How can compliance enhance locomotion?

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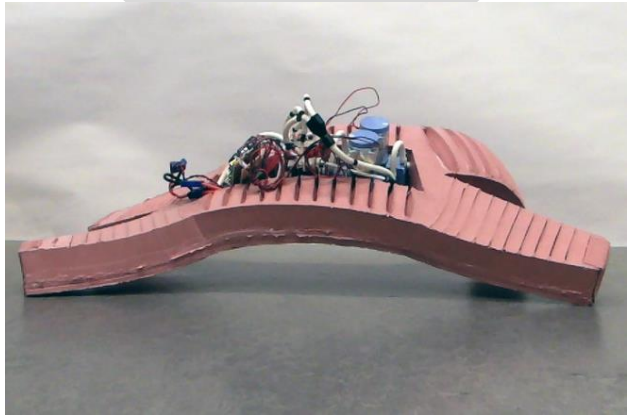
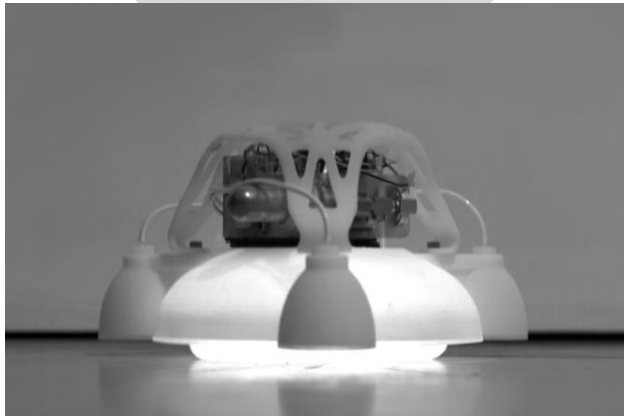
Biologically Inspired Robotics

Autonomous
Soft Systems



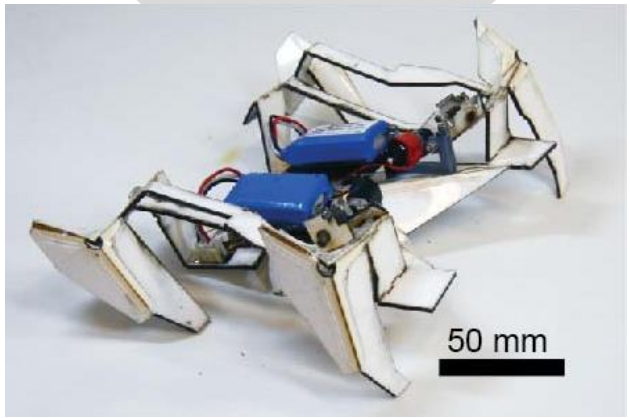
Soft Robotics, 1:3, pp. 213-223

Functionally
Graded Materials



Science, 349:6244, pp. 161-165

Self-Assembly
by Folding



Science, 345:6197, pp. 644-646

Nature provides inspiration for an alternative to rigid robots:

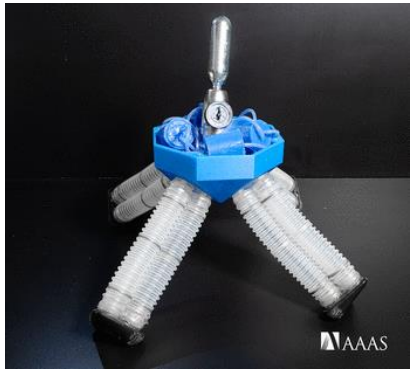
Soft actuated structures have the potential to greatly simplify control tasks for:

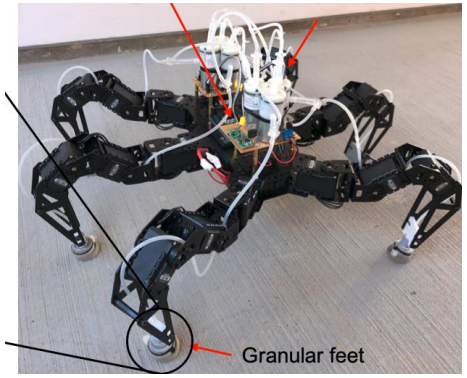
- Safe interaction with humans
- Versatile manipulation
- Interactions with a complex environment

"Incredible Suckers", PBS

Our Recent Work in Biologically Inspired Soft Robots

- **How can soft legs simplify walking?**
  - Soft pneumatic legs [ICRA 2017, T-Mech 2018]
  - Pneumatic CPG controller [Science Robotics 2021]
- **How can control of stiffness be useful?**
  - Soft jamming feet [Robosoft 2020]
  - Fiber jamming [Soft Robotics 2021]
- **How can a soft body be beneficial for swimming?**
  - Cephalopod inspired robot [Bioinsp. Biomim. 2020]



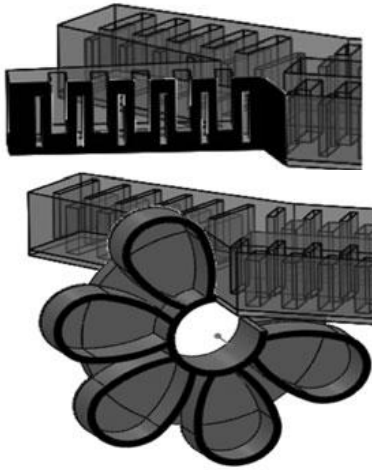


Untethered walking soft robot

Soft Quadruped in Extreme Conditions

ΔP = 0

ΔP > 0

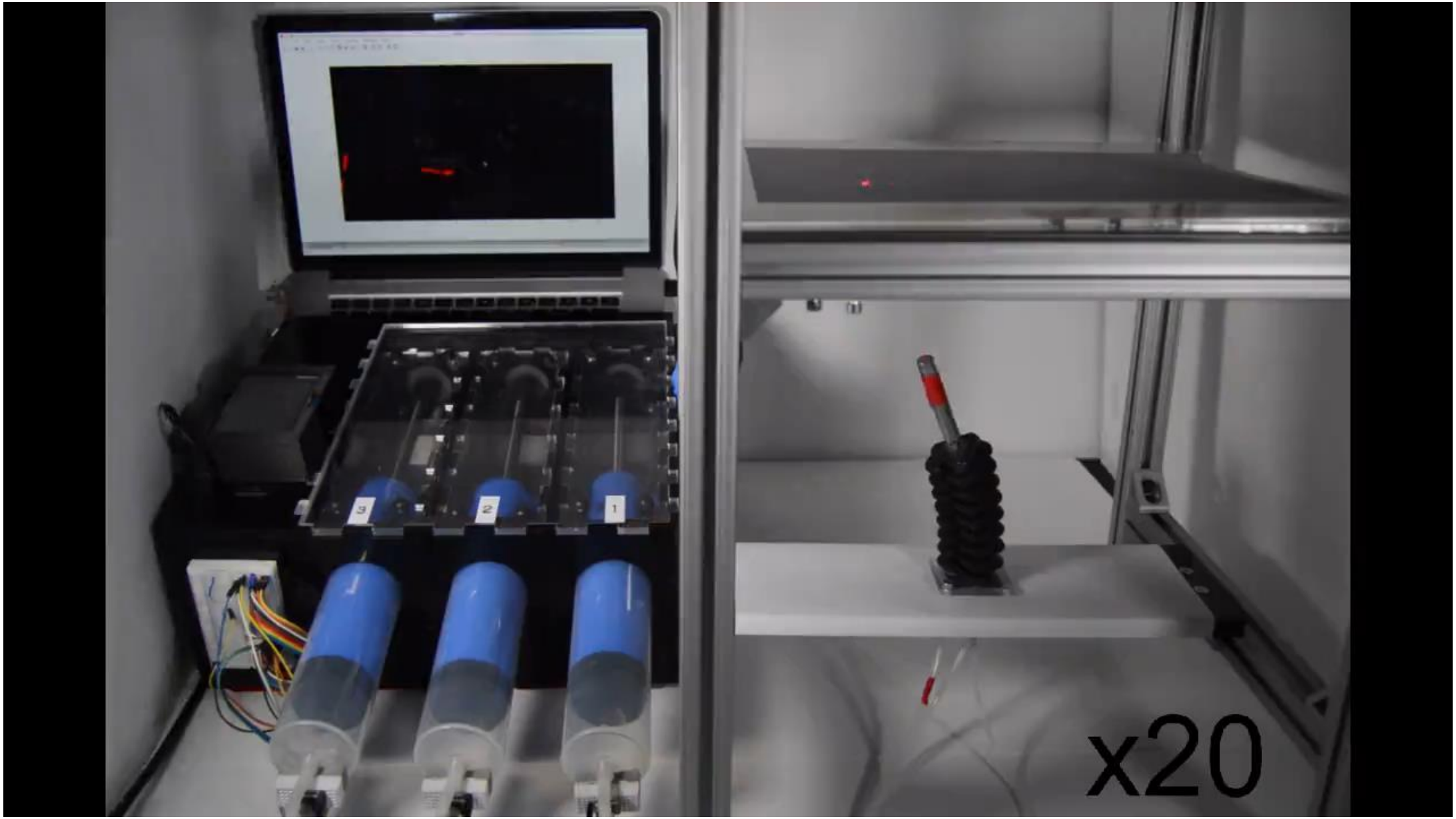


Challenges

- Fabrication
- Speed
- Dexterity
- Control
- Sensing
- Underwater locomotion

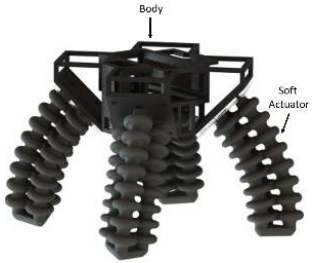
Tolley M. T., Mosadegh B., Shepherd R. F., Galloway K., Wehner M., Karpelson M., Wood R. J., Whitesides G. M., ***Soft Robotics,*** 2014.

3D printed soft modules with three active DoF

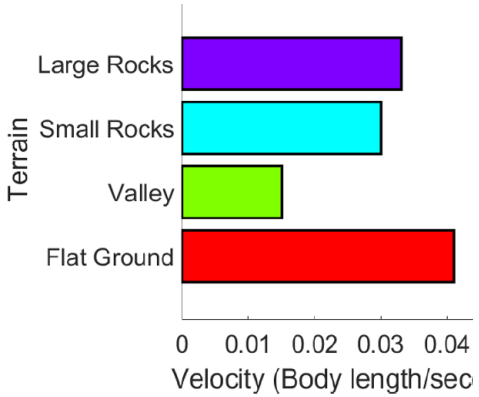


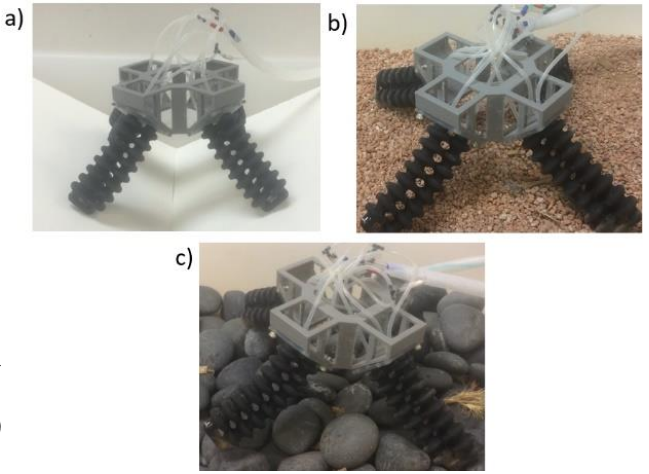
T. Kalisky, Y. Wang, B. Shih, D. Drotman, S. Jadhav, E. Aronoff-Spencer, M. T. Tolley, IROS 2017.

