Ritsumeikan University
Soft Robotics
November 15/22, 2024
16:20-17:50

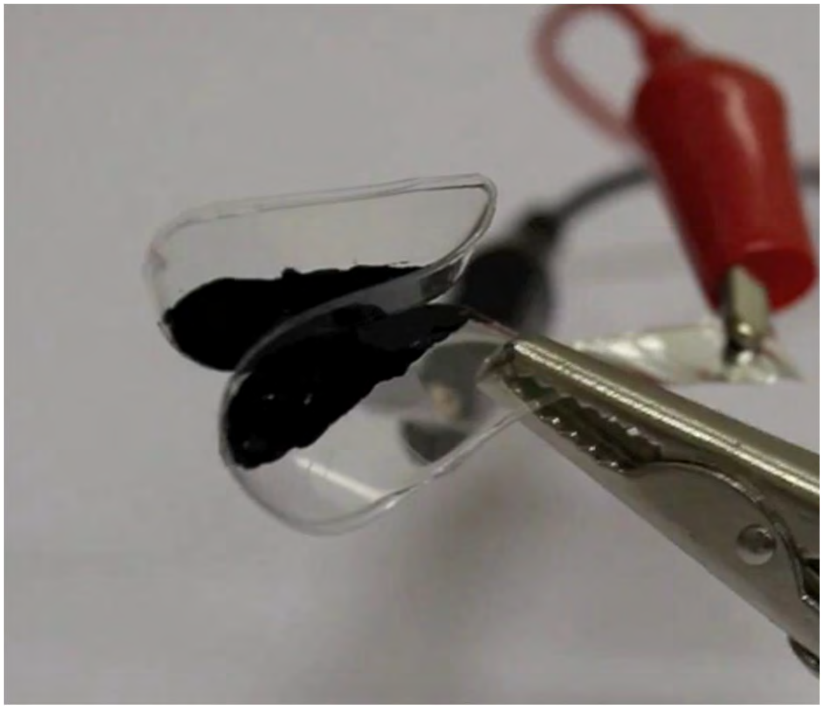
Soft Actuators

Jun Shintake

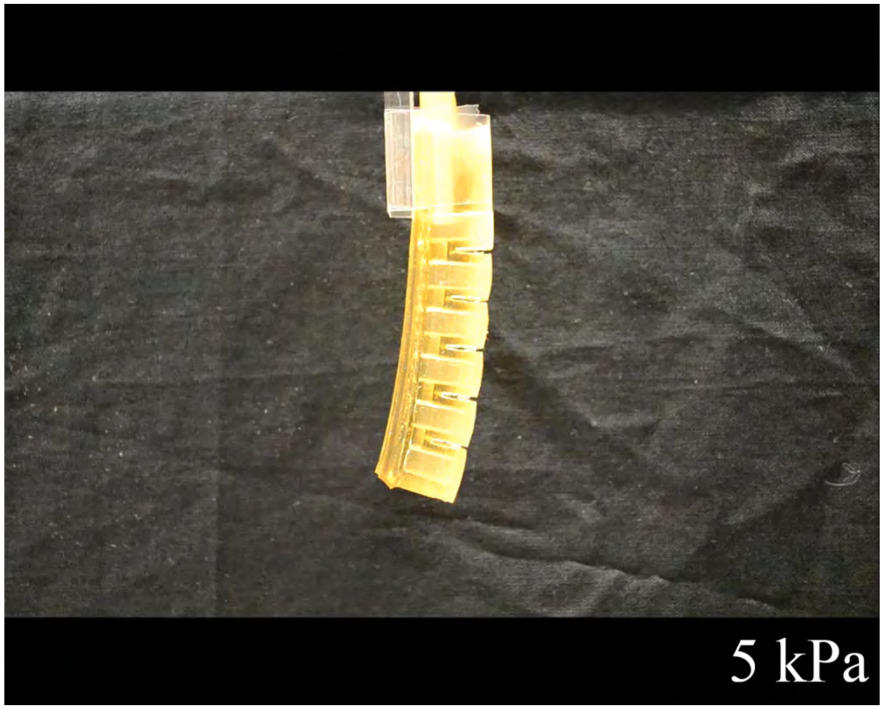
Department of Mechanical and Intelligent Systems Engineering,
The University of Electro-Communications (UEC), Tokyo, Japan.

Soft actuators

- Made of compliant materials
- Materials or compliant structures themselves deform by external stimuli (*stimuli ≈ inputs)
- Simpler than conventional rigid actuators
- Often called as Artificial Muscle
- Examples:



Electrical soft actuator



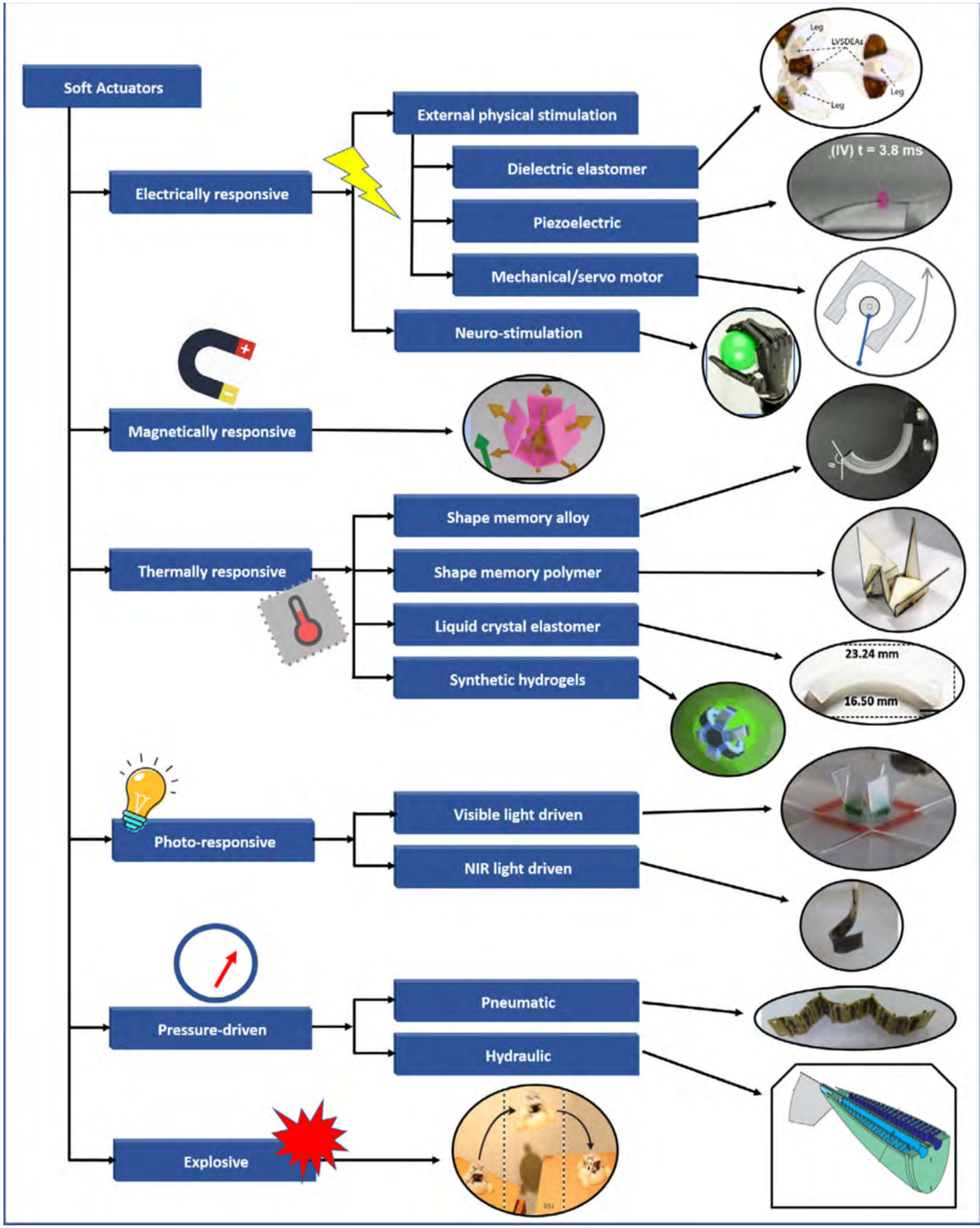
Fluidic soft actuator

Soft actuators

They rely on stimuli of:

- Electric
- Magnetic
- Thermal
- Light
- Pressure

Under which many sub-classes and configurations are being developed.



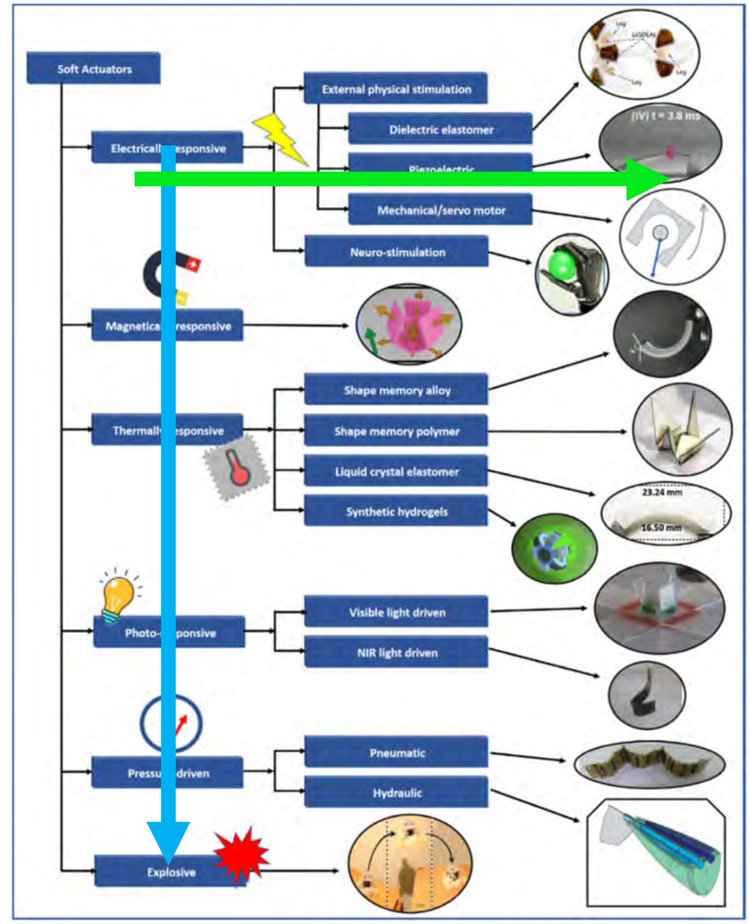
El-Atab, Nazek, et al. "Soft actuators for soft robotic applications: A review." Advanced Intelligent Systems 2.10 (2020): 2000128.

Aim of the topic “Soft Actuators”

~~11/15: Detail a single soft actuator technology and describe how it enables various actuator configurations and robotic systems.~~

11/22: Overview existing soft actuators and discuss their pros and cons*, followed by homework.

*Focus on representative (i.e., widespread) soft actuator technologies.



El-Atab, Nazek, et al. "Soft actuators for soft robotic applications: A review." Advanced Intelligent Systems 2.10 (2020): 2000128.

Class of key soft actuator technologies

- **Pressure responsive**
  - Fluidic elastomer actuators
  - Mckibben actuators
  - Film based soft actuators
- **Electrically responsive**
  - Electroactive polymers
  - Electro-hydraulic soft actuators
  - Biohybrid actuators
- **Thermally responsive**
  - Fishing line artificial muscles
  - Shape memory alloys
  - Shape memory polymers
- **Magnetically responsive**
  - Magnetic elastomer actuators

Provide basic principle and share movies to show movements of actuators and robots for getting a better insight.

Shintake, Jun, et al. "Bio-inspired tensegrity fish robot." 2020 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2020.

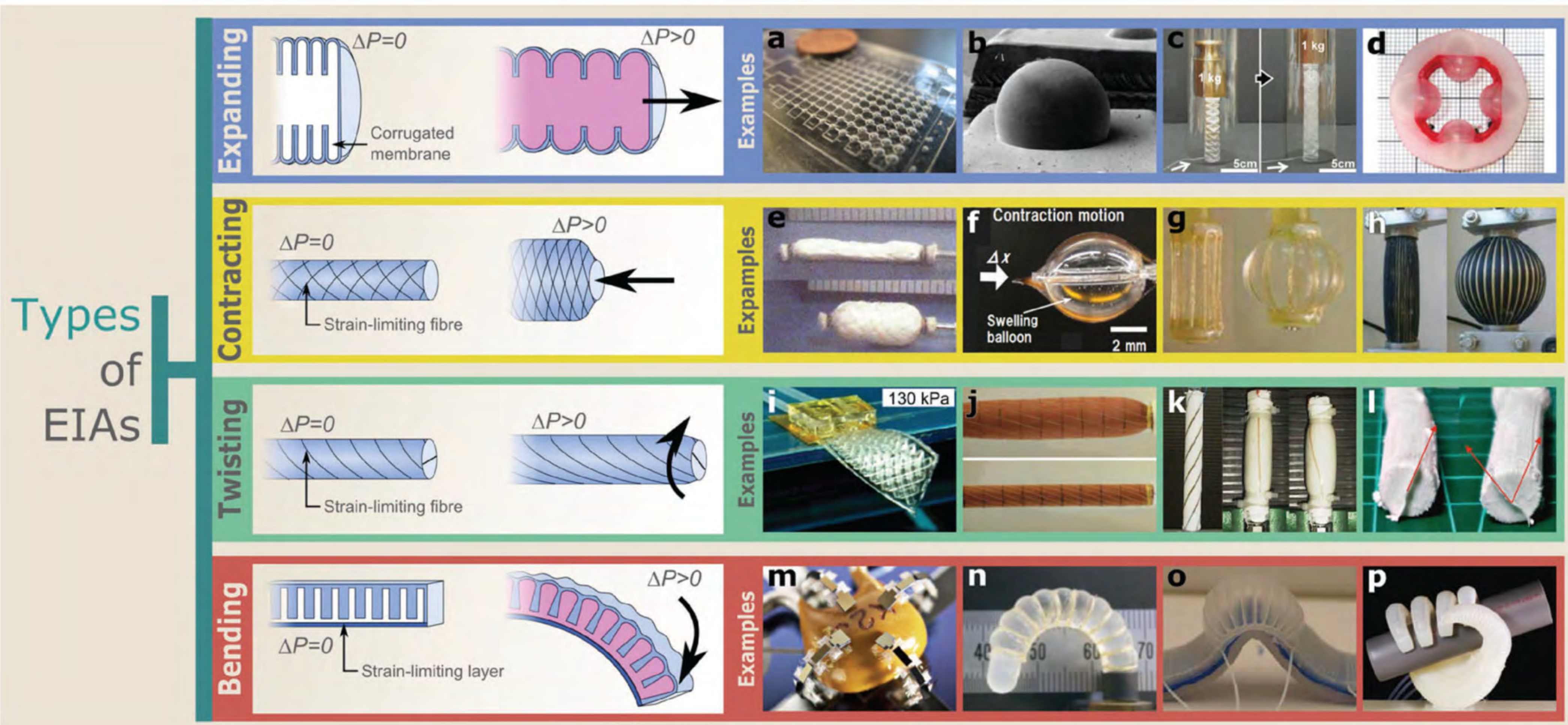
Pressure responsive soft actuators

- Fluidic elastomer actuators
- Mckibben actuators
- Film based soft actuators

- All of them exploit inflation of the actuator structure by pressurization of gas (e.g., air) or liquid (e.g., water).
- Easy to make (by molding, 3D printing, heat sealing), high actuation output, relatively fast, require external pumps and compressors.

Pressure responsive soft actuators: Fluidic elastomer actuators

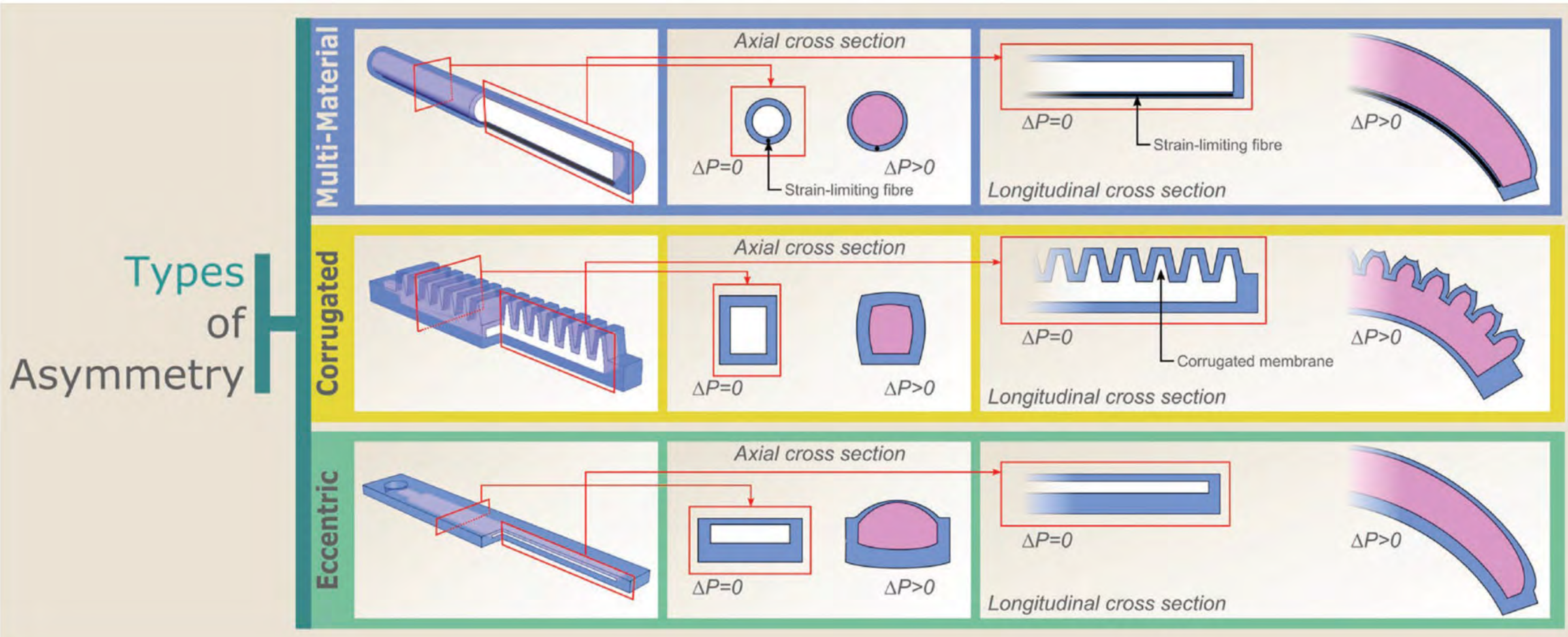
- Also called as “Elastic inflatable actuators (EIAs)”, “Pneumatic soft actuators (SPAs)”, etc.
- Base material: Silicone rubbers



Gorissen, Benjamin, et al. "Elastic inflatable actuators for soft robotic applications." Advanced Materials 29.43 (2017): 1604977.

