Underwater Soft Robotics

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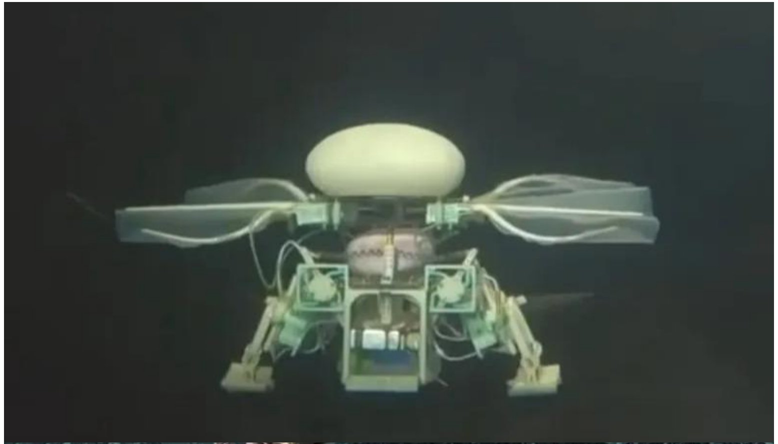
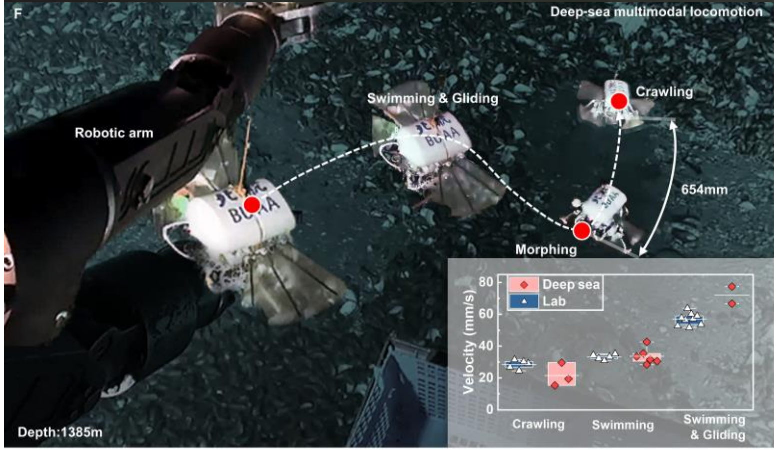
Learning goals

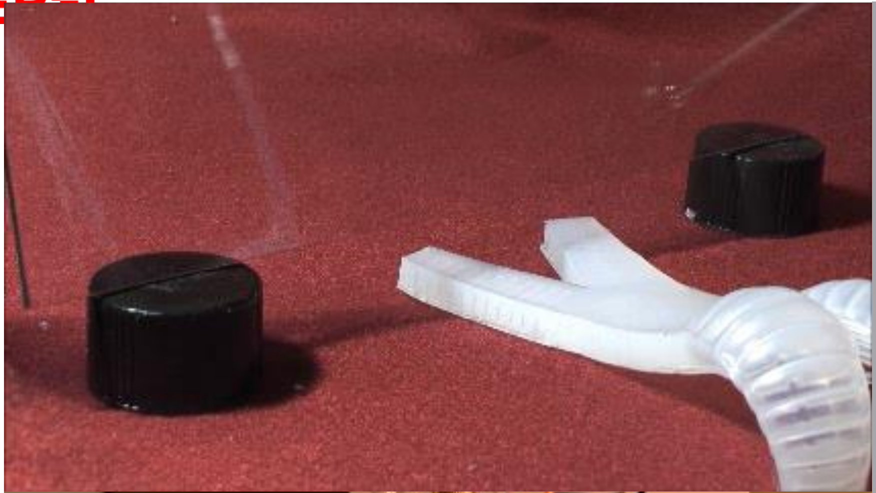
- ❑ *What is soft robotics?*
  - ❑ *Materials*
  - ❑ *Actuation*
  - ❑ *Sensing*
- ❑ *What does soft robotics add to the conversation of underwater robotics?*
- ❑ *What are the case studies that highlight this?*

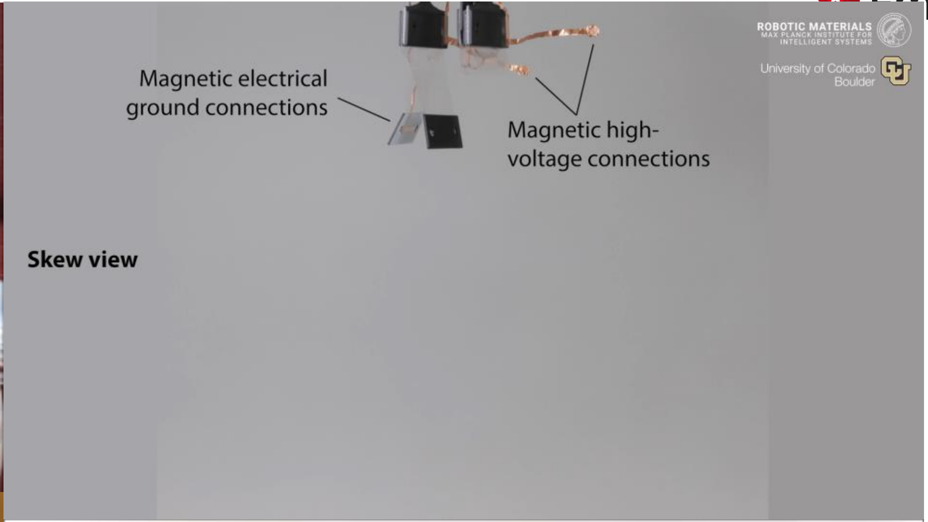


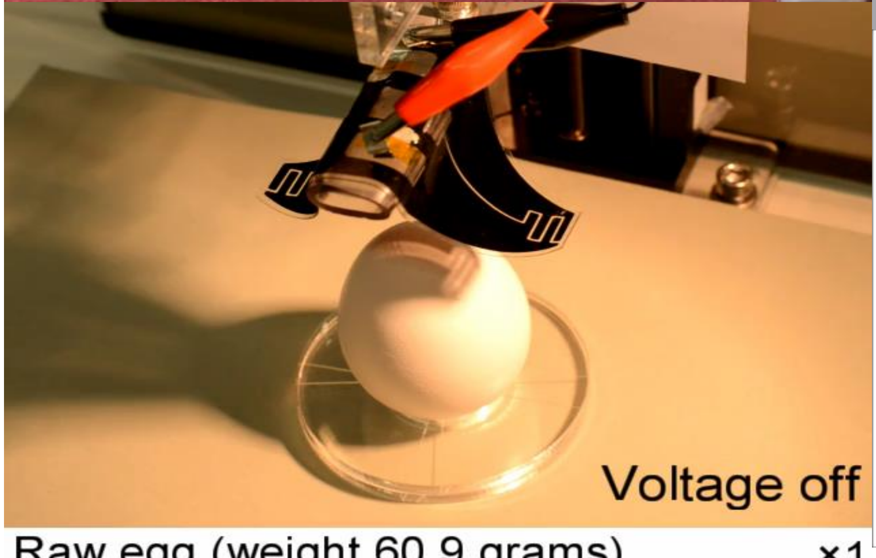


Pan, F., Liu, J., Zuo, Z., He, X., Shao, Z., Chen, J., Wang, H., Zhang, Q., Yuan, F., Chen, B. and Jin, T., 2025. Miniature deep-sea morphable robot with multimodal locomotion. *Science Robotics*, *10*(100), p.eadp7821.


The deep sea remains one of the least-explored regions of our planet.

