M2794.007700 Smart Materials and Design

Smart materials and structures : Introduction

April 27, 2017

Prof. Sung-Hoon Ahn (安成勳)

School of Mechanical and Aerospace Engineering
Seoul National University
http://fab.snu.ac.kr
ahnsh@snu.ac.kr

Outline

Introduction to smart materials:

- **Shape memory effect and shape memory alloy**
- **Shape memory polymer**
- **Electro-active polymer**
- **Ionic polymer-metal composite**
- **Pneumatic actuators**

Application examples of smart materials to engineering

INTRODUCTION TO SMART MATERIALS

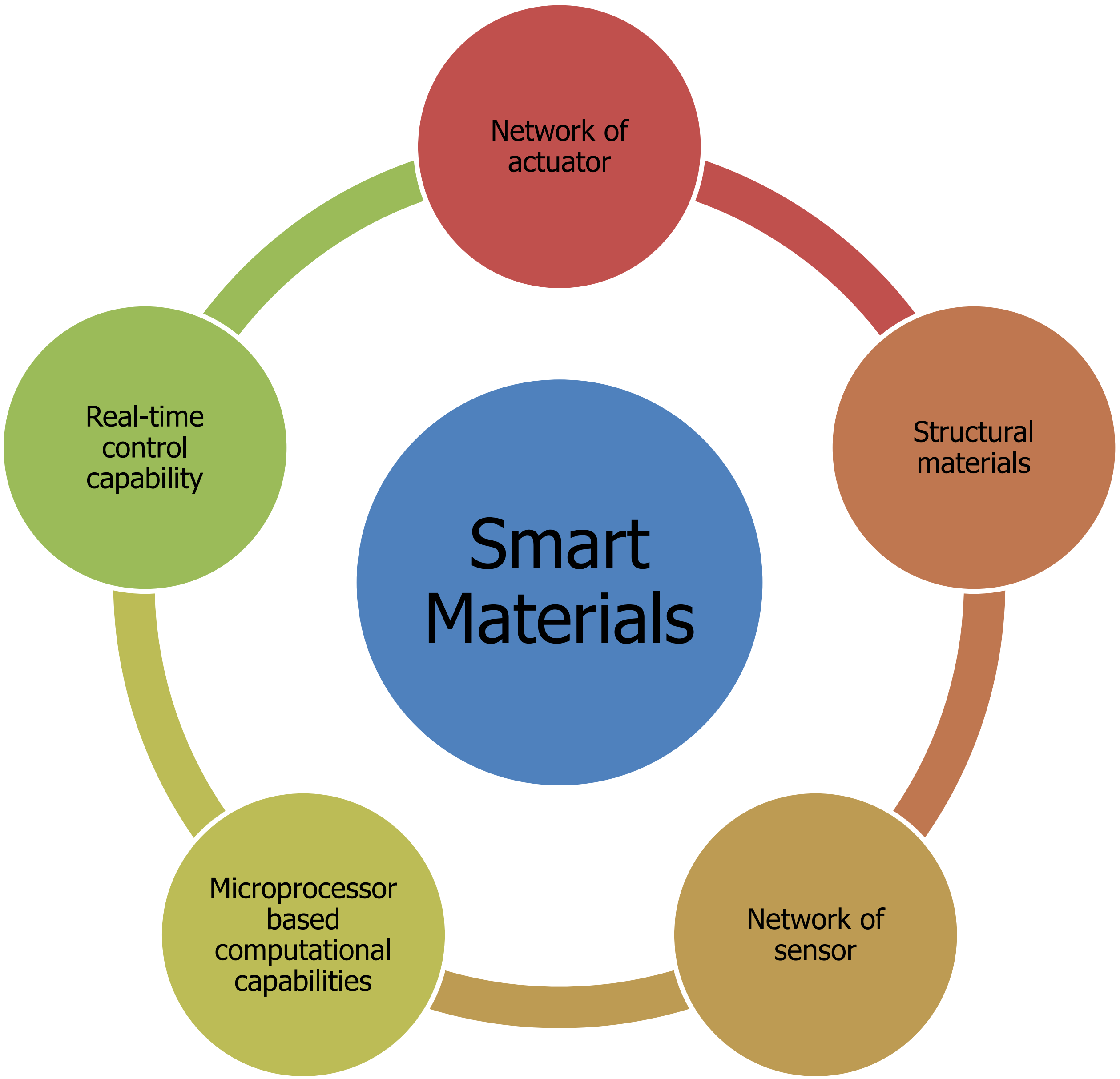
What is Smart Materials??

Can we design analogous mechanisms that can intelligently interact with their environment??

Yes, Smart Materials can

***"Smart materials"* is a combination of sensors, actuators, and processors by responding intelligently and autonomously to dynamically-changing environmental conditions**

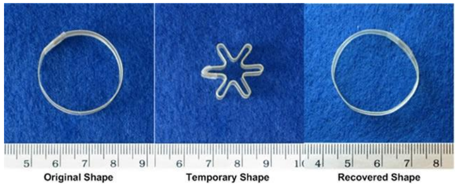
Ingredients of Smart Materials



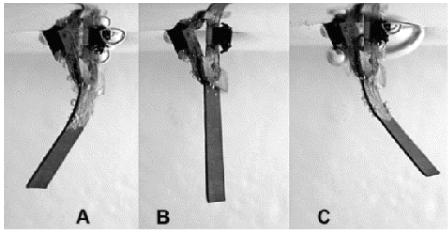
Classification of Smart Materials

- **Smart materials**
  - Shape memory materials
    - Shape memory alloys

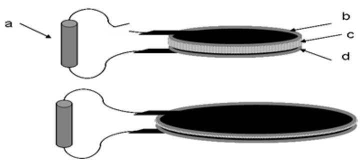
    - Shape memory polymers



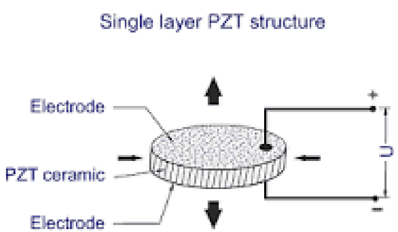
  - EAPs
    - Ionic EAP
      - Ionic gels
      - IPMC

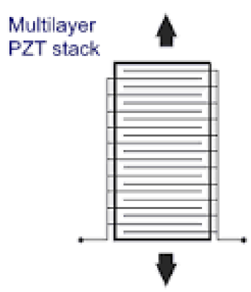


      - Conducting
      - Electrorheological fluids
    - Electronic EAP
      - Ferroelectric polymer
      - Dielectric EAP



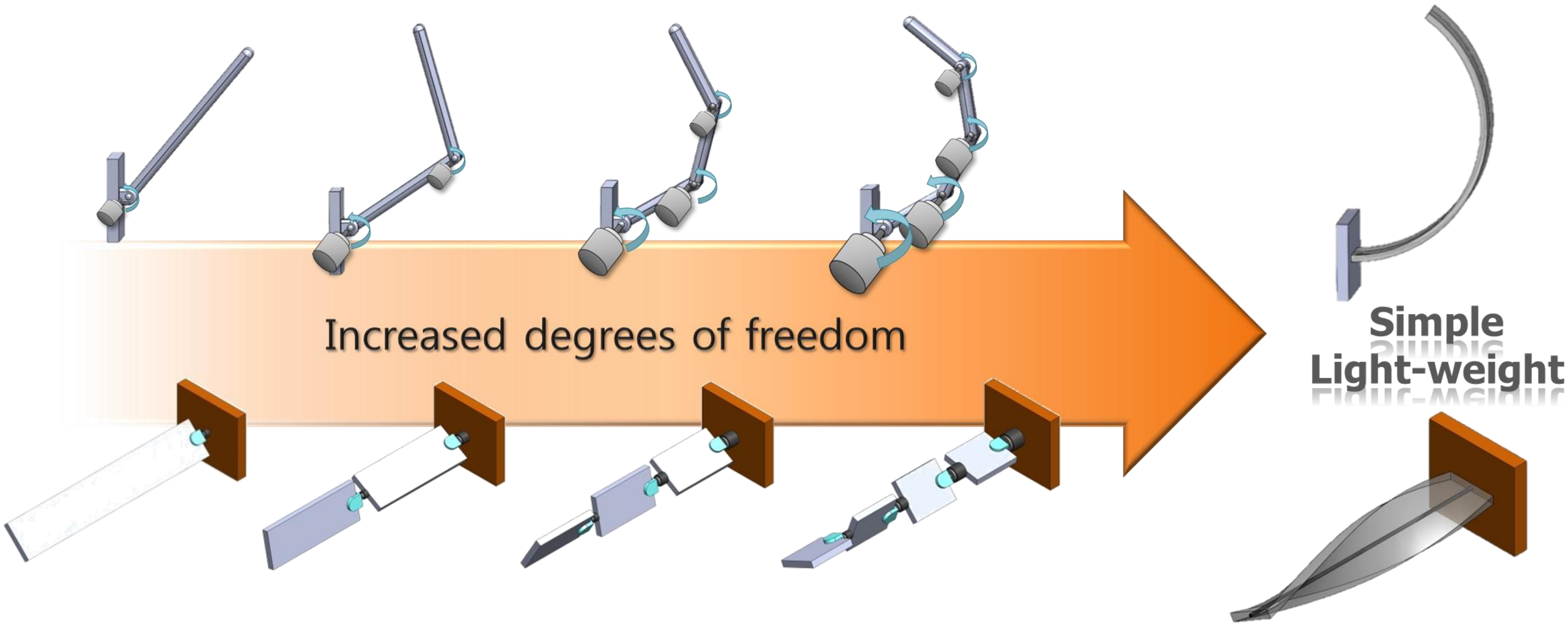
      - Electrostrictive graft elastomers
      - Liquid crystal elastomers
  - Piezoelectric materials
    - Piezoceramics





Advantage of smart material

- **Continuous deformation**
  - Realize continuous deformation in simple & light weight structure



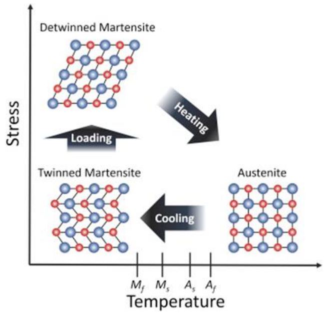
Shape memory materials

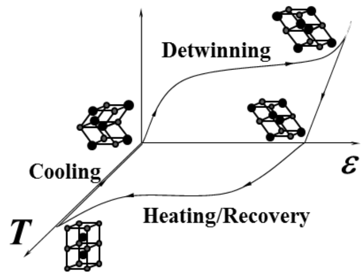
- **Shape memory effect (SME)**
  - A change in shape caused by a change in temperature is called a thermally induced shape memory effect
  - Typical shape memory materials
    - Shape memory alloy
    - Shape memory polymer

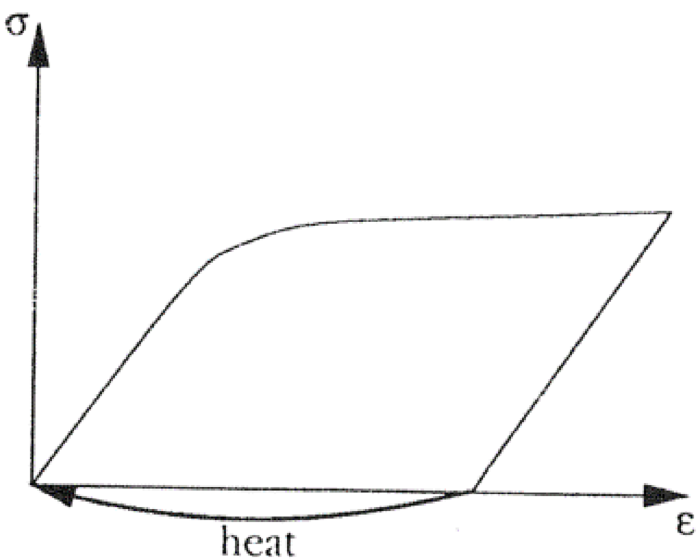
SMA Spring vs Hot Water

Shape memory effect *(http://www.biosmart.co.kr)*

Shape memory alloy



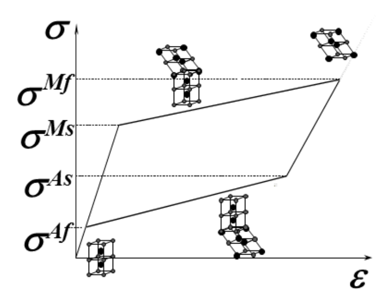


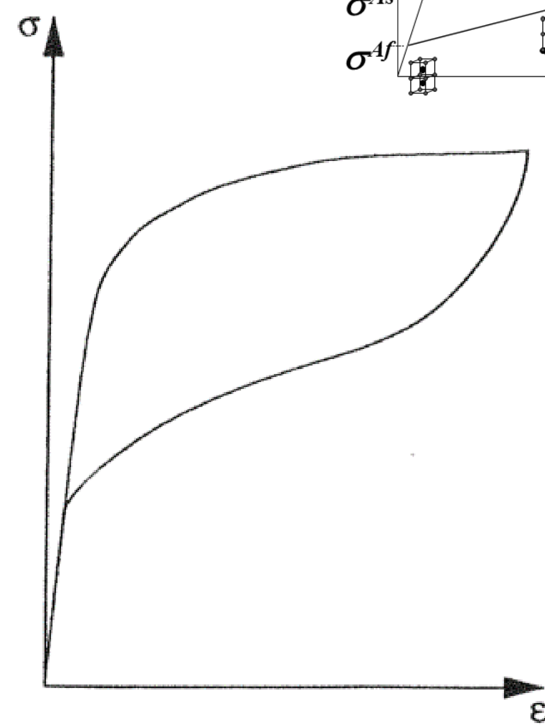


(a)