Pressure responsive soft actuators: Fluidic elastomer actuators

- Bending type is most common actuator configuration



Gorissen, Benjamin, et al. "Elastic inflatable actuators for soft robotic applications." Advanced Materials 29.43 (2017): 1604977.

Pressure responsive soft actuators: Fluidic elastomer actuators

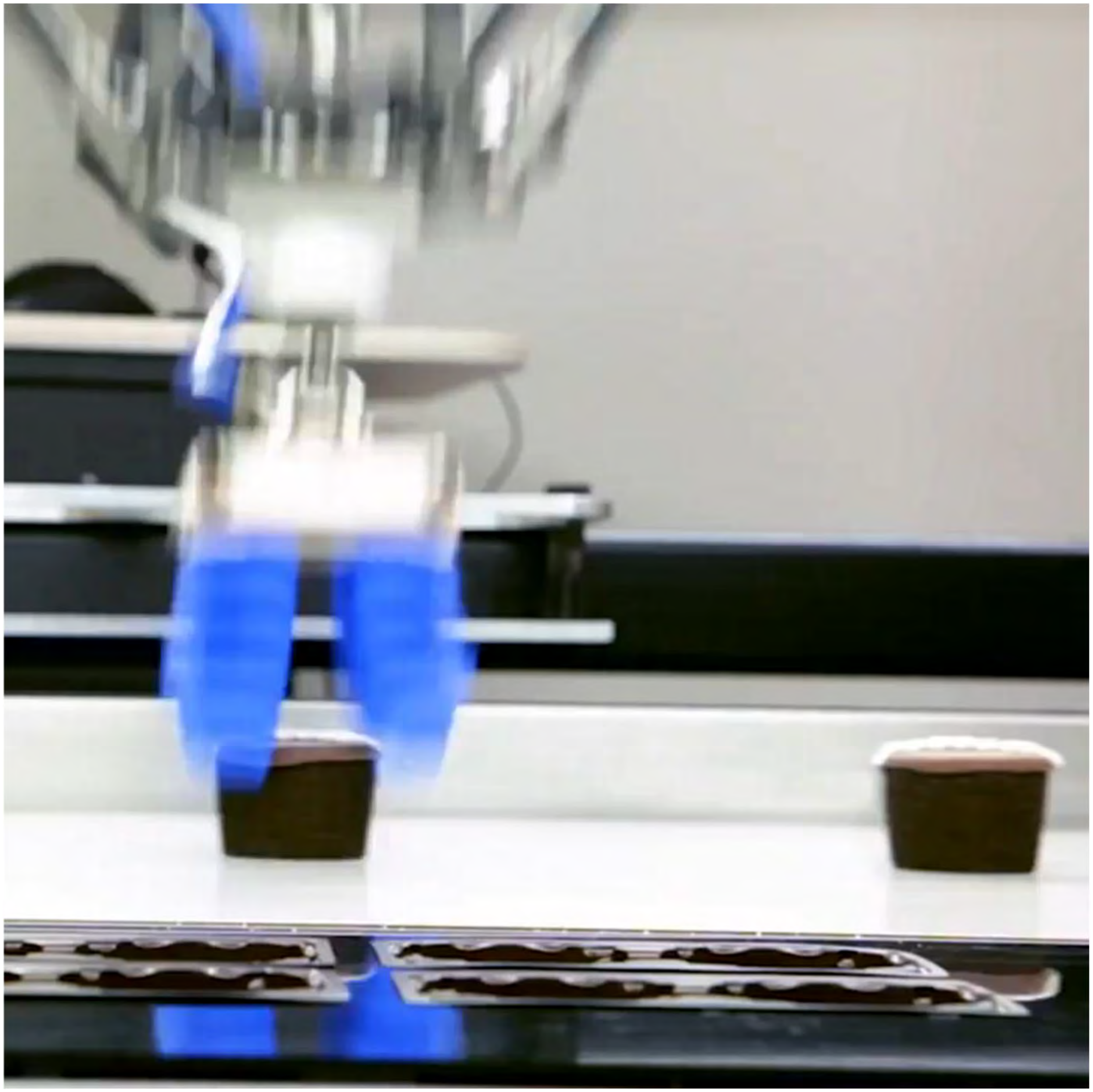
“膨らんで曲がるシリコンアクチュエータ”
http://opensoftmachines.com/2018/03/silicone-bending-actuator/?lang=ja

Pressure responsive soft actuators: Fluidic elastomer actuators

Suzumori, Koichi, Shoichi Iikura, and Hirohisa Tanaka. "Development of flexible microactuator and its applications to robotic mechanisms." Proceedings. 1991 IEEE International Conference on Robotics and Automation. IEEE Computer Society, 1991.

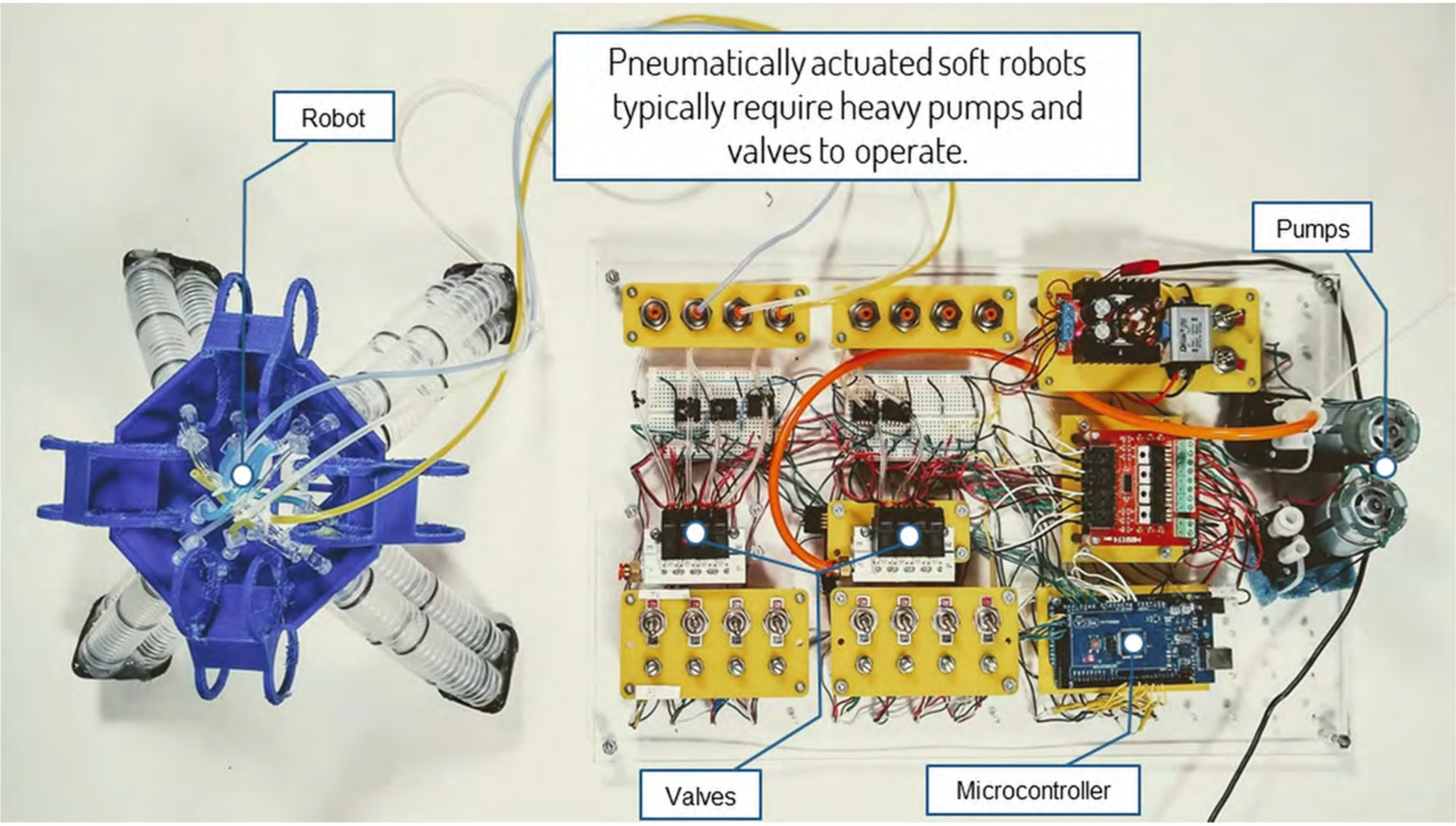
Soft Robotics 01: Flexible Microactuator
https://www.youtube.com/watch?v=kHGLYRUKWeM

Pressure responsive soft actuators: Fluidic elastomer actuators



'Soft Robots' Handle Food With Care
https://www.youtube.com/watch?v=gngeaoJ--9Q

Pressure responsive soft actuators: Fluidic elastomer actuators



Drotman, Dylan, et al. "Electronics-free pneumatic circuits for controlling soft-legged robots." Science Robotics 6.51 (2021): eaay2627.

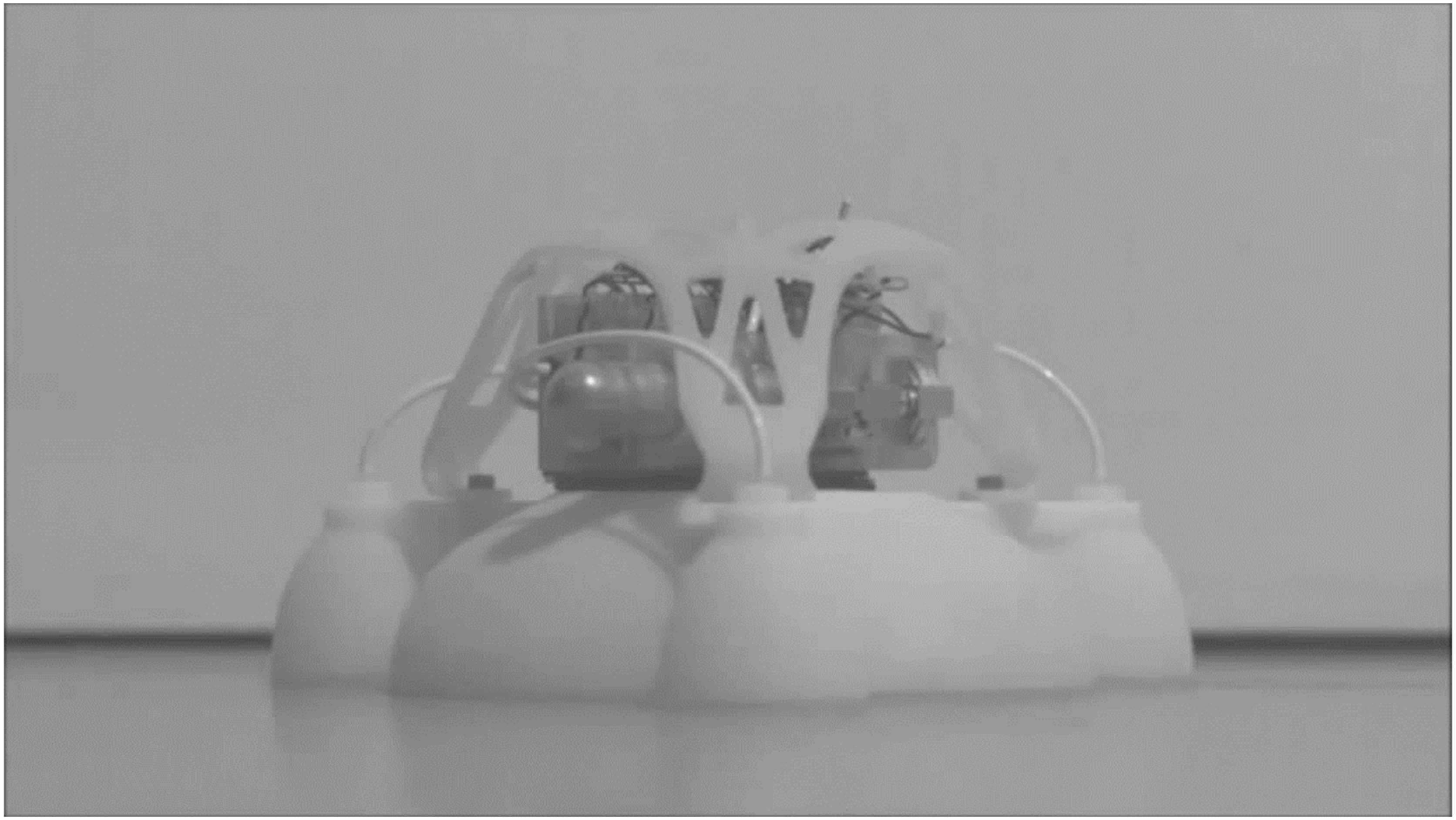
Electronics-Free Soft Legged Robot
https://www.youtube.com/watch?v=bnT6BBkDYlc

Pressure responsive soft actuators: Fluidic elastomer actuators

Katzschmann, Robert K., et al. "Exploration of underwater life with an acoustically controlled soft robotic fish." Science Robotics 3.16 (2018): eaar3449.

SoFi MIT Robot Fish | Inverse
https://www.youtube.com/watch?v=2vy861m2MAE

Pressure responsive soft actuators: Fluidic elastomer actuators



A 3-D Printed Functionally Graded Soft Robot
https://www.youtube.com/watch?v=u5F4ECFGgJ8

Bartlett, Nicholas W., et al. "A 3D-printed, functionally graded soft robot powered by combustion." Science 349.6244 (2015): 161-165.

Pressure responsive soft actuators: Mckibben actuators

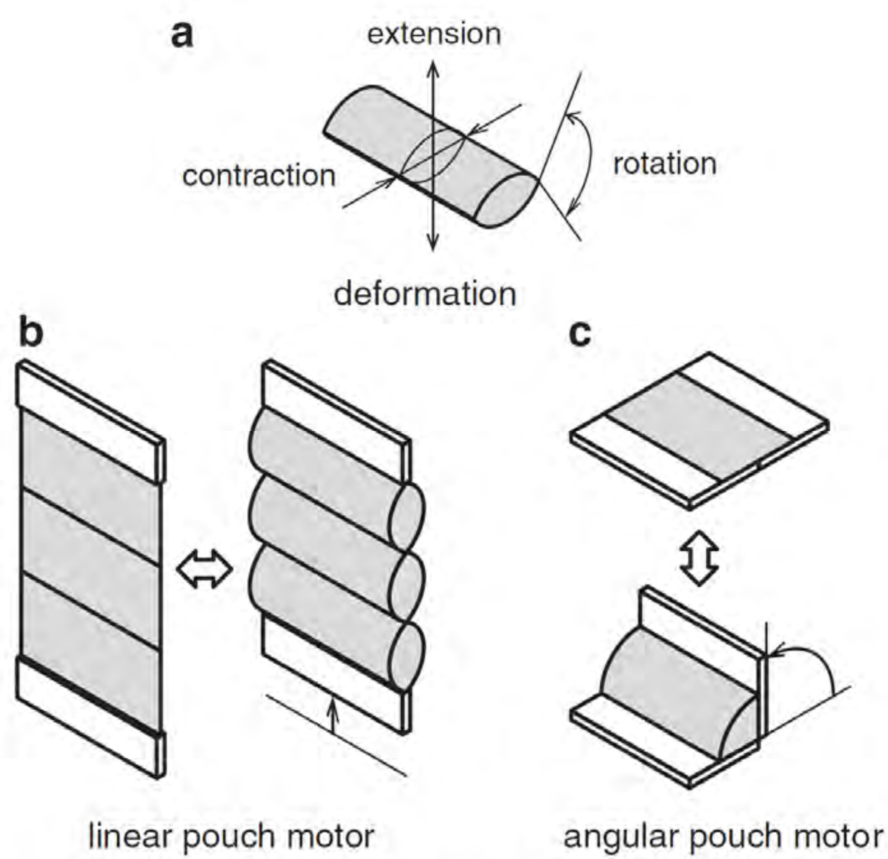
Hydraulic McKibben Muscles
https://www.youtube.com/watch?v=NDQlOqsr84s

Pressure responsive soft actuators: Mckibben actuators

Mowgli: jumping legged robot driven by artificial muscles
https://www.youtube.com/watch?v=QcjEsTPn5I0

Pressure responsive soft actuators: Film based soft actuators

- Also called as “Pouch motors”.
- Base material: Inextensible films (e.g., Oriented Polypropylene (OPP))



Niiyama, Ryuma, et al. "Pouch motors: Printable soft actuators integrated with computational design." Soft Robotics 2.2 (2015): 59-70.