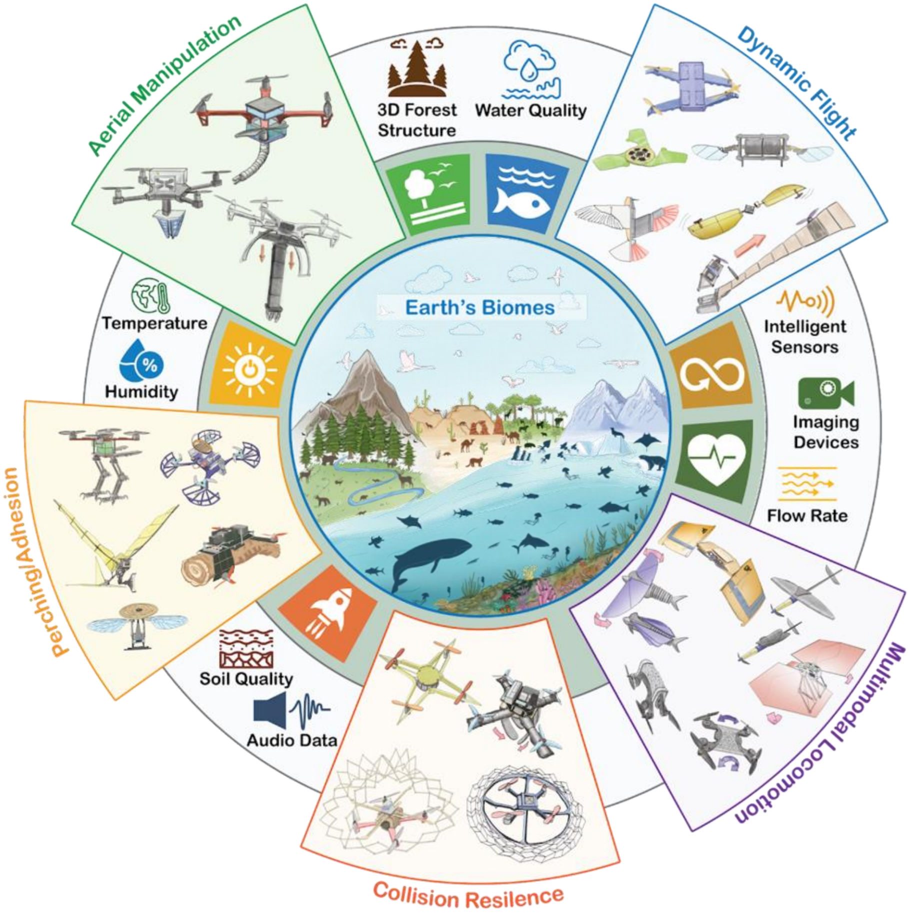



Magnetic electrical
ground connections
Magnetic high-
voltage connections
Skew view
ROBOTIC MATERIALS
MAX PLANCK INSTITUTE FOR INTELLIGENT SYSTEMS
University of Colorado Boulder


Voltage off
Raw egg (weight 60.9 grams)


An Anthropomorphic Soft Hand
Skeleton Piano Playing
BIRL
Bio-Inspired Robotics Lab
UNIVERSITY OF CAMBRIDGE

Why do we need soft underwater robots?



There various **abiotic data** we can sense:

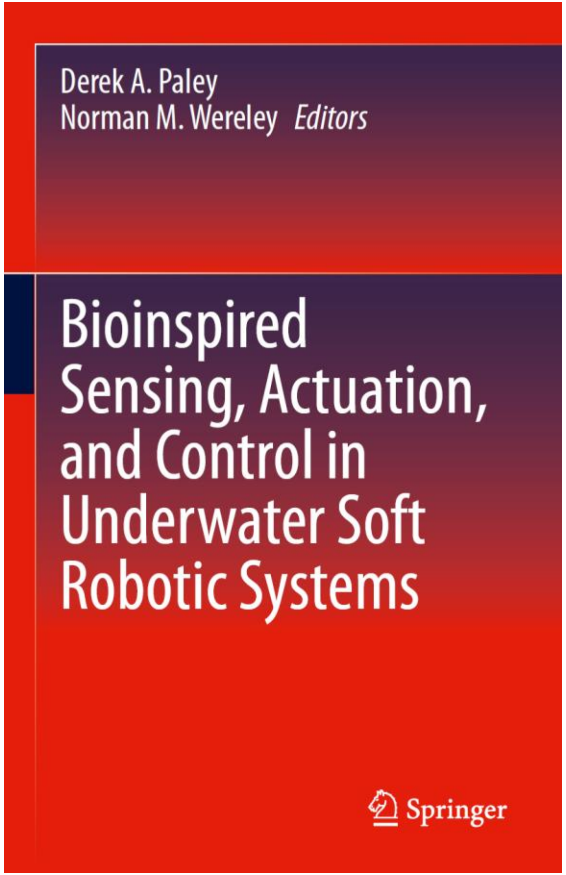
- Forest structure
- Water quality
- Humidity
- Temperature
- Soil Quality
- Flow rate

There are various **biotic data** that we can sense:

- Visual feed
- Audio data
- eDNA

Contents

- Soft Robotics Overview
- Materials (smart & soft matter)
- Mechanisms and motion of underwater soft robots
- Sensing
- Modeling and Control

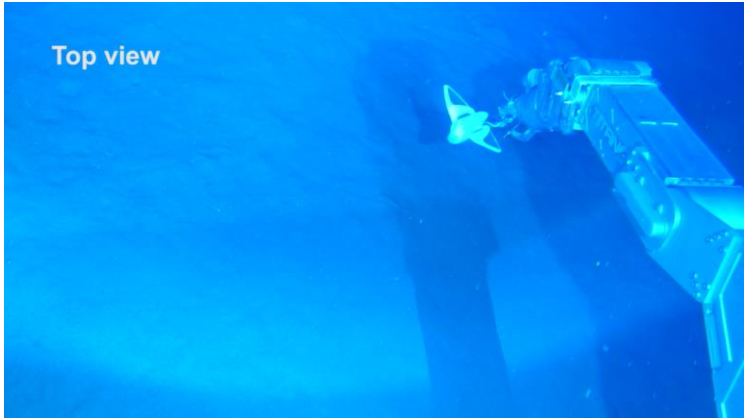


Underwater soft robotics

1. Stretchable elastomers
2. Ionic polymer metal composites
3. Electroactive polymers
4. Shape memory polymers
5. Liquid crystal elastomers
6. Responsive hydrogels

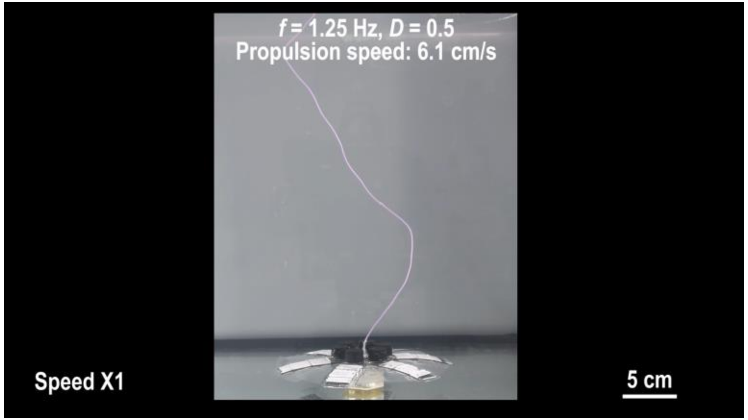
Underwater soft robotics

Flapping fish robot



Manta ray robot

Jetting robot



Jerry fish robot

Sourde: Katzschmann, R. K., DelPreto, J., MacCurdy, R., & Rus, D. (2018). Exploration of underwater life with an acoustically controlled soft robotic fish. Science Robotics, 3(16), eaar3449., Li, G., Chen, X., Zhou, F., Liang, Y., Xiao, Y., Cao, X., ... & Yang, W. (2021). Self-powered soft robot in the Mariana Trench. Nature, 591(7848), 66-71Christianson, C., Cui, Y., Ishida, M., Bi, X., Zhu, Q., Pawlak, G., & Tolley, M. T. (2020). Cephalopod-inspired robot capable of cyclic jet propulsion through shape change. Bioinspiration & biomimetics, 16(1), 016014. Wang, T., Joo, H. J., Song, S., Hu, W., Keplinger, C., & Sitti, M. (2023). A versatile jellyfish-like robotic platform for effective underwater propulsion and manipulation. Science Advances, 9(15), eadg0292.

Materials

What is smart & soft matter materials?

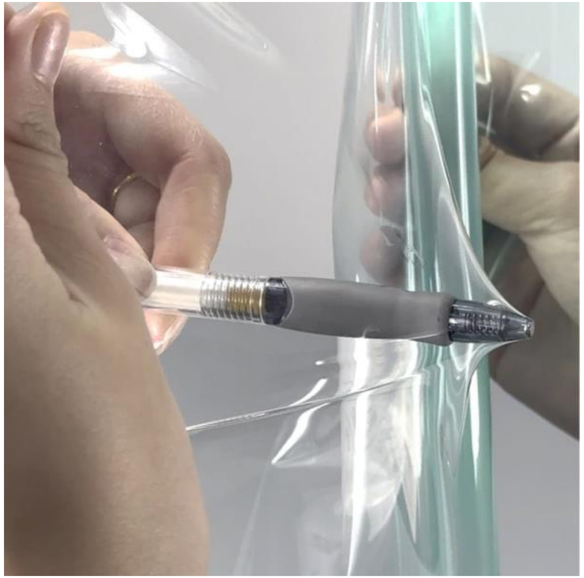
1. Stretchable elastomers
2. Ionic polymer metal composites
3. Electroactive polymers
4. Shape memory polymers
5. Liquid crystal elastomers
6. Responsive hydrogels

Stretchable Elastomers

Elastomers are polymers that stretch and return to their original shape.