$T<A_s$, beginning with 100% twinned martensite

Shape Memory Effect





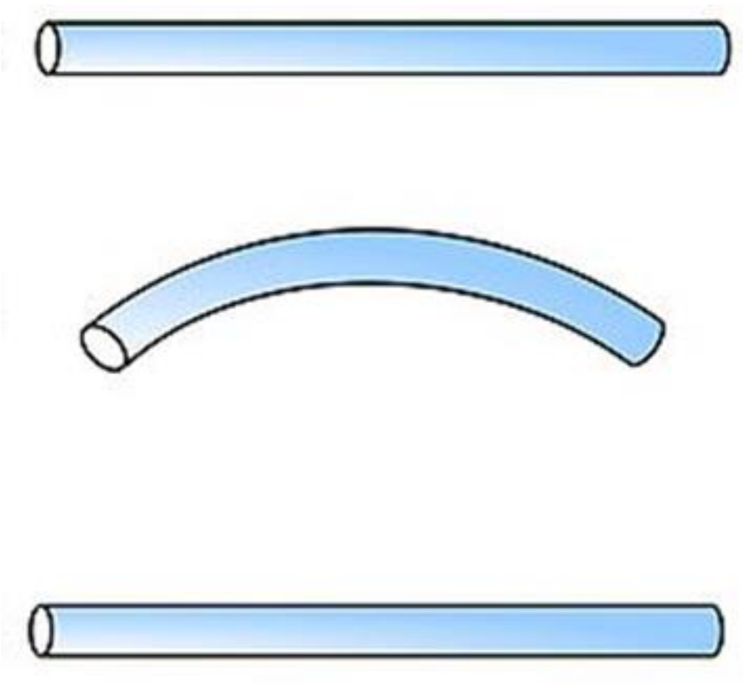
(d)

$T>A_f$, beginning with 100% austenite

Superelasticity (Pseudoelastic effect)

Shape memory alloy

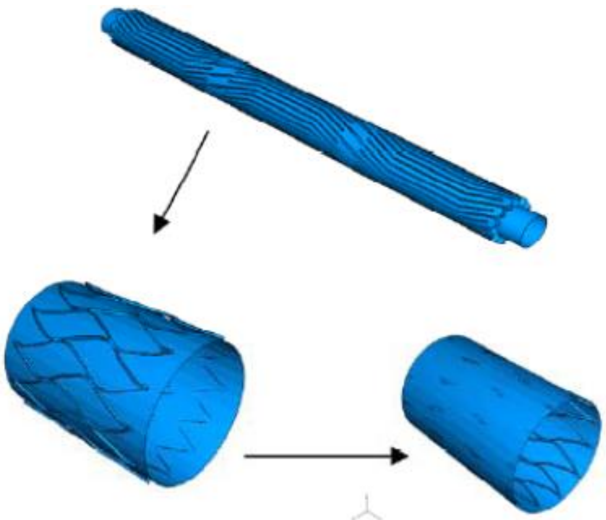
- **Shape memory effect**
  - When its cold state (below A_s), it can be bent or stretched and will hold its shape until heated above the transition temperature
  - Upon heating, the shape changes to its original shape
  - When the metal cools again it will remain in the hot shape until deformed again.



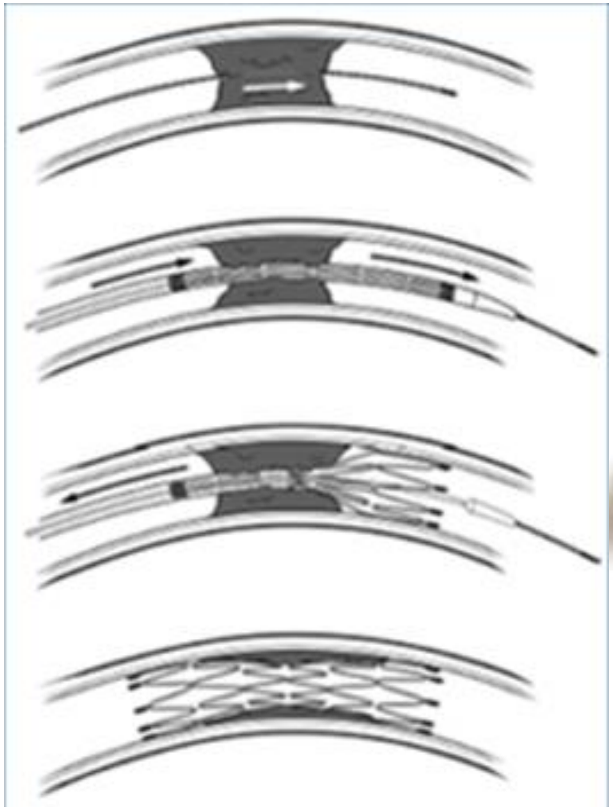
Tube coupling

- Pipe couplings for the connection of Titanium tubing in Spacecrafts based on the thermal effect in ternary NiTiNb alloys.
- Memory-Metalle Company

Vascular Stent



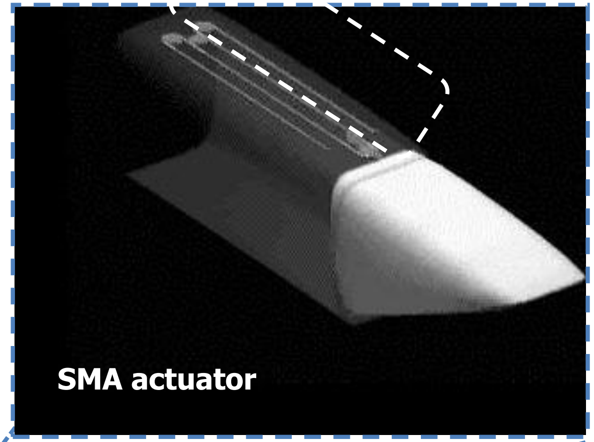
Stent actuation



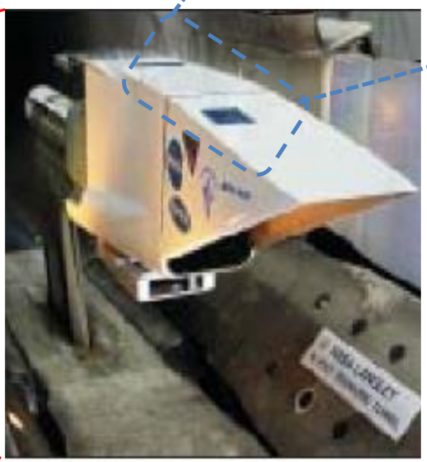
SMA vascular stent

Materials for soft morphing structures

- **SMA embedded composite**
  - Smart structure for actuator
  - Limitation
    - Small actuating deformation
  - Application



F-15 aircraft engine inlet



Adaptive air inlet : 20% range increase

Wind tunnel test of a full scale F-15 aircraft inlet

SAMPSON project - smart inlet structure

(Pitt et. al., SAMPSON Smart Inlet Design Overview and Wind Tunnel Test, Part II: Wind Tunnel Test)

SMA smart tentacle

3D printed smart tentacle
https://www.youtube.com/watch?v=Ej-eMAemTDI

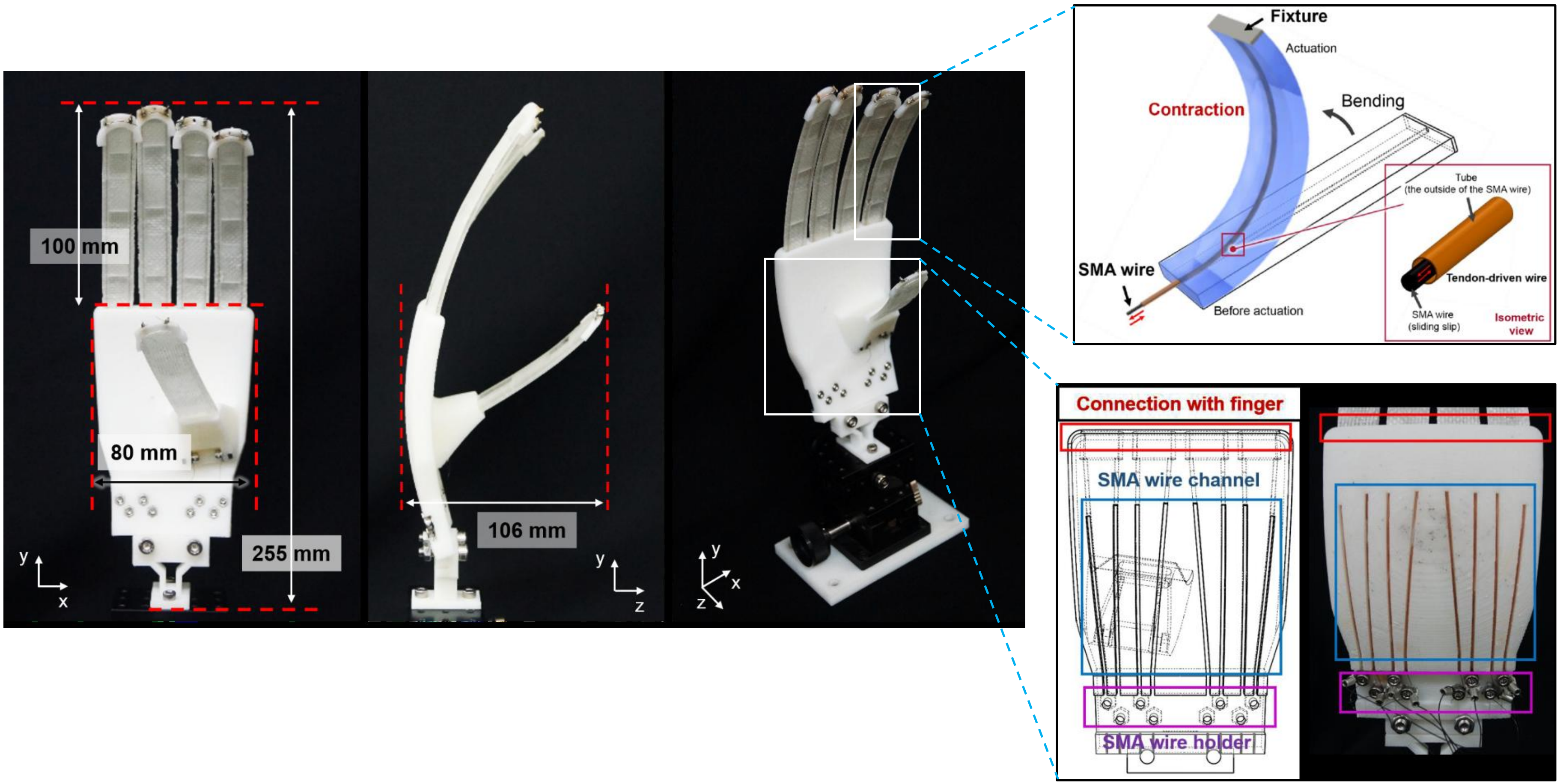
SMA robotic octopus

Robot Octopus "Shape-memory Alloy" - European robotics
https://www.youtube.com/watch?v=45Dc36dbQC8

SMA robotic hand

Shape Memory Alloy (SMA) Robotic Hand - University of Utah Mechanical Engineering
https://www.youtube.com/watch?v=zQih9tLbEzo

Soft hand driven by SMA tendon wire



Prototype of the soft robotic hand with four SSC artificial fingers and a thumb
(Submitted to *Composites Part B*)

Confidential

Soft hand driven by SMA tendon wire

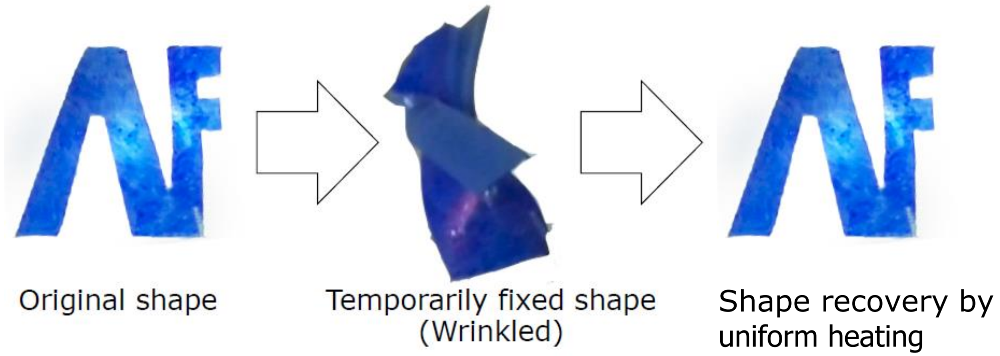
Sequences of images showing the bending actuation of the soft robotic hand prototype with a current of 0.8 A

Photographs showing the grasping of various objects by the soft robotic hand: (a) a soda can, (b) a yogurt bottle, (c) a light bulb, (d) a paper cup, (e) a toilet paper roll, (f) a mouse, (g) a pair of scissors, (h) a ball of crumpled paper, and (i) a plastic bottle.