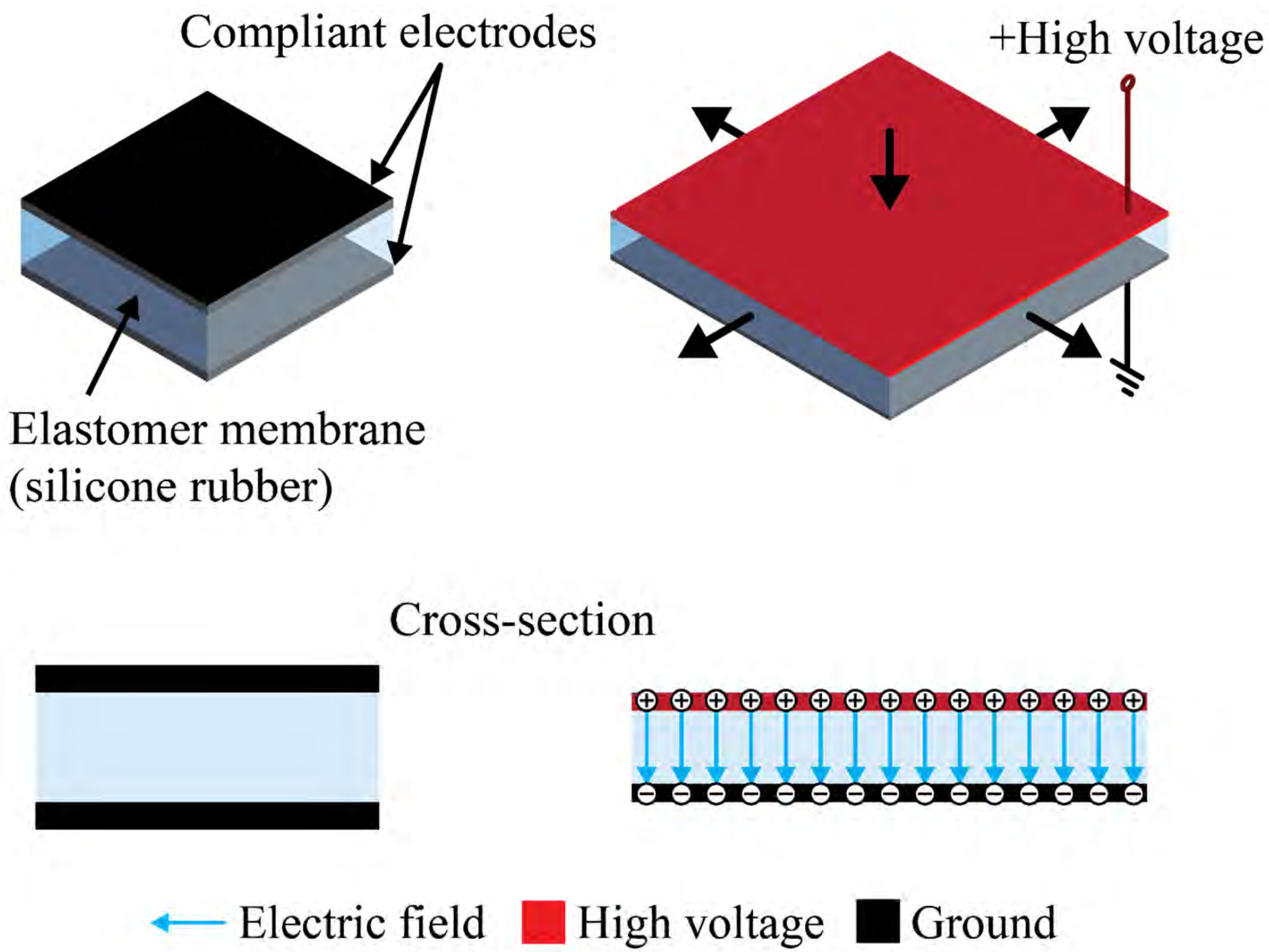
Pouch Motors: Printable/Inflatable Soft Actuators for Robotics
https://www.youtube.com/watch?v=YIiJ4ka-Owk

Electrically responsive soft actuators

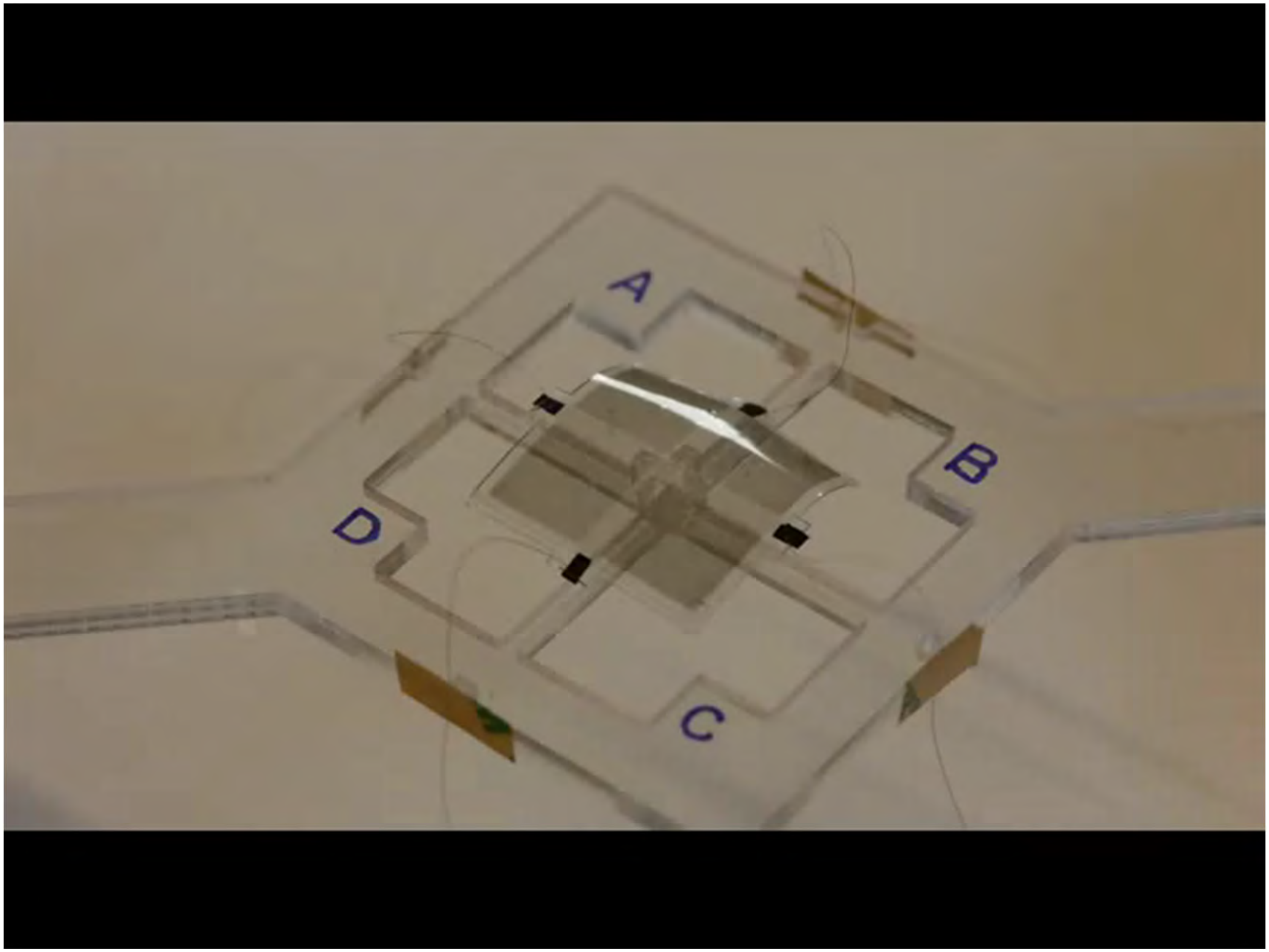
- Electroactive polymers
- Electro-hydraulic soft actuators
- Biohybrid actuators

Electrically responsive soft actuators: Electroactive polymers: Dielectric elastomer actuators (DEAs)

- Work with electrostatic force between the electrodes.
- Large deformation, fast movements but often low force and require high voltage.
- Common material: Silicone rubbers

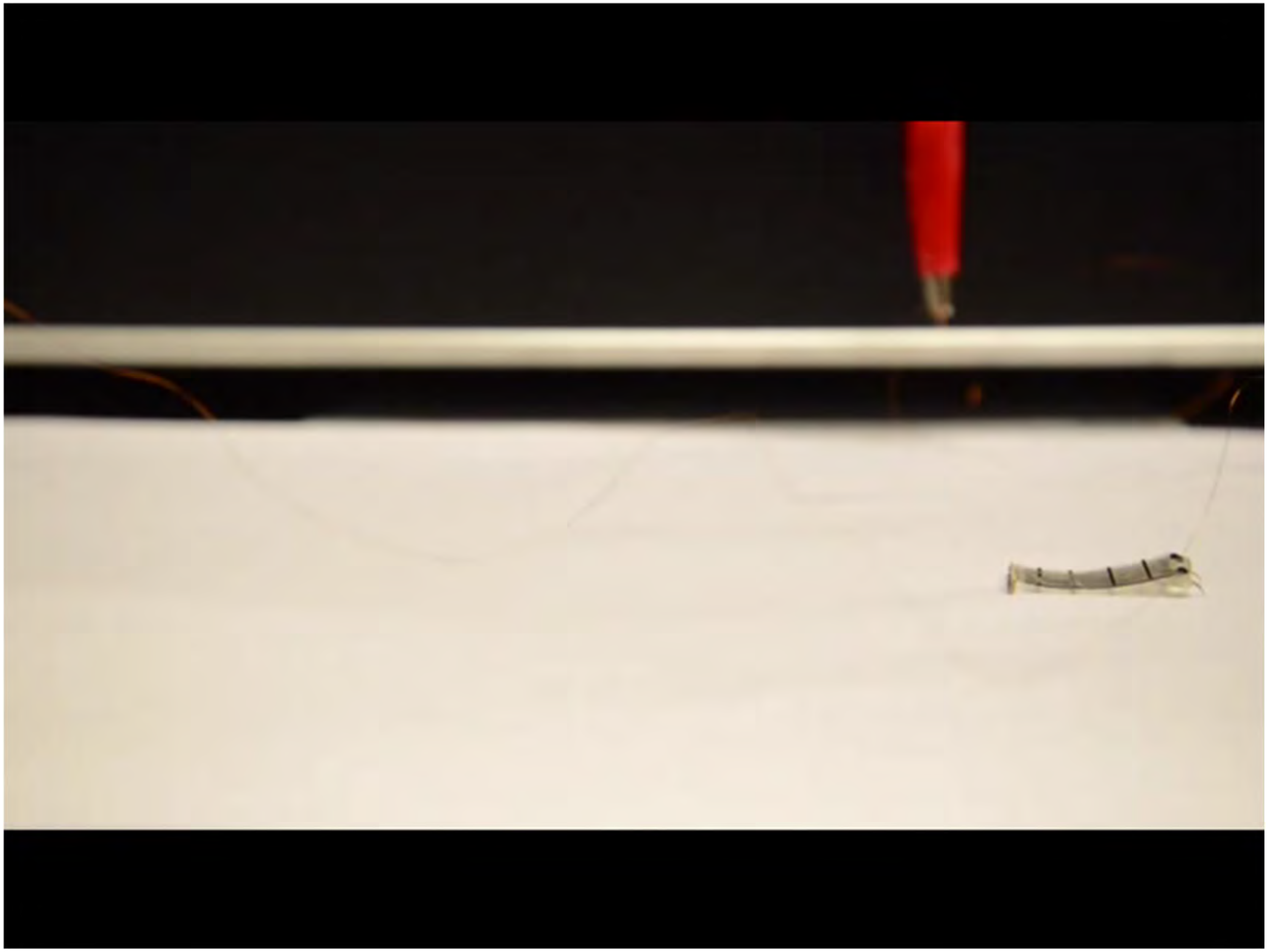


Electrically responsive soft actuators: Electroactive polymers: Dielectric elastomer actuators (DEAs)



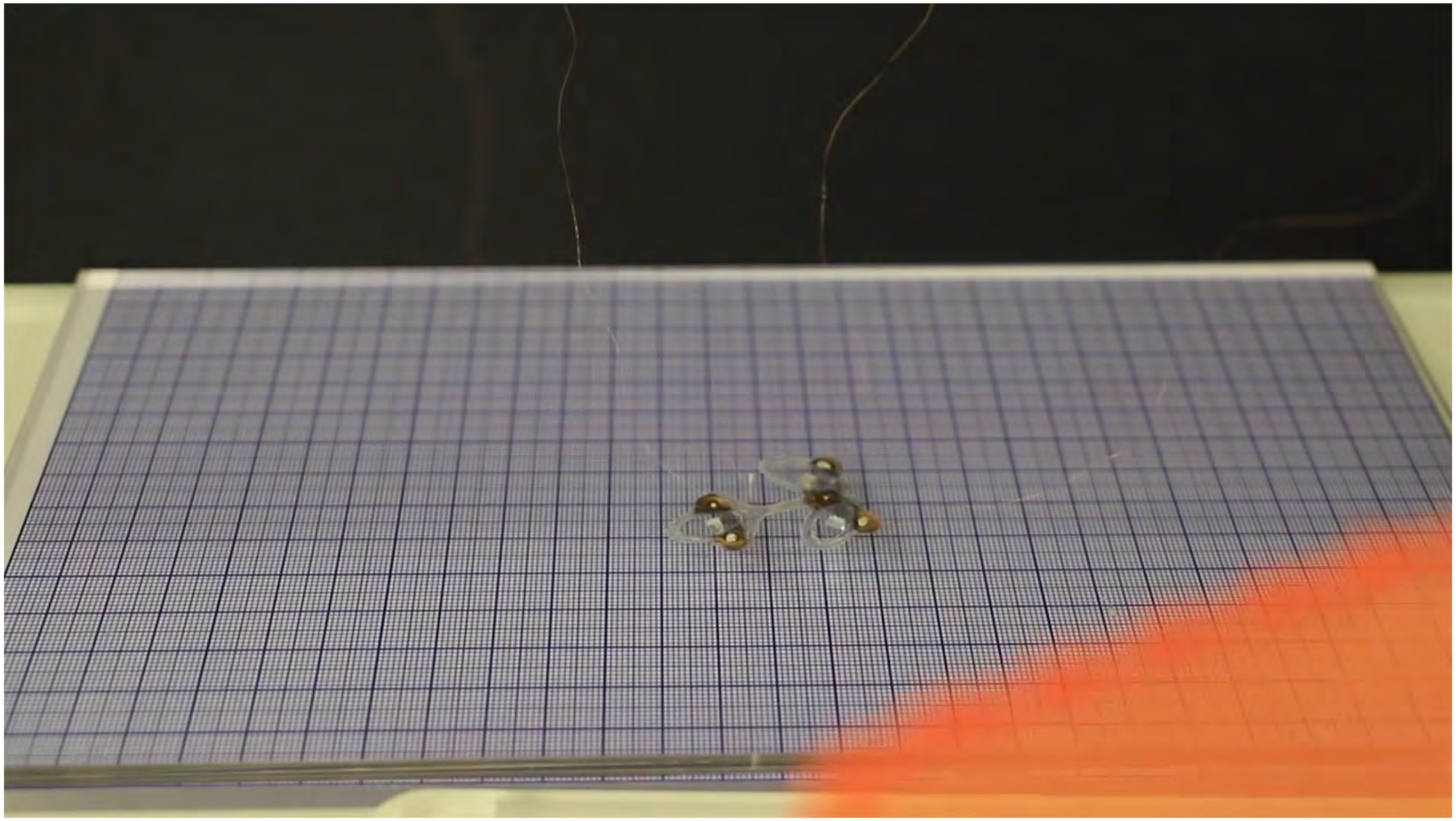
Duduta, Mihai, Robert J. Wood, and David R. Clarke. "Multilayer dielectric elastomers for fast, programmable actuation without prestretch." Advanced Materials 28.36 (2016): 8058-8063.

Electrically responsive soft actuators:
Electroactive polymers:
Dielectric elastomer actuators (DEAs)



Duduta, Mihai, David R. Clarke, and Robert J. Wood. "A high speed soft robot based on dielectric elastomer actuators." 2017 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2017.

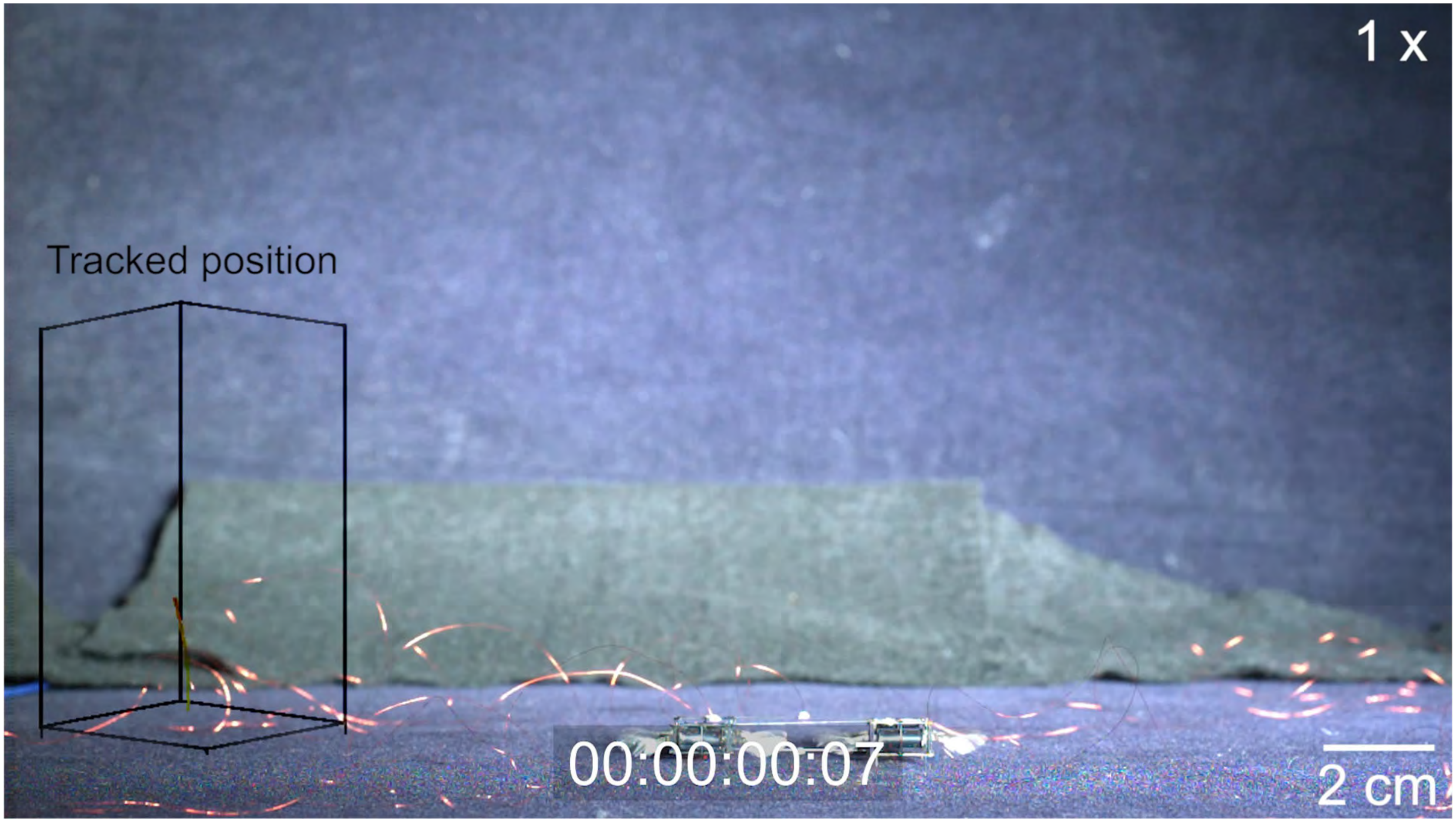
Electrically responsive soft actuators:
Electroactive polymers:
Dielectric elastomer actuators (DEAs)



A soft robotic insect that survives being flattened by a fly swatter
https://www.youtube.com/watch?v=s_qhmBsG_ZQ

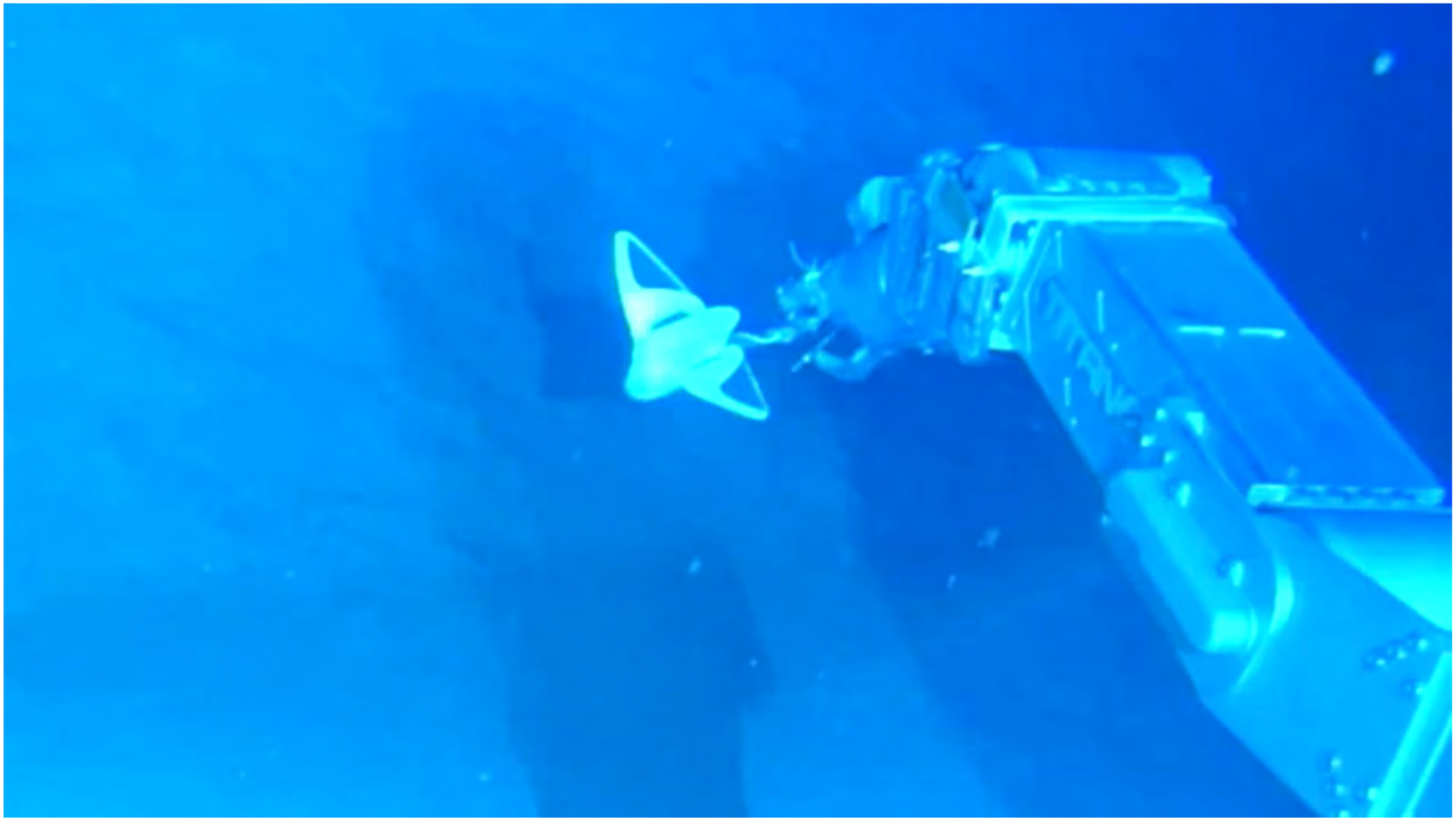
Ji, Xiaobin, et al. "An autonomous untethered fast soft robotic insect driven by low-voltage dielectric elastomer actuators." Science Robotics 4.37 (2019): eaaz6451.