Soft legs simplify walking on rough terrain

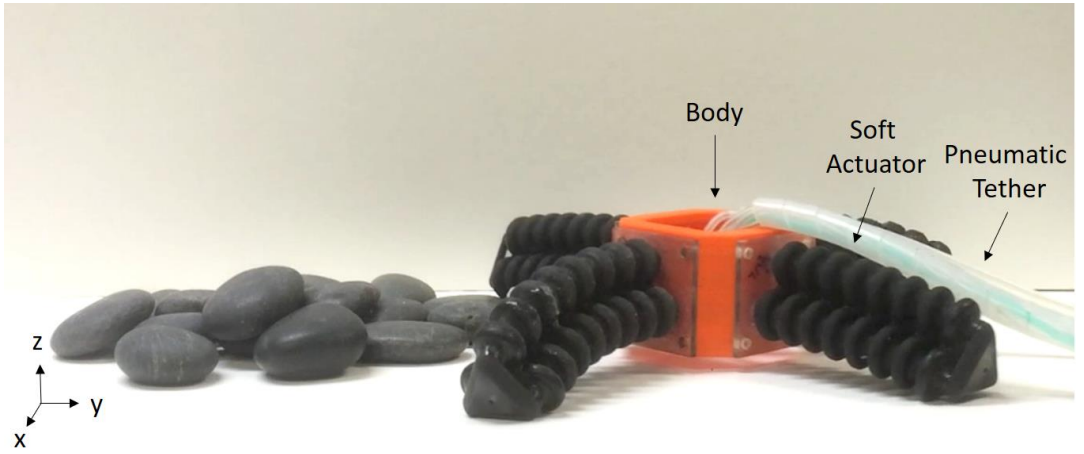


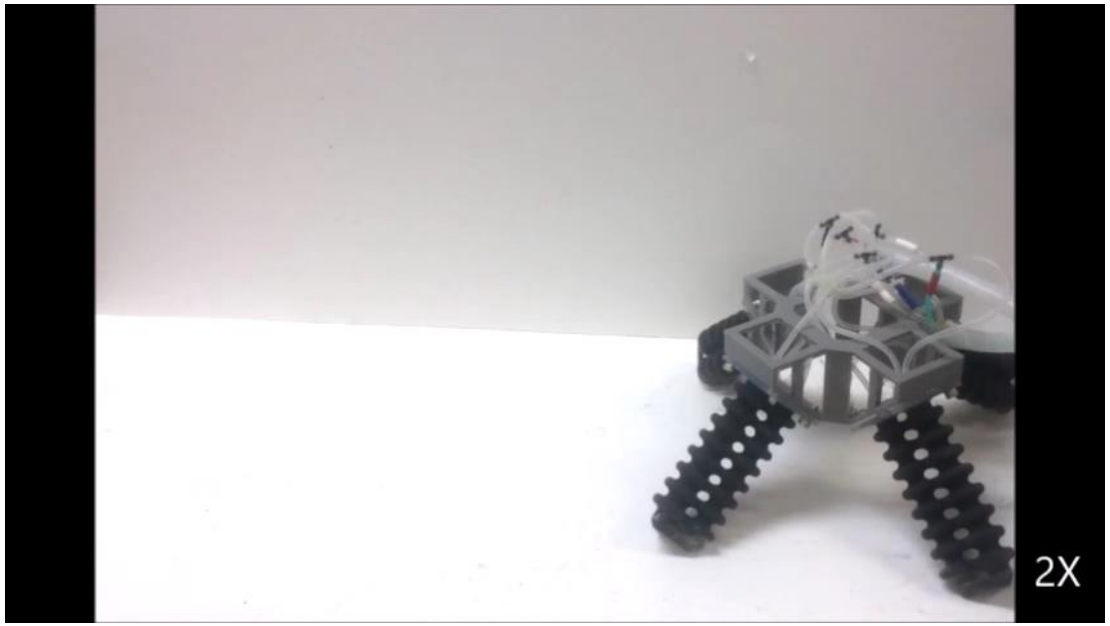
Terrain

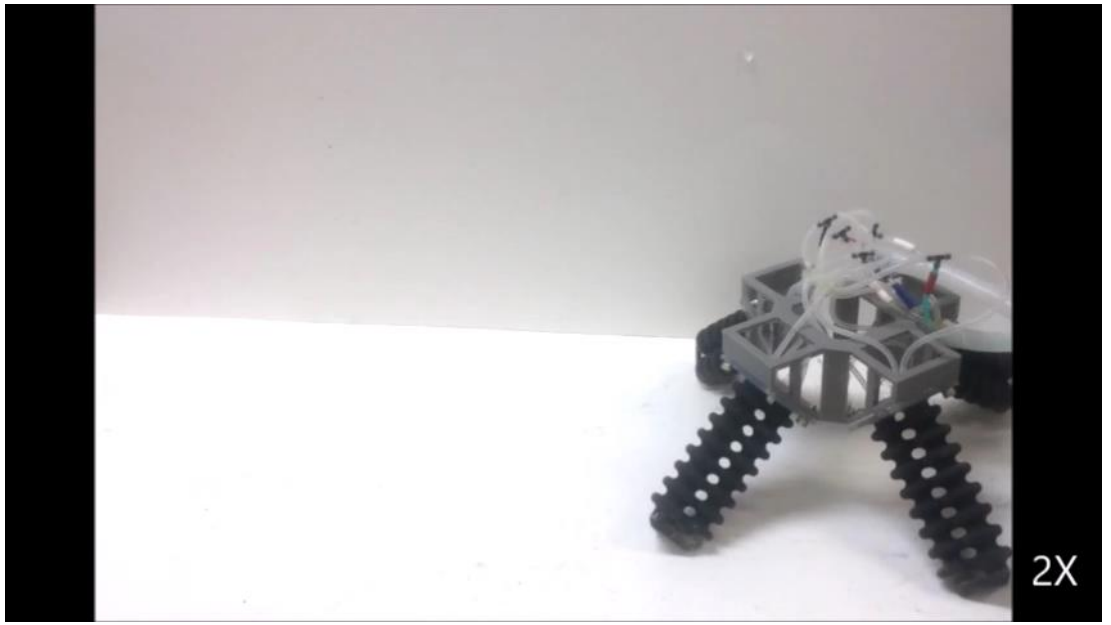




Horizontal Leg Configuration

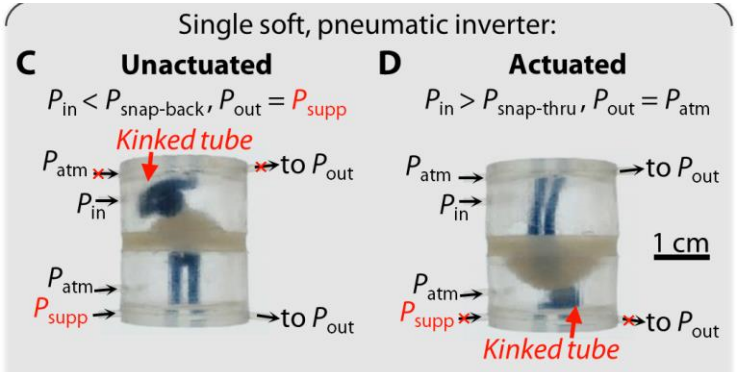


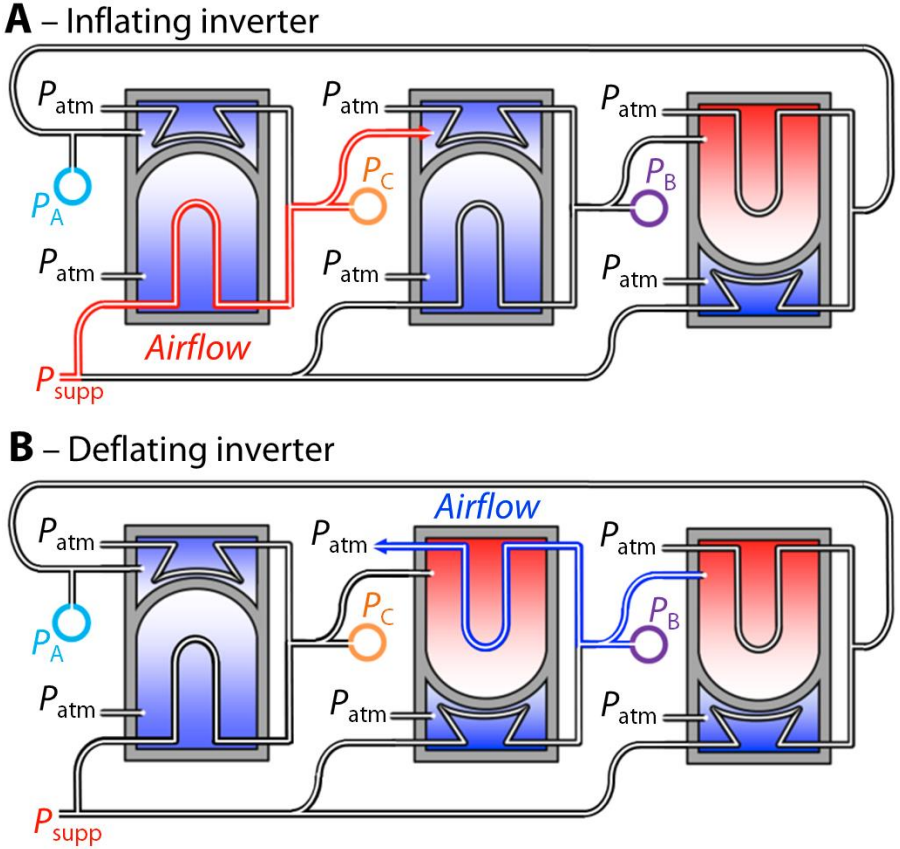


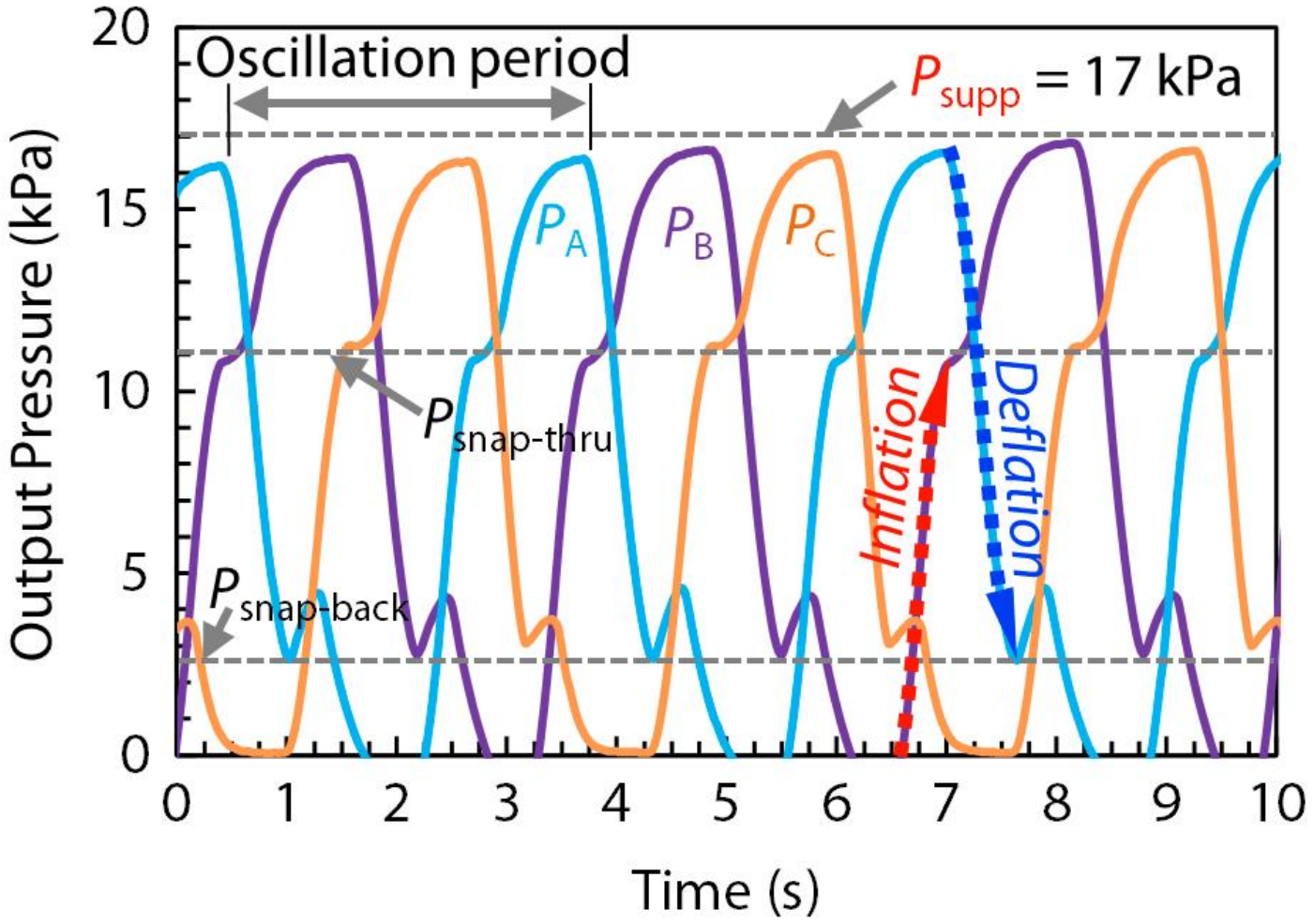


D. Drotman, S. Jadhav, M. Karimi, P. deZonia, M. T. Tolley (2016), ICRA 2017.

Previous work: Soft Ring Oscillator