Submitted to *Composites Part B*

Shape memory polymer

- **Shape memory polymer**
  - Polymeric smart material that have ability to return from a deformed state (temporary shape) to their original (permanent) shape induced by an external stimulus, such as temperature change.

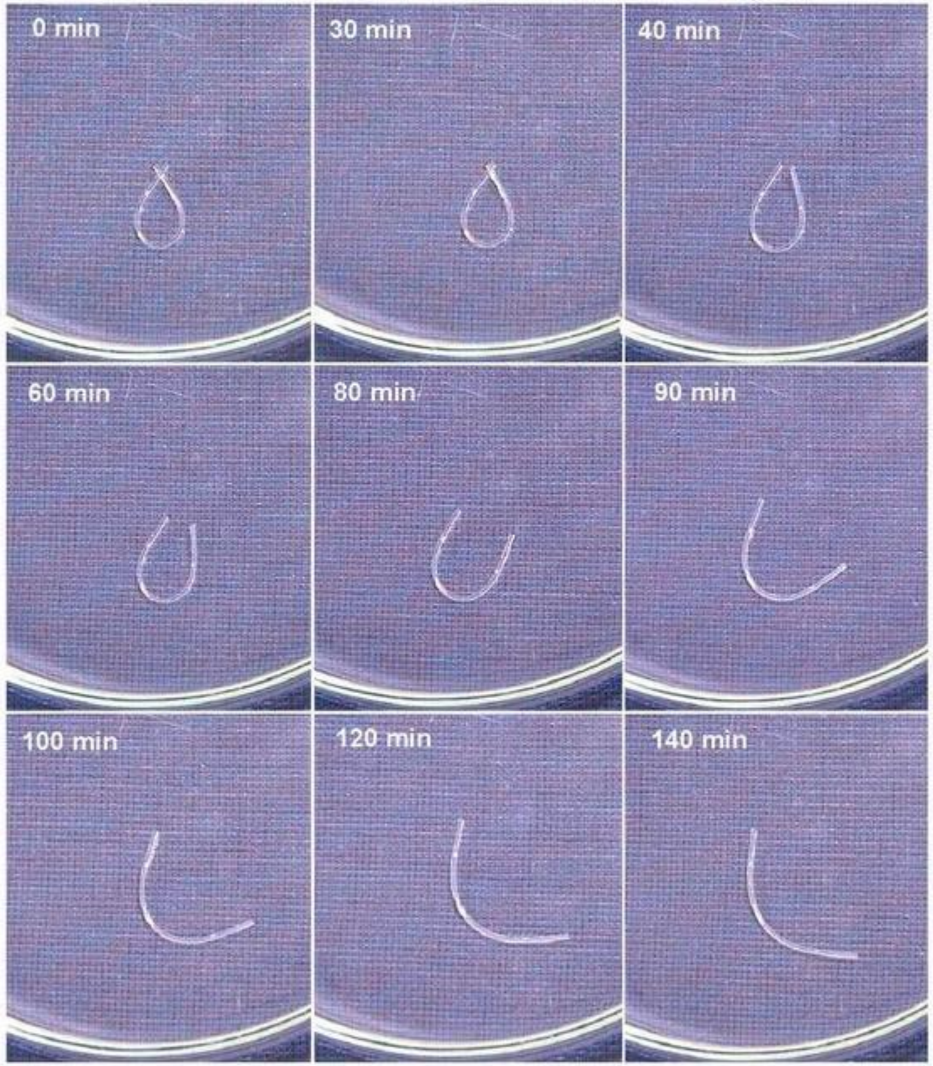


Description of the thermally induced shape memory effect in SMP

Shape memory polymer

- **Advantages**
  - Large recoverable strain (~400%)
  - Easy processing
  - Light weight
  - Low cost
- **Drawbacks**
  - Low mechanical properties
- **Applications**
  - Alternatives to shape memory alloys (SMAs)
  - Heat shrinkable tubes, wraps, foams, and self-adjustable utensils
  - Biomedical devices, aerospace structures, and smart textiles

Programmable/Water Actuatable SMP



Propose a novel way to fabricate functionally gradient shape memory polymers, which can be actuated by water.

This technique provides an approach for recovery of shape memory polymers inside, e.g., human body, without any heating system and in a programmable manner.

Difference between SMA and SMP

Shape memory polymers differ from shape memory alloys by

- Glass transition or melting transition from a hard to a soft phase which is responsible for the shape memory effect.
- In shape memory alloys martensitic/austenitic transitions are responsible for the shape memory effect.

Advantages of SMPs which is more attractive than SMA.

1. High capacity for elastic deformation (up to 200% in most cases)
2. Low cost
3. Low density
4. Broad range of application temperatures which can be tailored
5. Easy processing
6. Potential biocompatibility and Biodegradability

Introduction to electro active polymer

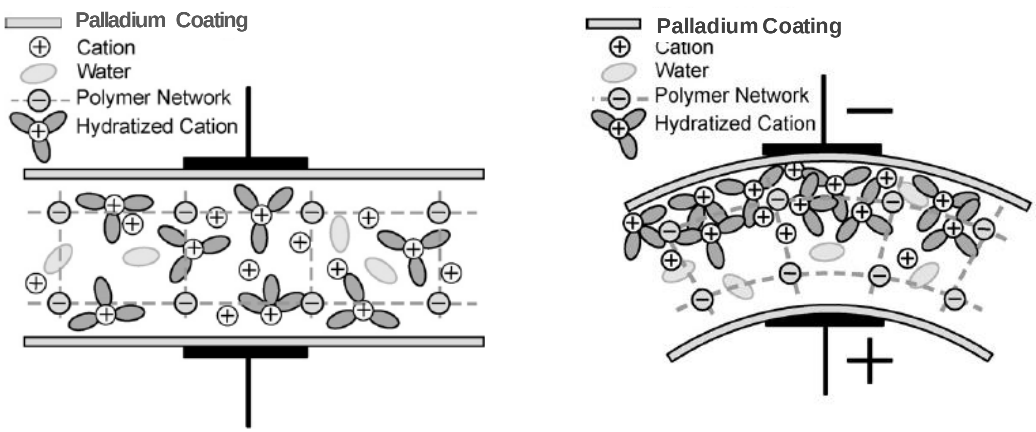
- **Electroactive polymers**
  - Polymers that exhibits a change in size or shape when stimulated by an electric field
  - Large deformation
  - Major application field : robotics in the development of artificial muscles
  - Often referred to as artificial muscles

- **List of leading electroactive polymer (EAP) materials**

Electronic EAP	Ionic EAP
Dielectric elastomers	Ionic polymer gels (IPG)
Electrostrictive graft elastomers	Ionic polymer metal composite (IPMC)
Electrostrictive paper	Conducting polymers (CP)
Electro-viscoelastic elastomers	Carbon nanotubes (CNT)
Ferroelectric polymers	
Liquid crystal elastomers (LCE)	

Introduction to electro-active polymer

- **Electroactive polymers**



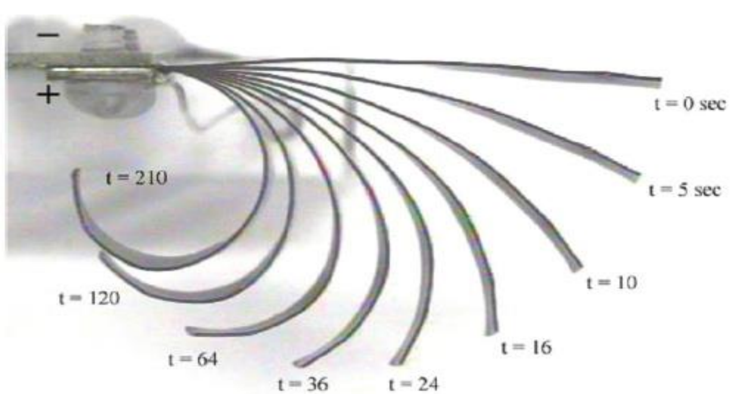
Bending mechanism of ionic polymer metal composite (IPMC)

Actuation of ionic polymer metal composite (IPMC) [1]

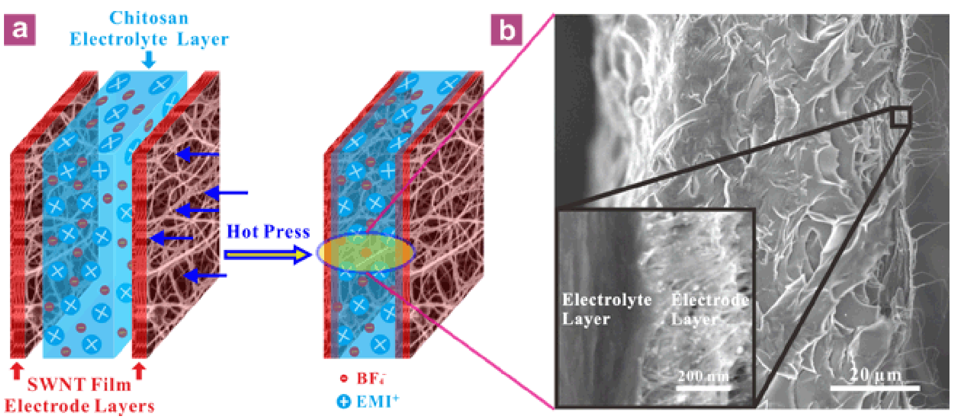
[1] https://www.youtube.com/watch?v=Nn4b7Wi7RIo

Ionic Polymer Metal Composites

- IPMC is consist of base ion exchange polymer and electrode metal (Platinum, Gold, Palladium, Silver,…)
- The metal electrode is formed by special chemical plating or physical treatments
- Bending motion due to uni-directional electro-osmosis by cation with their polar solvent(hydratized cation) toward the cathode



IPMC actuator (Nemat-Nasseret et al. 2003)