- Flexible
  - Allows a wide range of bending and stretching
- Durable
  - Withstand harsh conditions
- Compliant
  - Adapts to irregular surfaces easiliy
- Soft
  - Comfortable to the touch

PDMS membrane

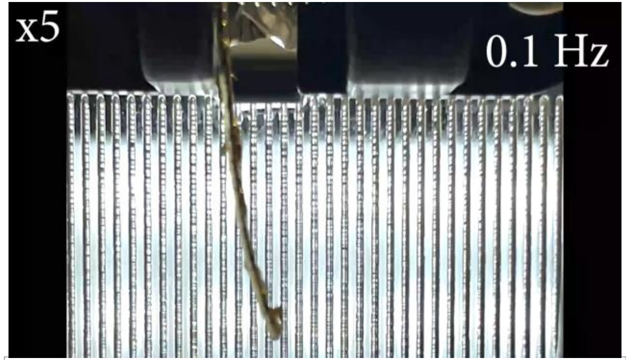


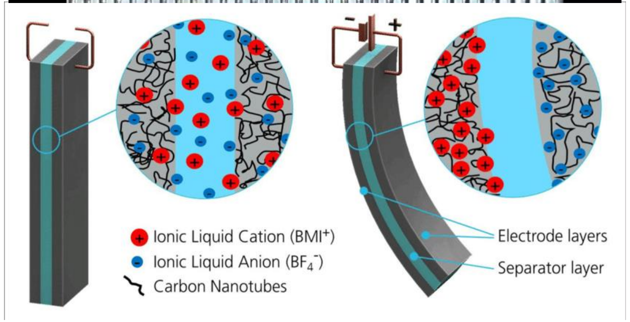
Source: https://www.amazon.com/Polydimethylsiloxane-Transparent-Hydrophobic-Temperature-Stretchable/dp/B0D8TQP7W2

Ionic Polymer Metal Composites

Electroactive Response: Deforms in response to an applied electric field.

- **Flexible, Lightweight**
  - Can bend, twist, and adapt to various forms.
- **Soft Actuation**
  - Generates smooth, gentle motions
- **Low Operating Voltage**
  - Requires a low voltage to achieve actuation

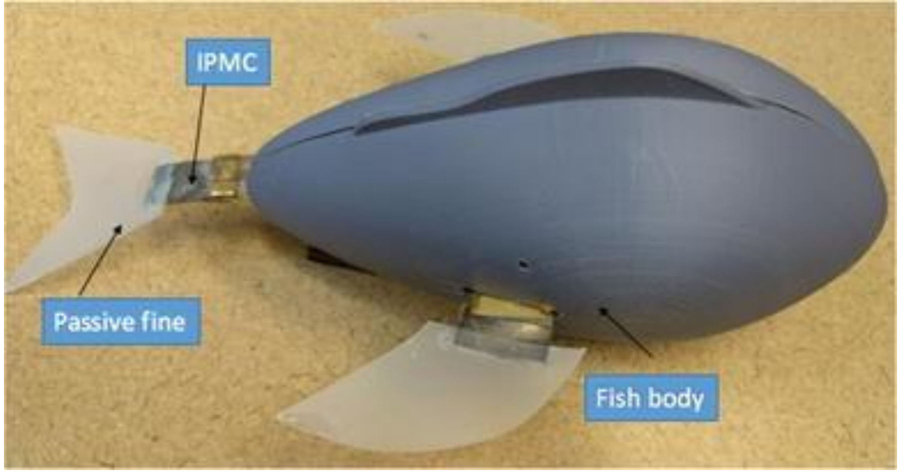




Source: Neuhaus, R., Zahiri, N., Petrs, J., Tahouni, Y., Siegert, J., Kolaric, I., ... & Bauernhansl, T. (2020). Integrating ionic electroactive polymer actuators and sensors into adaptive building skins–potentials and limitations. Frontiers in Built Environment, 6, 95., Trümpler, N., Kanno, R., David, N., Huch, A., Nguyen, P. H., Jurinovs, M., ... & Kovac, M. (2025). Low-Cost 3D printed, Biocompatible Ionic Polymer Membranes for Soft Actuators. arXiv preprint arXiv:2501.12025.

Case study

- Ionic Polymer Metal Composites are driven by low voltage, current (~3V, ~20mA) and can operate underwater. It can be used for untethered swimming fish robot.

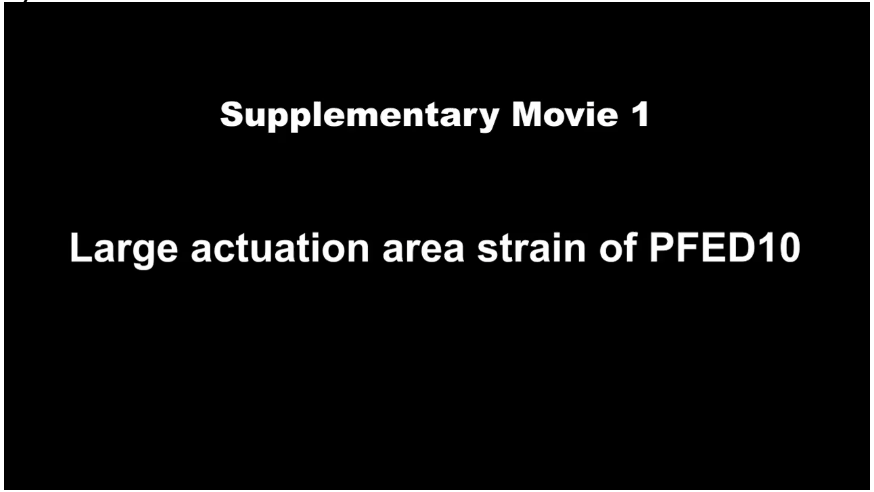


Source: Ye, Z., Hou, P., Chen, Z., & IEEE Member. (2017). 2D maneuverable robotic fish propelled by multiple ionic polymer–metal composite artificial fins. International Journal of intelligent robotics and applications, 1(2), 195-208.

Electroactive Polymers

Electromechanical Response: Capable of changing shape or size when exposed to an electric field (Maxwell stress).

- **High Deformation:** Can achieve large strains
- **Lightweight and Flexible:** Easy to integrate into systems
- **Soft and Compliant**
  - Mimic the behavior of biological muscles
- **Rapid Response Time** to electric stimulation
- **Low Power Consumption**



Source: Feng, W., Sun, L., Jin, Z., Chen, L., Liu, Y., Xu, H., & Wang, C. (2024). A large-strain and ultrahigh energy density dielectric elastomer for fast moving soft robot. Nature Communications, 15(1), 4222.

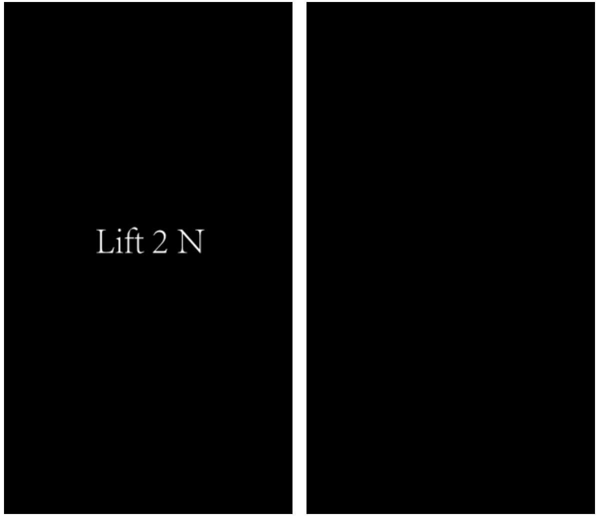
Case study

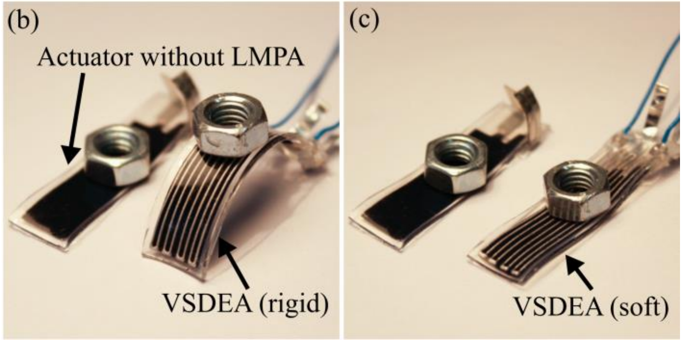
- Dielectric elastomer actuators are with compact system, intrinsic stiffness, which enables to swim in Mariana trench (~10000 meter deep sea)

Source: Li, G., Chen, X., Zhou, F., Liang, Y., Xiao, Y., Cao, X., ... & Yang, W. (2021). Self-powered soft robot in the Mariana Trench. Nature,

Shape Memory Polymers

- **Shape Recovery Ability**
  - Can return to original shape when exposed to an external stimulus (e.g., heat, light, or magnetic field).
- **High Deformation Capability**
  - Can undergo large deformation
- **Biocompatibility**
  - Many of them are biocompatible, enabling use in medical applications such as stents, sutures, and drug delivery systems.