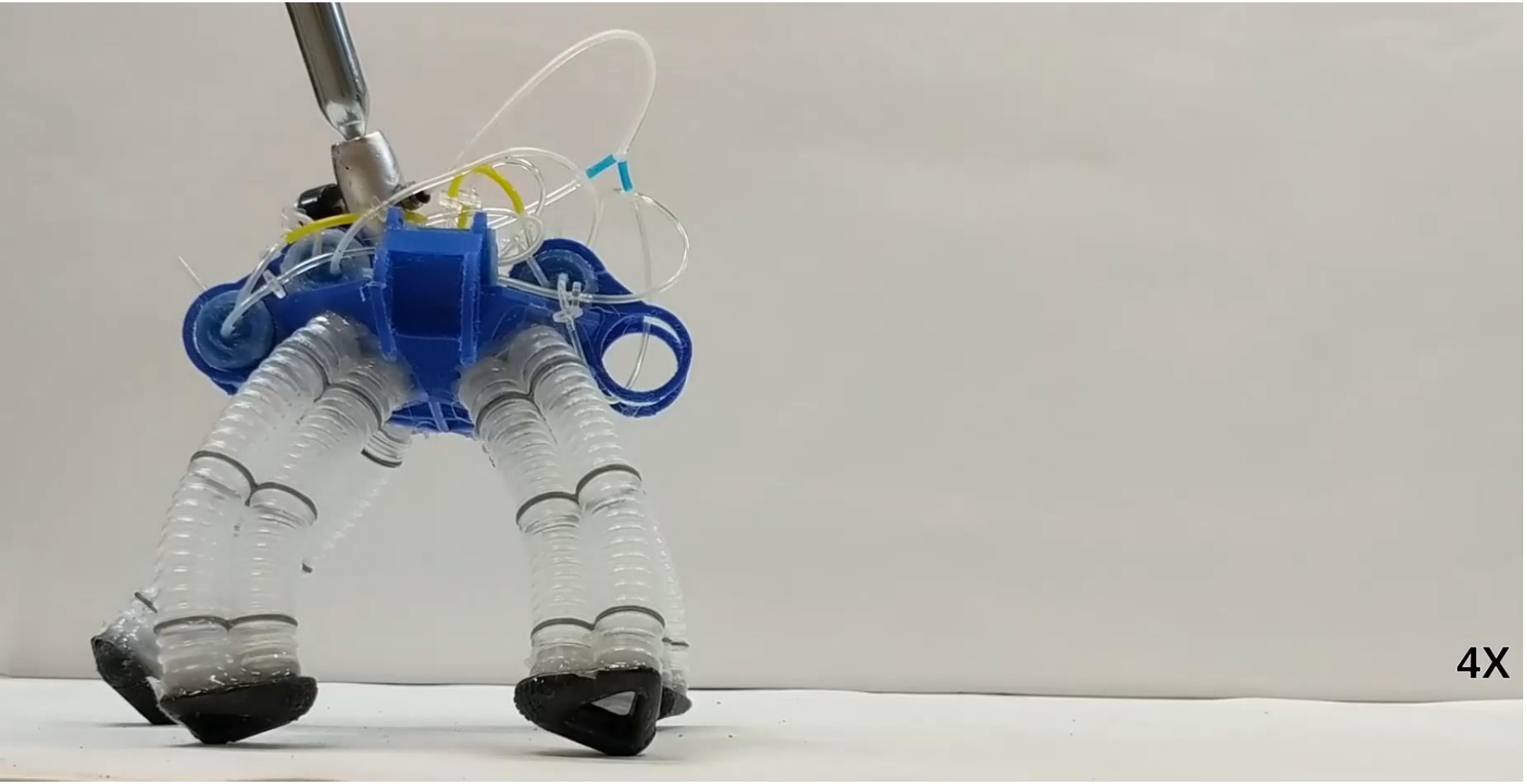


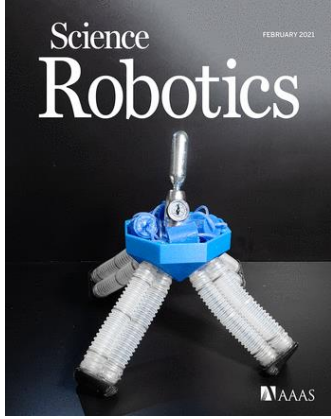




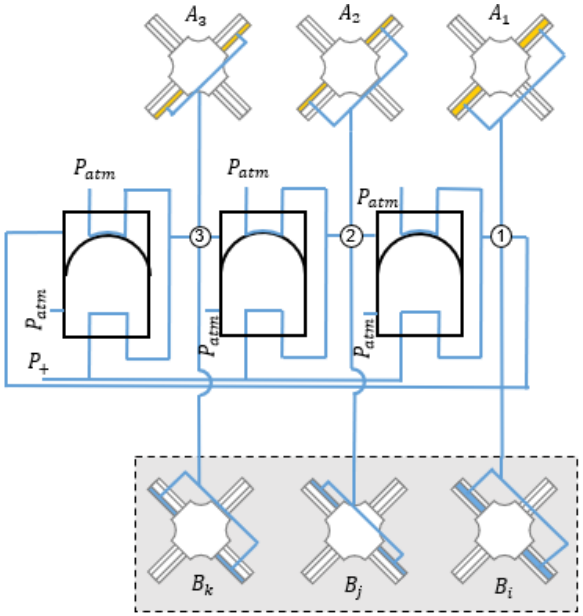
Preston, Jiang, Sanchez, Rothemund, Rawson, Nemitz, Lee, Suo, Walsh, Whitesides, ***Science Robotics***, 2019.

Untethered Pneumatic Quadruped



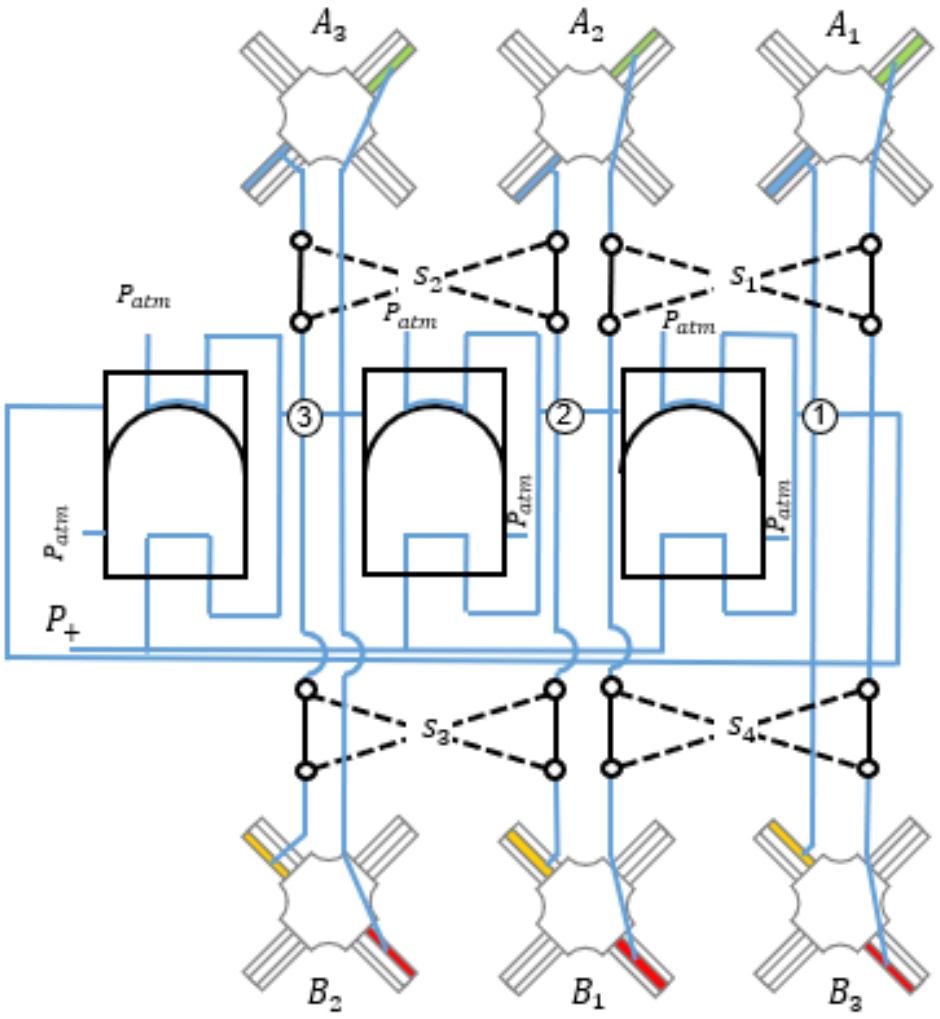


Simplest diagonal couplet gait controller

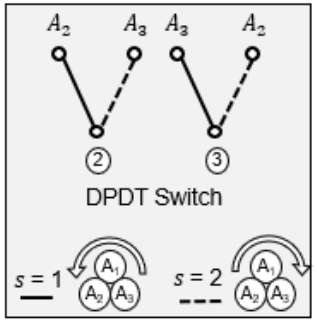


Drotman, Jadhav, Sharp, Chan, Tolley, ***Science Robotics**, 2021*.