Manufacturing and composition of IPMC

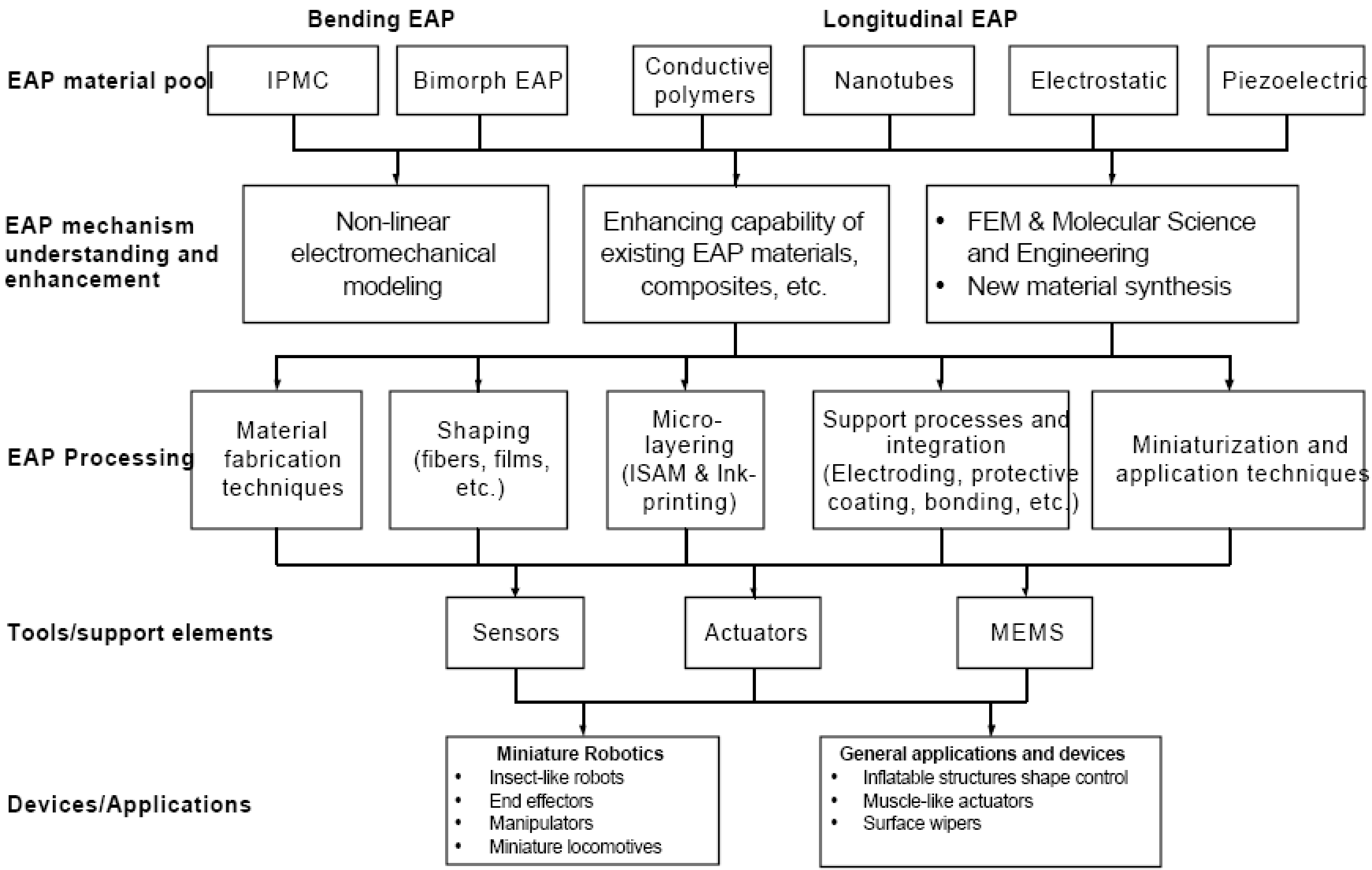
IPMC jelly fish

Artificial Muscle Jelly Fish/Squid
https://www.youtube.com/watch?v=J2mE0tUk7vA

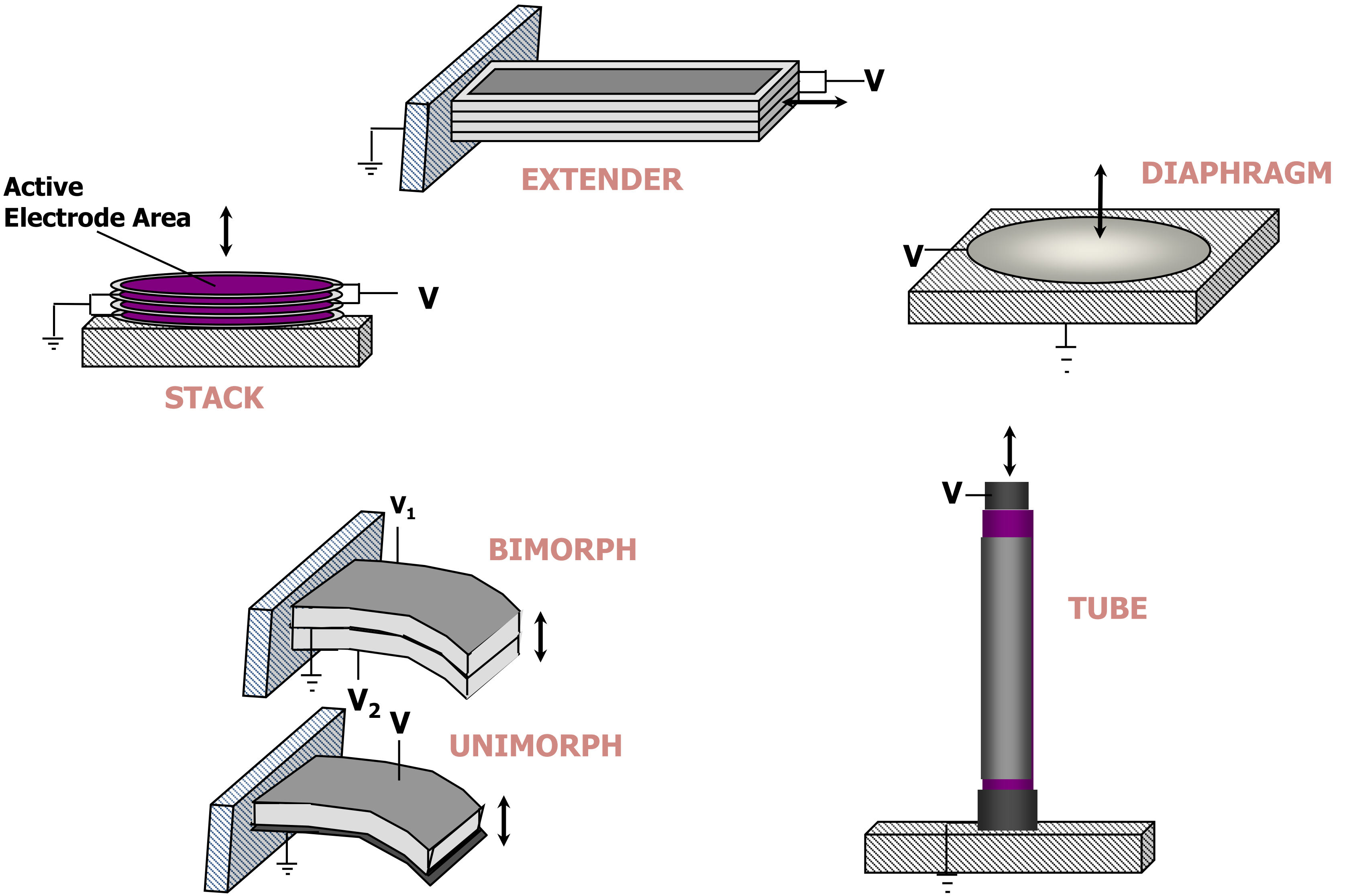
IPMC fish

IPMC
https://www.youtube.com/watch?v=Jd7Cg-pyHRU

EAP infrastructure and areas needing attention



EAP Configurations



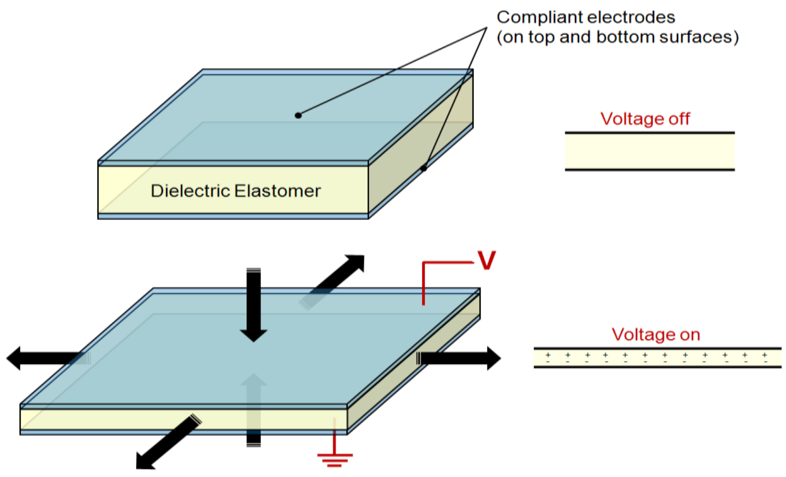
Dielectric elastomer

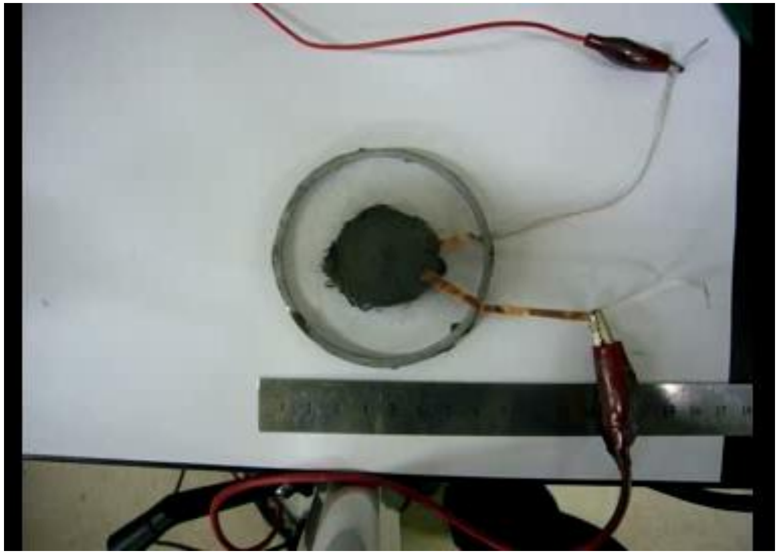
- **Smart material systems which produce large strains (up to 300%)**
- **Transform electric energy directly into mechanical work**
- **Compliant capacitor (see image), where a passive elastomer film is sandwiched between two compliant electrodes**
- **When V voltage is applied, the electrostatic pressure p_{el} arising from the Coulomb forces acting between the electrodes**
- **The equivalent electromechanical pressure p_{eq} is given by the following equation**