Electrically responsive soft actuators: Electroactive polymers: Dielectric elastomer actuators (DEAs)



Ren, Zhijian, et al. "A high-lift micro-aerial-robot powered by low-voltage and long-endurance dielectric elastomer actuators." Advanced Materials 34.7 (2022): 2106757.

Electrically responsive soft actuators: Electroactive polymers: Dielectric elastomer actuators (DEAs)

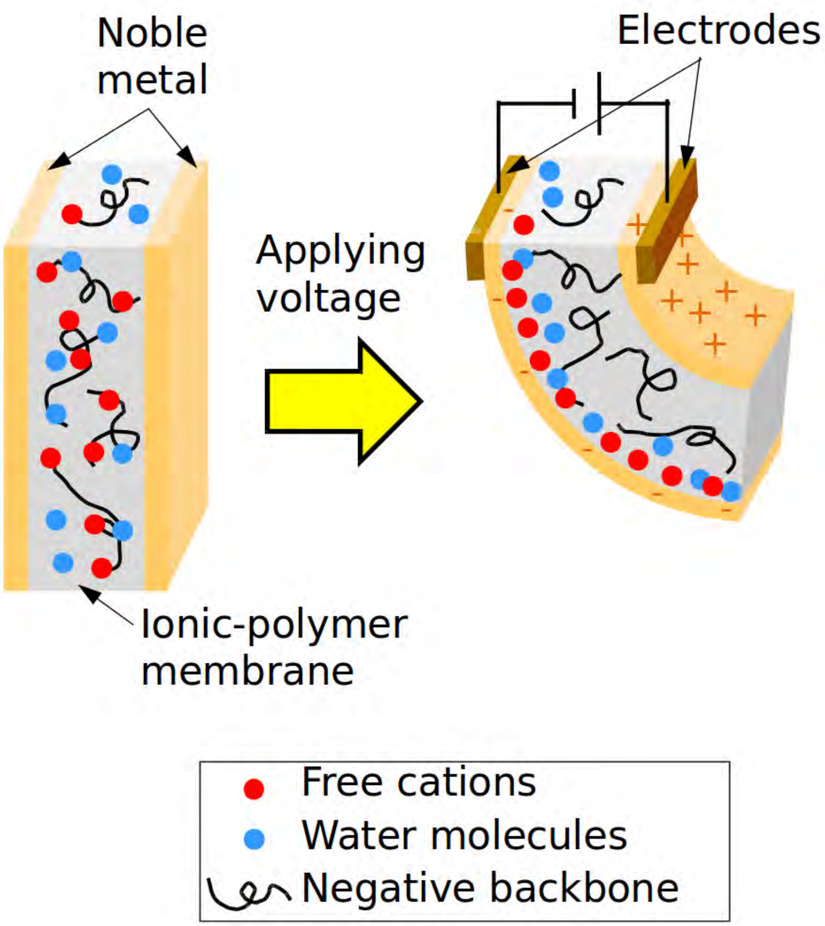


China's soft robot realizes deep sea exploration and free swimming
https://www.youtube.com/watch?v=QMHy8cI681w

Li, Guorui, et al. "Self-powered soft robot in the Mariana Trench." Nature 591.7848 (2021): 66-71.

Electrically responsive soft actuators: Electroactive polymers: Ionic polymer-metal composites (IPMCs)

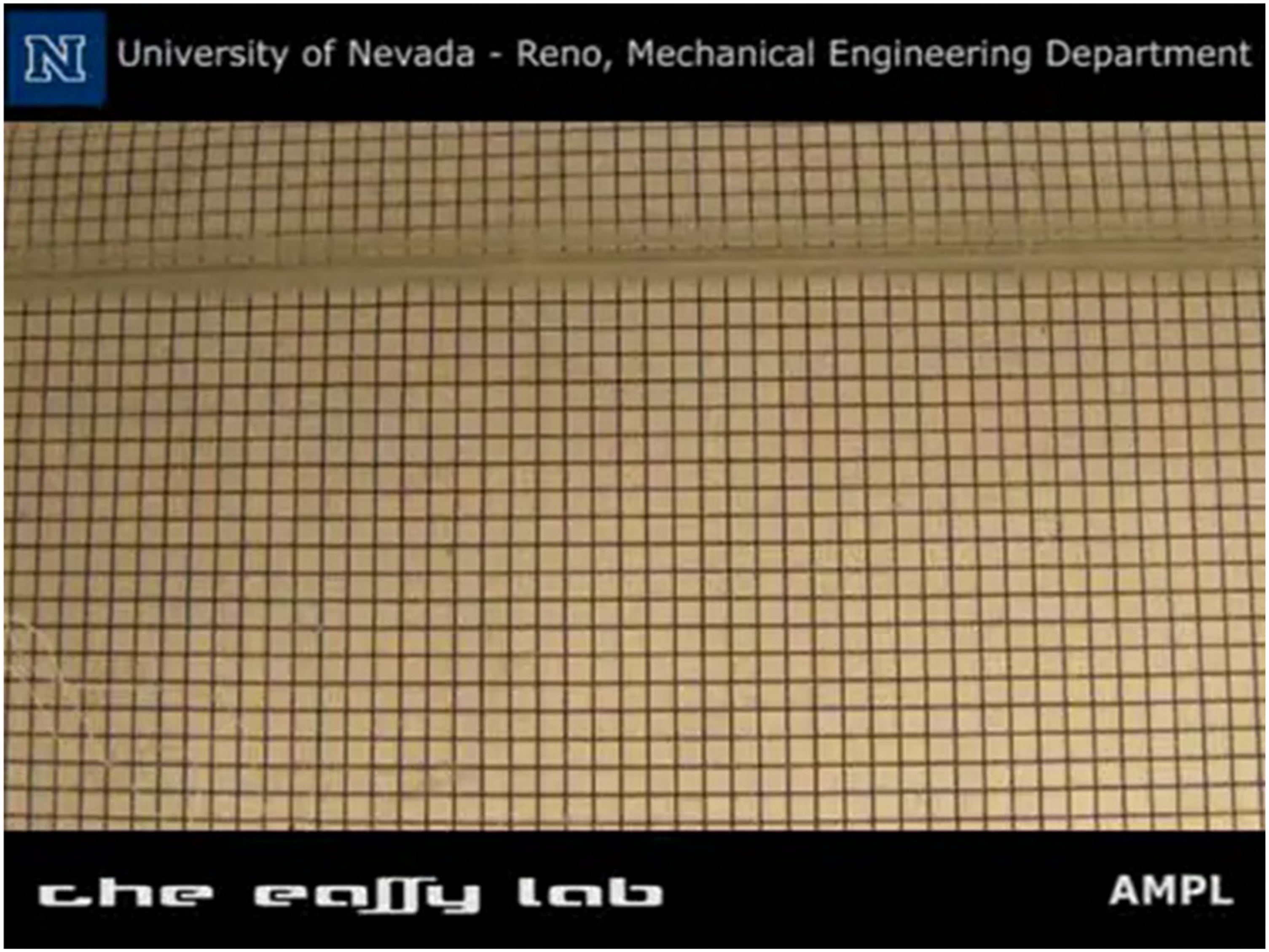
- Relies on physical movements of positive ions (cations).
- Large deformation and low voltage but slow. Need of water encapsulation.
- Common material: Nafion (kind of polymer)



Shahinpoor, Mohsen. "17 Review of Ionic Polymer–Metal Composites (IPMCs) as Smart Materials." Fundamentals of Smart Materials (2020): 203.

An ionic polymer-metal composite (IPMC) artificial muscle slowly oscillating at 0.15 Hz https://www.youtube.com/watch?v=Nn4b7Wi7RIo

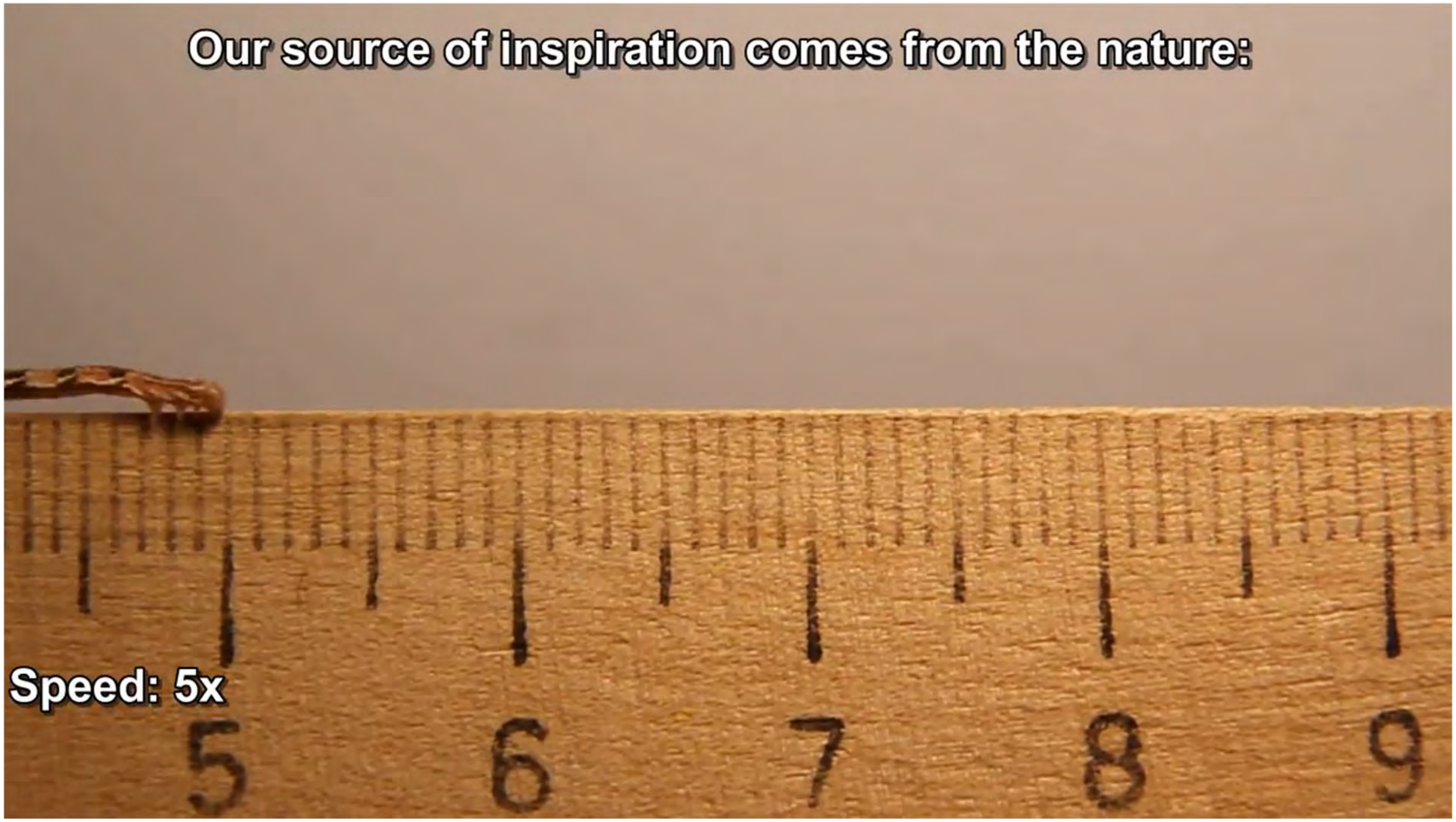
Electrically responsive soft actuators: Electroactive polymers: Ionic polymer-metal composites (IPMCs)



IPMC Robotic Fish
https://www.youtube.com/watch?v=GpLcA5YCwls

Hubbard, Joel J., et al. "Monolithic IPMC fins for propulsion and maneuvering in bioinspired underwater robotics." IEEE Journal of Oceanic Engineering 39.3 (2013): 540-551.

Electrically responsive soft actuators: Electroactive polymers: Ionic polymer-metal composites (IPMCs)

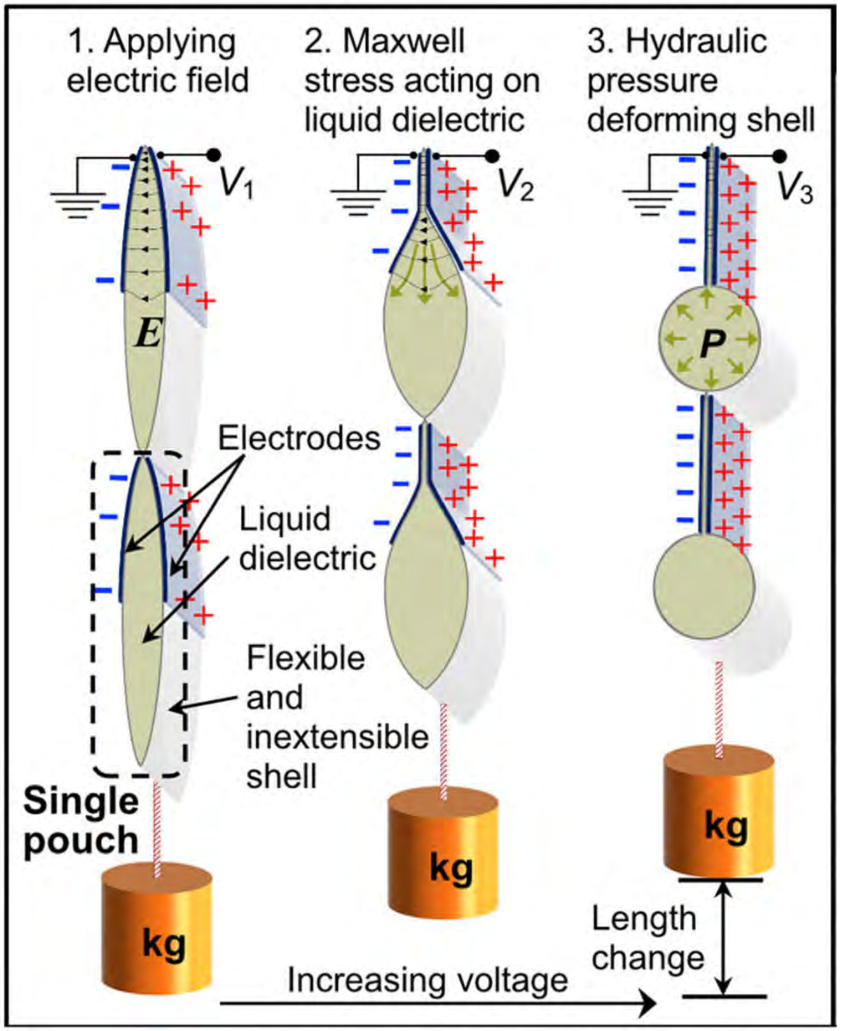


Must, Indrek, et al. "Ionic and capacitive artificial muscle for biomimetic soft robotics." Advanced Engineering Materials 17.1 (2015): 84-94.

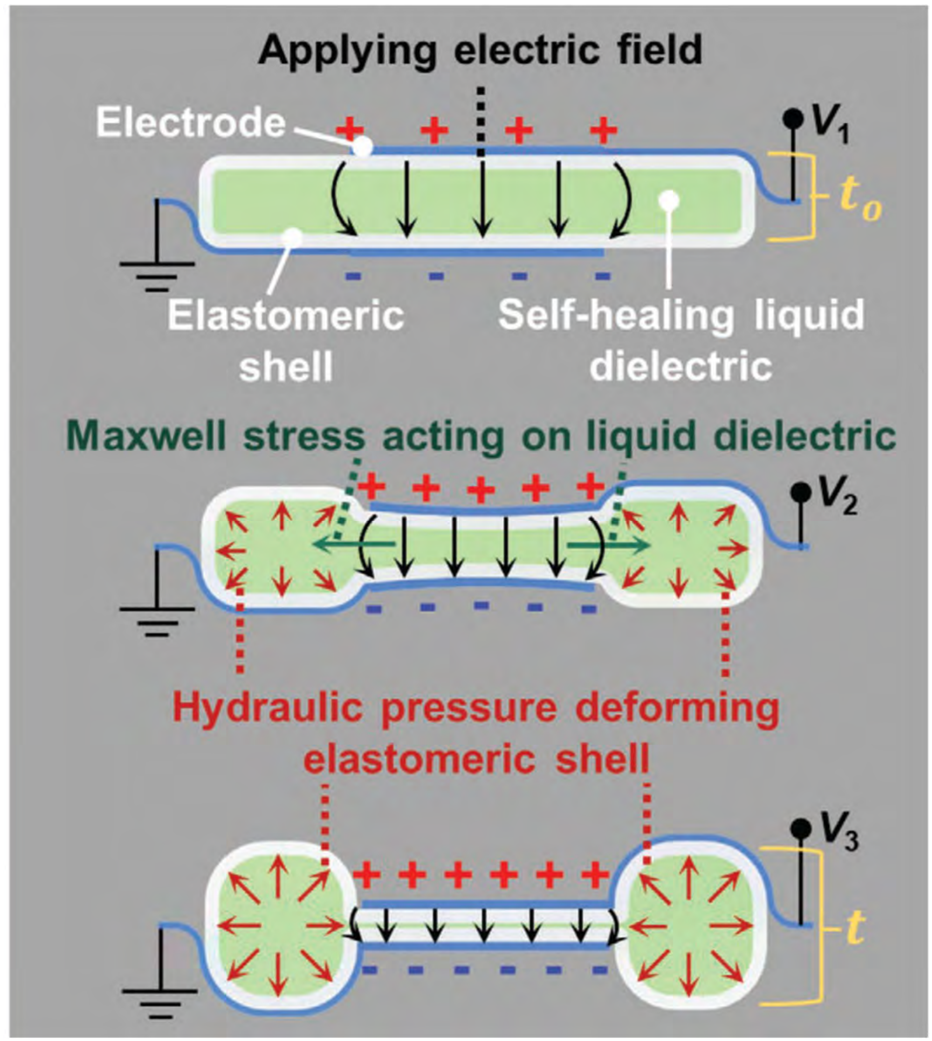
Ionic and Capacitive Artificial Muscle for Biomimetic Soft Robotics
https://www.youtube.com/watch?v=1mSMsIQMTnU

Electrically responsive soft actuators: Electro-hydraulic soft actuators

- Also known as "Hydraulically amplified self-healing electrostatic actuators (HASELs)".
- Fast, high actuation output but high voltage is required.