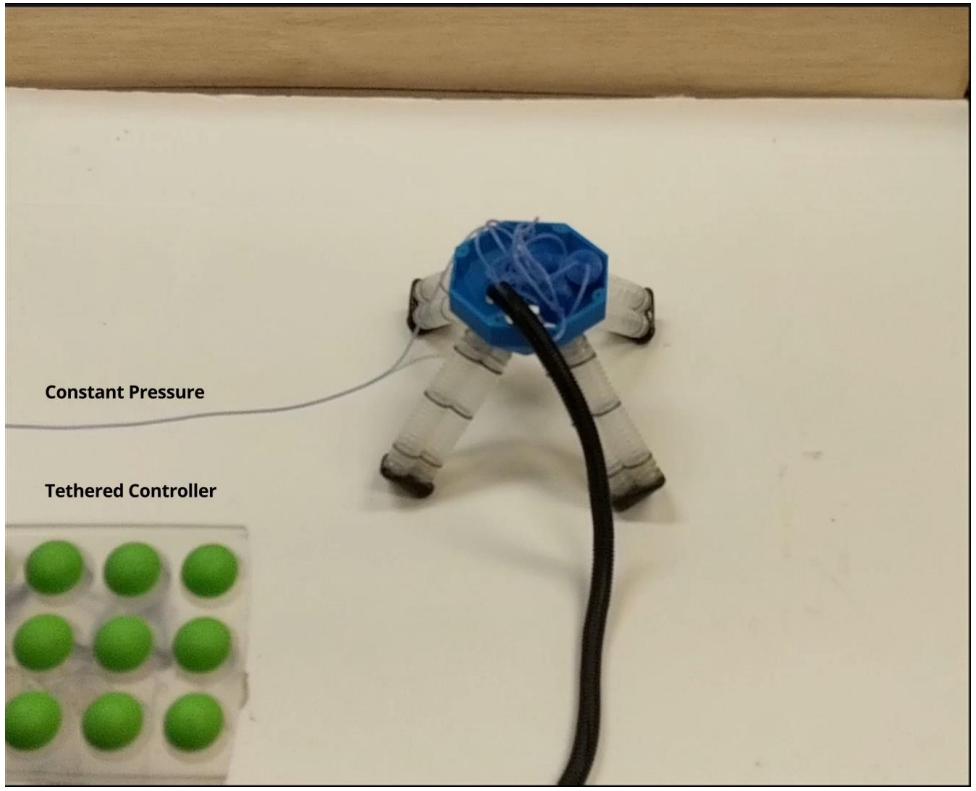
Omnidirectional Locomotion



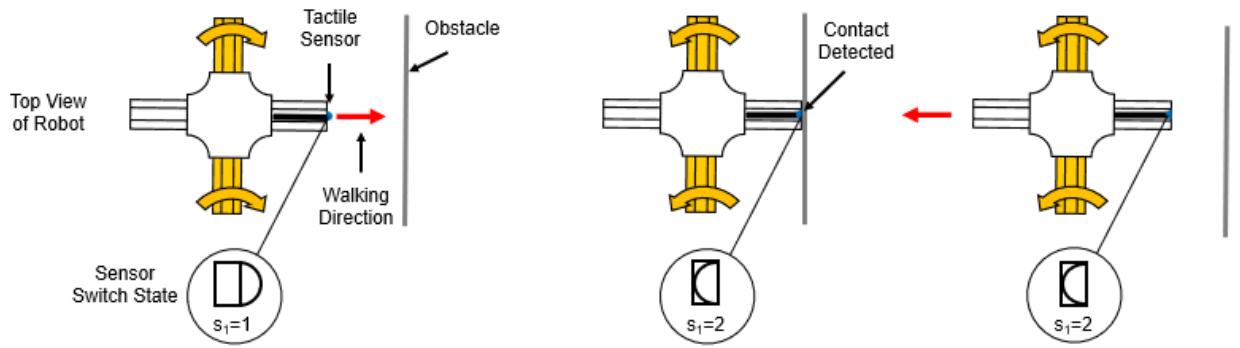
4-2 Bistable Control Valve

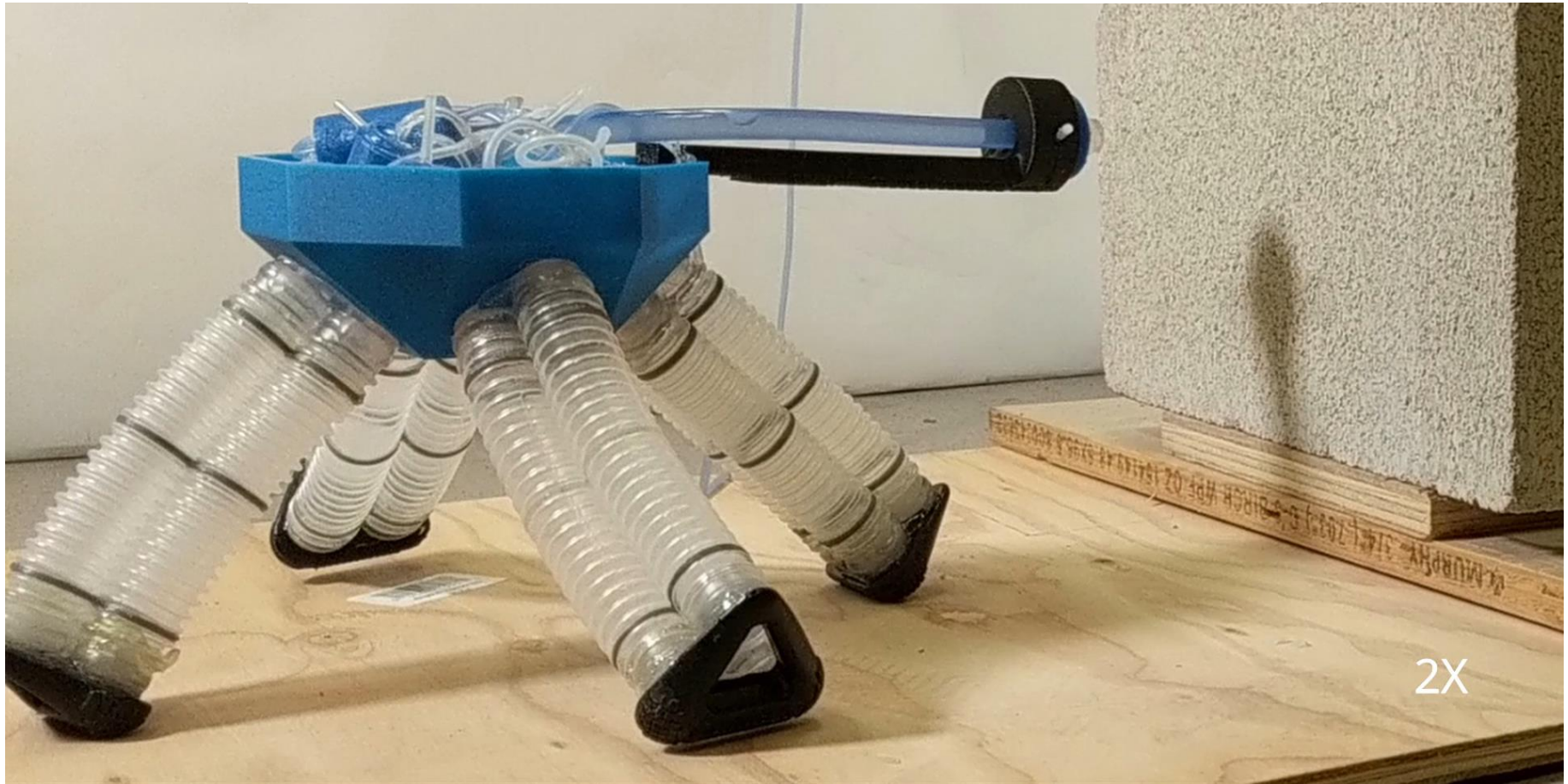


L_1 Switch State	L_2 Switch State	L_3 Switch State	L_4 Switch State	Walking Direction
$s_1 = 1$	$s_2 = 1$	$s_3 = 1$	$s_4 = 1$	Counter Clockwise
$s_1 = 2$	$s_2 = 2$	$s_3 = 2$	$s_4 = 2$	Clockwise

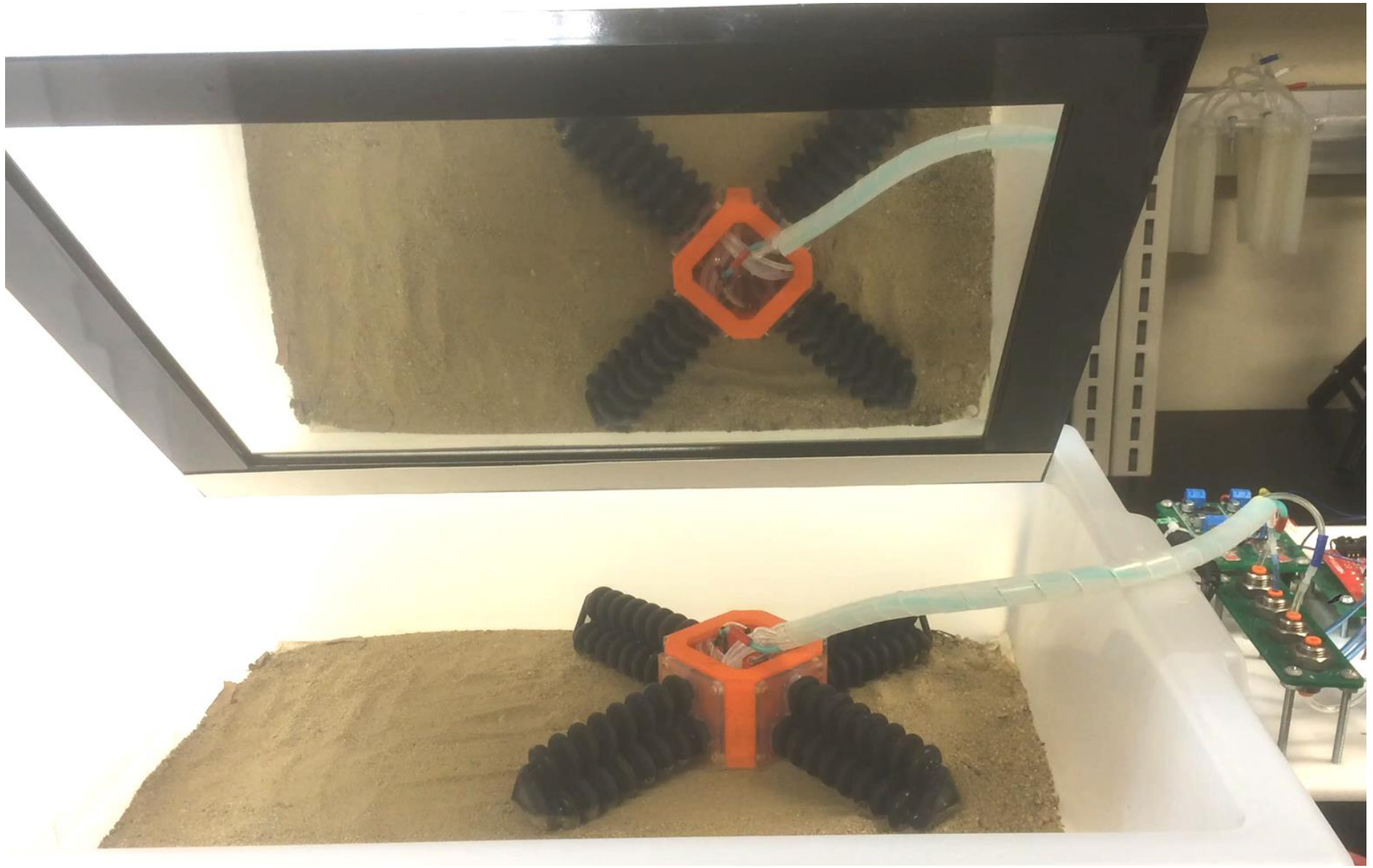


Switching gaits with tactile sensors





Challenge: soft robots in sand

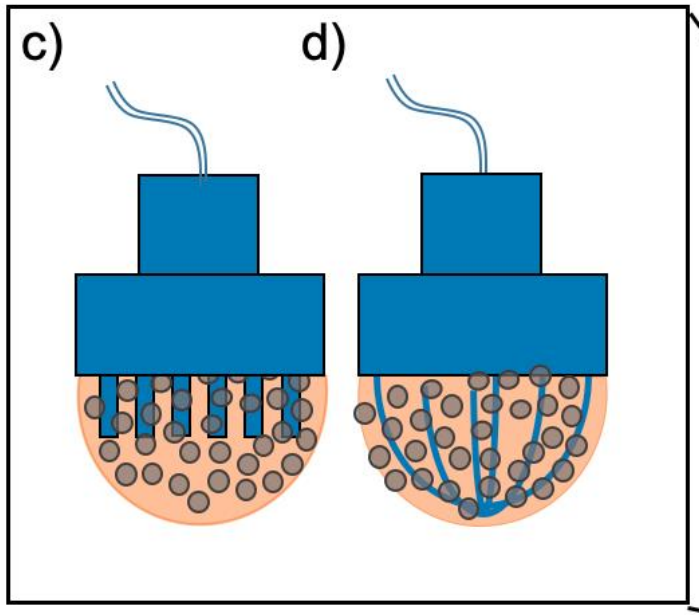


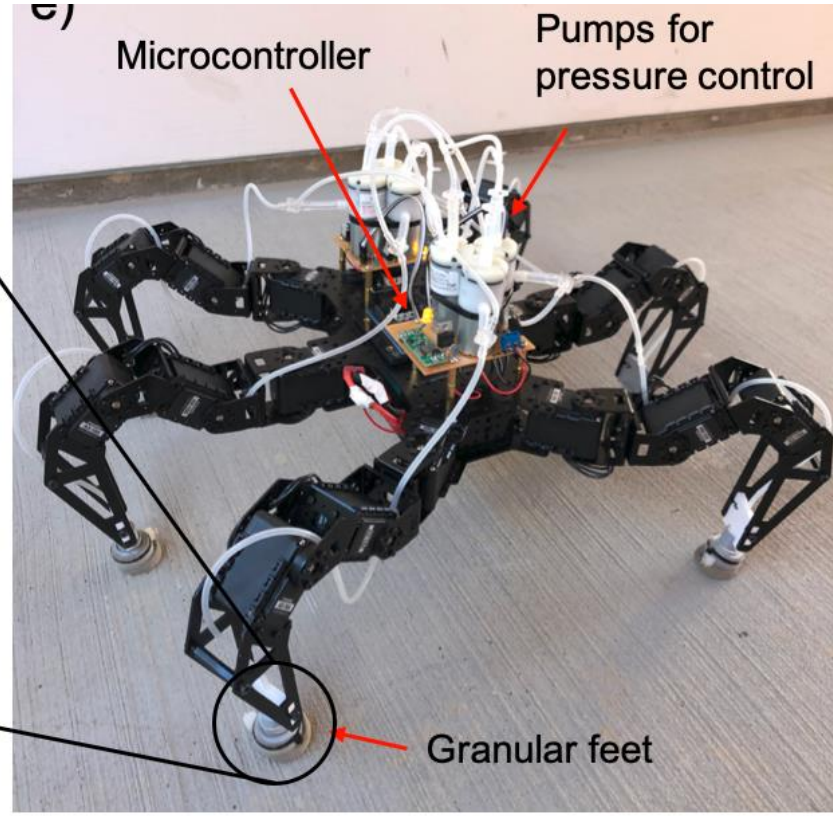
Previous work: Granular Jamming

Amend, Brown, Rodenberg, Jaeger, Lipson, 2012. *IEEE Transactions on Robotics*, *2012*.

Can variable stiffness feet improve locomotion on complex terrain?