$$p_{eq} = \varepsilon_0 \varepsilon_r \frac{V^2}{z^2}$$

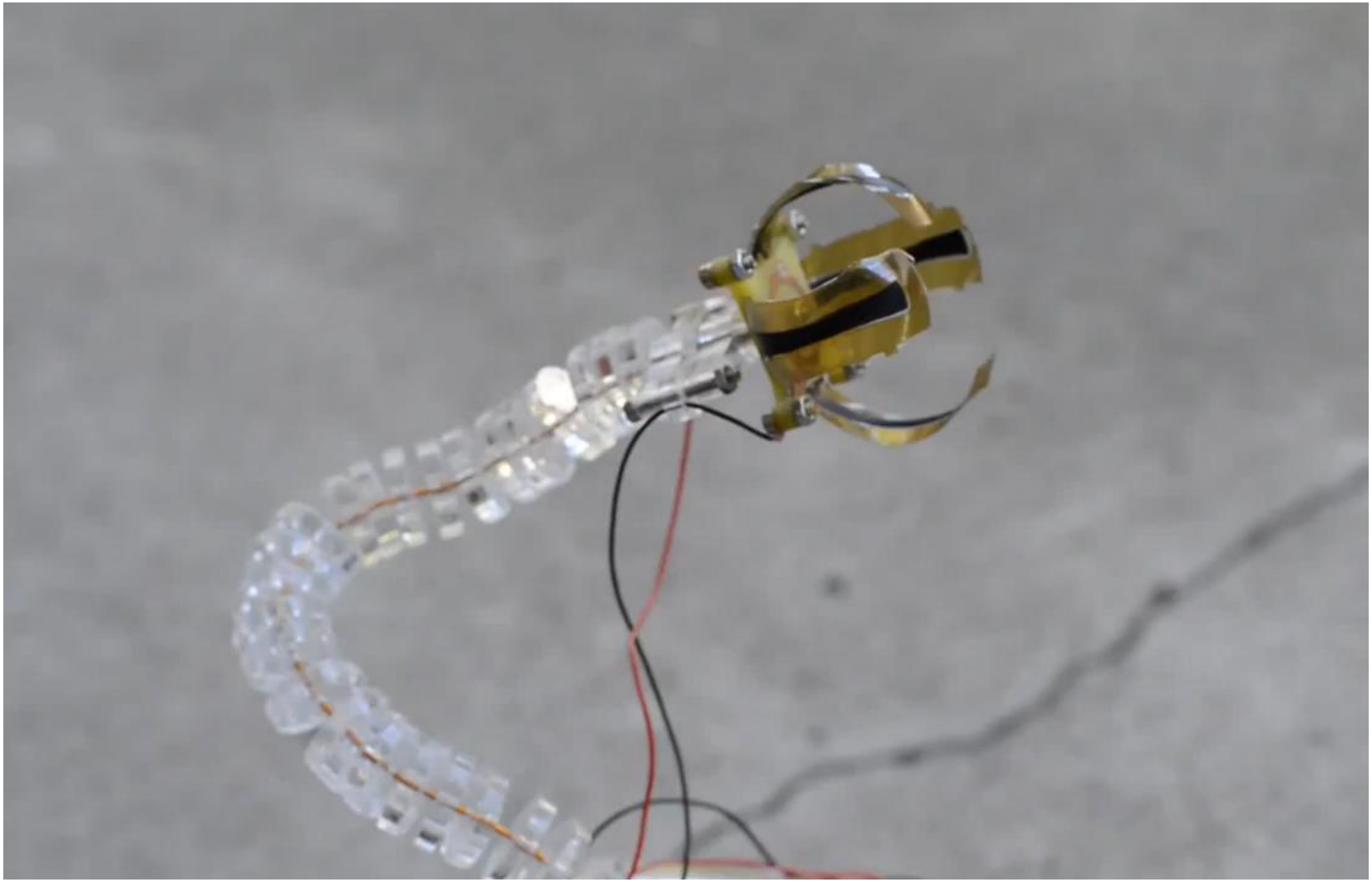
$\varepsilon_0 =$ Vacuum permittivity

$\varepsilon_r =$ Dielectric constant of polymer



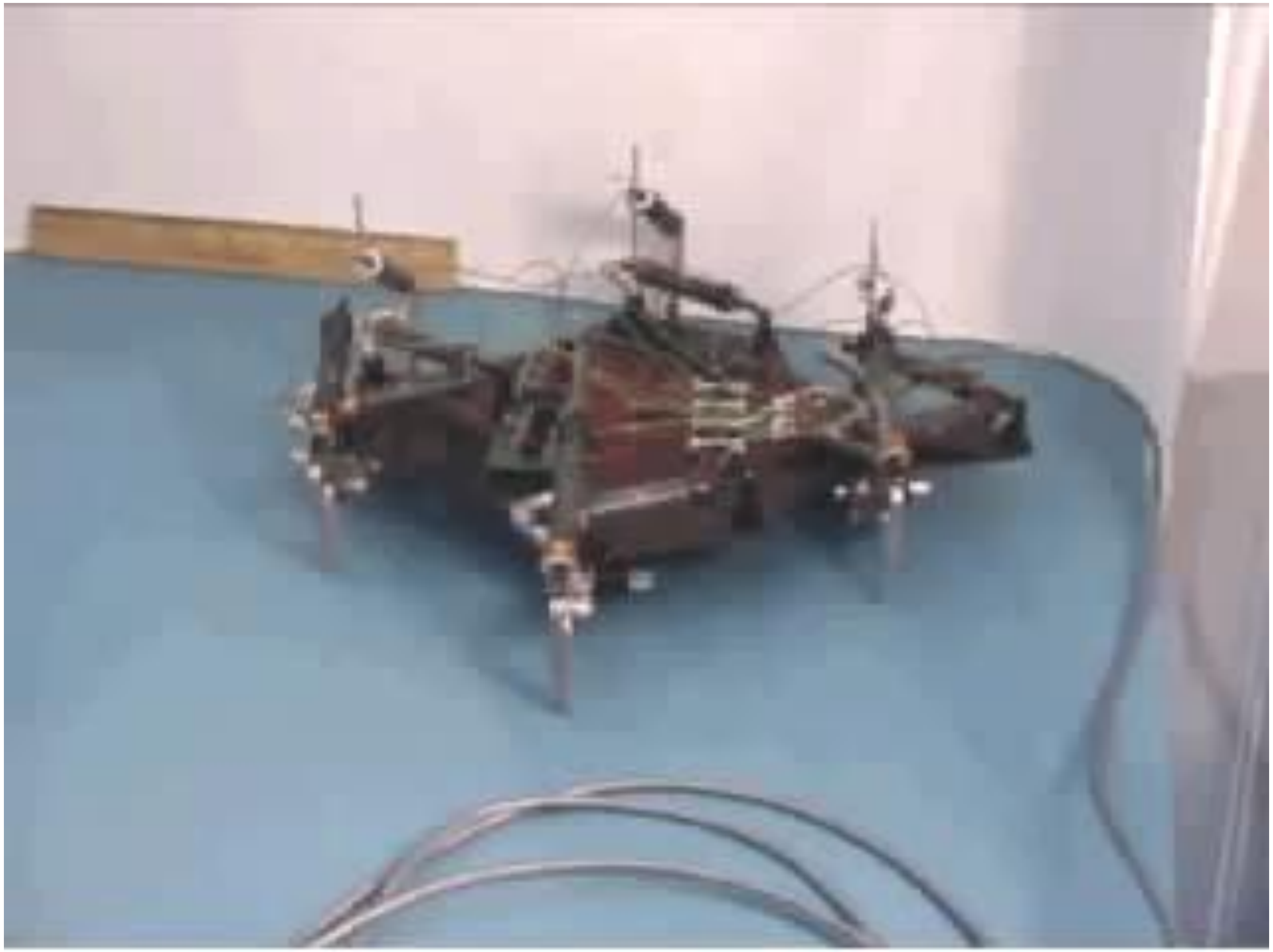


Dielectric elastomer gripper



DEMES gripper with four fingers
https://www.youtube.com/watch?v=uHlr6a1Uwbg

Dielectric EAP muscle Flex robot

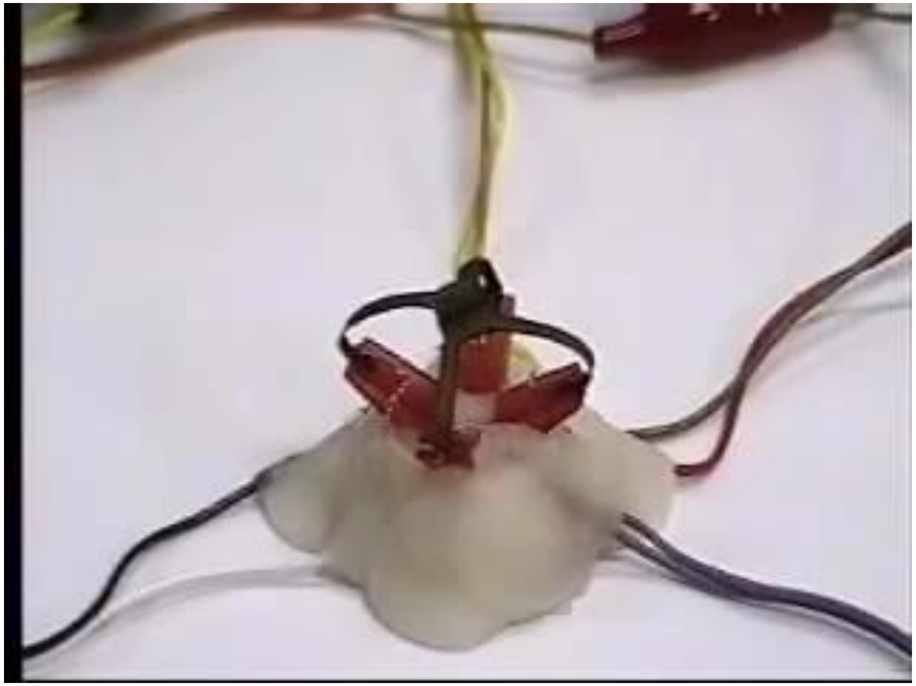


Electroactive Polymer Artificial Muscle (EPAM) Flex Robot
https://www.youtube.com/watch?v=nl4-s-DDO-M

EAP robot blimp

Electroactive Polymer (EAP) Robot Blimp
https://www.youtube.com/watch?v=6cdfWdHZRrE

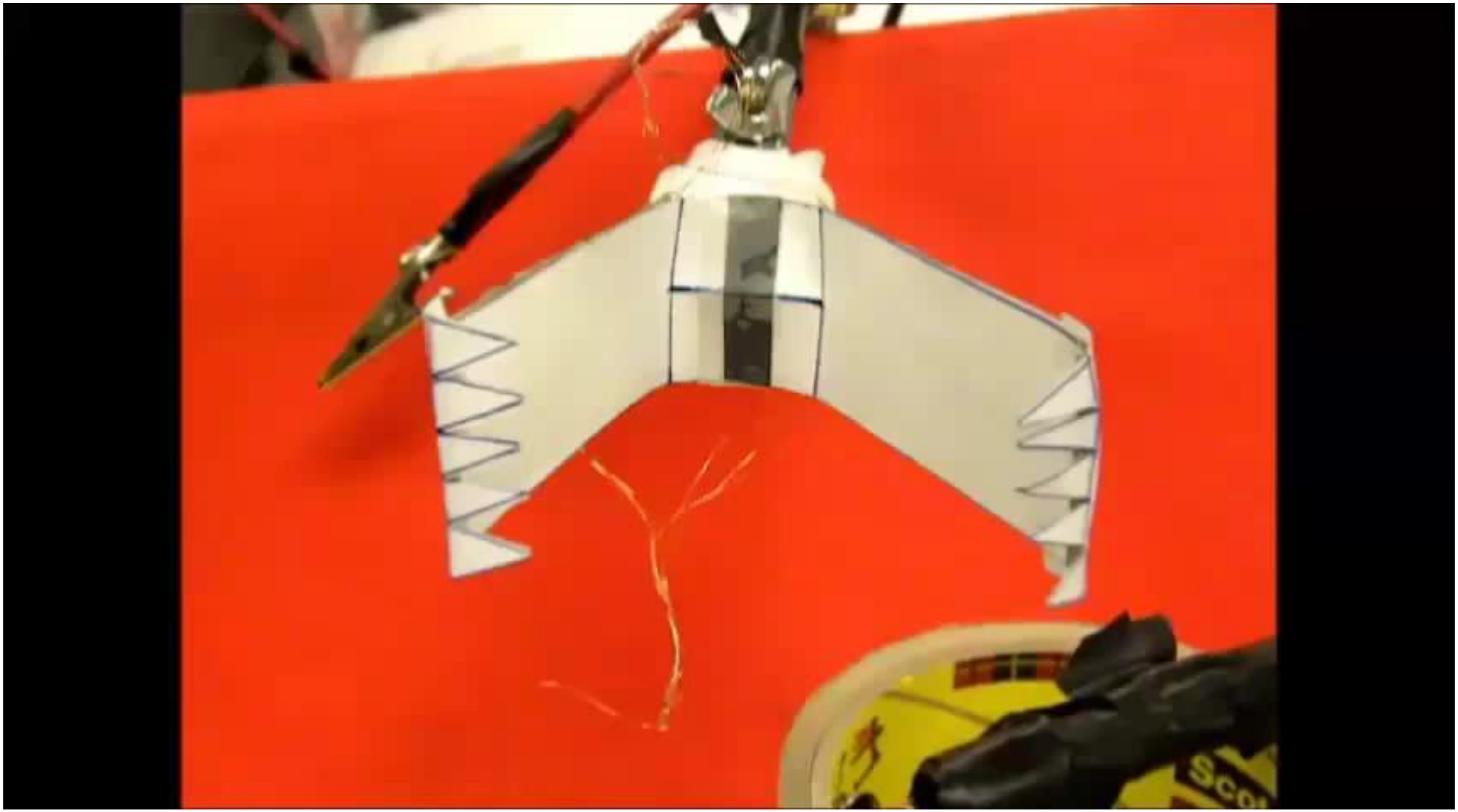
EAP head and eye



Electroactive Polymers (EAP) for a Robot Head
https://www.youtube.com/watch?v=XoyA_w0DDDc

Electroactive Polymer (EAP) eye
https://www.youtube.com/watch?v=kqEf-HaK8zg

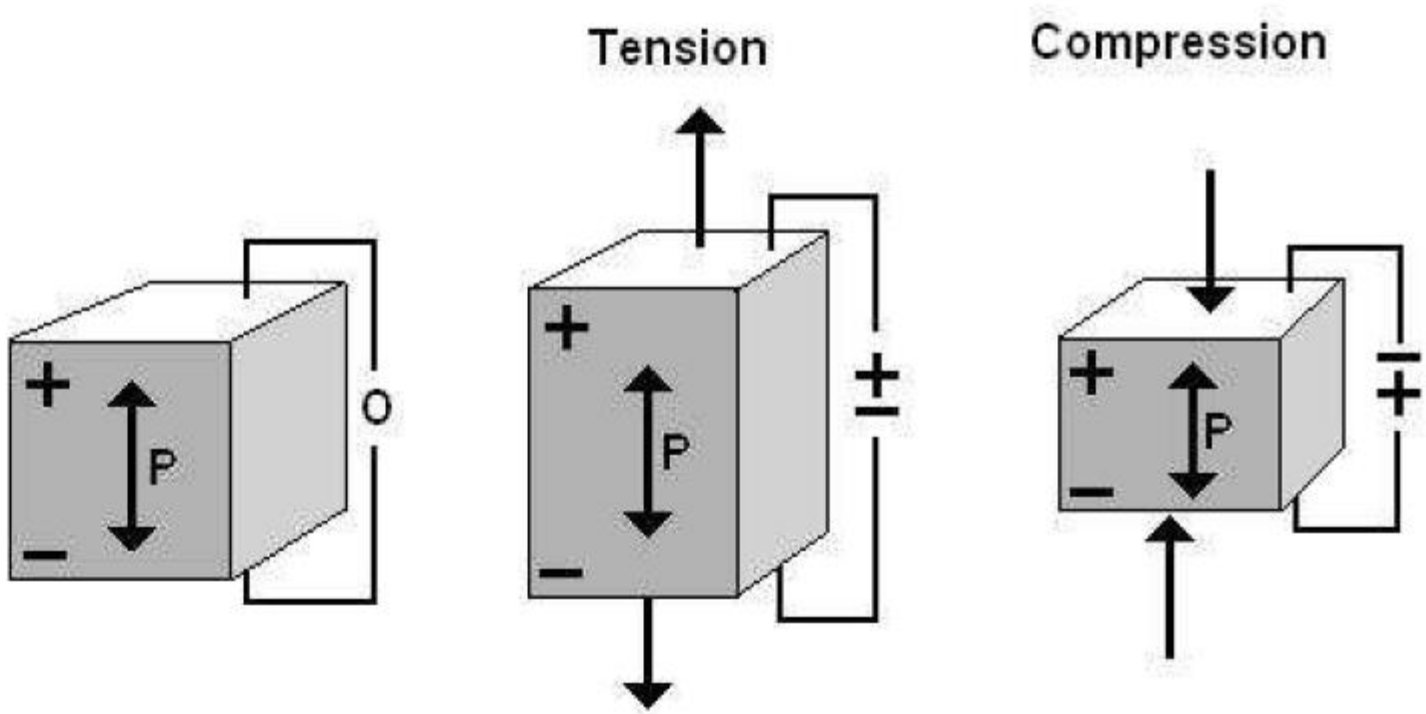
Origami-inspired DEA



Origami-Inspired Dielectric Elastomer Actuator
https://www.youtube.com/watch?v=oM4TSSx90yw

