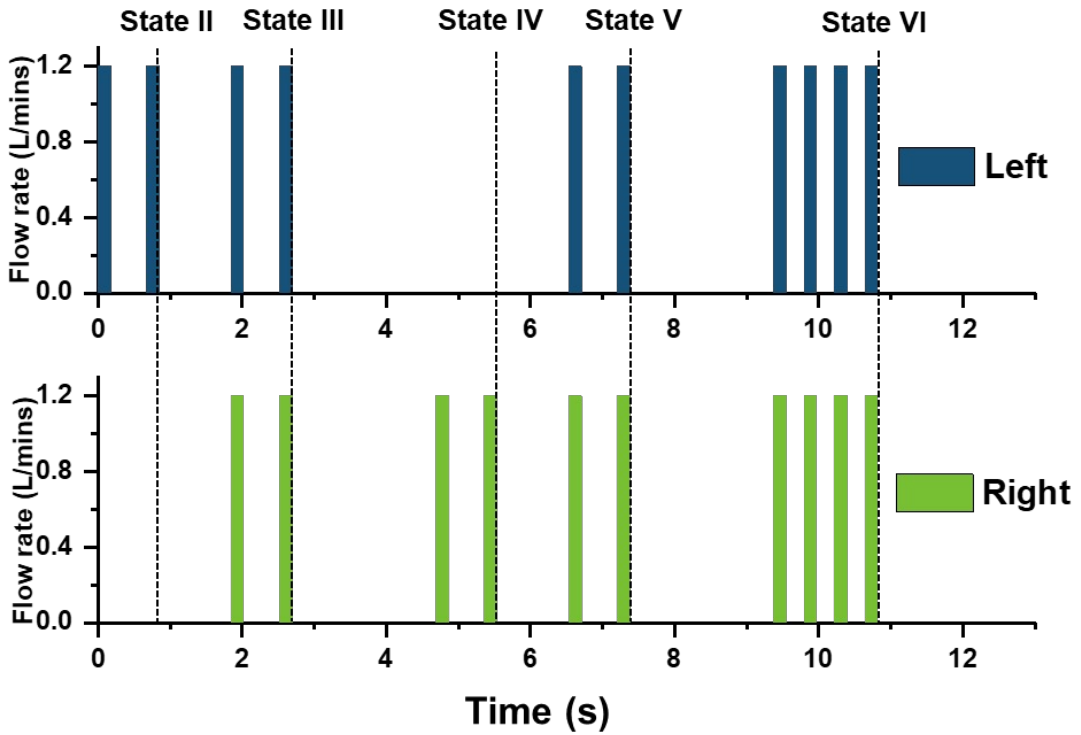
Thank you!

Questions?


A
Extended fins
Flexible films
Soft bending actuators
Flexible frame


B
State I
State II
State IV
State III
State V
State VI


D
Left
Right
0
10
20
30
Steering angle (°)
Speed (BL/s)
0.8
1.0
1.2
1.4
0.4
0.5
0.6
0.7
0.8
0.9
Frequency (Hz)


C
State II
State III
State IV
State V
State VI
Flow rate (L/mins)
0.0
0.4
0.8
1.2
0
2
4
6
8
10
12
Left
Right
Time (s)