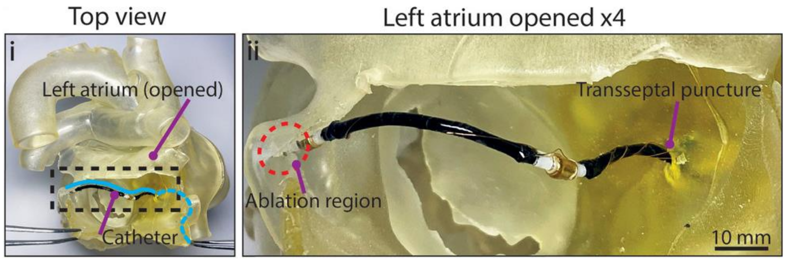




Source: Zhang, H., Oh, S., Mahato, M., Yoo, H., & Oh, I. K. (2022). Knot-architectured fabric actuators based on shape memory fibers. Advanced Functional Materials, 32(43), 2205732., Shintake, J., Schubert, B., Rosset, S., Shea, H., & Floreano, D. (2015, September). Variable stiffness actuator for soft robotics using dielectric elastomer and low-melting-point alloy. In 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 1097-1102). IEEE.

Case study

- Many shape memory polymers are biocompatible. It can be used for catheter for surgery



- Two-segmented catheter consists of two VSTs
- Each of the VSTs can be independently softened or stiffened

EPFL

Source: Piskarev, Y., Shintake, J., Chautems, C., Lussi, J., Boehler, Q., Nelson, B. J., & Floreano, D. (2022). A variable stiffness magnetic catheter made of a conductive phase-change polymer for minimally invasive surgery. Advanced Functional Materials, 32(20), 2107662.

Liquid Crystal Elastomers

- **Anisotropic Mechanical Properties**
  - Combines the elastic properties of polymers with the anisotropic properties of liquid crystals, leading to directional deformation
- **Thermo-Responsive Actuation**
  - Exhibit mechanical deformations when exposed to changes in temperature
- **Reversible Deformation**
  - Capable of repeated, reversible shape changes
- **Soft and Flexible**

Source: He, Q., Wang, Z., Wang, Y., Minori, A., Tolley, M. T., & Cai, S. (2019). Electrically controlled liquid crystal elastomer–based soft tubular actuator with multimodal actuation. *Science advances*, *5*(10), eaax5746.

Case study

- Liquid Crystal Elastomers are light weight, and robust since it is operated by magnet or heat

Source: Nemati, Y., Yang, Q., Sohrabi, F., Timonen, J. V., Sánchez-Somolinos, C., Honkanen, M., ... & Priimagi, A. (2025). Magneto-Photochemically Responsive Liquid Crystal Elastomer for Underwater Actuation. ACS Applied Materials & Interfaces.

Responsive Hydrogels

Stimuli-Responsiveness: Swell or shrink in response to external stimuli such as pH, temperature, light, or electric fields

- **High Water Content**
  - Capable of absorbing large amounts of water
- **Biocompatibility**
  - Generally biocompatible, allowing for use in medical devices, wound dressings, and implants.
- **Soft and Flexible**
  - Exhibits soft, flexible properties similar to natural tissues

Source: Zhao, Y., Xuan, C., Qian, X., Alsaid, Y., Hua, M., Jin, L., & He, X. (2019). Soft phototactic swimmer based on self-sustained hydrogel oscillator. *Science robotics*, *4*(33), eaax7112.

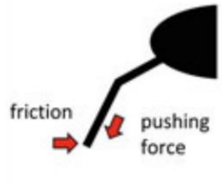
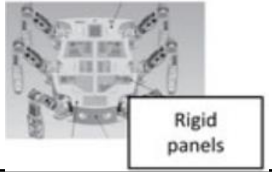
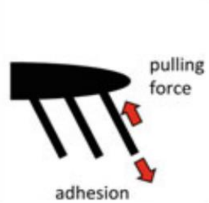
Summary

- Smart & soft matter materials have several characteristics such as soft, stretchable, flexible with unique response.

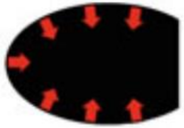
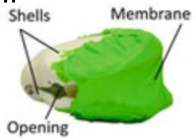
- These unique property allows for bioinspired design for underwater robots.

Designs and Motion

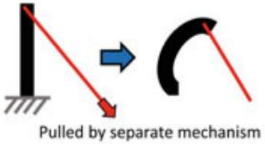
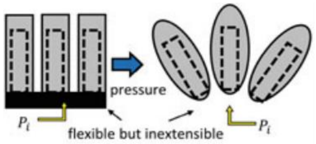
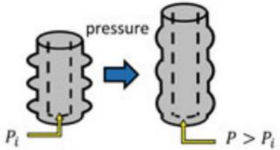
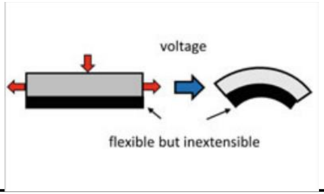
Bioinspired design (1)

Types of Locomotion	Description	Inspired Animal	Schematic	Robot
Friction-based Crawiling	Friction between appendage and substrate allows appendage to push body	Crustaceans 		Hexapod 
Adhesion-based crawling	Adhesion between appendage and substrate allows appendage to pull body	Echinoderms 		Tube feet 
Rear-body undulation	Thrust generated by reverse von Karman street vortex shedding	Cetaceans 		Soft robotic fish 

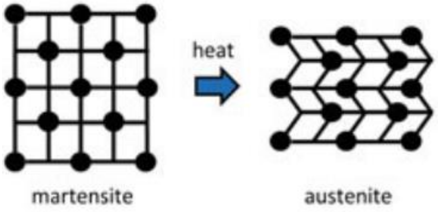
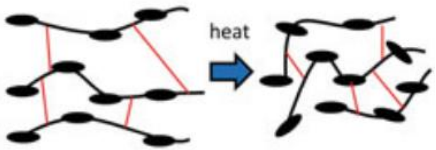
Bioinspired design (2)

Types of Locomotion	Description	Inspired Animal	Schematic	Robot
Fully-body undulation	Entire body actuation	Eels. Manta ray fins 		Eel-inspired soft robot 
Drag-induced swimming	Drag force opposing direction of motion of appendage	Duck, turtle 		Turtle-inspired limb 
Jet Propulsion	Water Jet out of rear nozzle	Salps, squid, octopus 		Scallop-inspired robot 

Actuation detail (1)