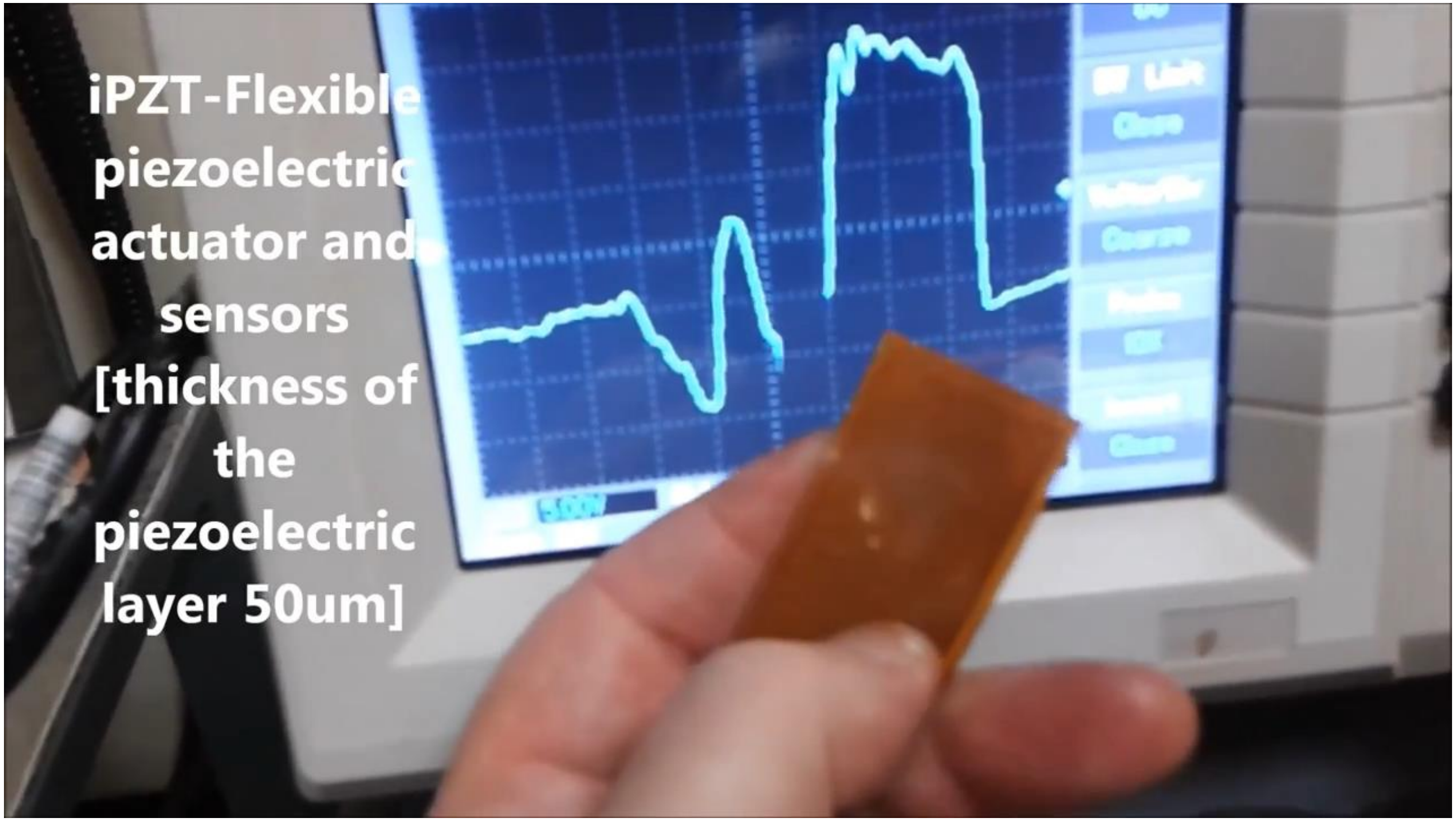
Piezoelectric effect

- **Direct piezo effect**
  - A mechanical stress on a material produces an electrical polarization



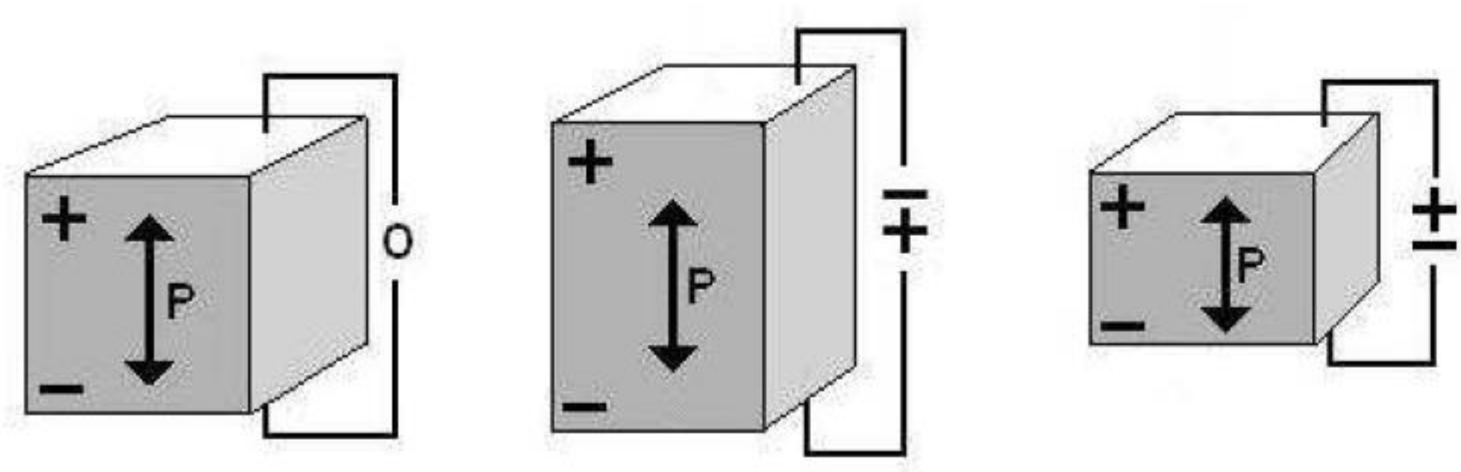
Piezoelectric effect

- **Direct piezo effect**
  - A mechanical stress on a material produces an electrical polarization



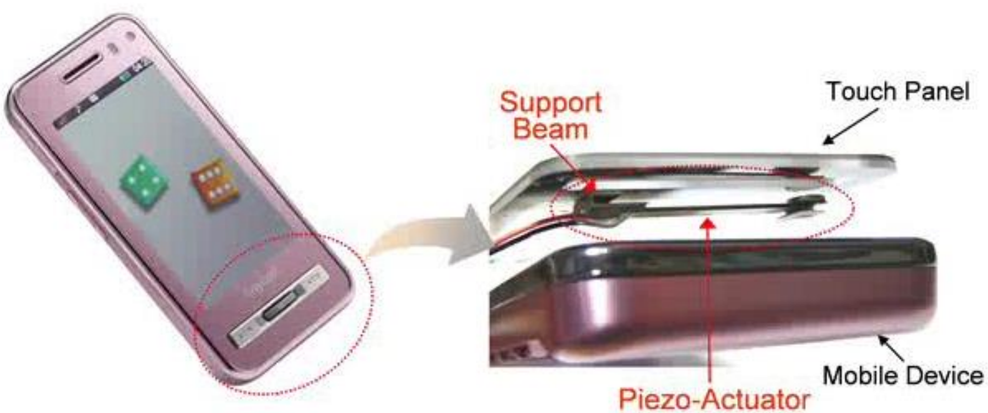
Piezoelectric effect

- **Converse (inverse) piezo effect**
  - An applied electric field in a material produces dimensional changes and stresses within a material

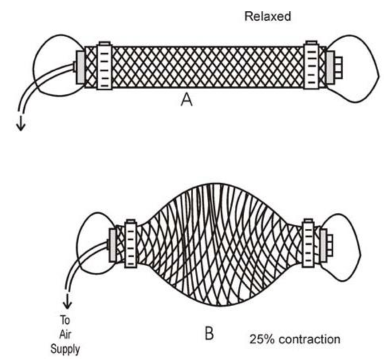


Piezoelectric effect

- **Converse (inverse) piezo effect**
  - An applied electric field in a material produces dimensional changes and stresses within a material

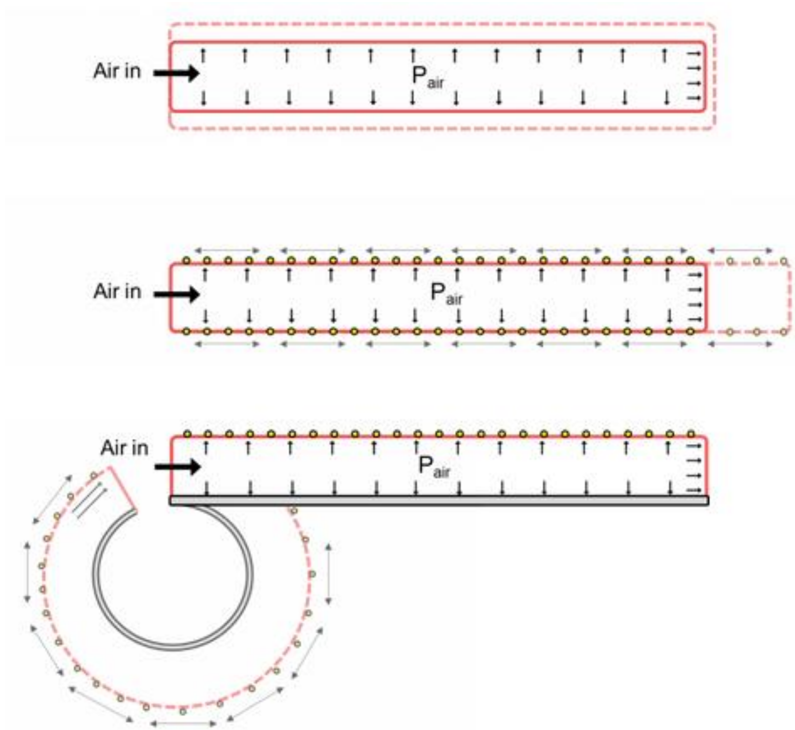


Pneumatic actuators



Linear pneumatic actuator

- Inflatable inner tube/bladder inside a braided mesh, clamped at the ends. Pressurization = Contraction



Fiber reinforced soft pneumatic actuators

- Without any restriction, the soft material expands in all directions.

- If constrained in one direction (using inextensible fiber), the actuator expands in only on direction

- Using inextensible material on one side prevents axial extension on one side, causing bending of the actuator