We retrofit the stock feet of a commercial legged robot with granular jamming feet to allow variable stiffness



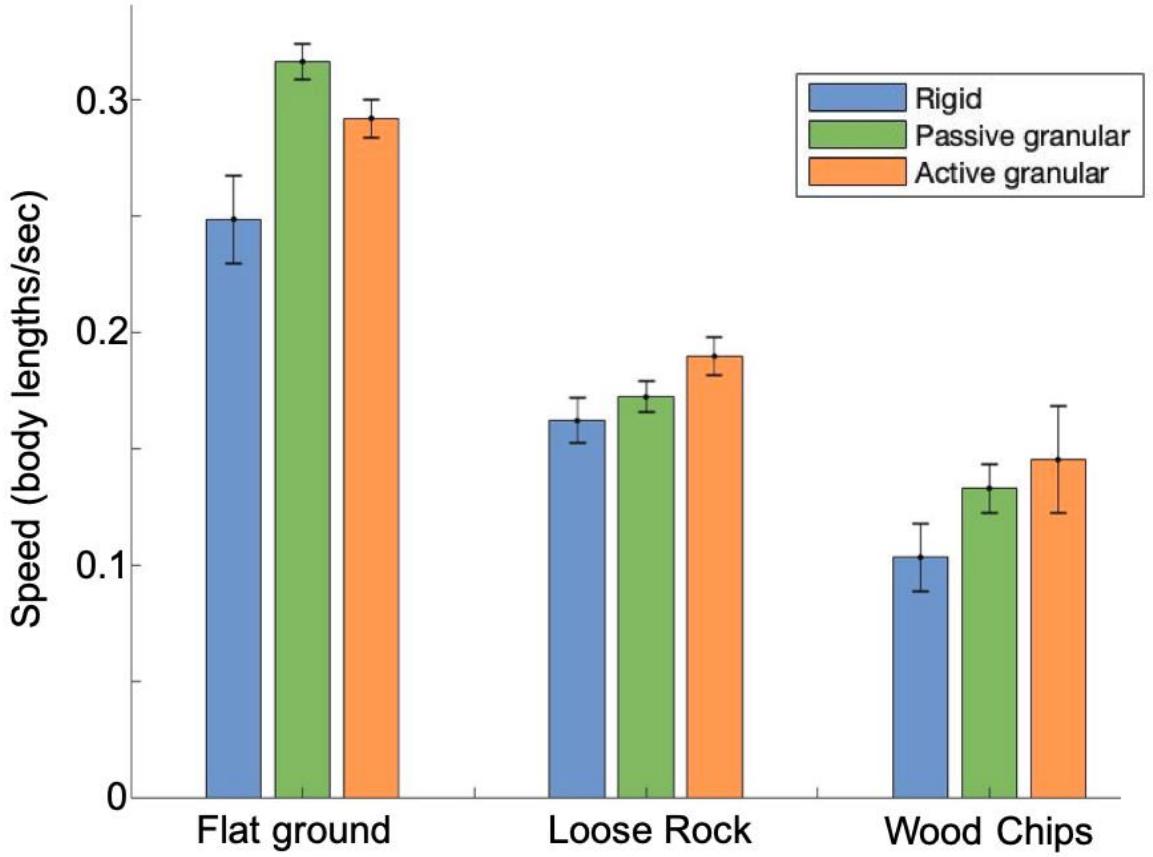


Hypotheses:

1) Soft feet would improve locomotion on soft ground
2) Jamming before push-off would improve locomotion speed

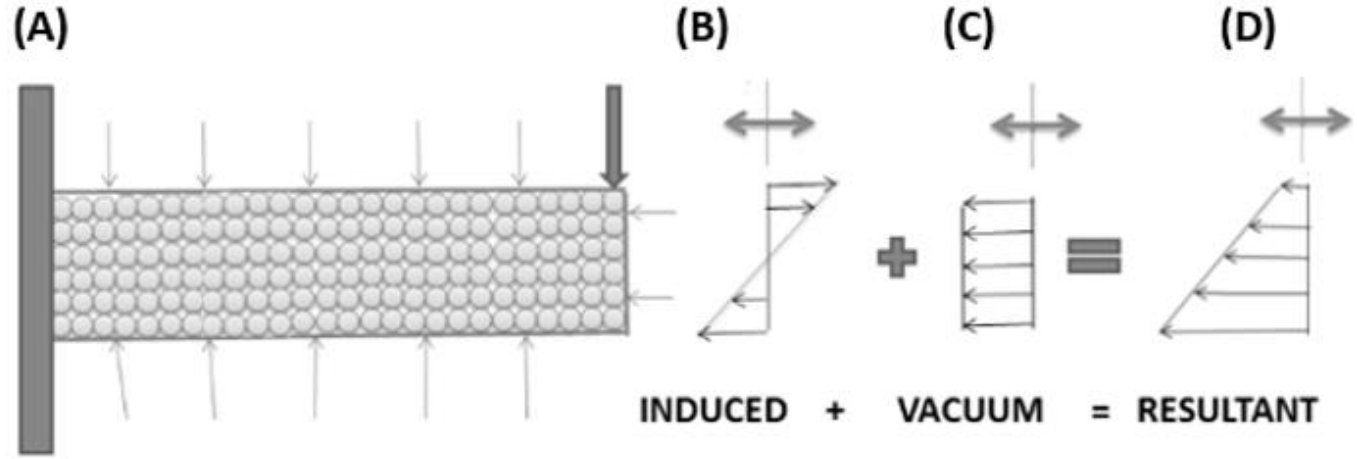
Lathrop, Adibnazari, Gravish, Tolley, *RoboSoft 2020*.

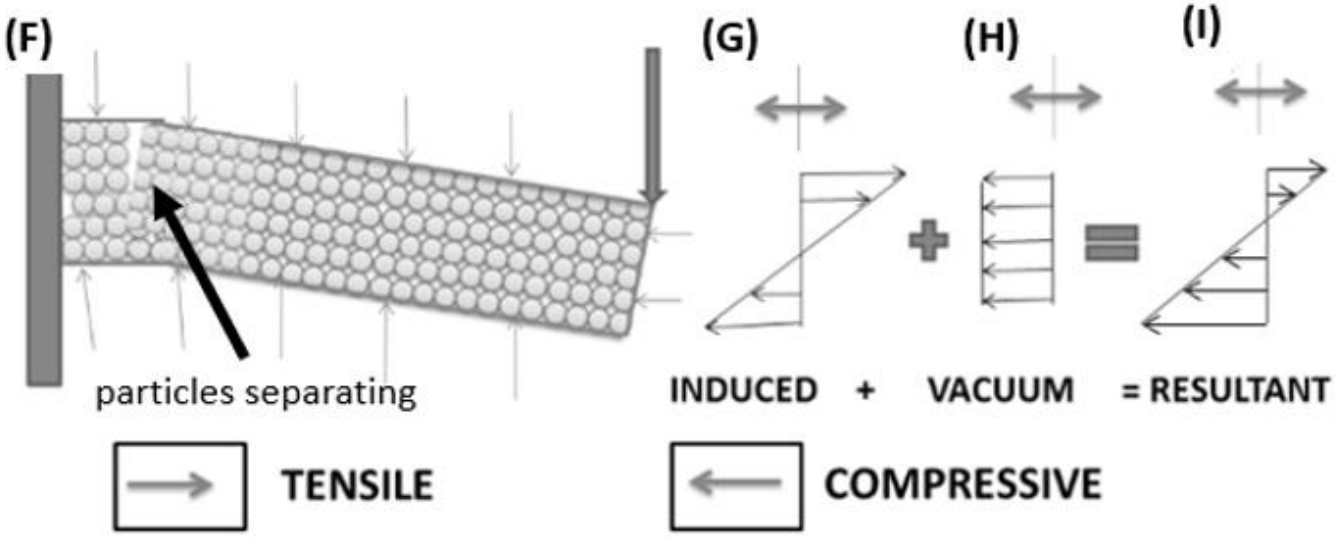
Variable stiffness feet for complex terrain

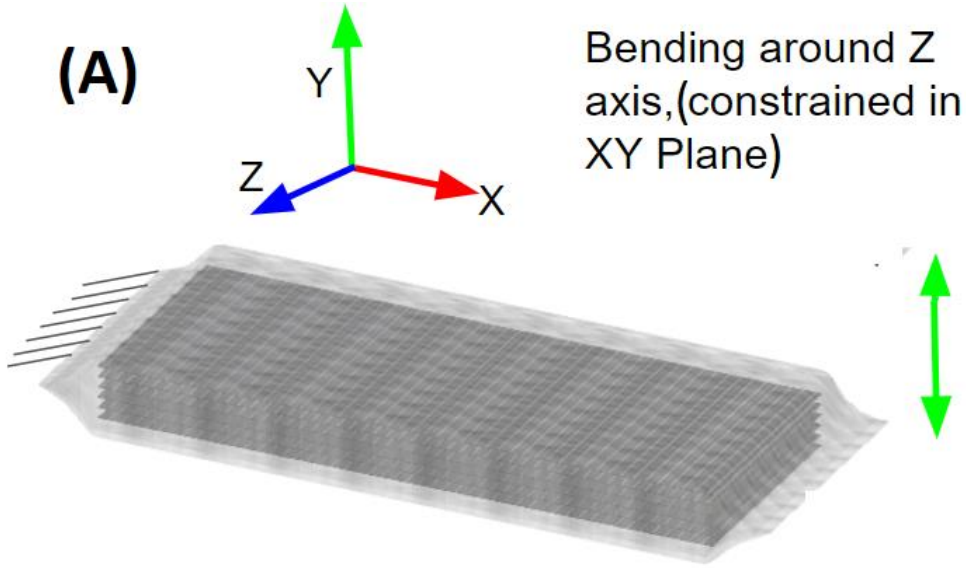


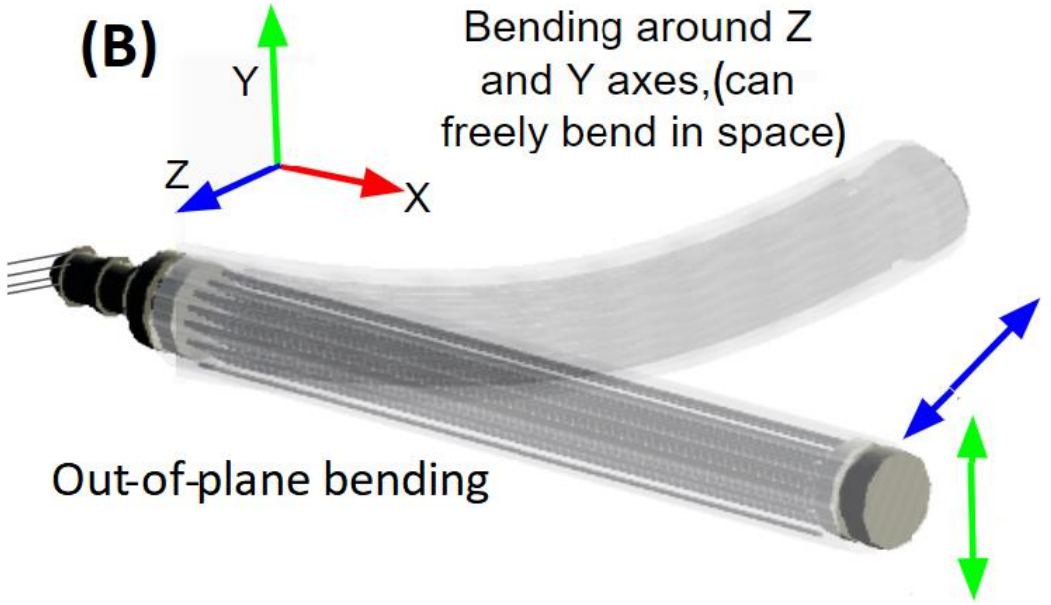
Lathrop, Adibnazari, Gravish, Tolley, *RoboSoft 2020*.

What about variable stiffness bending?