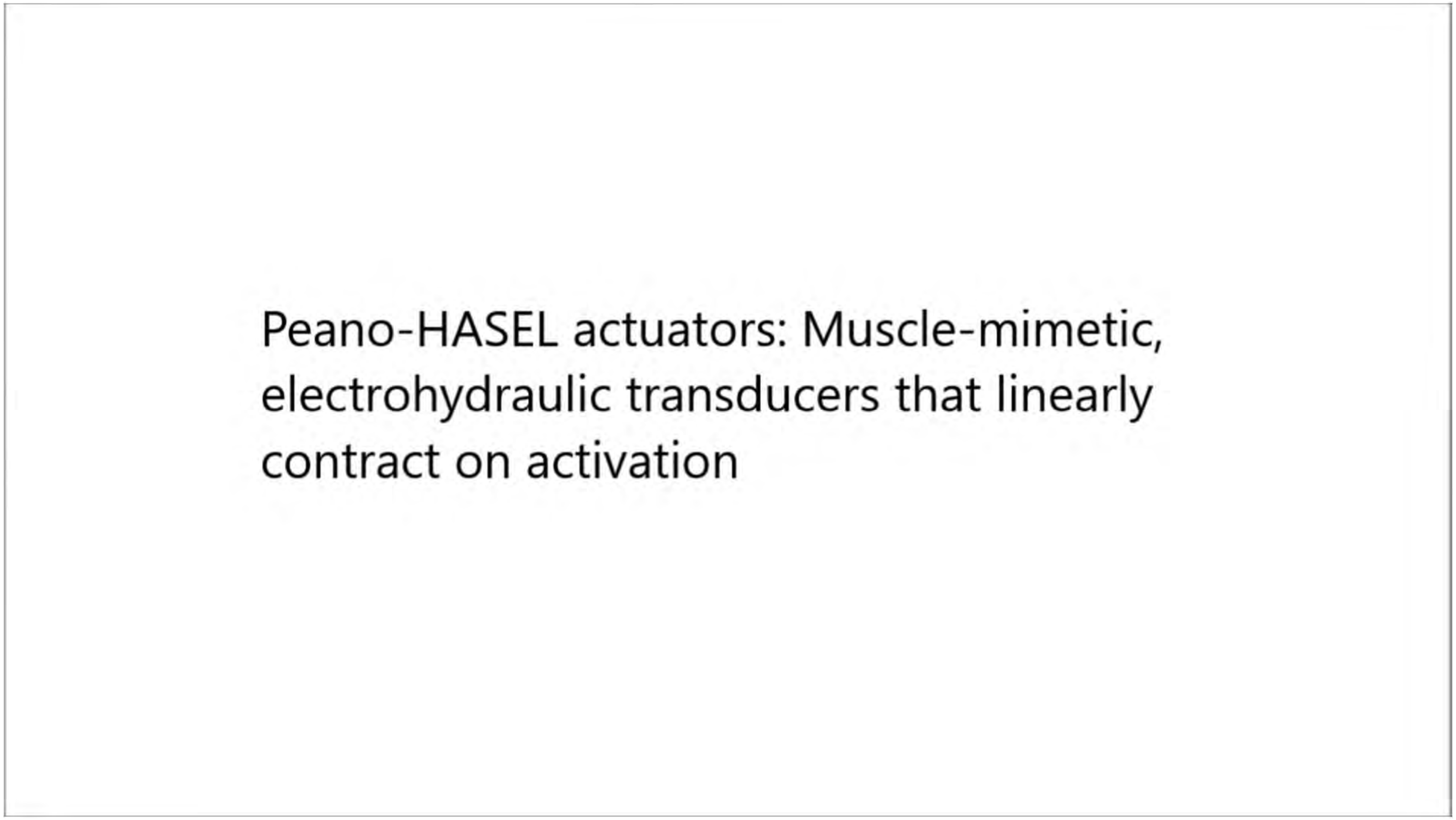


Yoder, Zachary, et al. "Design of a high-speed prosthetic finger driven by Peano-HASEL actuators." Frontiers in Robotics and AI (2020): 181.



Rothemund, Philipp, et al. "HASEL artificial muscles for a new generation of lifelike robots—recent progress and future opportunities." Advanced materials 33.19 (2021): 2003375.

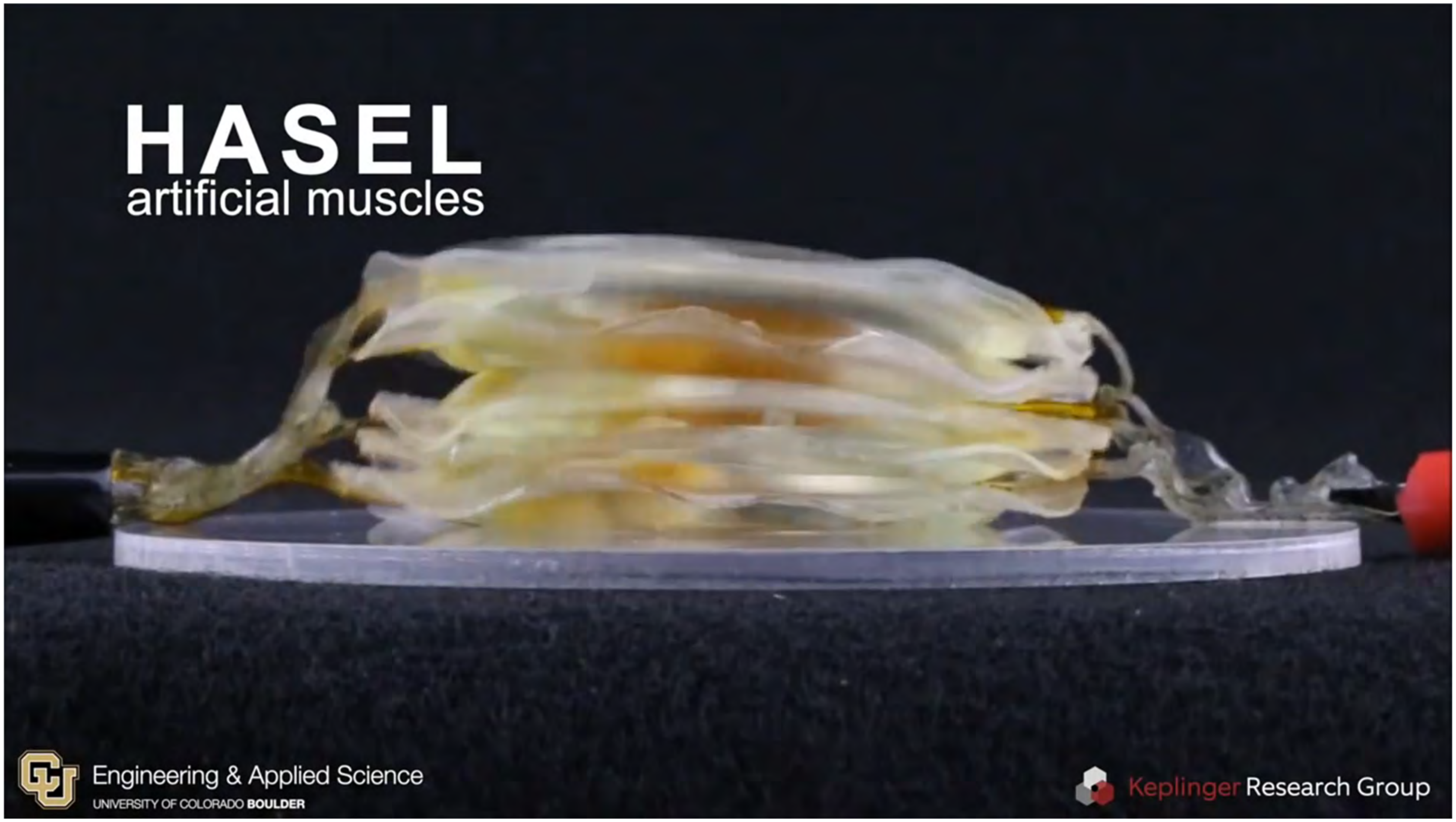
Electrically responsive soft actuators: Electro-hydraulic soft actuators



Kellaris, Nicholas, et al. "Peano-HASEL actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract on activation." Science Robotics 3.14 (2018): eaar3276.

Peano-HASEL actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract
https://www.youtube.com/watch?v=k5XH1MDLzi0

Electrically responsive soft actuators: Electro-hydraulic soft actuators



Acome, Eric, et al. "Hydraulically amplified self-healing electrostatic actuators with muscle-like performance." Science 359.6371 (2018): 61-65.

HASEL actuators with muscle-like performance
https://www.youtube.com/watch?v=M4qcvTeN8k0

Electrically responsive soft actuators: Electro-hydraulic soft actuators

Yoder, Zachary, et al. "A soft, fast and versatile electrohydraulic gripper with capacitive object size detection." Advanced Functional Materials 33.3 (2023): 2209080.

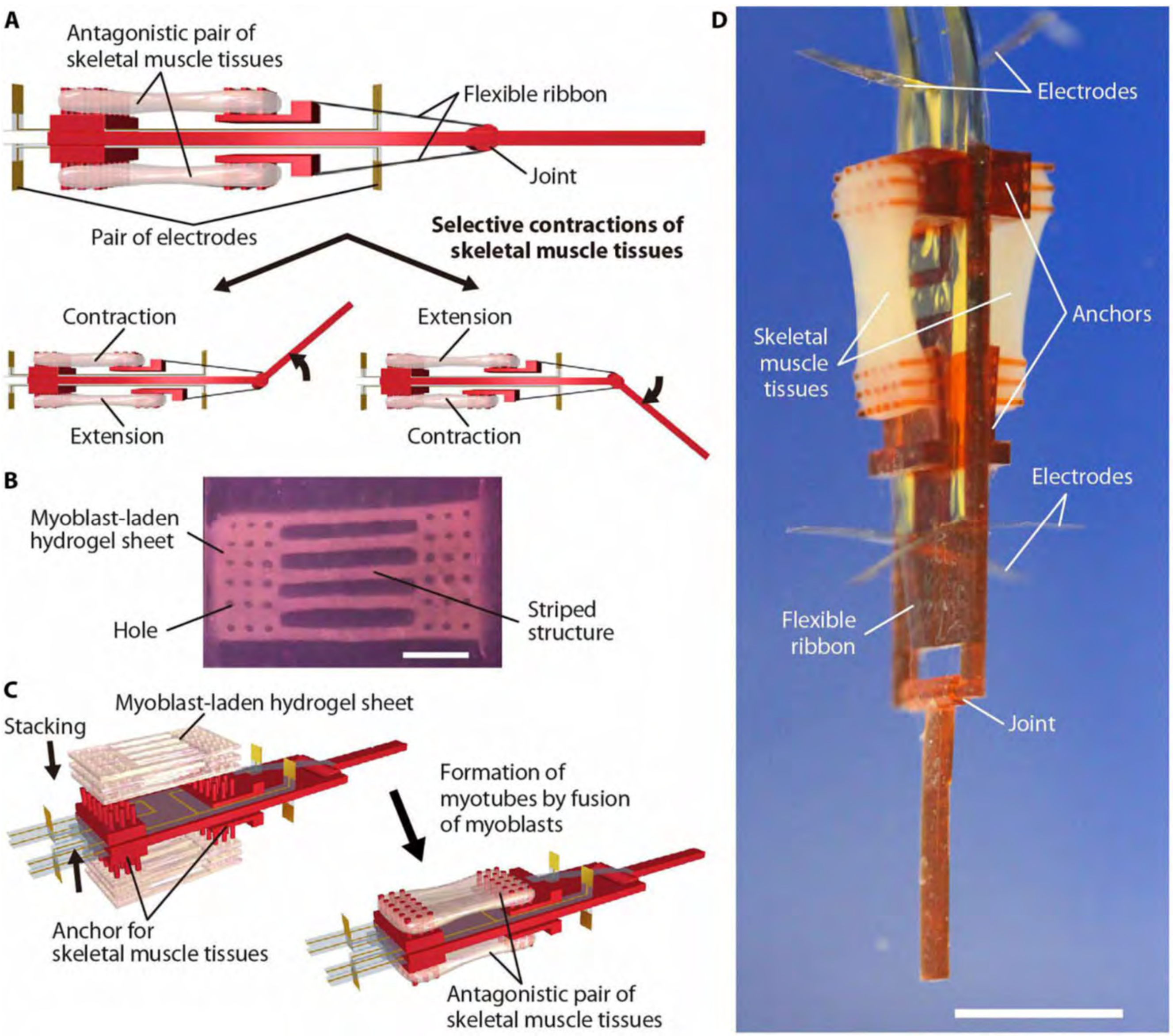
A Soft, Fast and Versatile Electrohydraulic Gripper with Capacitive Object Size Detection
https://www.youtube.com/watch?v=wWL5oMK_CRk

Electrically responsive soft actuators: Electro-hydraulic soft actuators

Mitchell, Shane K., Trent Martin, and Christoph Keplinger. "A Pocket-Sized Ten-Channel High Voltage Power Supply for Soft Electrostatic Actuators." Advanced Materials Technologies 7.8 (2022): 2101469.

A Pocket-Sized Ten-Channel High Voltage Power Supply for Soft Electrostatic Actuators
https://www.youtube.com/watch?v=Gh-hbT7Iq6E

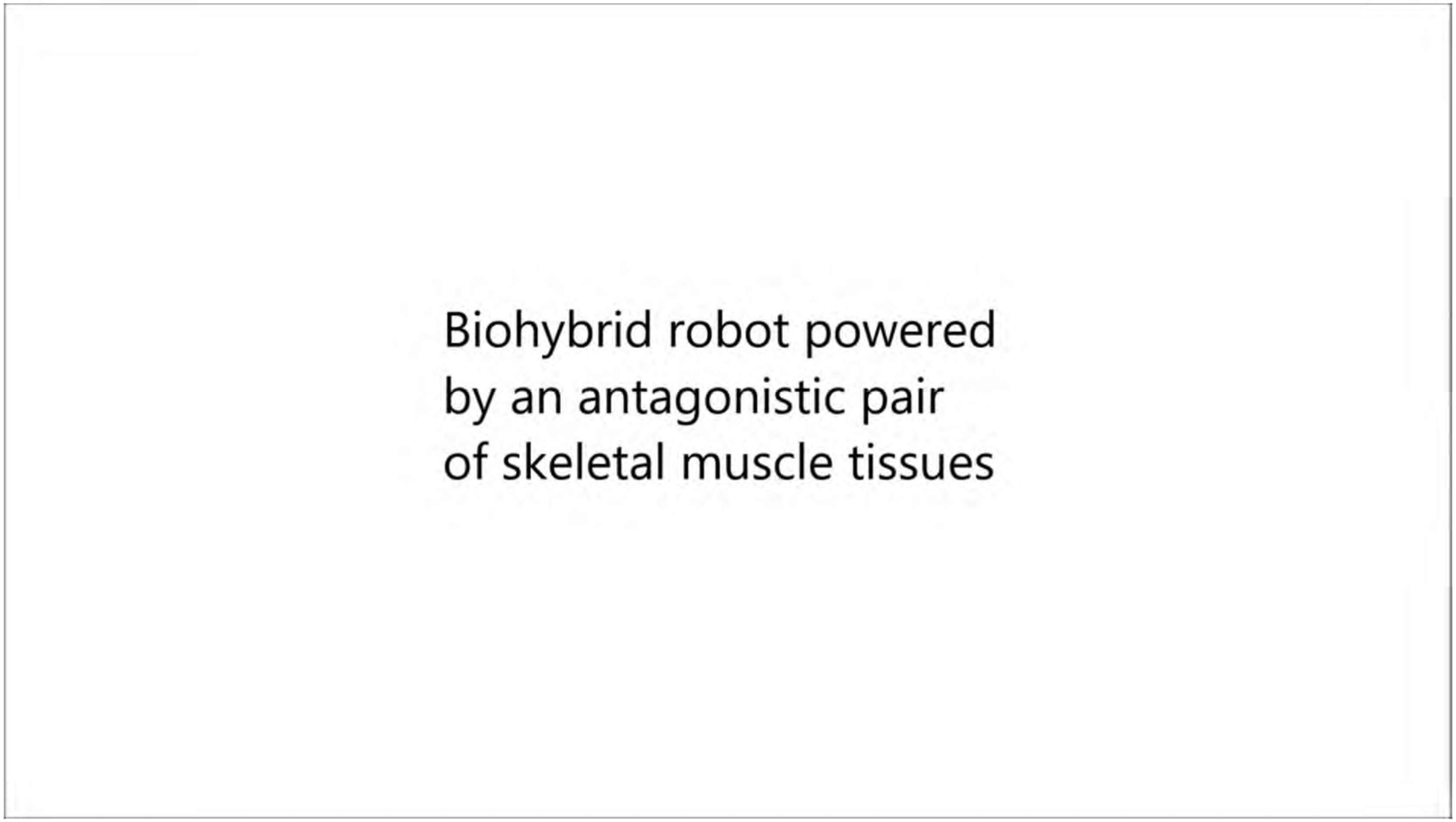
Electrically responsive soft actuators: Biohybrid actuators



- Exploit movements of cultivated muscle tissue.

Morimoto, Yuya, Hiroaki Onoe, and Shoji Takeuchi. "Biohybrid robot powered by an antagonistic pair of skeletal muscle tissues." Science robotics 3.18 (2018): eaat4440.