More info on design and manufacturing at softroboticstoolkit.com

Pneumatic bending actuator

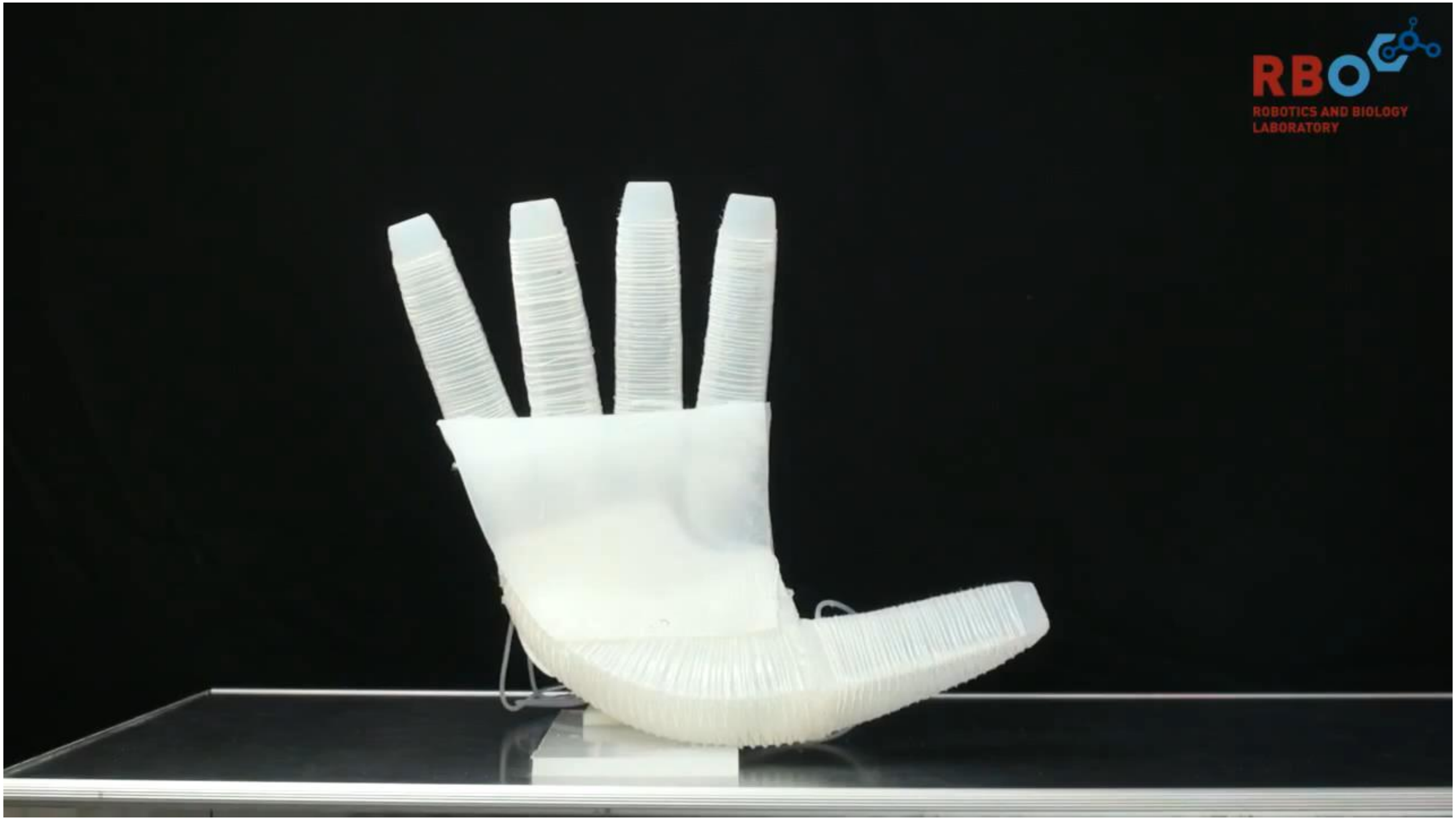
Bending Actuator Fabricated Using Elastomer and Paper
https://www.youtube.com/watch?v=t5cun9UqjDc

Fabrication demo 1:
https://www.youtube.com/watch?v=Yji7Ssuw8y4

Social robots

Baymax from "Big Hero 6" by Walt Disney

Pneumatic hand



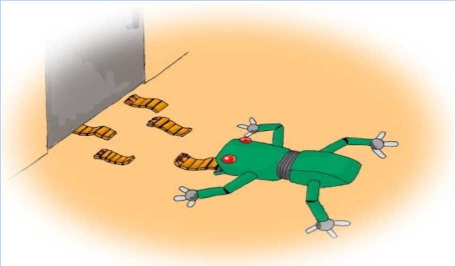
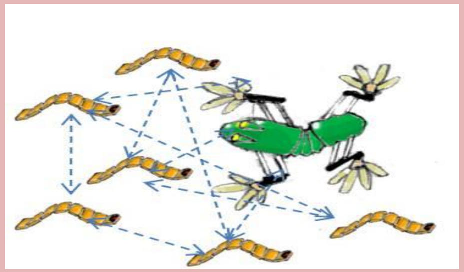
Soft anthopomorphic hand - first demo
https://www.youtube.com/watch?v=ziY-pHSpH5Q

PneuFlex actuator step-by-step production tutorial
https://www.youtube.com/watch?v=Ss-9iXRUeGc

Pneumatic hand

Soft Robot Walking and Crawling
https://www.youtube.com/watch?v=2DsbS9cMOAE

Multi-scale mass deployable cooperative robots

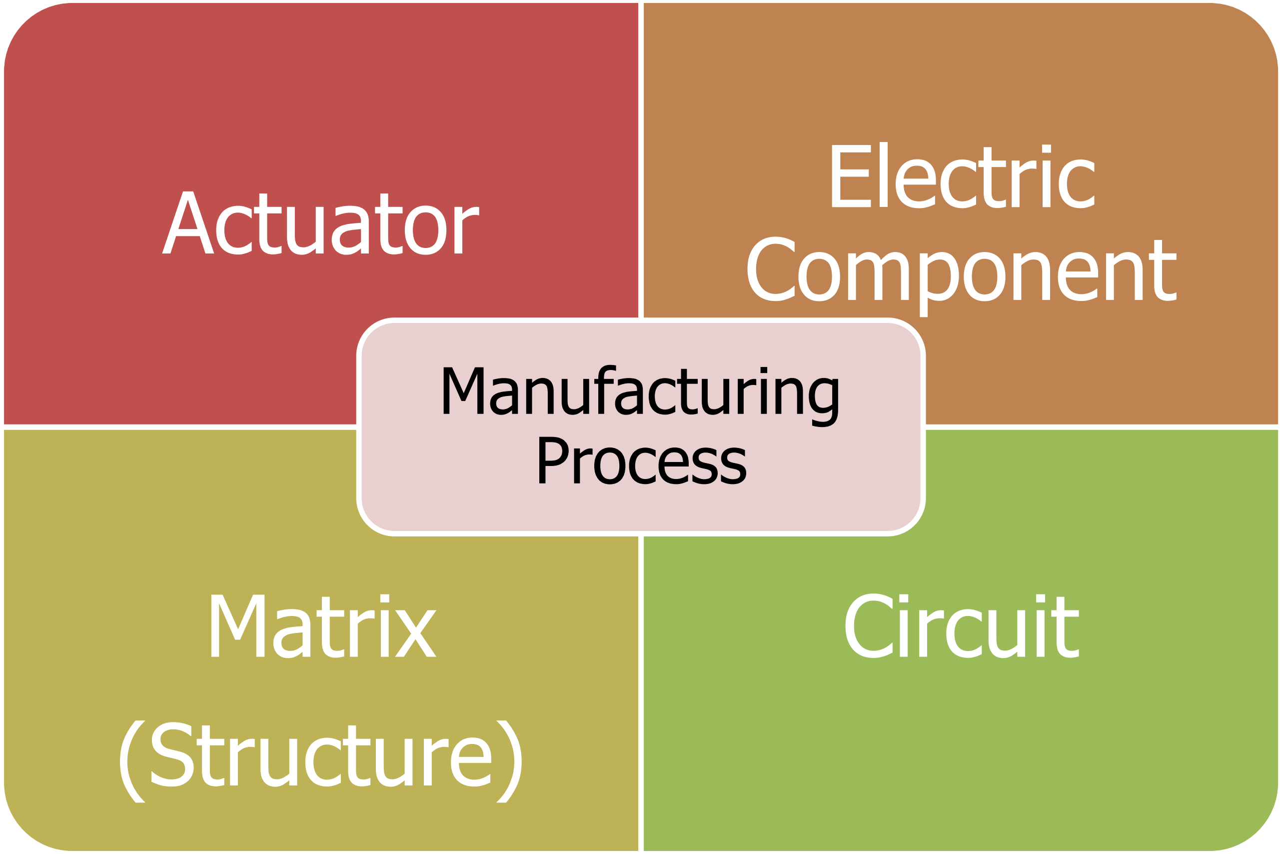
Multi-scale	Mass-deployable	Cooperative
		

Multi-scale Mass-deployable Cooperative Robots

x2

The stability of the RHyMo on a rough terrain

MANUFACTURING PROCESSES

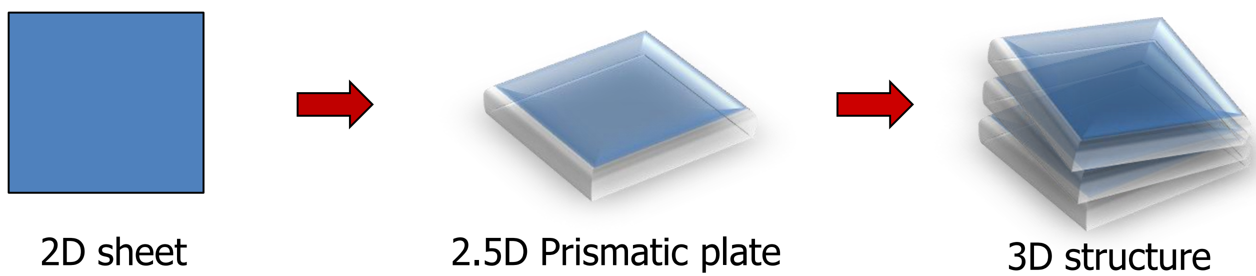


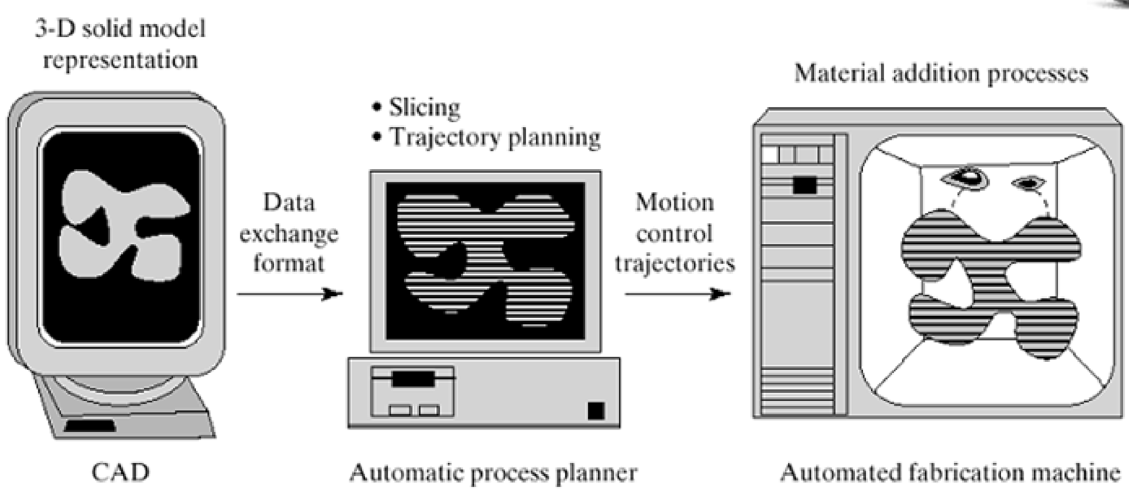
Manufacturing processes of smart structures

- **Fabrication methods**
  - Composite laminates
  - Rapid Prototyping
  - Training and characterization of shape memory alloy
  - Nano Composite Deposition System
  - Nano Particle Deposition System

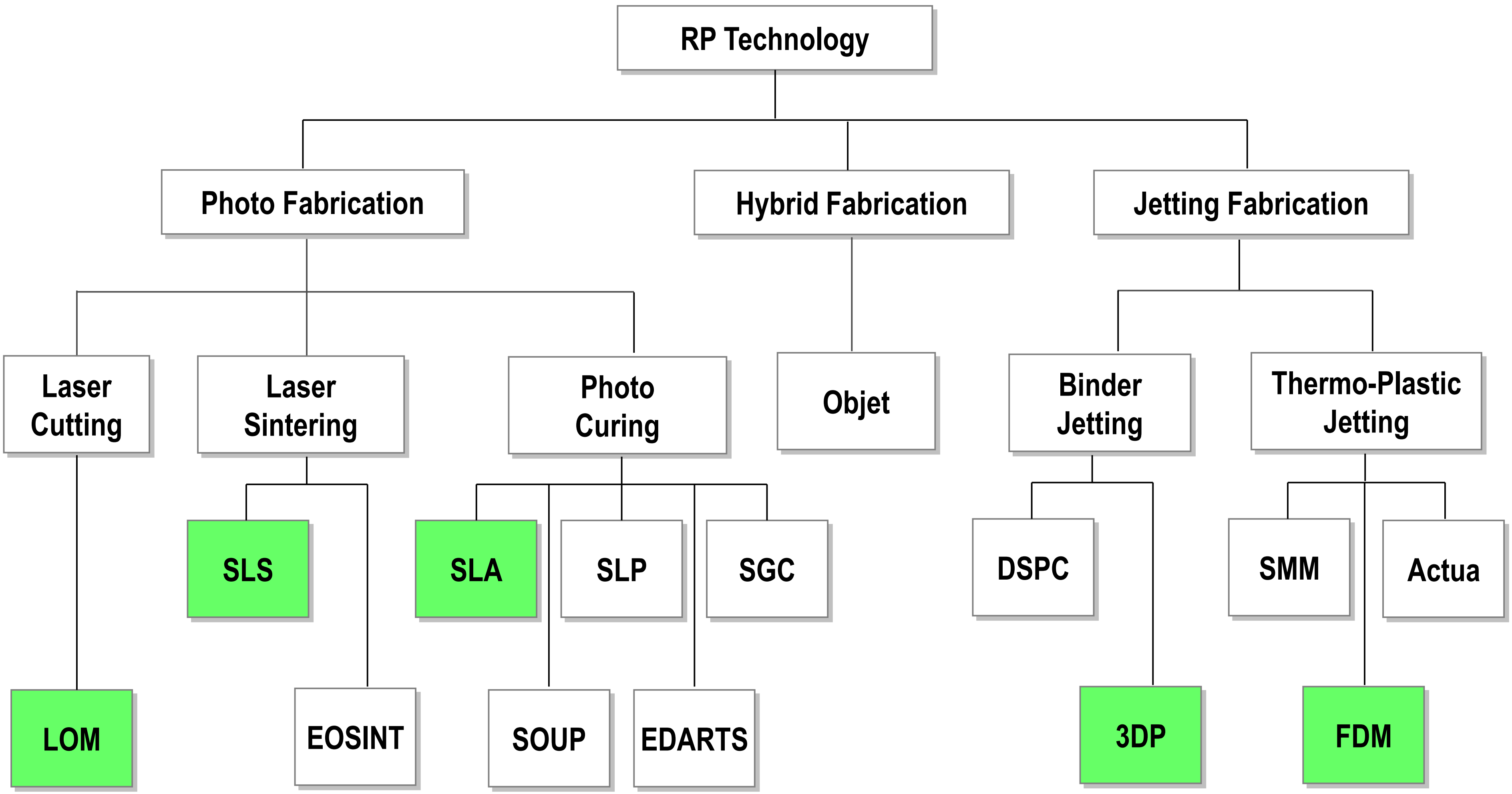
- **Fabrication systems**
  - Nano Composite Deposition System (NCDS)
    - Rapidly fabricate the parts with composite (nano compoiste) materials
    - Applications: DDS, medical devices, functional parts, etc.
  - Nano Particle Deposition System (NPDS)
    - Metal and ceramic particle deposition at room temperature
    - Applications: functional film coating, conductive line deposition, etc.