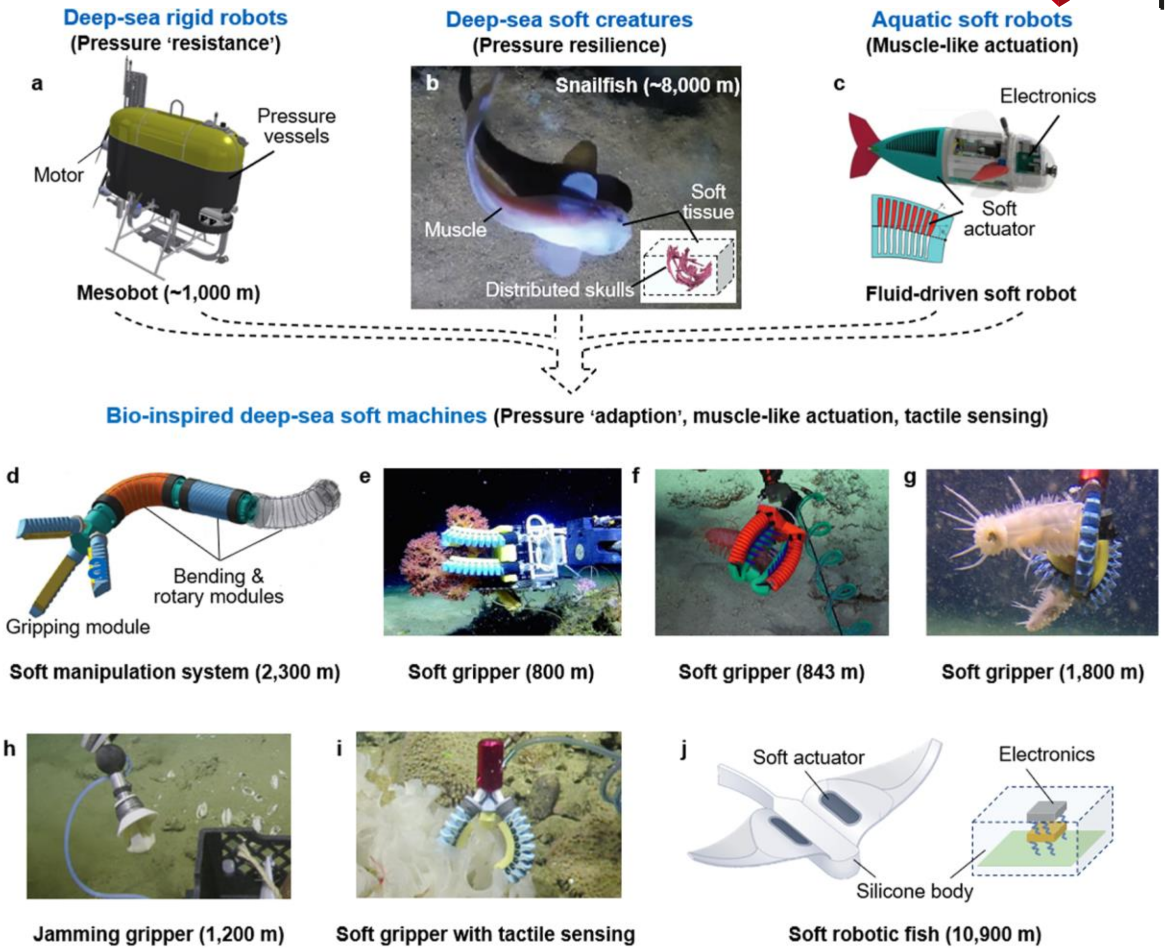
Types of actuator	Description	Schematic	Robot
Tendon-driven	Bulk soft material pulled by cable		Robotic fish 
Pneumatically pressurized fluidic elastomer	Pressure input causes deformation constrained by inextensible layer		Soft Robotic fish 
Fluidic elastomer: bellows	Pressure input causes linear deformation from unfolding material		Soft walking robot 
Smart material: dielectric elastomer	Maxwell stress causes compression in one plate and extension in the other		Soft eel-inspired robot 

Actuation detail (2)

Types of actuator	Description	Schematic	Robot
Smart material: shape memory alloy	Restores to a trained shape at high temperatures		Soft starfish-inspired robot 
Smart material: liquid crystal elastomer	External stimulus changes cross-linking in polymer, creating deformation		Soft echinoderm-inspired robot 

Case study

- Deep sea exploration can be carried out utilizing soft actuators with collecting samples.



Source: Li, G., Wong, T. W., Shih, B., Guo, C., Wang, L., Liu, J., ... & Li, T. (2023). Bioinspired soft robots for deep-sea exploration. Nature Communications, 14(1), 7097.


The deep ocean is one of Earth's
least explored environments

Summary

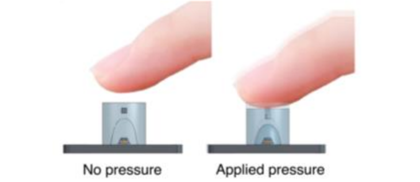
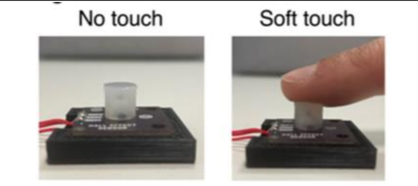
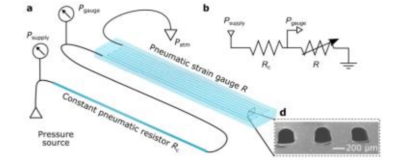
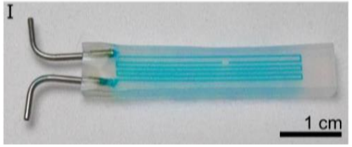
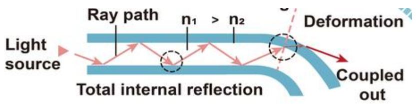
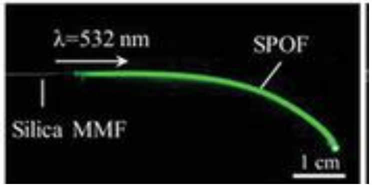
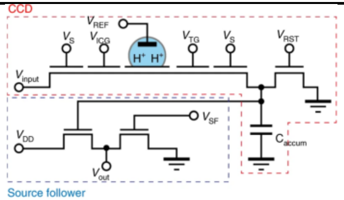
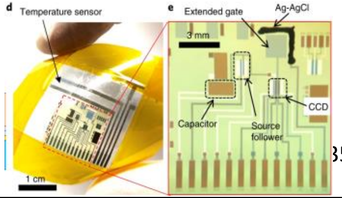
Researchers have been developing bio-inspired underwater soft robots with different actuation methods.

Actuation Principle

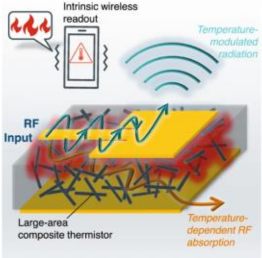
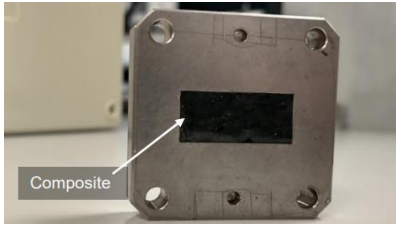
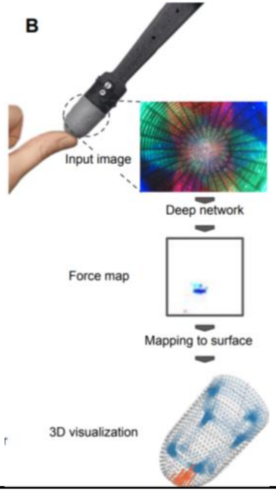
- Tendon driven
- Pneumatically/hydraulically pressurized fluidic elastomer
- Smart material with electric/thermal/pH input
- Responsive hydrogel

Sensing

Sensing: Category

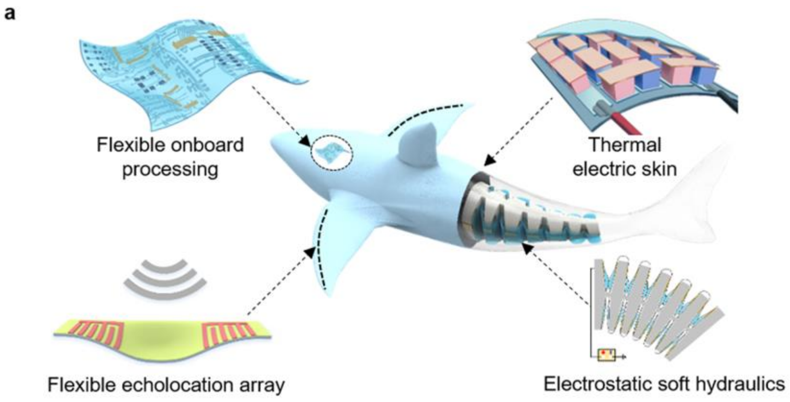
Sensing method	Description	Schematic	Sensor
Pressure	Measure changes in pressure using magnetic, piezoelectric, capacitive, or resistive materials		
Strain	Measure deformation using capacitance, or resistance		
Optical	Use changes in light intensity or optical properties		
Chemical	Detect specific ions, pH levels, or dissolved oxygen in water using electrochemical		