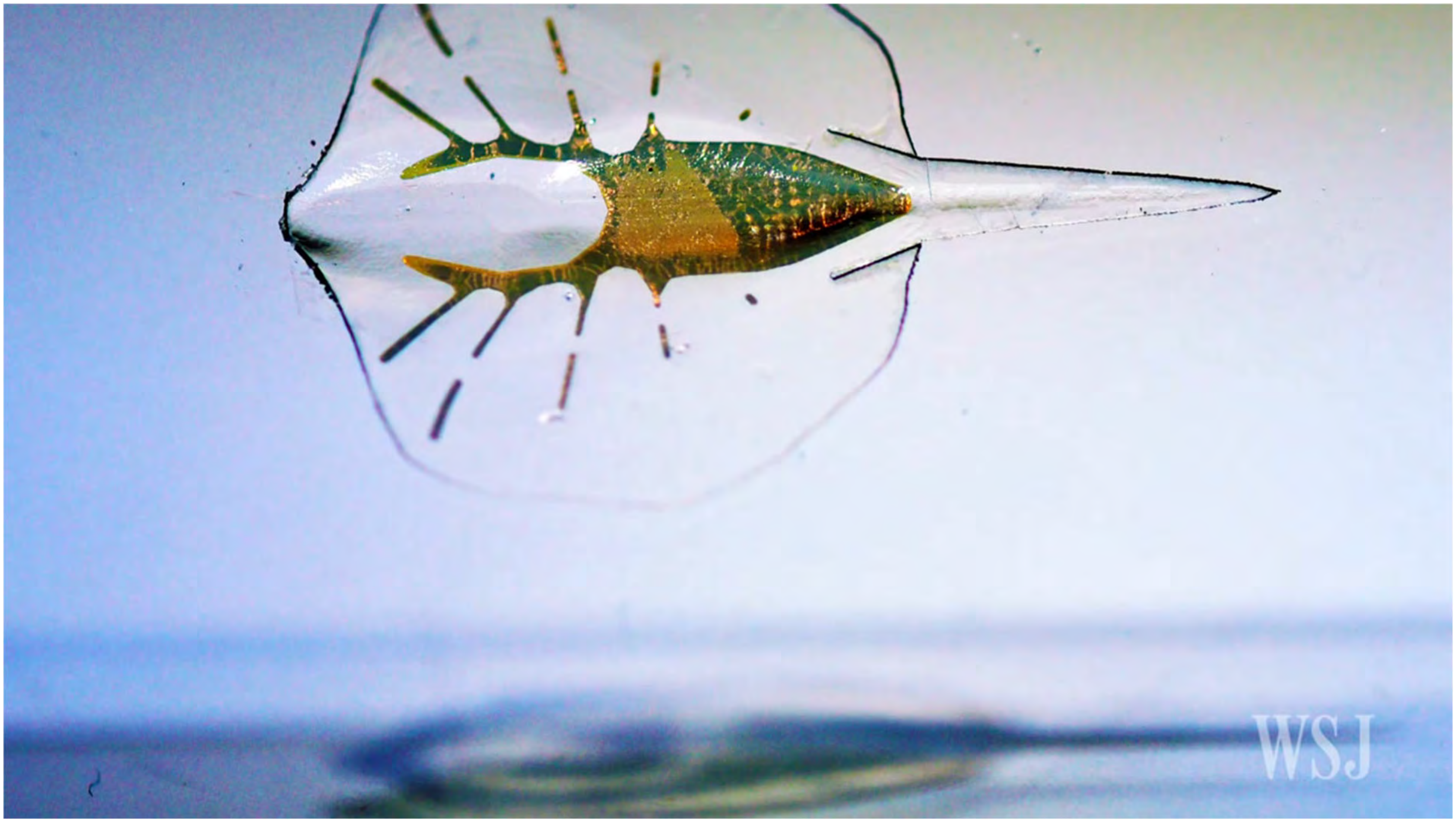
Electrically responsive soft actuators: Biohybrid actuators



Morimoto, Yuya, Hiroaki Onoe, and Shoji Takeuchi. "Biohybrid robot powered by an antagonistic pair of skeletal muscle tissues." Science robotics 3.18 (2018): eaat4440.

Biohybrid robot powered by an antagonistic pair of skeletal muscle tissues
https://www.youtube.com/watch?v=3UXG4xL0S4g

Electrically responsive soft actuators: Biohybrid actuators



Park, Sung-Jin, et al. "Phototactic guidance of a tissue-engineered soft-robotic ray." Science 353.6295 (2016): 158-162.

A Robotic Stingray Harnesses Living Cells
https://www.youtube.com/watch?v=8Sw6xRAG8XA

Electrically responsive soft actuators: Biohybrid actuators

Xu, Nicole W., and John O. Dabiri. "Low-power microelectronics embedded in live jellyfish enhance propulsion." Science Advances 6.5 (2020): eaaz3194.

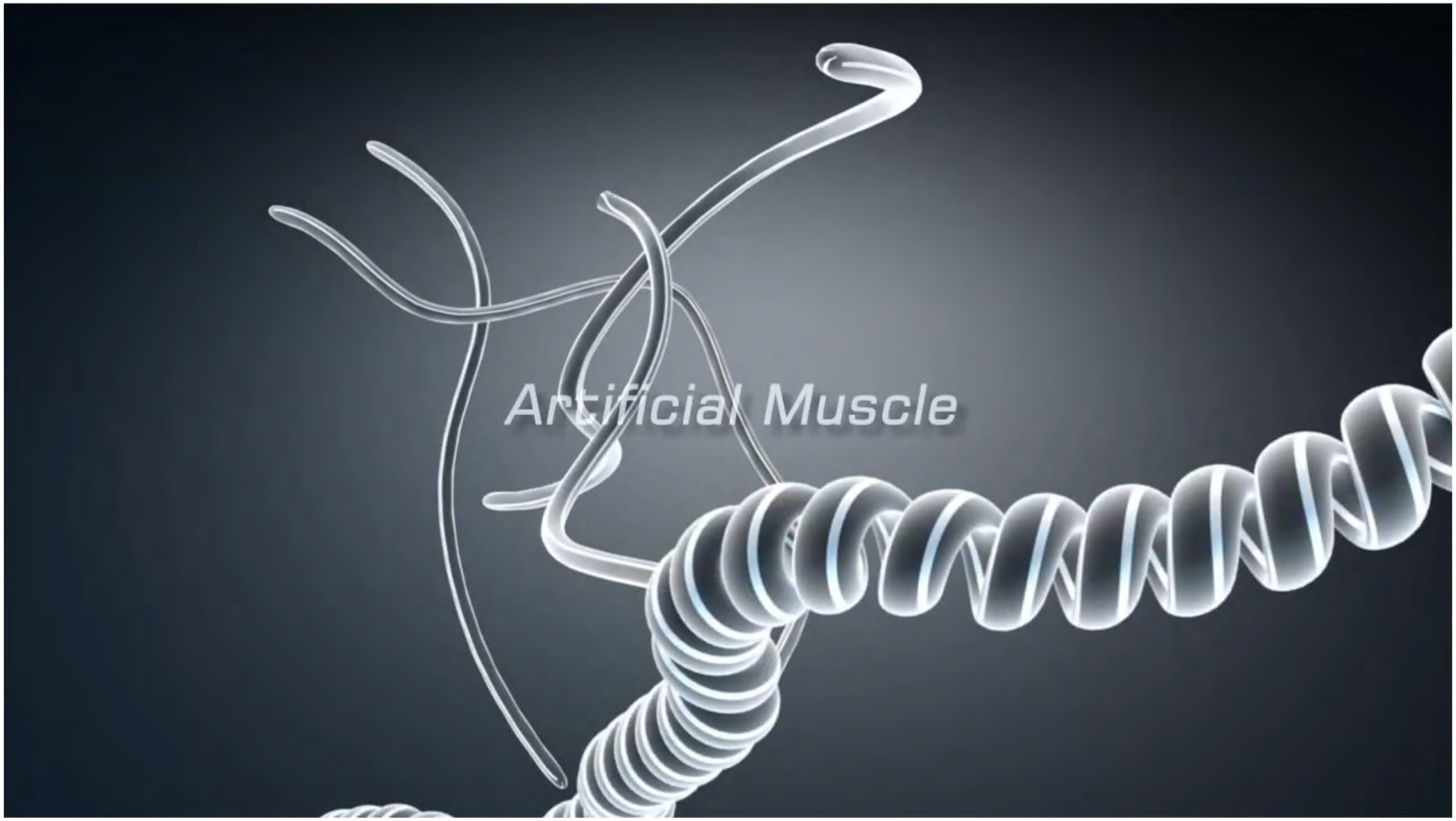
Bionic Jellyfish Swim Faster, More Efficiently
https://www.youtube.com/watch?v=pH5CVb7yjFw

Thermally responsive soft actuators

- Fishing line artificial muscles
- Shape memory alloys
- Shape memory polymers

Thermally responsive soft actuators: Fishing line artificial muscles

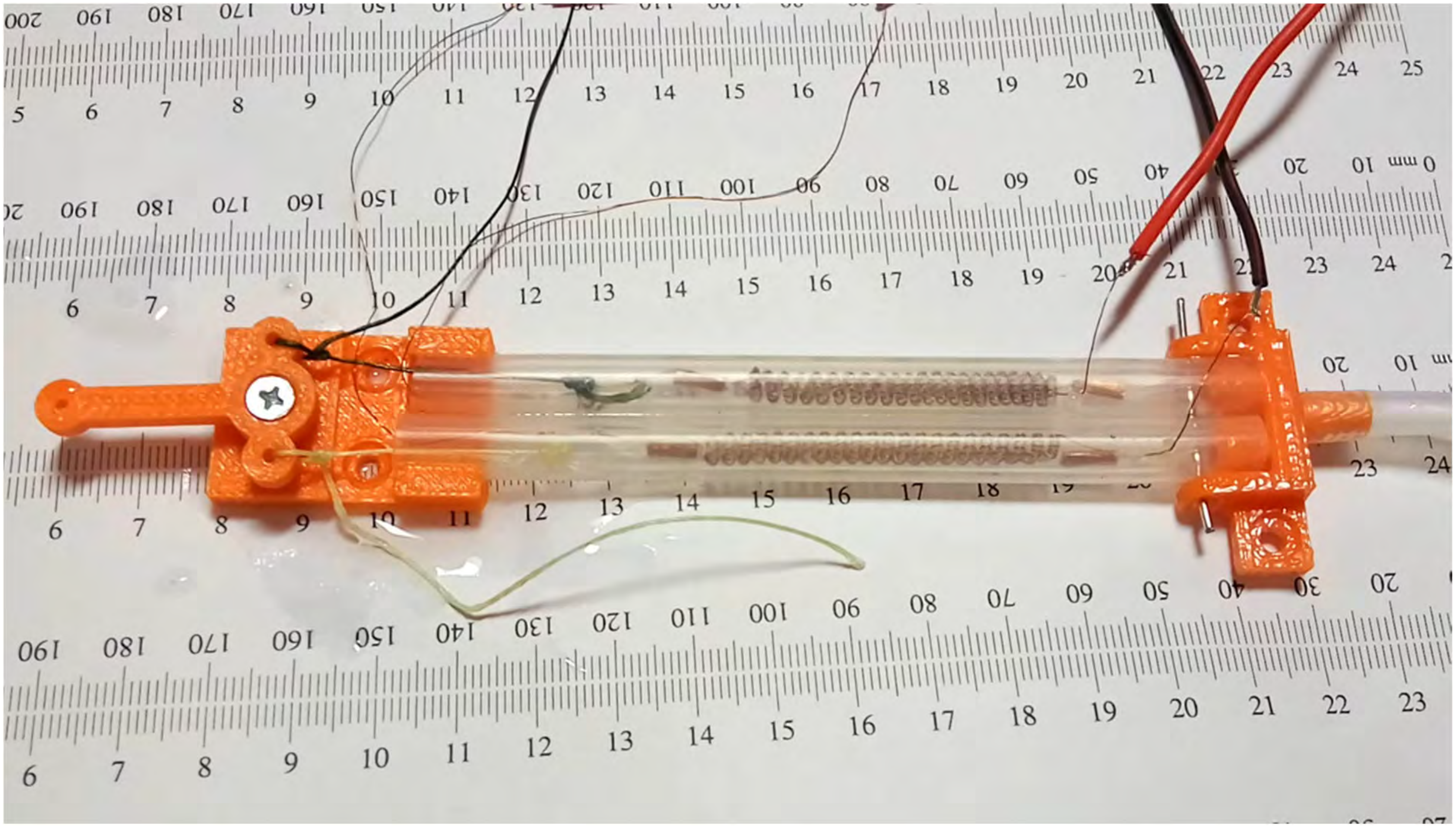
- Also called as “Twisted and coiled polymer (TCP) actuators”.
- Negative thermal expansion causes contraction of twisted fiber.
- High actuation output but slow. Normally require a heating element.
- Common material: Nylon and polyethylene



Haines, Carter S., et al. "Artificial muscles from fishing line and sewing thread." science 343.6173 (2014): 868-872.

Fishing Line Artificial Muscles
https://www.youtube.com/watch?v=Tba8Nf02OSI

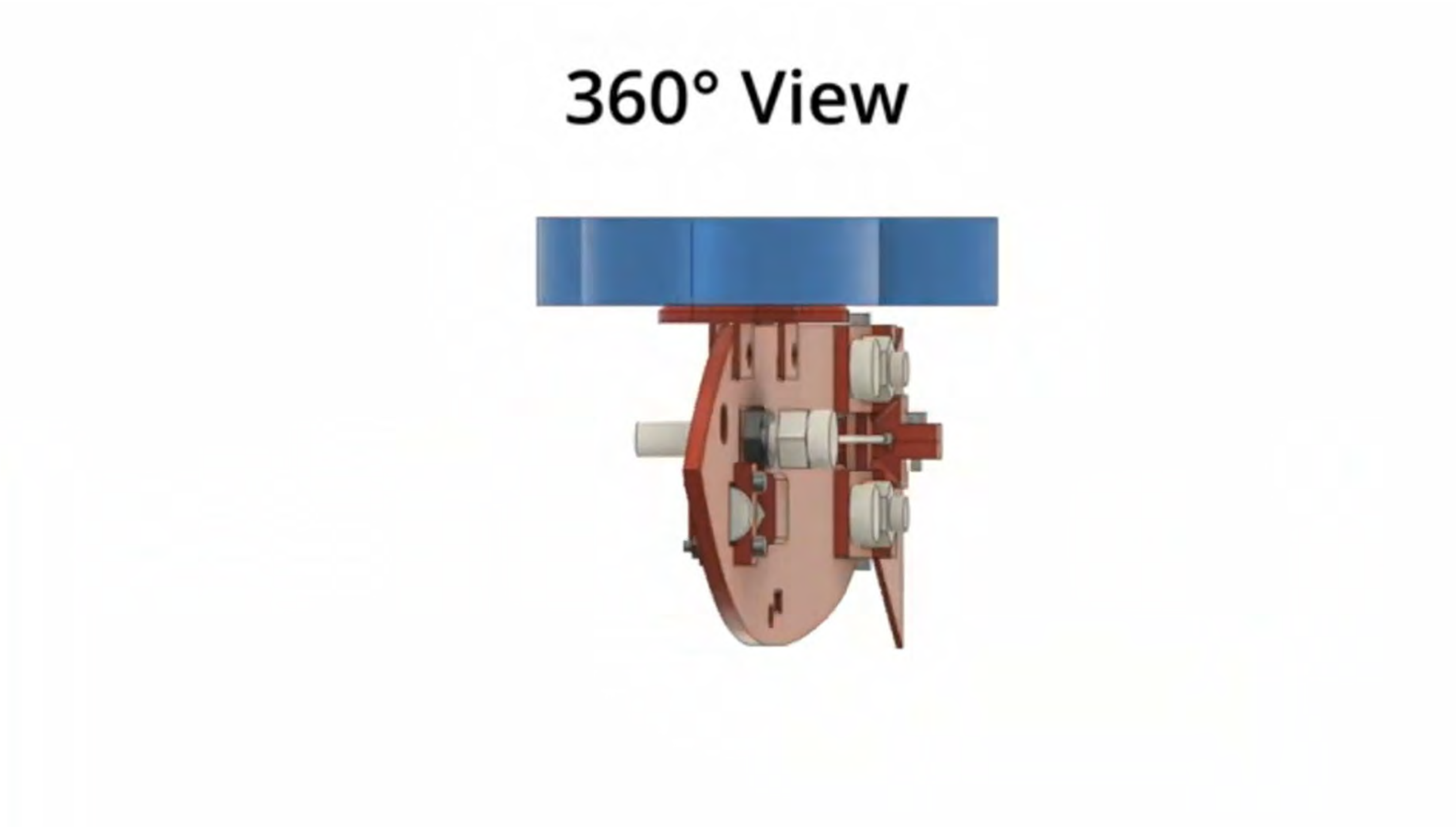
Thermally responsive soft actuators: Fishing line artificial muscles



Semochkin, Aleksandr N. "A device for producing artificial muscles from nylon fishing line with a heater wire." 2016 IEEE International Symposium on Assembly and Manufacturing (ISAM). IEEE, 2016.

Artificial Muscles from Fishing Line in action
https://www.youtube.com/watch?v=UbvNW7ONiTc

Thermally responsive soft actuators: Fishing line artificial muscles



Robotic Fish driven by Twisted and Coiled Polymer Actuators at High Frequencies
https://www.youtube.com/watch?v=47YDNPuuWlg

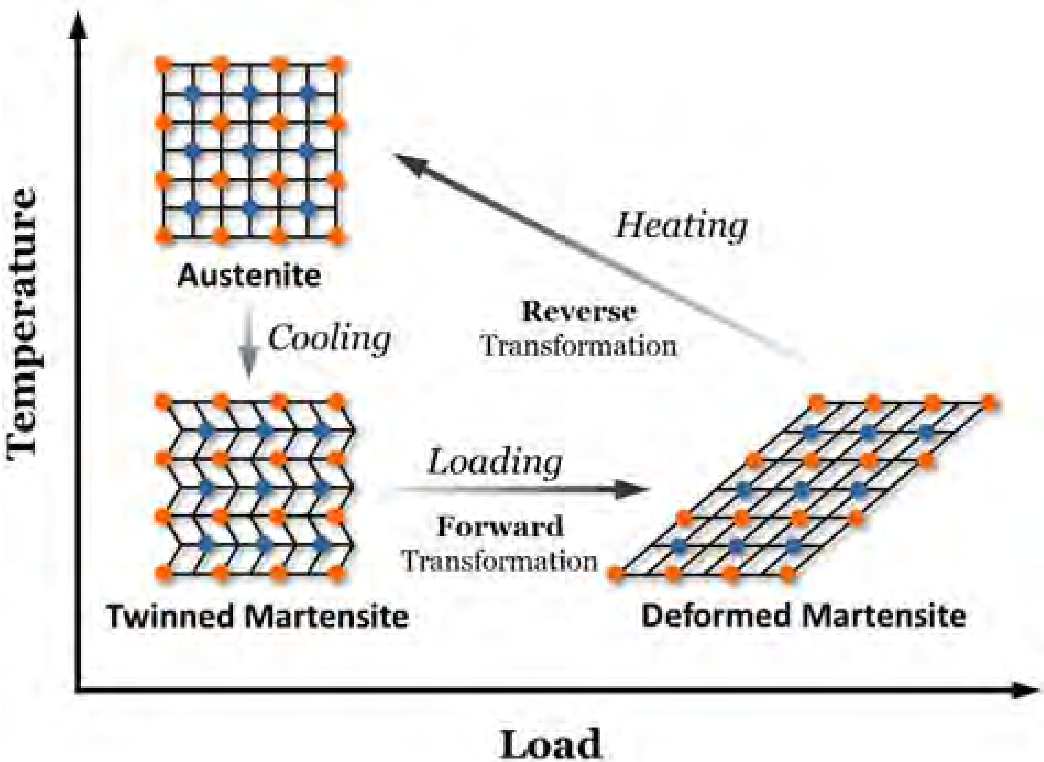
Thermally responsive soft actuators: Fishing line artificial muscles

Sun, Jiefeng, et al. "Twisted-and-coiled actuators with free strokes enable soft robots with programmable motions." Soft robotics 8.2 (2021): 213-225.