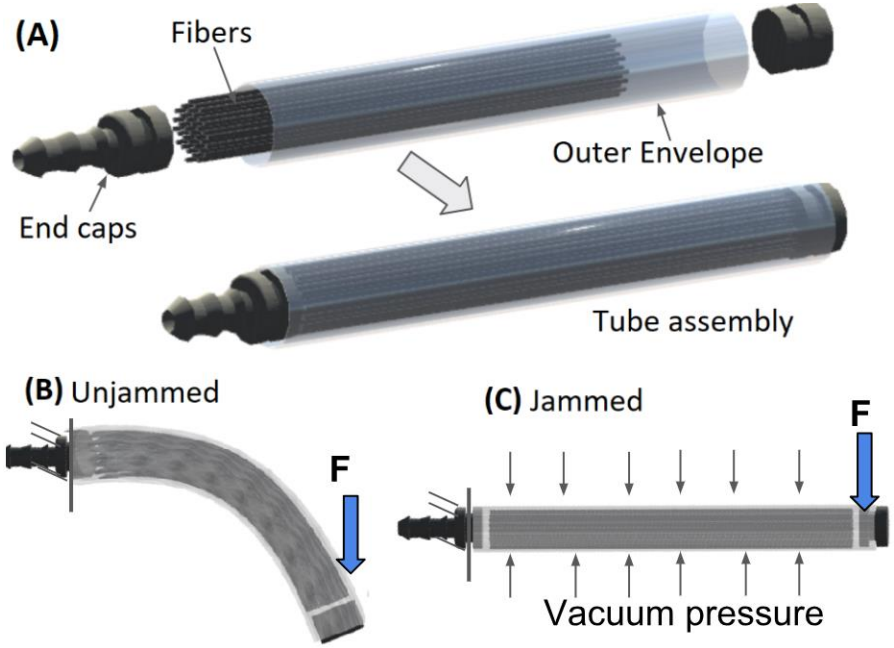




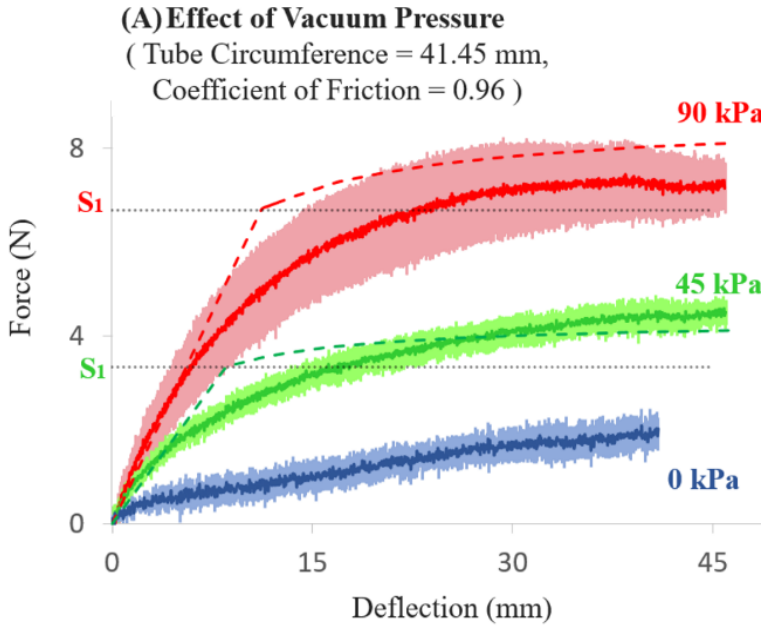




Another kind of variable stiffness actuator: Fiber Jamming

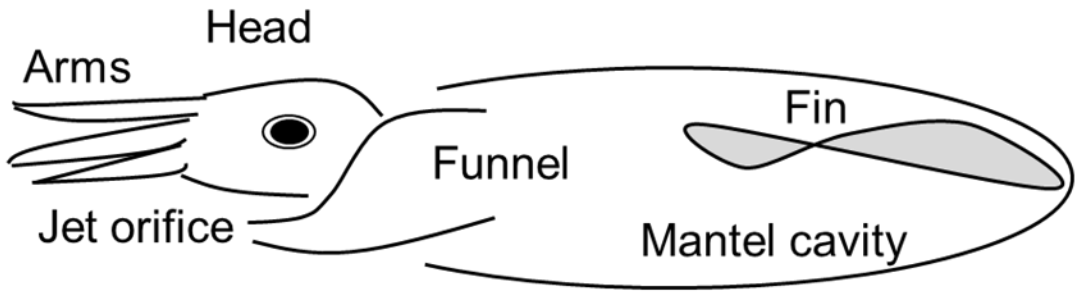


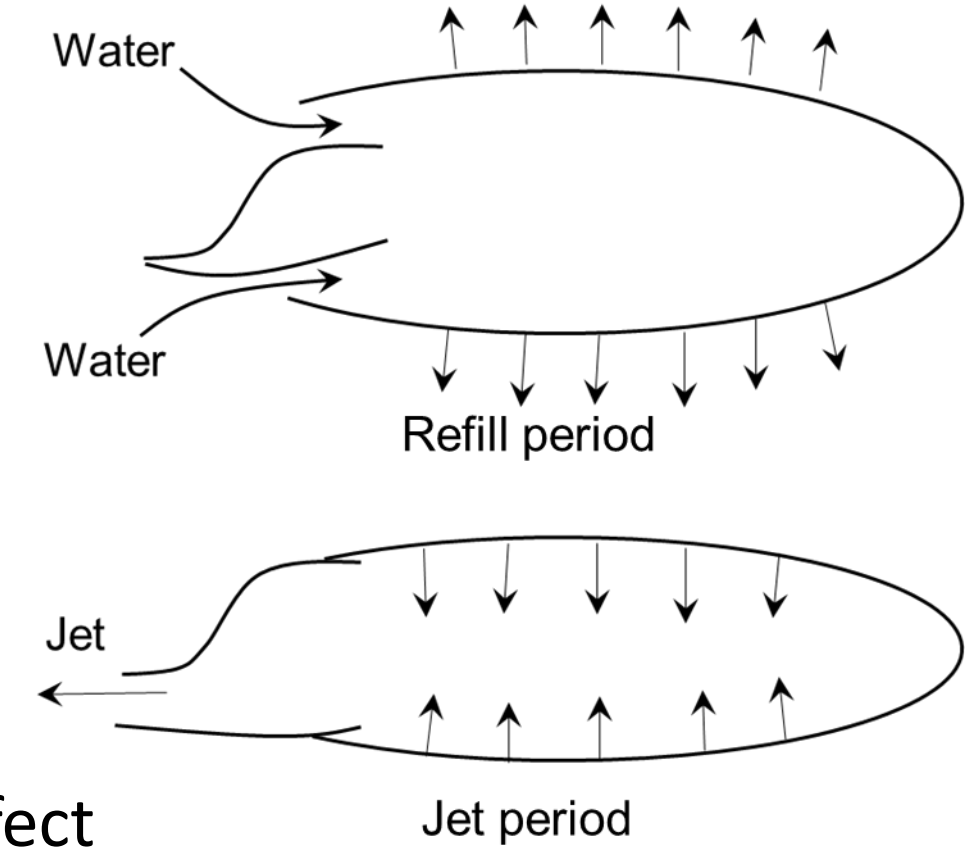
Use as a haptic interface



Jadhav, S., Majit, M. R. A., Shih, B., Schulze, J. P., & Tolley, M. T., **Soft Robotics**, *in press*.

Jet Propulsion in Cephalopods

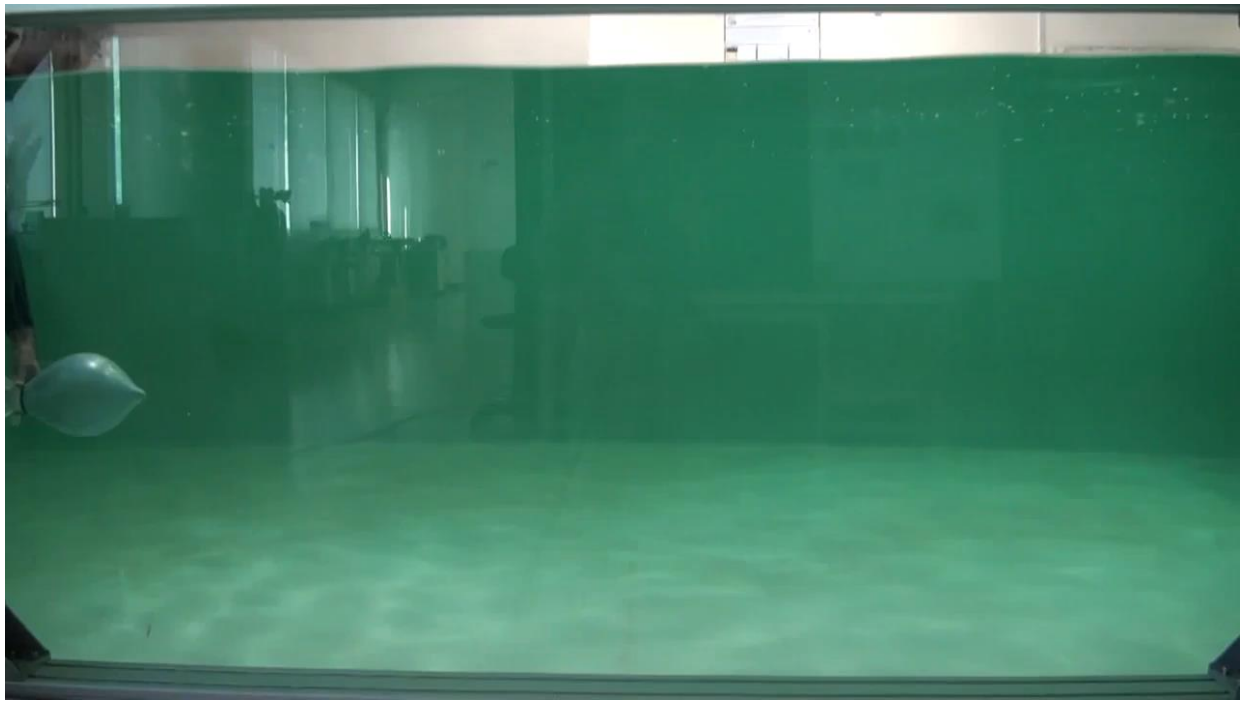




Key for efficient swimming:

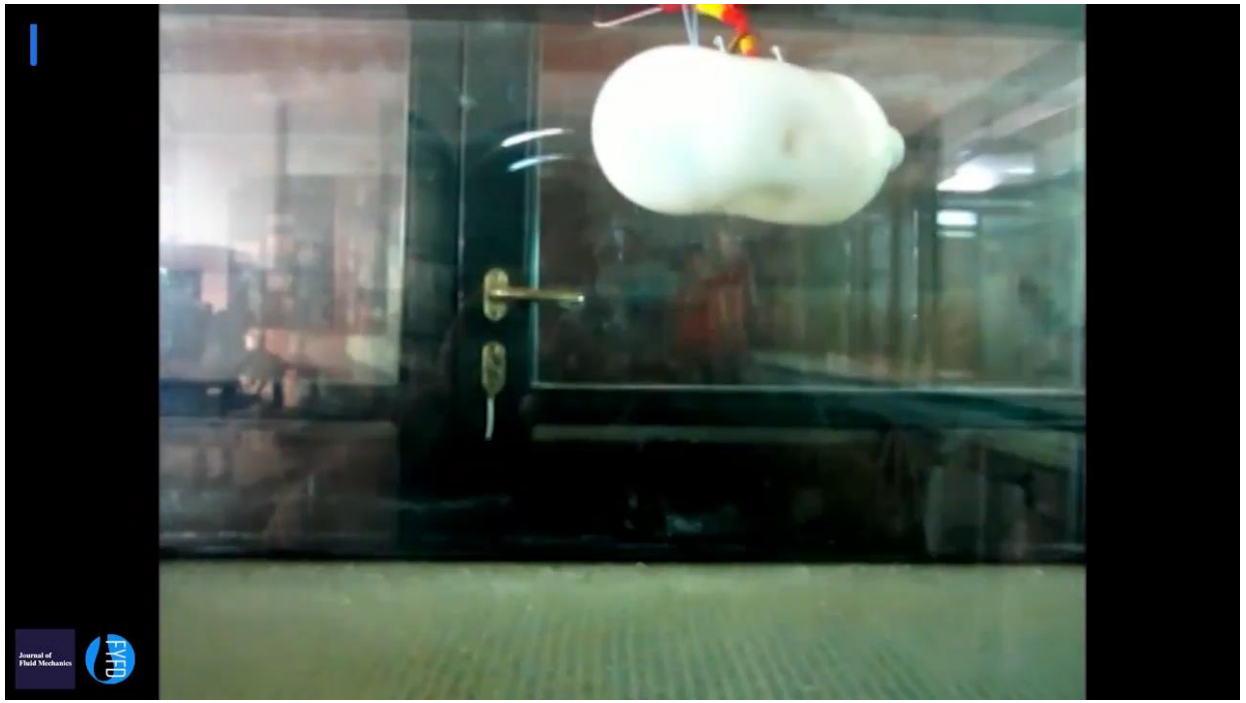
- Squid takes advantage of added mass effect (water carried along with the squid as it swims)
- Added mass reduced as water is expelled

Previous Cephalopod-Inspired Robots



Weymouth et al., Bioinspiration and Biomimetics, 2015.