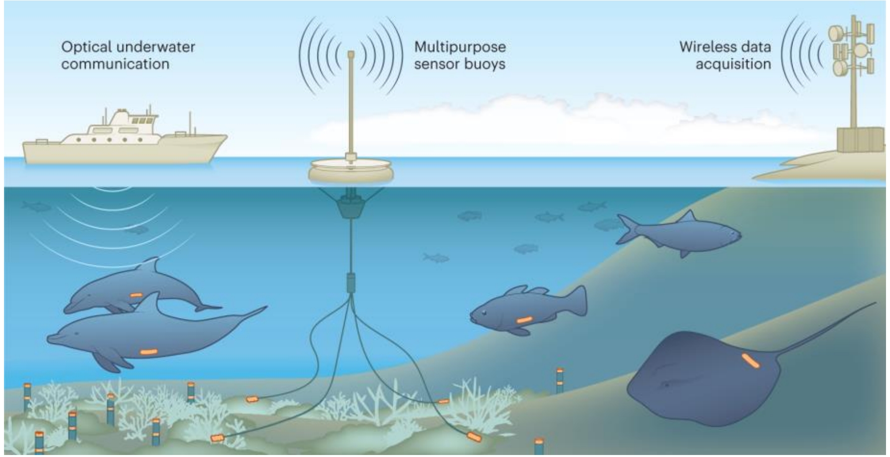
Sensing: Category

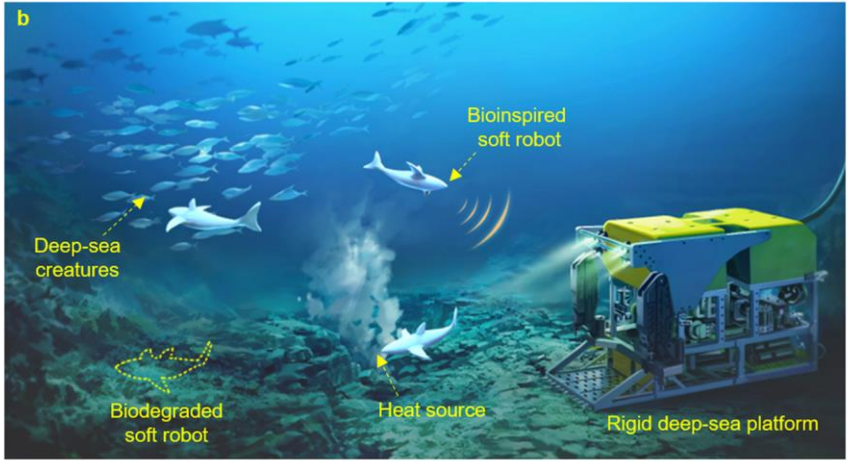
Sensing method	Description	Schematic	Sensor
Temperature	Measure temperature changes in water		
Vision	Use cameras with image processing to detect surroundings		

Case study

Sea animals are able to monitor utilizing soft/flexible sensors.







Source: Kaidarova, A., Geraldi, N. R., Wilson, R. P., Kosel, J., Meekan, M. G., Eguíluz, V. M., ... & Duarte, C. M. (2023). Wearable sensors for monitoring marine environments and their inhabitants. *Nature biotechnology*, *41*(9), 1208-1220., Li, G., Wong, T. W., Shih, B., Guo, C., Wang, L., Liu, J., ... & Li, T. (2023). Bioinspired soft robots for deep-sea exploration. Nature Communications, 14(1), 7097.

Sensing: Summary

Researchers have been developing underwater soft sensor.

Sensing Principle

- Pressure
- Strain
- Optical
- Chemical
- Temperature
- Vision

Modeling and Control

What is different with rigid robots?

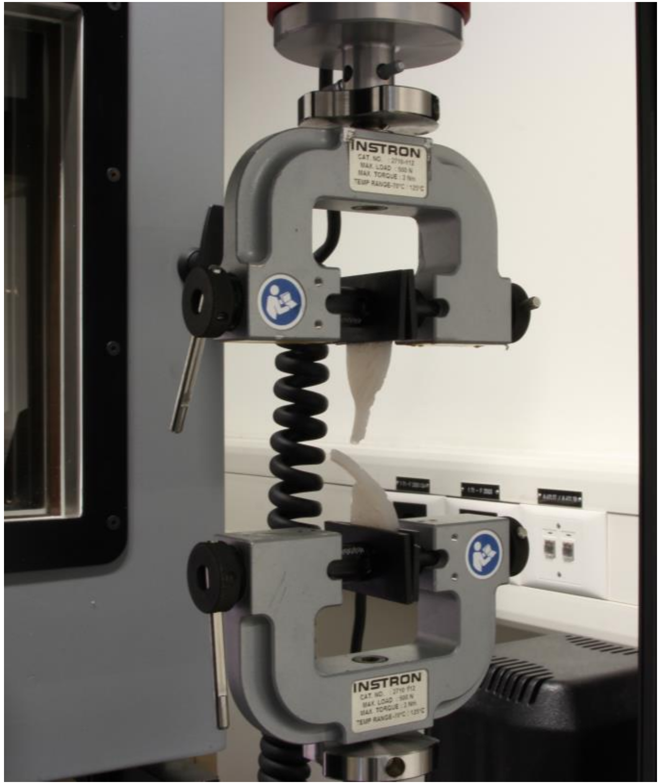
Aspect	Rigid Robots	Soft Robots
Structure	Stiff, discrete joints	Flexible, continuous deformation
Degrees of freedom	Finite	Infinite
Modeling methods	Classical mechanics	Continuum/numerical methods
Material behavior	Rigid	Hyperelastic, viscoelastic
Control	Joint-based trajectories	Distributed, data-driven
Applications	High precision, structured tasks	Adaptability, unstructured tasks

Modeling procedures

- Define the **geometry**
  - Shape, size
- **Material** characterization
  - Young's modulus
  - Poisson's ratio
  - Density
  - Viscoelasticity
- Model using discrete **calculations**
  - Finite Element Method
  - Discrete Elastic Rods
  - Mass-Spring model

Material characterization

Tensile testing



Young's modulus: Testing methods

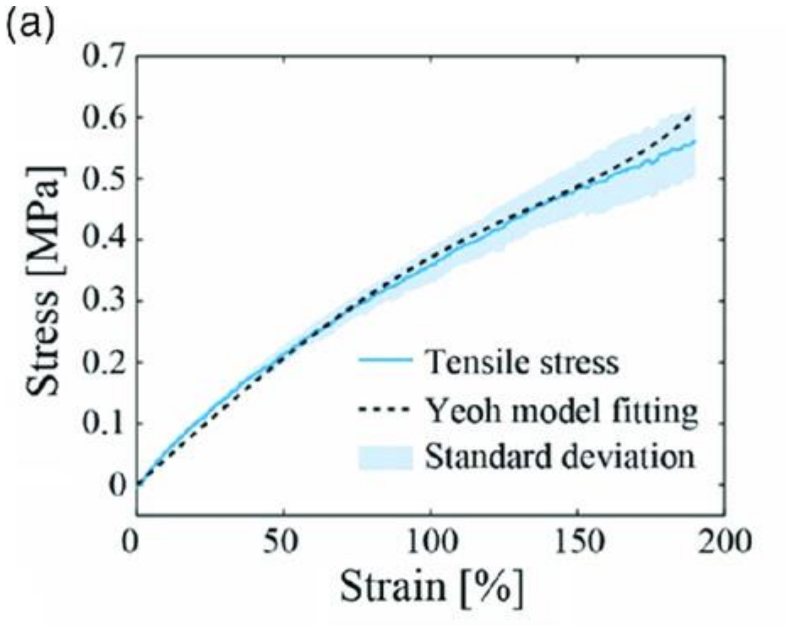
- Tensile
  - Used in most cases
- Compression test
  - Used in case that sample is bulk and is difficult to make dogbone shape
- 3 point bending test
  - Used in case that sample flat and difficult to make dogbone shape

Source: Kanno, R., Kwak, B., Pankhurst, M., Shintake, J., & Floreano, D. (2024). Edible Soft Actuators Based on Konjac Glucomannan for Underwater Operation. *Advanced Intelligent Systems*, *6*(5), 2300473.

Material characterization

- Calculations of Young's modulus
  - Hyperelastic models
    - Neo-Hooken (simpliest: 1 parameter)
    - Mooney-Rivlin (intermidiate: 2 parameter)
    - Yeoh (more complex: 3 parameter)
- Calculations of Poisson's ratio
  - Ratio of lateral strain to axial strain under elastic regions

Yeoh model fitted at stress-strain curve

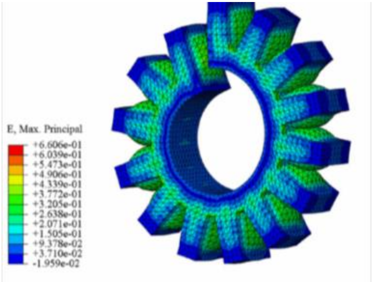


Source: Kanno, R., Nagai, T., & Shintake, J. (2021). Rapid Fabrication Method for Soft Devices Using Off-the-Shelf Conductive and Dielectric Acrylic Elastomers. *Advanced Intelligent Systems*, *3*(4), 2000173.