Soft Robots Driven by Twisted-and-Coiled Actuators
https://www.youtube.com/watch?v=i8mjU3i3QWE

Thermally responsive soft actuators: Shape memory alloys

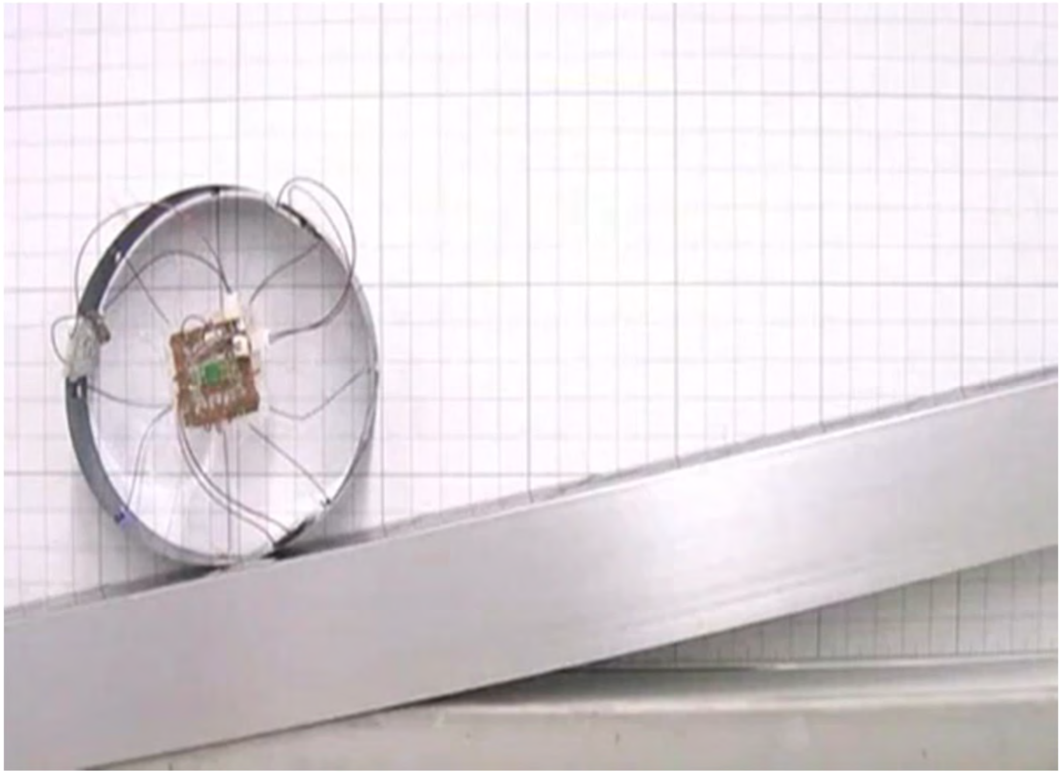
- Crystallographic change induced by temperature between martensite and austenite states.
- High actuation output with moderate speed. Temperature can be applied by Joule-heating.
- Common material: Nickel-Titanium (Nitinol) alloy



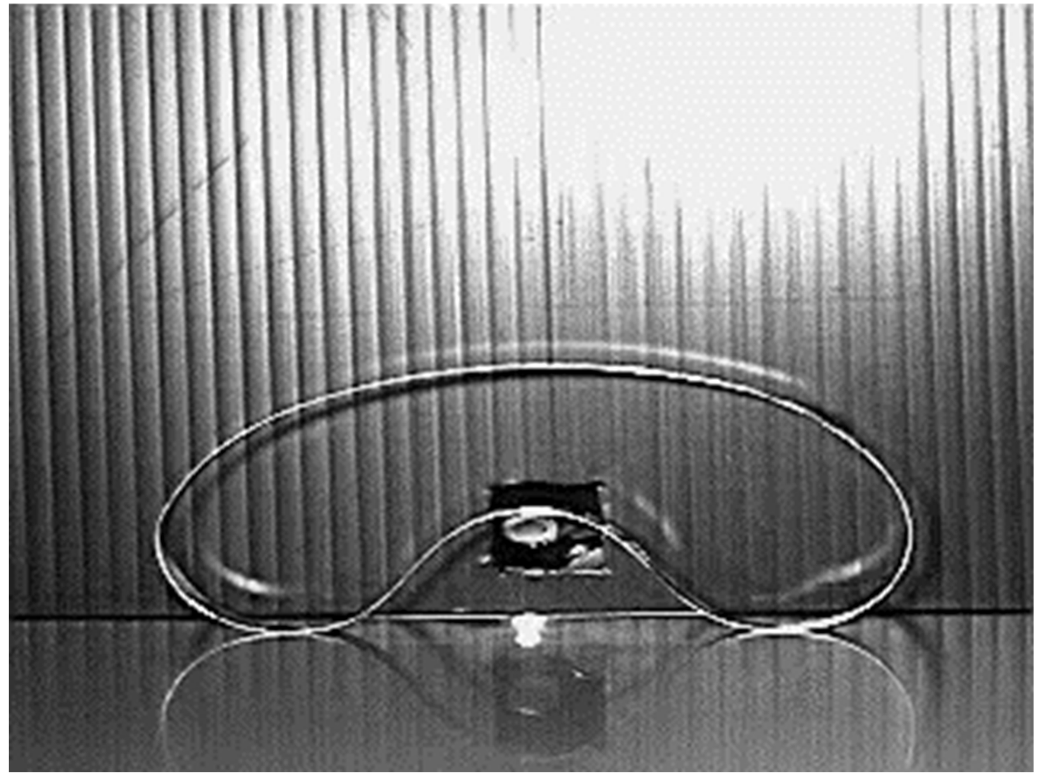
Chu, Won-Shik, et al. "Review of biomimetic underwater robots using smart actuators." International journal of precision engineering and manufacturing 13 (2012): 1281-1292.

Shape Memory Alloy Demo
https://www.youtube.com/watch?v=231O7jlgwxI

Thermally responsive soft actuators: Shape memory alloys



Circular soft robot with built-in power source
https://www.youtube.com/watch?v=FOdeaMbJPmE



Jump from Cap shape
https://www.youtube.com/watch?v=V6TjMazI9W4

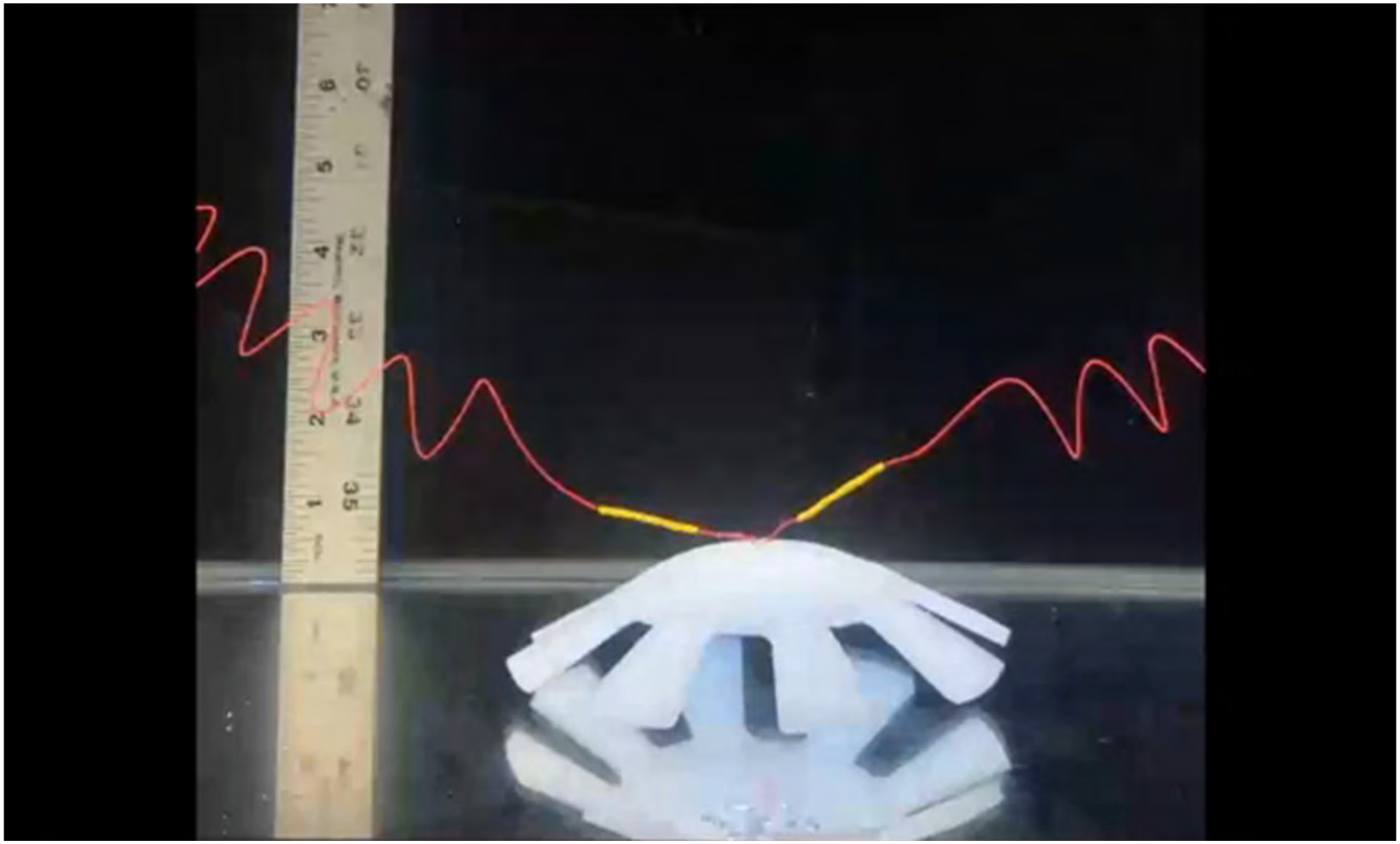
Sugiyama, Yuuta, and Shinichi Hirai. "Crawling and jumping by a deformable robot." The International journal of robotics research 25.5-6 (2006): 603-620.

Thermally responsive soft actuators: Shape memory alloys

Koh, Je-Sung, et al. "Jumping on water: Surface tension–dominated jumping of water striders and robotic insects." Science 349.6247 (2015): 517-521.

Robot Jumps Off Water- Emulating the natural locomotion of water strider insects
https://www.youtube.com/watch?v=yqX0V2LDWog

Thermally responsive soft actuators: Shape memory alloys

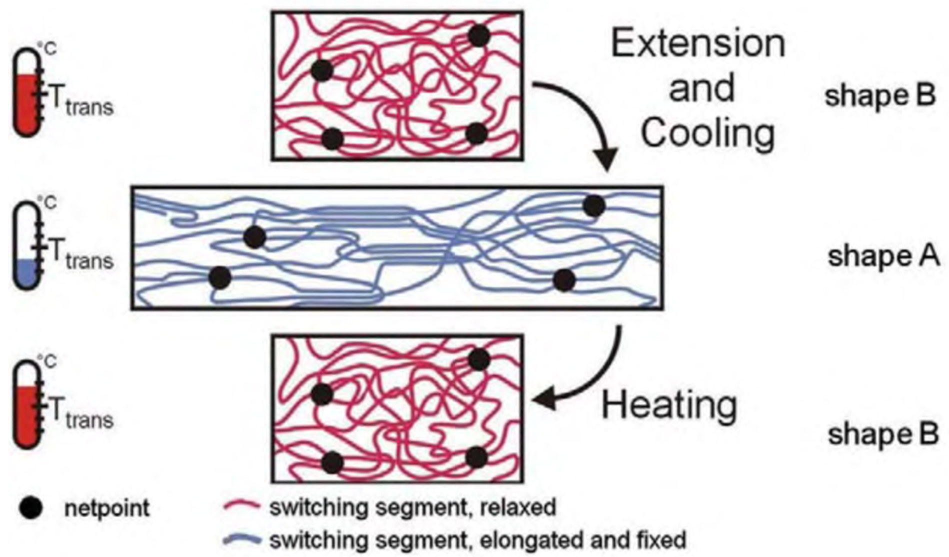


Kazemi-Lari, Mohammad AA, et al. "Robotic jellyfish actuated with a shape memory alloy spring." Bioinspiration, Biomimetics, and Bioreplication IX. Vol. 10965. SPIE, 2019.

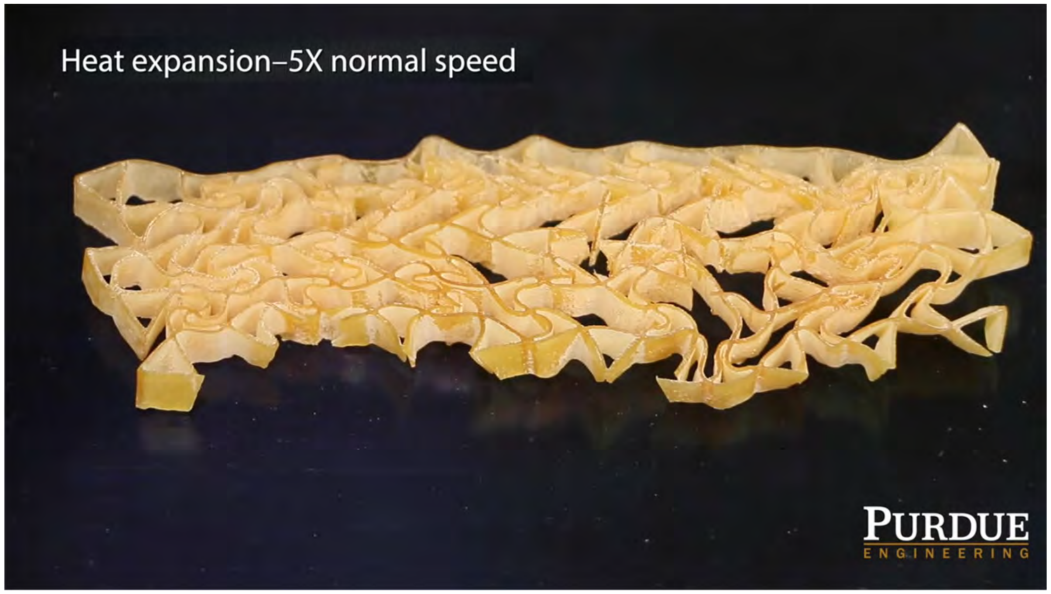
Robotic jellyfish actuated with a shape memory alloy spring
https://www.youtube.com/watch?v=GT-6qOqzTVs

Thermally responsive soft actuators: Shape memory polymers

- Polymers that become rubbery state at certain temperature turn into soft and back to its initial shape when it is heated from a deformed shape.
- Actuation can be large but mostly slow. Need a heating element.
- Common material: Thermoplastic polyurethane (TPU)

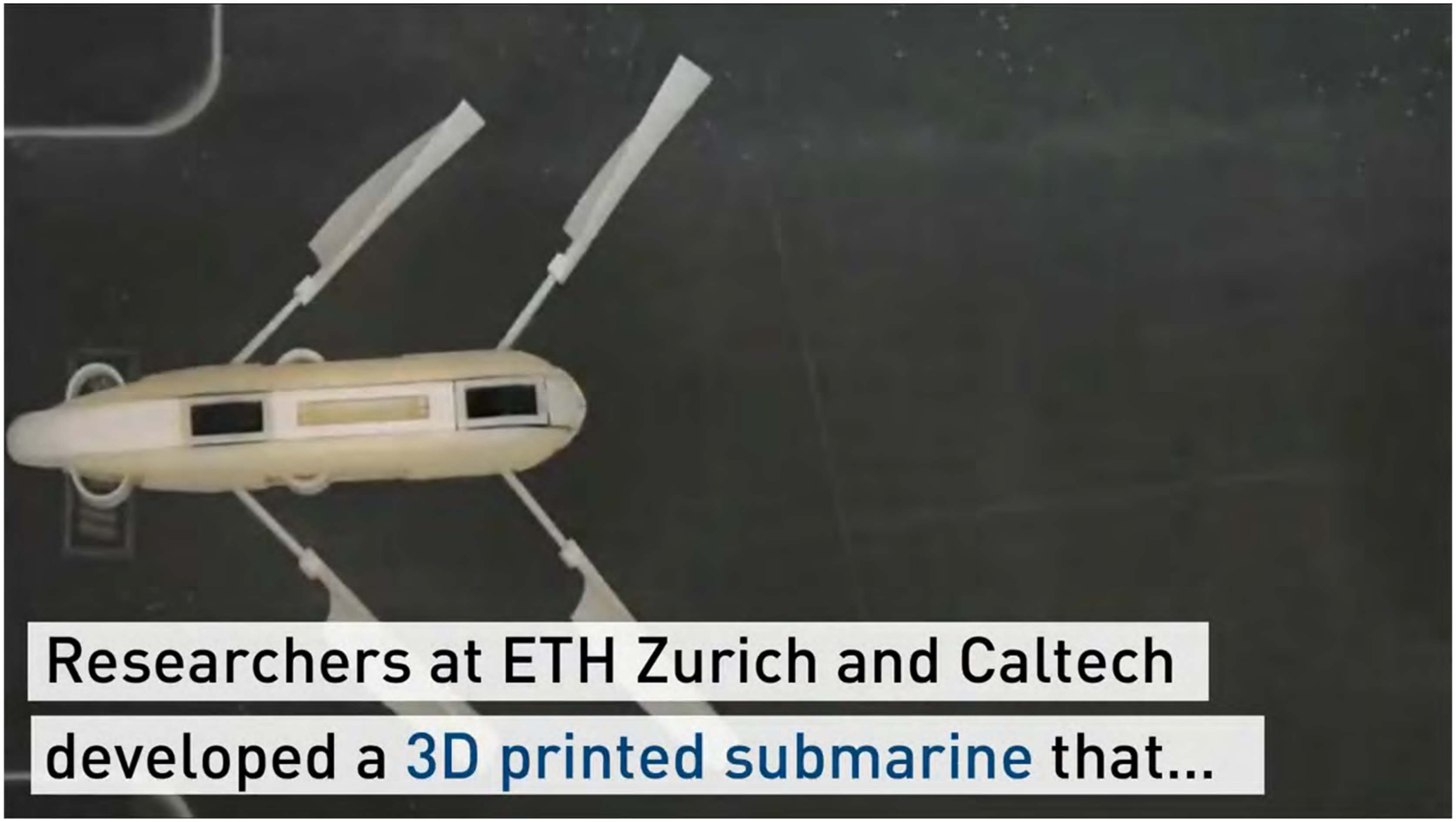


Lendlein, Andreas, and Steffen Kelch. "Shape-memory polymers." Angewandte Chemie International Edition 41.12 (2002): 2034-2057.