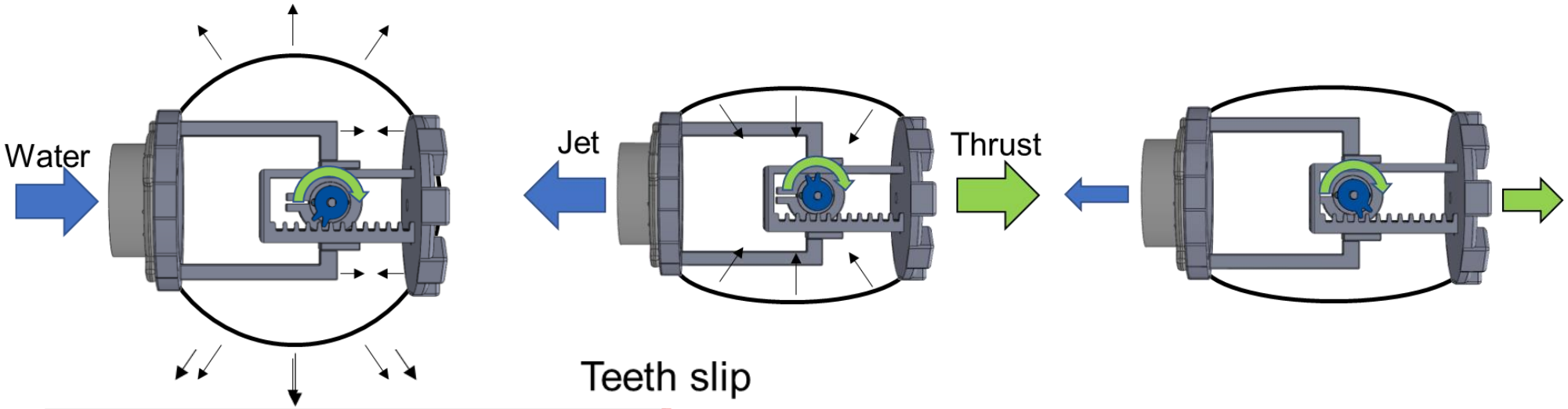
Takes advantage of added mass, but one-shot

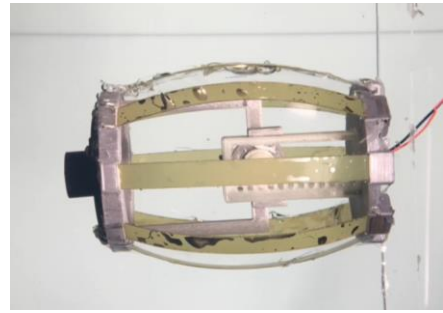


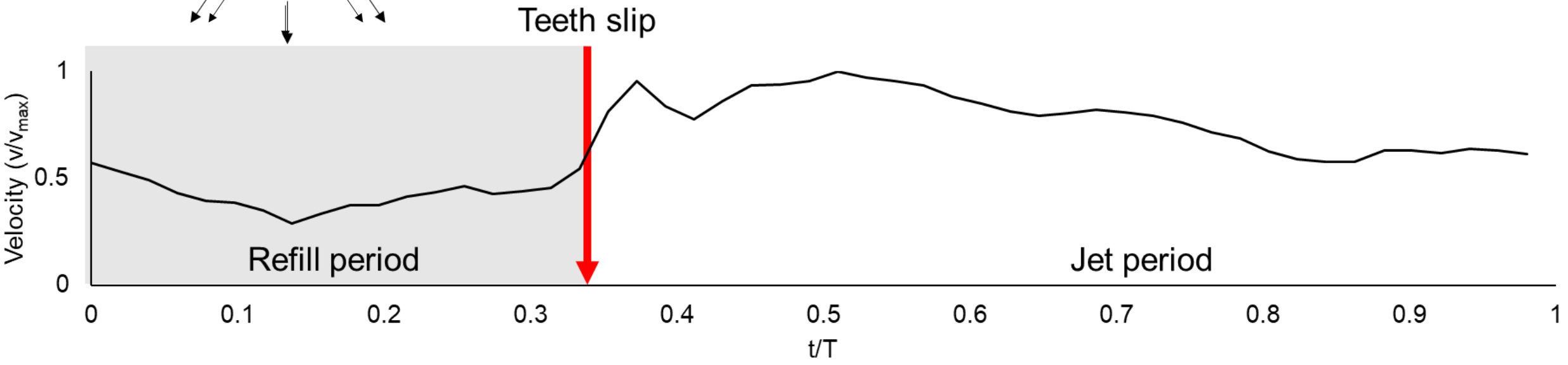
Giorgio-Serchi et al, Int. J. Rob. Res., 2016.

Cyclic, but constant projected frontal area

Cyclic hydrodynamic shape change

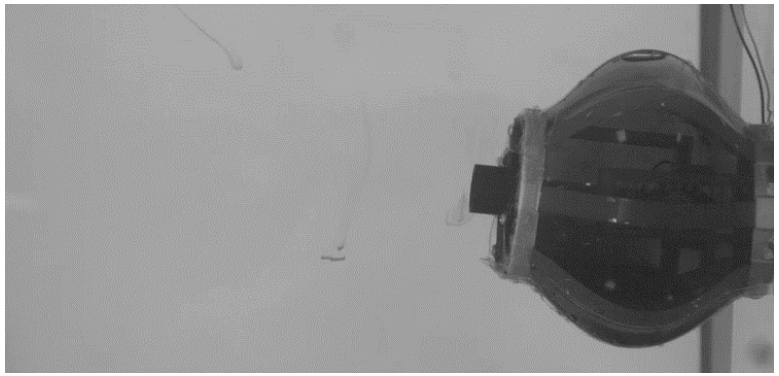


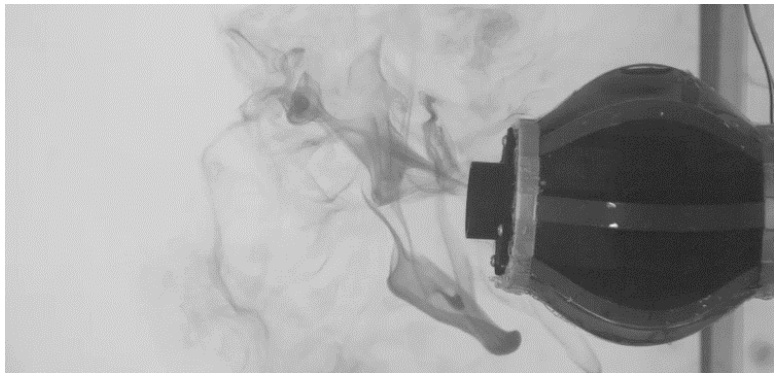


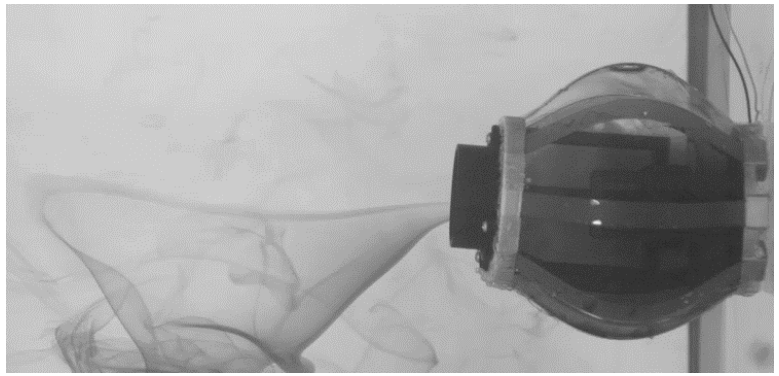


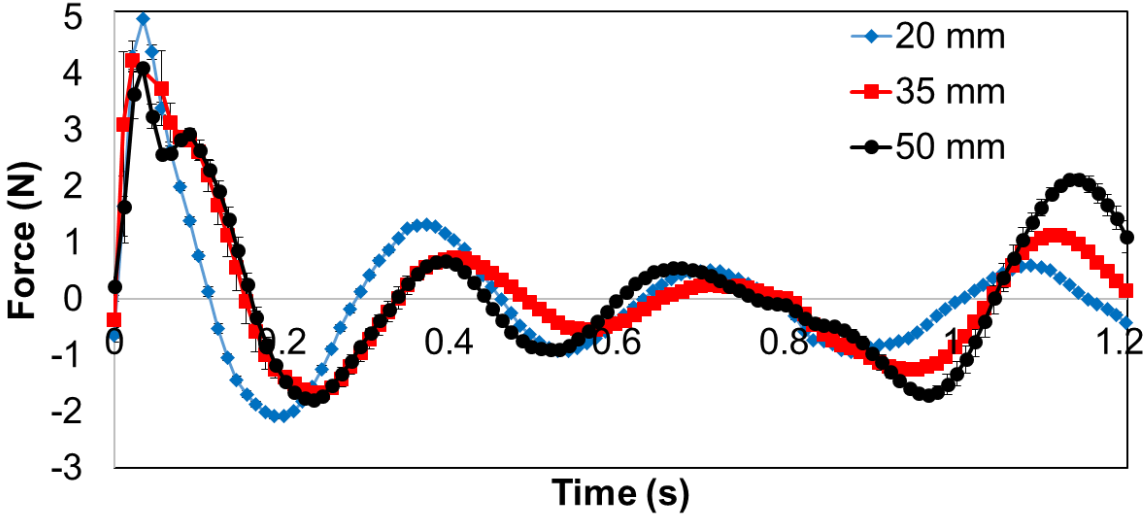
Christianson, Cui, Bi, Zhu, Pawlak, Tolley, *Bioinspiration and Biomimetics,* 2020.