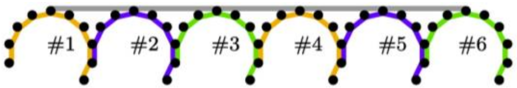
Model using discrete calculations

- Finite Element Method
  - Divides the soft robot into small elements, applying material models and external forces
  - Allows for detailed stress, strain, and deformation analysis
- Discrete Elastic Rods
  - Models soft robots as a chain of rigid segments connected by elastic joints.
  - Efficient for rod-like structures (e.g., tentacle robots).
- Mass-Spring model
  - Approximates soft robots as a network of masses connected by springs.
  - Simpler than FEA, suitable for real-time simulations but less accurate for large deformations.

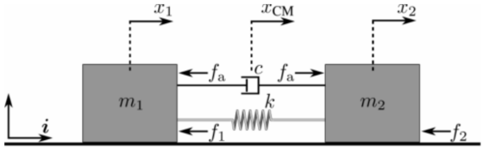
Finite Element Method



Discrete Elastic Rods



Mass-Spring model

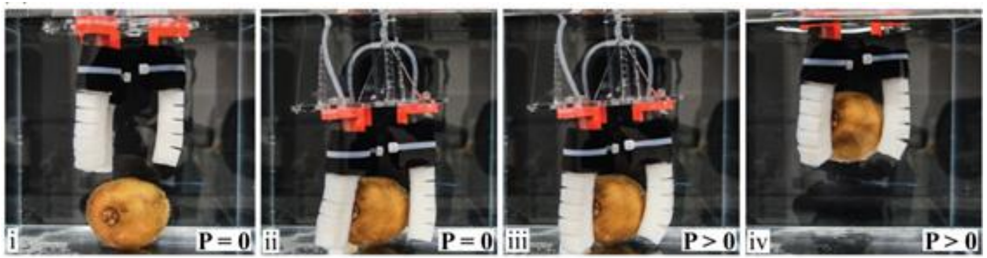


Source: Polygerinos, P., Lyne, S., Wang, Z., Nicolini, L. F., Mosadegh, B., Whitesides, G. M., & Walsh, C. J. (2013, November). Towards a soft pneumatic glove for hand rehabilitation. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems* (pp. 1512-1517). IEEE., Goldberg, N. N., Huang, X., Majidi, C., Novelia, A., O'Reilly, O. M., Paley, D. A., & Scott, W. L. (2019). On planar discrete elastic rod models for the locomotion of soft robots. *Soft robotics*, *6*(5), 595-610., Joey, Z. G., Calderón, A. A., & Pérez-Arancibia, N. O. (2017, December). An earthworm-inspired soft crawling robot controlled by friction. In *2017 IEEE international conference on robotics and biomimetics (ROBIO)* (pp. 834-841). IEEE.

Control methods

- On-Off
  - Owing to the flexibility, soft grasper can handle objects by switching voltage or input pressure
- Open-loop
  - Without feedback control
- Closed-loop
  - With feedback control
- Model predictive, Machine learning control