Programmable Materials: Shape-Memory Polymers
https://www.youtube.com/watch?v=abGAVzueSUc

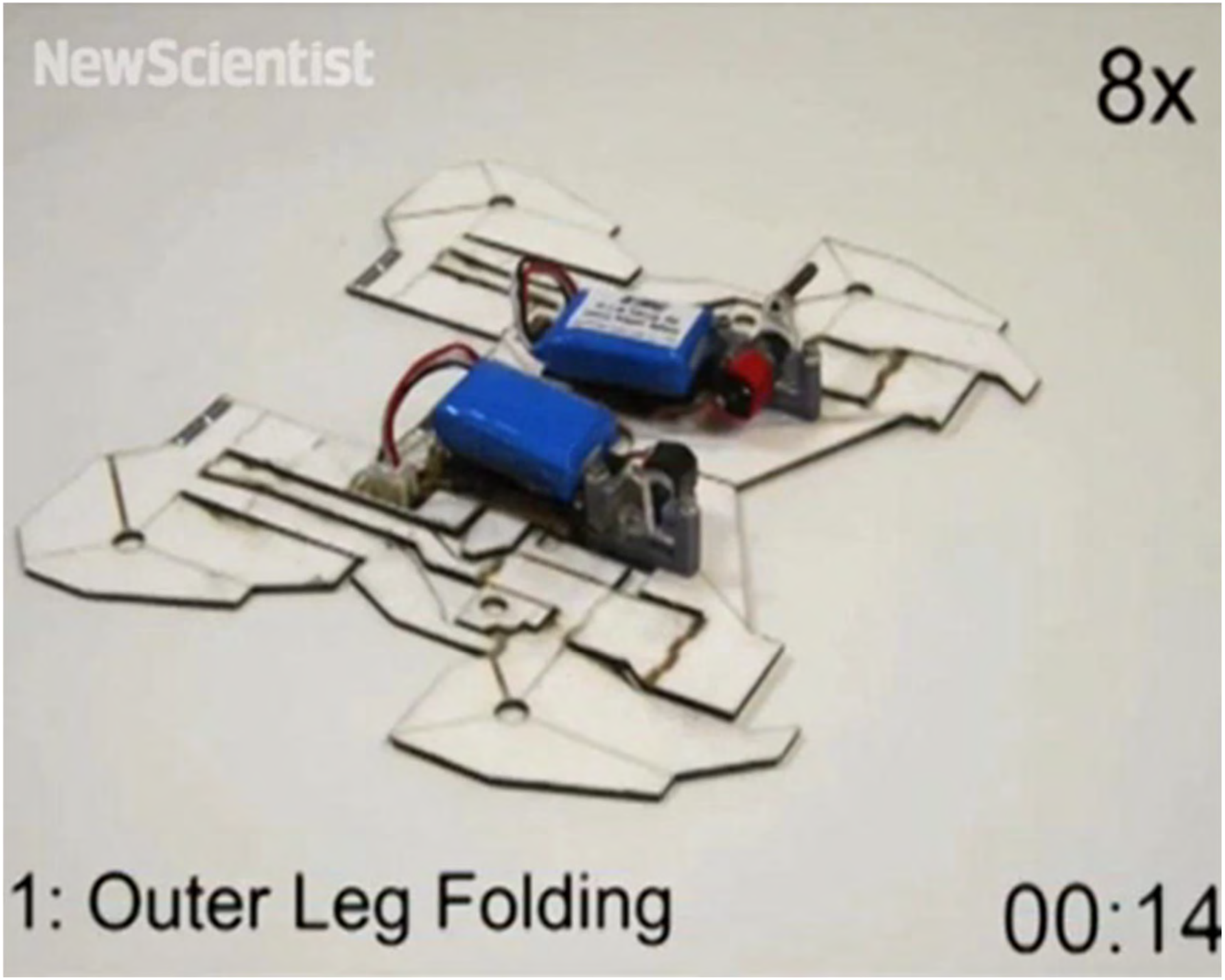
Thermally responsive soft actuators: Shape memory polymers



Chen, Tian, et al. "Harnessing bistability for directional propulsion of soft, untethered robots." Proceedings of the National Academy of Sciences 115.22 (2018): 5698-5702.

Motorless submarine
https://www.youtube.com/watch?v=ulF1xEfCHBs

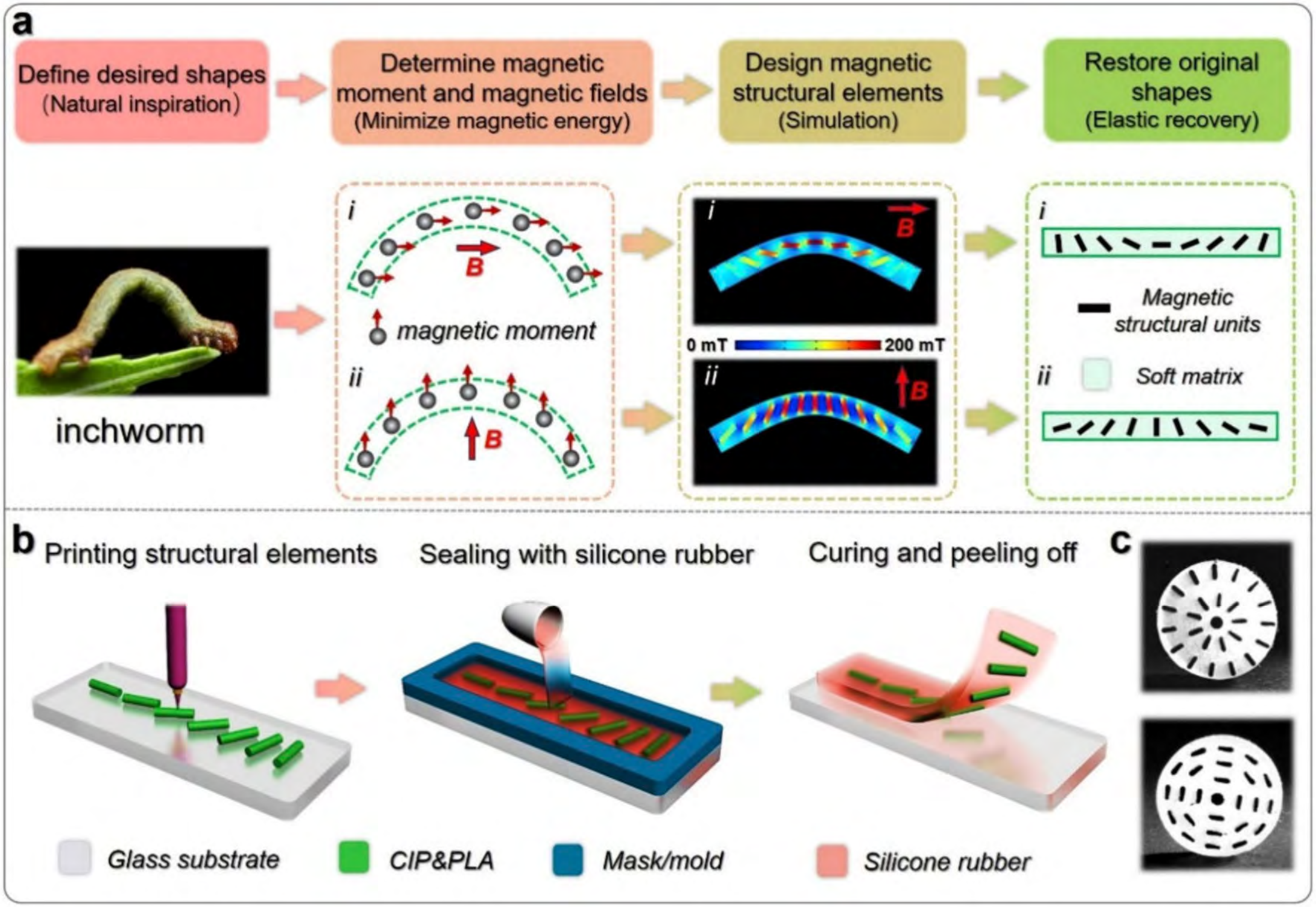
Thermally responsive soft actuators: Shape memory polymers



Self-folding origami robot walks on its own
https://www.youtube.com/watch?v=CihMimZc3Ac

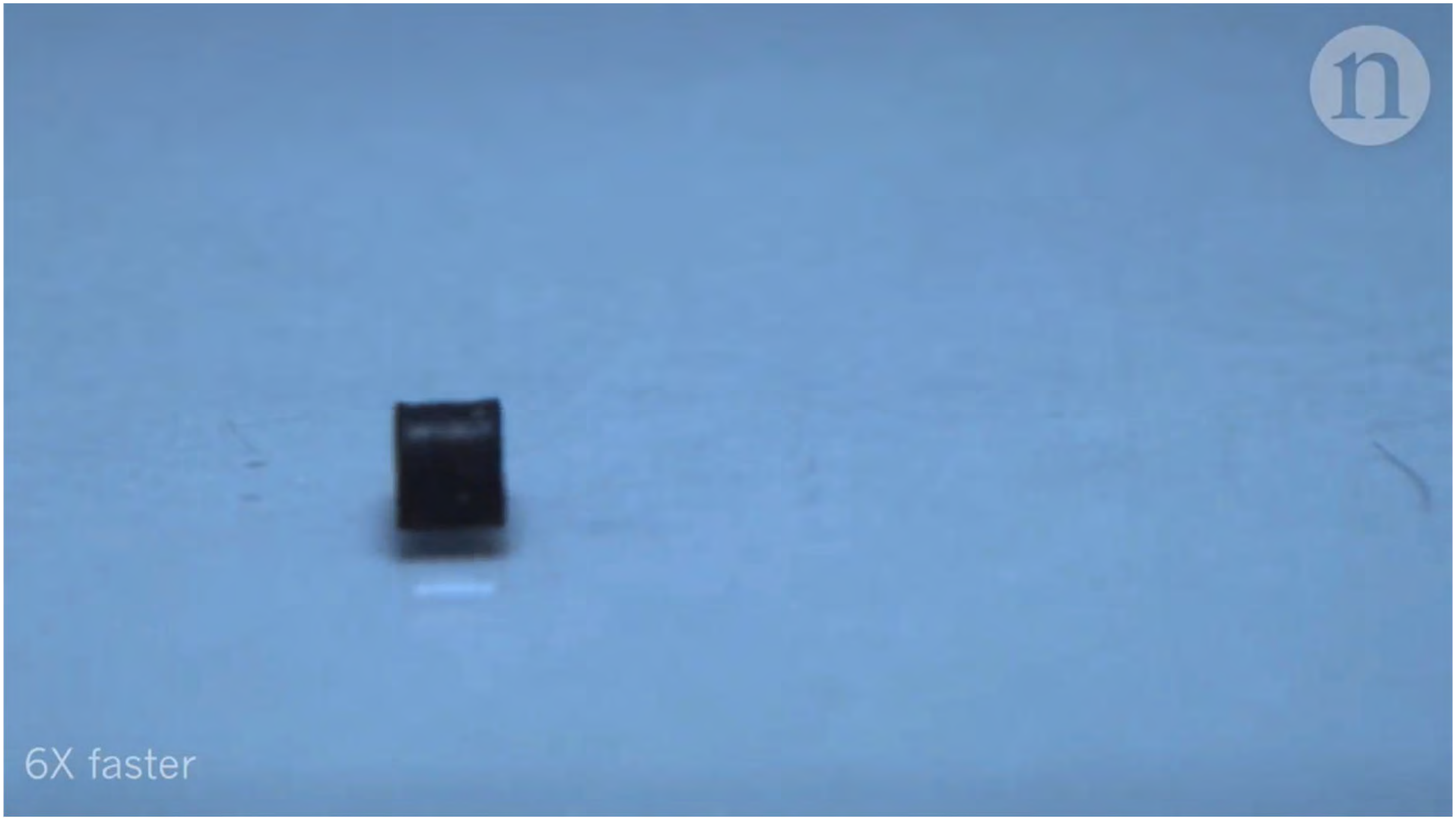
Magnetically responsive soft actuators: Magnetic elastomer actuators

- Embed/mix ferromagnetic materials/magnets into soft materials.
- Fast, moderate actuation output, external magnetic field required.



Qi, Song, et al. "3D printed shape-programmable magneto-active soft matter for biomimetic applications." Composites Science and Technology 188 (2020): 107973.

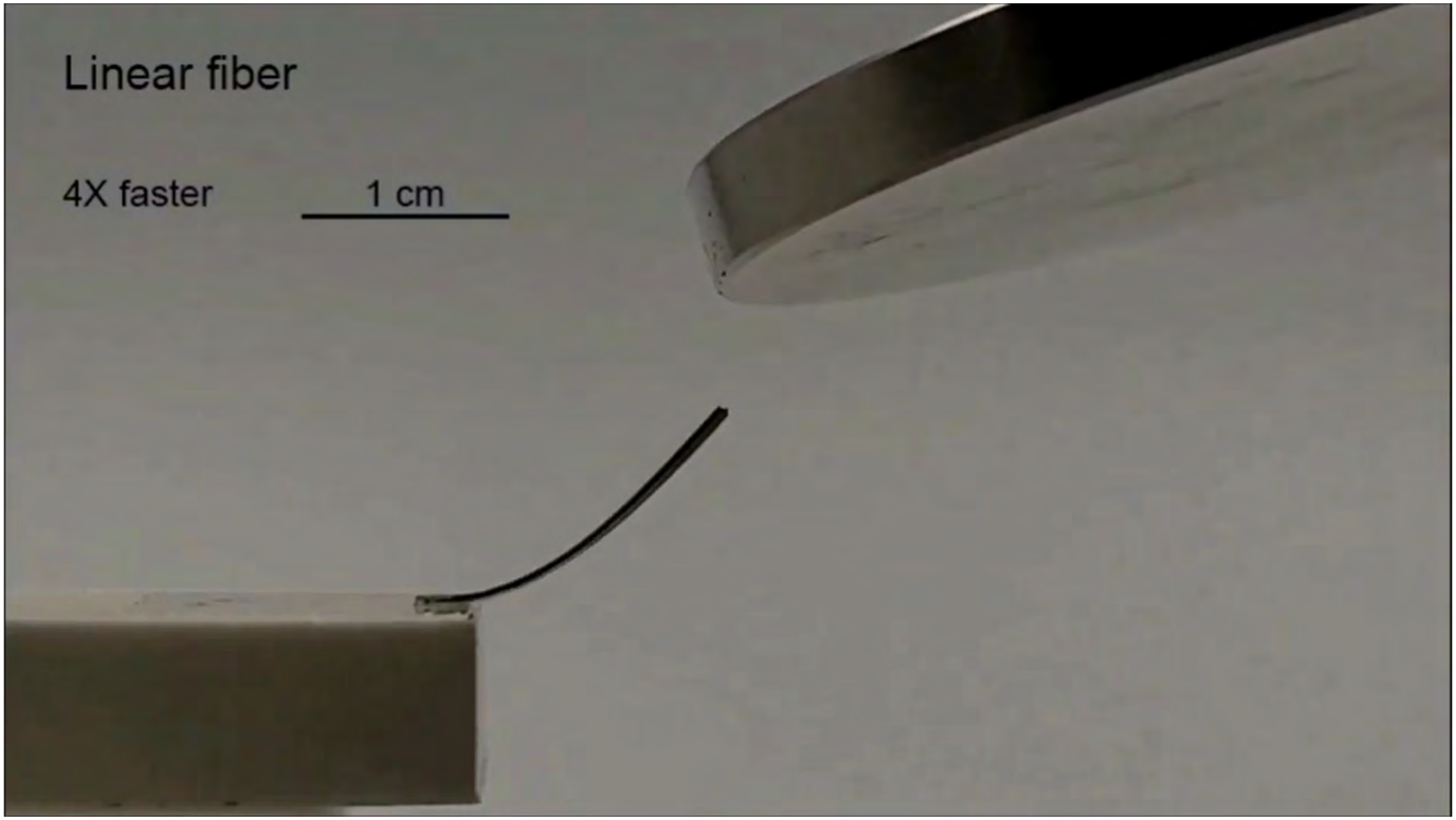
Magnetically responsive soft actuators: Magnetic elastomer actuators



Hu, Wenqi, et al. "Small-scale soft-bodied robot with multimodal locomotion." Nature 554.7690 (2018): 81-85.

A mini, magnetic, all-terrain robot
https://www.youtube.com/watch?v=OXRmxuB60DQ

Magnetically responsive soft actuators: Magnetic elastomer actuators



Lee, Youngbin, et al. "Magnetically Actuated Fiber-Based Soft Robots." Advanced Materials 35.38 (2023): 2301916.

Creating magnetic soft robots using fiber-based processes and unidirectional magnetic fields
https://www.youtube.com/watch?v=dQtXeYN57wk

Pros and cons; Yet no perfect soft actuator.

Actuator type	Pros	Cons
• Pressure responsive • Fluidic elastomer actuators • Mckibben actuators • Film based soft actuators	High actuation output Relatively fast	External pumps and compressors
• Electrically responsive • Electroactive polymers • Electro-hydraulic soft actuators • Biohybrid actuators	High actuation output Fast (excl. ion-type)	High voltage required (excl. ion-type)
• Thermally responsive • Fishing line artificial muscles • Shape memory alloys • Shape memory polymers	High actuation output	Slow External heating
• Magnetically responsive • Magnetic elastomer actuators	Moderate actuation output Fast	External magnetic fields

References

- Rus, Daniela, and Michael T. Tolley. "Design, fabrication and control of soft robots." Nature 521.7553 (2015): 467-475.
- Rich, Steven I., Robert J. Wood, and Carmel Majidi. "Untethered soft robotics." Nature Electronics 1.2 (2018): 102-112.
- Wallin, T. J., James Pikul, and Robert F. Shepherd. "3D printing of soft robotic systems." Nature Reviews Materials 3.6 (2018): 84-100.
- Gorissen, Benjamin, et al. "Elastic inflatable actuators for soft robotic applications." Advanced Materials 29.43 (2017): 1604977.
- Hines, Lindsey, et al. "Soft actuators for small-scale robotics." Advanced materials 29.13 (2017): 1603483.
- El-Atab, Nazek, et al. "Soft actuators for soft robotic applications: A review." Advanced Intelligent Systems 2.10 (2020): 2000128.
- Li, Meng, et al. "Soft actuators for real-world applications." Nature Reviews Materials 7.3 (2022): 235-249.
- Shen, Zequn, et al. "Stimuli-responsive functional materials for soft robotics." Journal of Materials Chemistry B 8.39 (2020): 8972-8991.

Homework

Provide a report of at least one page containing the following points.

- Pick a specific soft actuator technology and then propose a soft robot or soft robotic application based on it.
- Explain the originality or novelty of what you proposed.
- Explain the reasons behind choosing the soft actuator technology and how it helps the proposed device.

Report should be provided within PDF format. It should include your name and student ID number.

Deadline: December 6th

Language: EN or JP