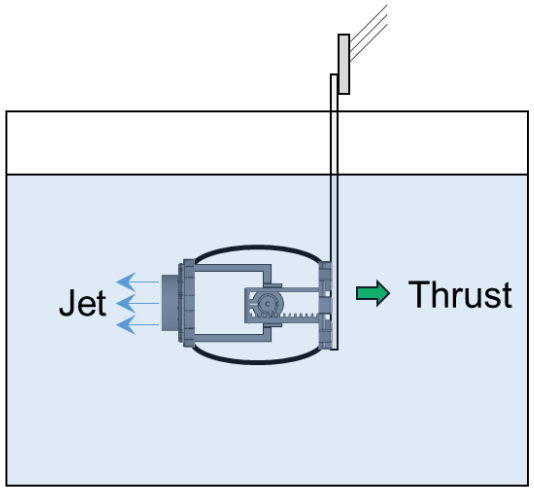
Effect of Nozzle Diameter

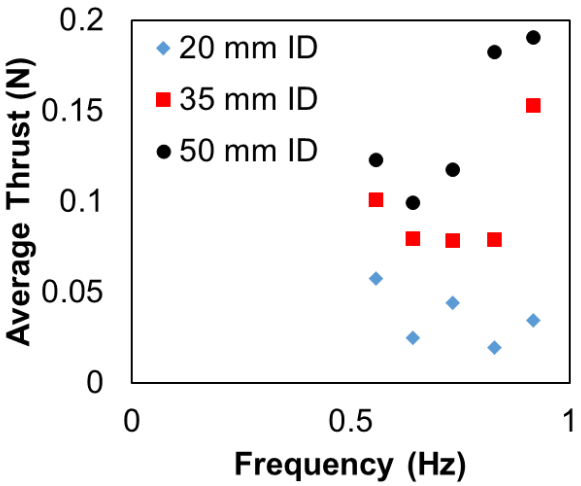






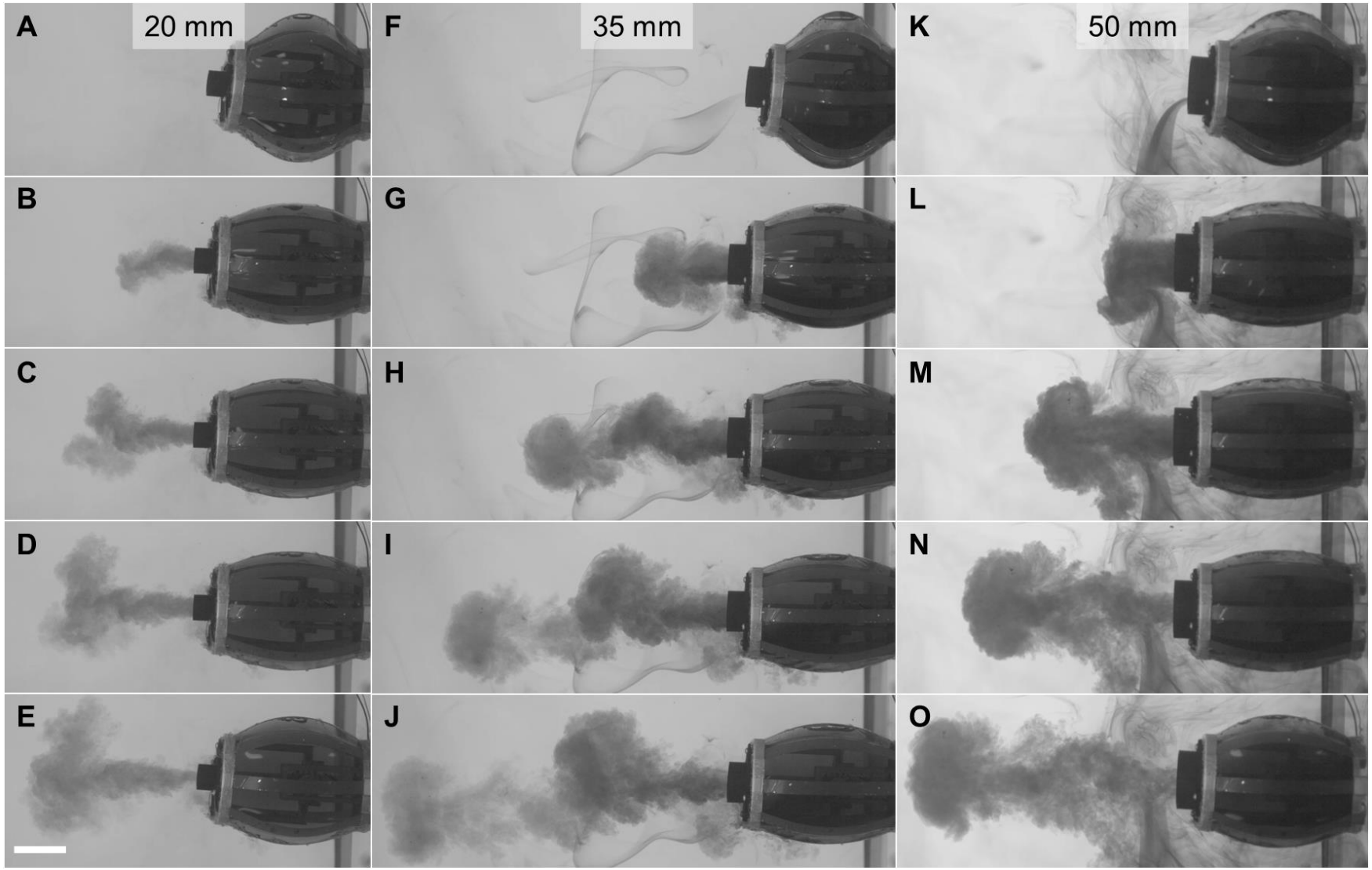






Christianson, Cui, Bi, Zhu, Pawlak, Tolley, *Bioinspiration and Biomimetics,* 2020.

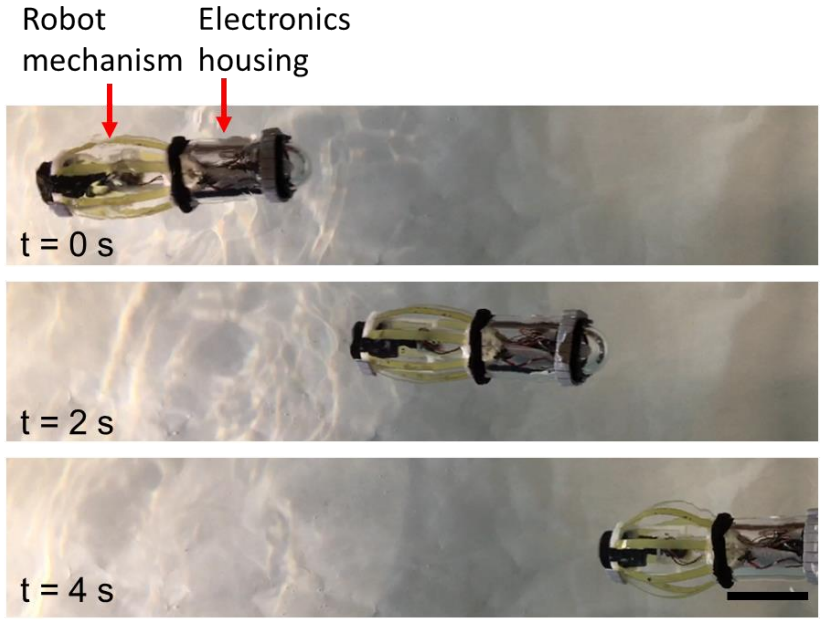
Flow Visualization Still Frames



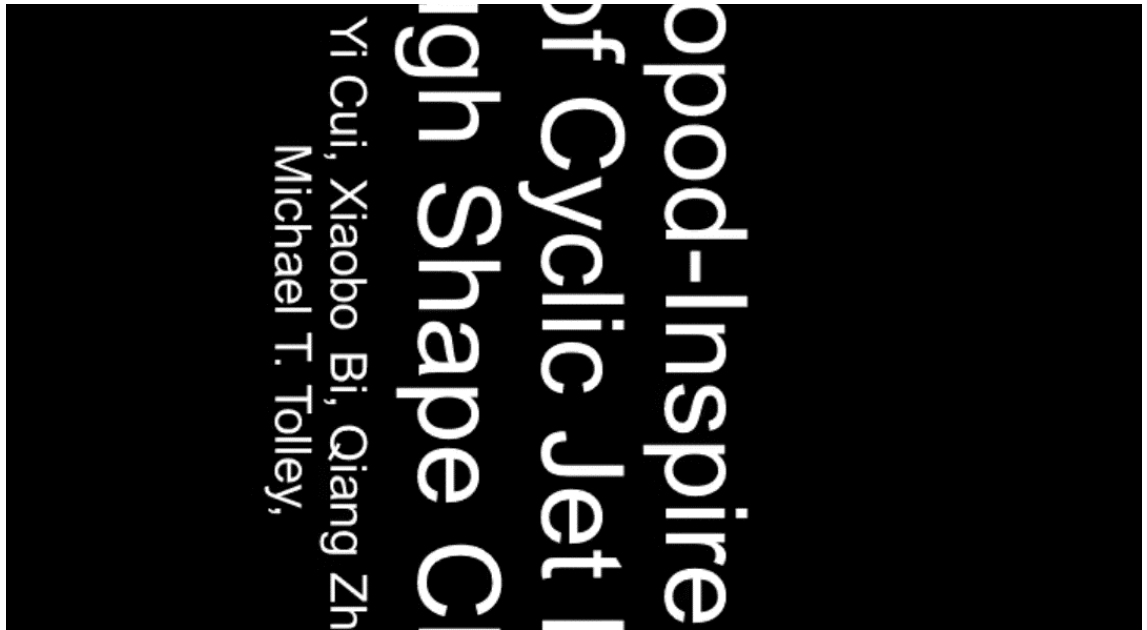
Christianson, Cui, Bi, Zhu, Pawlak, Tolley, *Bioinspiration and Biomimetics,* 2020.

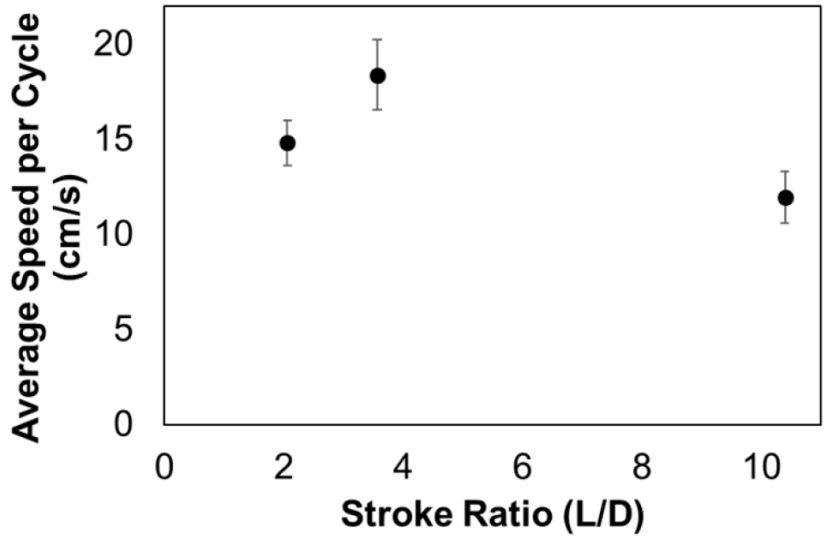
Untethered Swimming

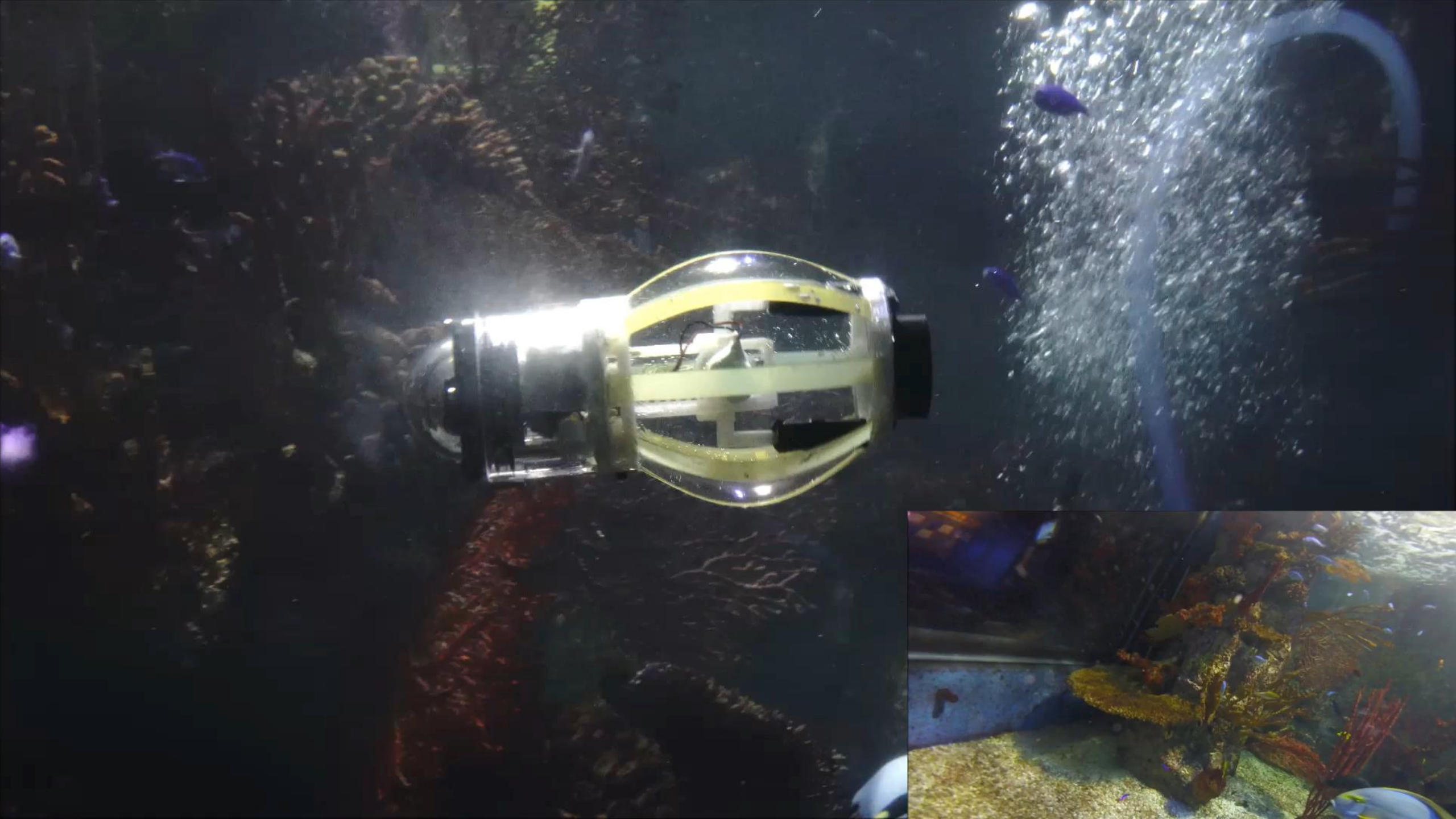
Straight Nozzle



Angled Nozzle







Acknowledgments

Collaborators

Prof. Tiefeng Li, Zhijiang University

Prof. Shengqiang Cai, UC San Diego

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Prof. Cecilia Laschi, Scuola Superiore Sant'Anna

Prof. Elliot Hawkes, UC Santa Barbara

Dr. Dimitri Deheyn, Scripps Institution for Oceanography

Prof. Henrik Christensen, UC San Diego

Prof. Eliah Aronoff-Spencer, UC San Diego

Prof. Rob Shepherd, Cornell University

Prof. George Whitesides, Harvard University

Prof. Rob Wood, Harvard University

Prof. Mark Cutkosky, Stanford University

Dr. Aaron Parness, Jet Propulsion Lab

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