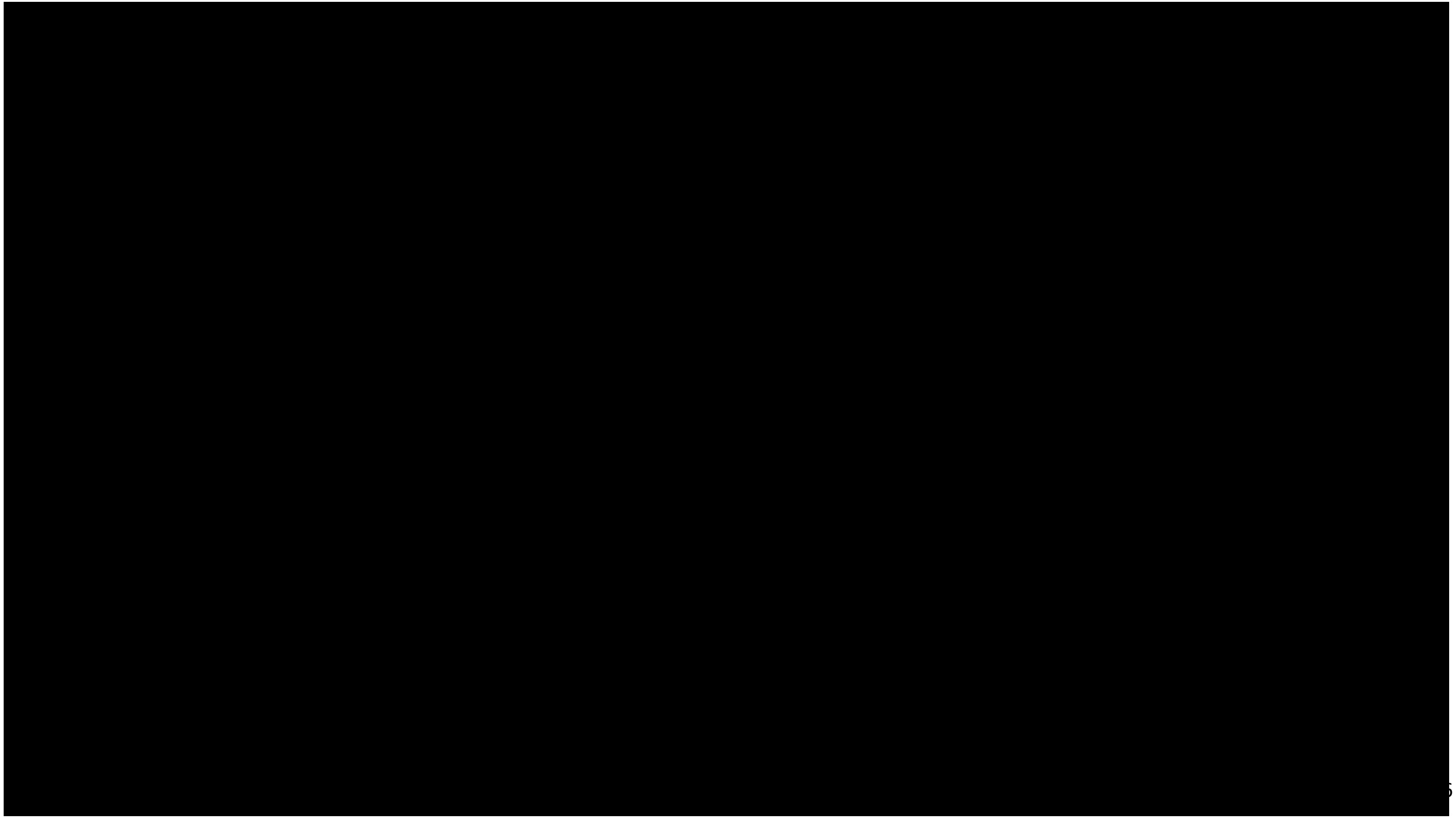
On-Off controlled underwater grasper

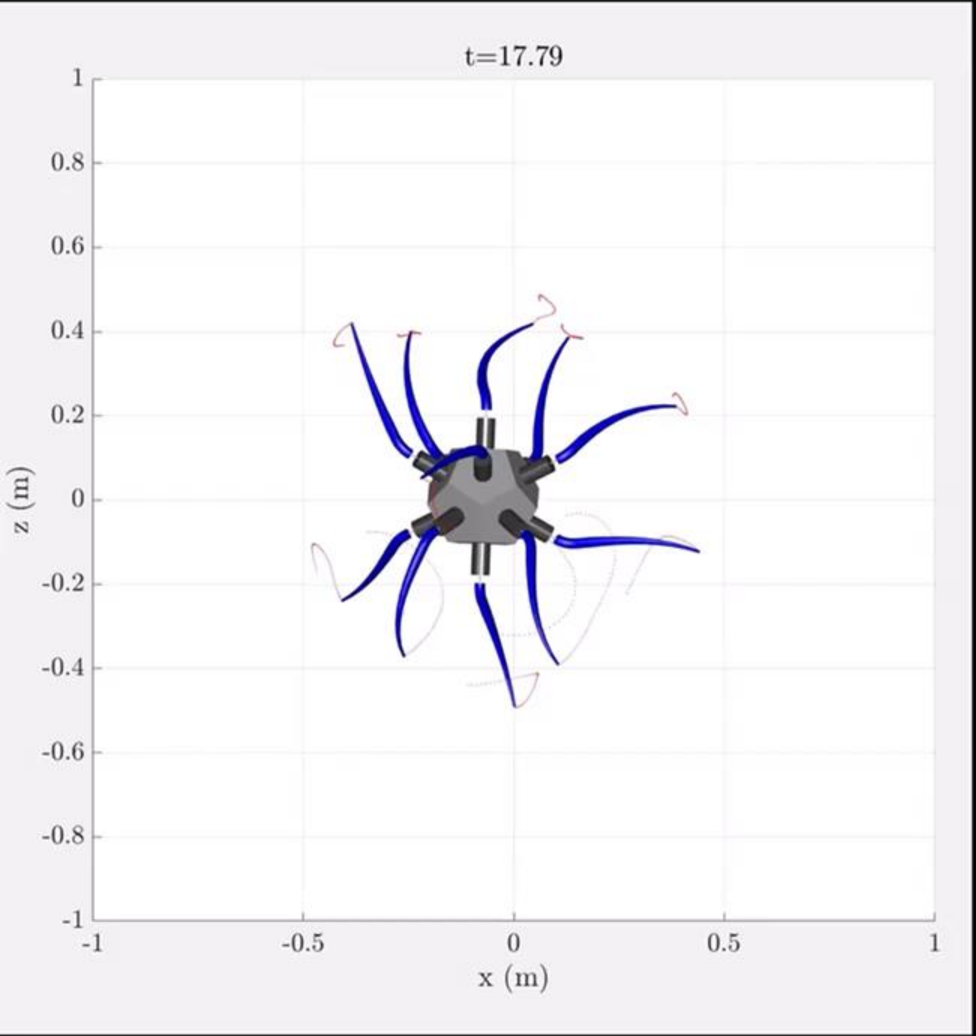


Source: Kanno, R., Kwak, B., Pankhurst, M., Shintake, J., & Floreano, D. (2024). Edible Soft Actuators Based on Konjac Glucomannan for Underwater Operation. *Advanced Intelligent Systems*, *6*(5), 2300473.

Case studies

Mathew, A.T., Feliu-Talegon, D., Abdullahi Adamu, Y., Ben Hmida, I., Armanini, C., Stefanini, C., Seneviratne, L. and Renda, F., 2025. ZodiAq: An Isotropic Flagella-Inspired Soft Underwater Drone for Safe Marine Exploration. *Soft Robotics*.

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0.6
0.4
0.2
0
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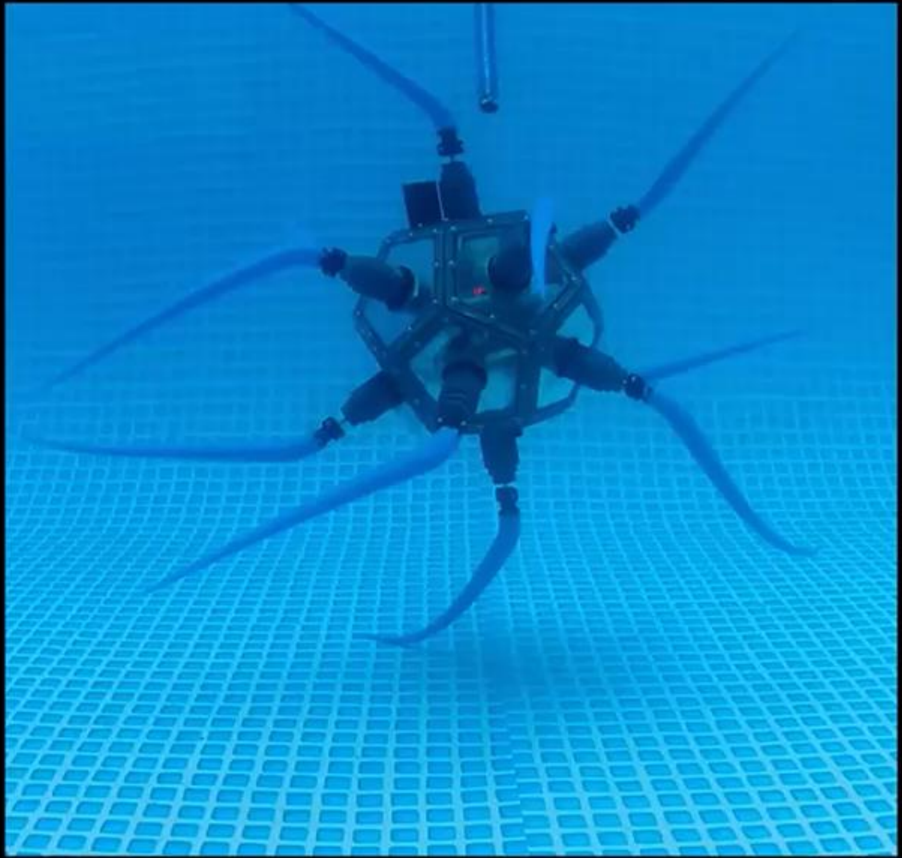
-0.4
-0.6
-0.8
-1
z (m)
-1
-0.5
0
0.5
1
x (m)

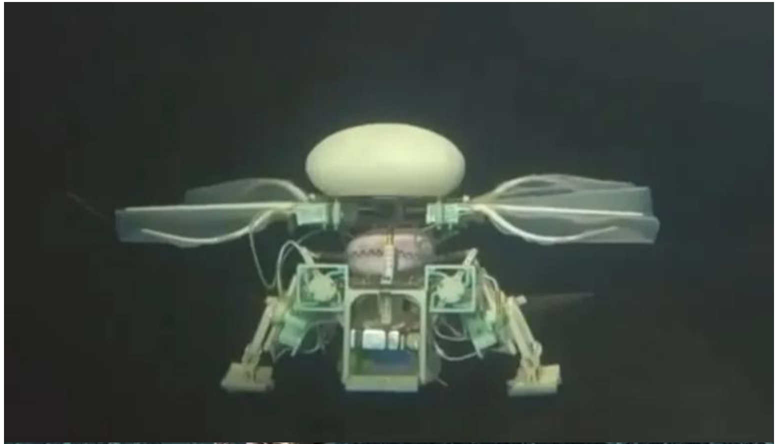


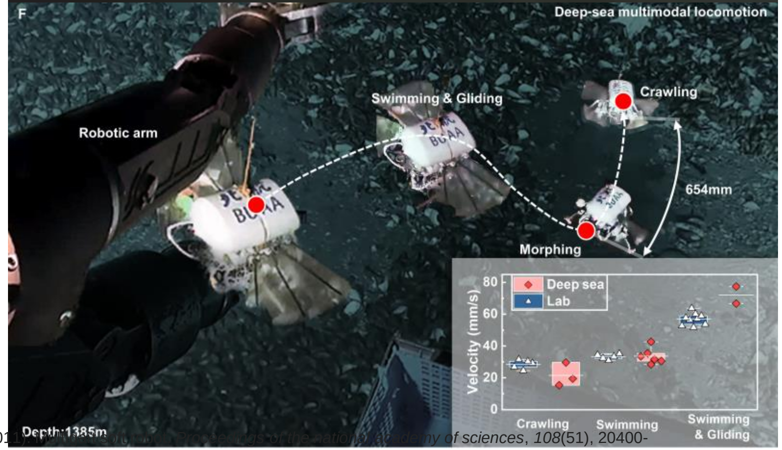
Summary of Underwater Soft Robotics

- Bio-inspired underwater robots have increasingly been developed owing to the smart & soft matter materials.
- Smart & soft matter materials have unique response such as maxwell stress, shape recovery, low voltage bending actuation, etc.
- The bioinspired design mimic the natural living's motion
- Modeling and control for the robots starts from material characterization.

Learning goals

- ❑ *What is soft robotics?*
  - ❑ *Materials*
  - ❑ *Actuation*
  - ❑ *Sensing*
- ❑ *What does soft robotics add to the conversation of underwater robotics?*
- ❑ *What are the case studies that highlight this?*





Pan, F., Liu, J., Zuo, Z., He, X., Shao, Z., Chen, J., Wang, H., Zhang, Q., Yuan, F., Chen, B. and Jin, T., 2025. Miniature deep-sea morphable robot with multimodal locomotion. *Science Robotics*, *10*(100), p.eadp7821.

- Source: Shepherd, R. F., Ilievski, F., Choi, W., Morin, S. A., Stokes, A. A., Mazzeo, A. D., ... & Whitesides, G. M. (2011). Multigait soft robot. *Proceedings of the national academy of sciences*, *108*(51), 20400-20403. Shintake, J., Rosset, S., Schubert, B. E., Floreano, D., & Shea, H. (2016). Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators. Advanced materials, 28(2), 231-238., Yoder, Z., Rumley, E. H., Schmidt, I., Rothemund, P., & Keplinger, C. (2024). Hexagonal electrohydraulic modules for rapidly reconfigurable high-speed robots. Science Robotics, 9(94), eadl3546.