3D printing (3DP)





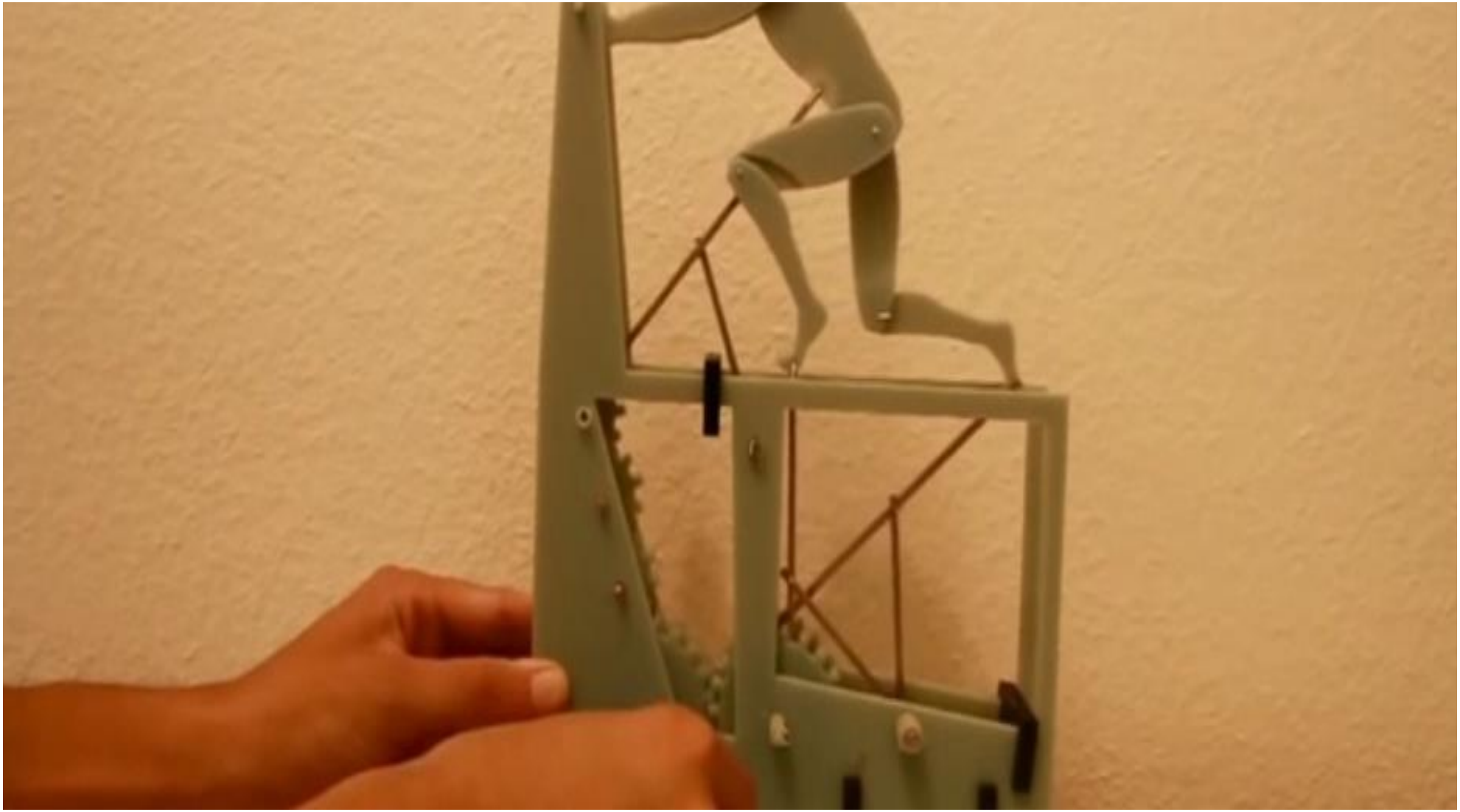
Classification of 3DP Technologies



Applications of 3D printing

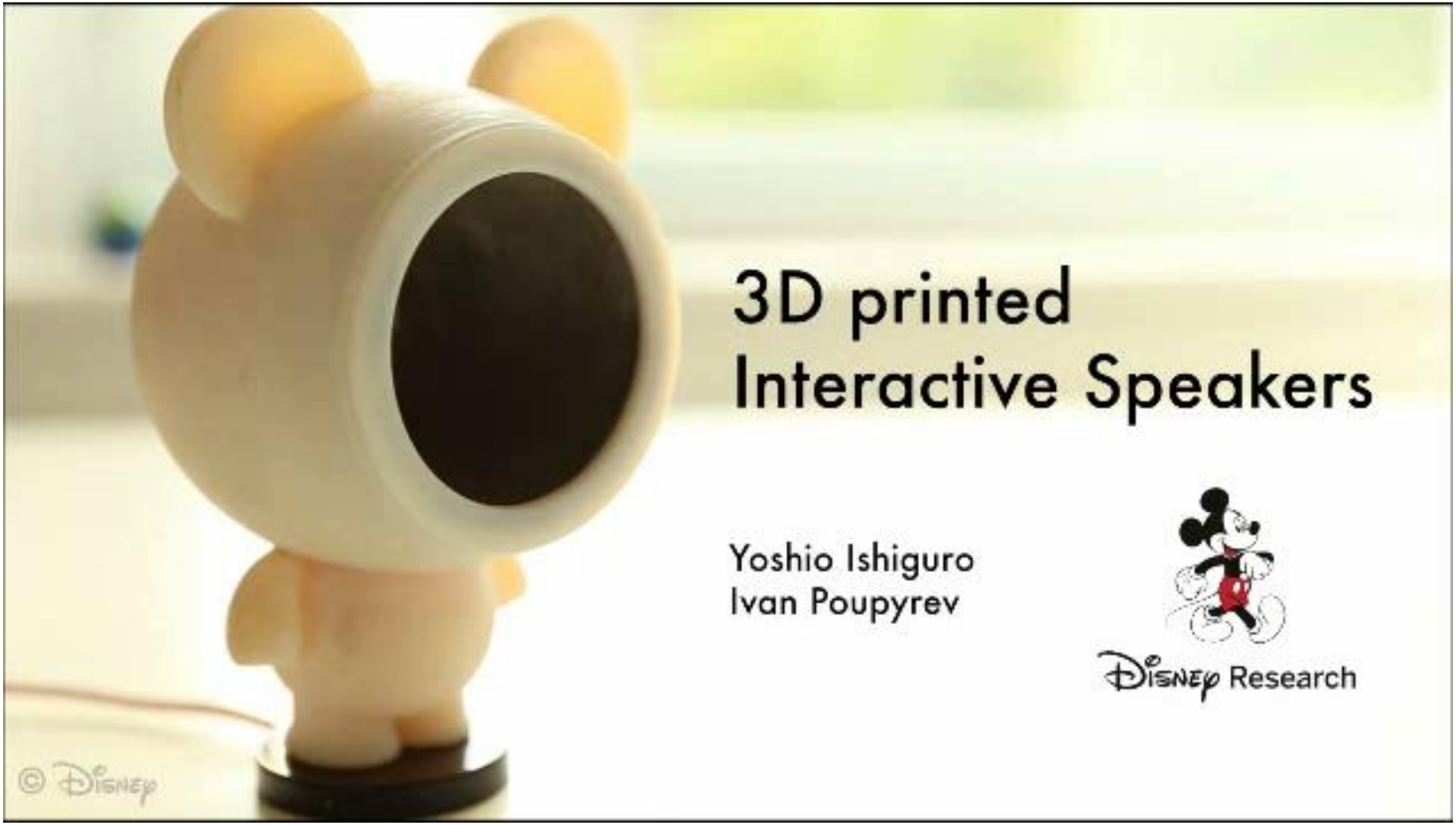
https://www.youtube.com/watch?v=0wWG_3MeyHk

3D printing robot



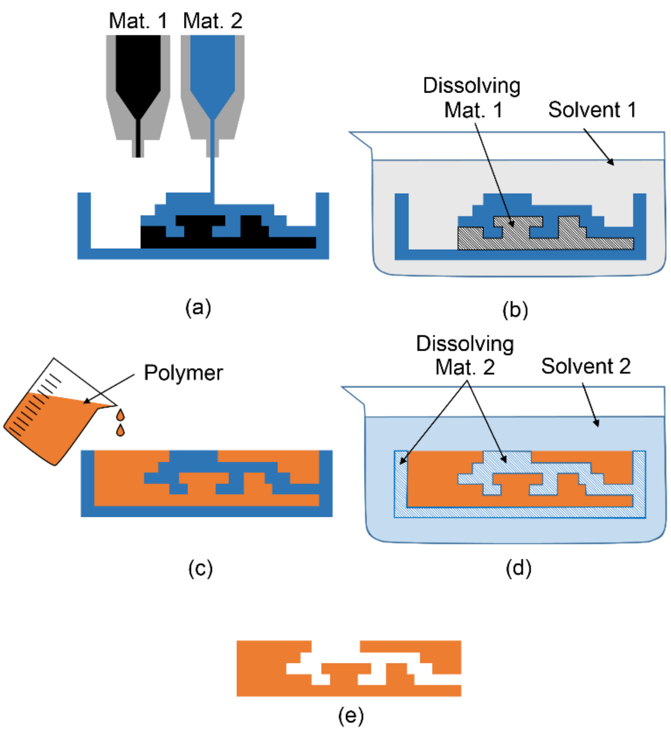
https://www.youtube.com/watch?v=DfznnKUwywQ

3D printing speaker

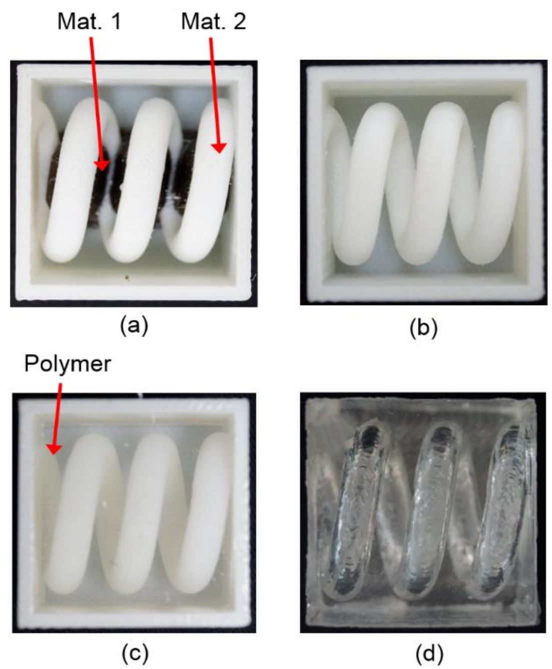


3D Soft Lithography

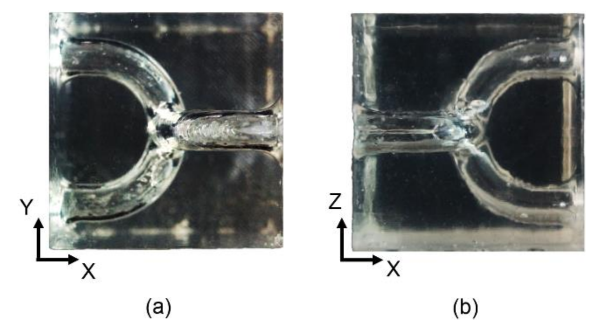
- **Manufacturing of thermocurable polymers with 3D external and internal features.**
  - Combine additive manufacturing processes with solvents to dissolve the mold's support and the mold.



Process



Using FDM and PDMS

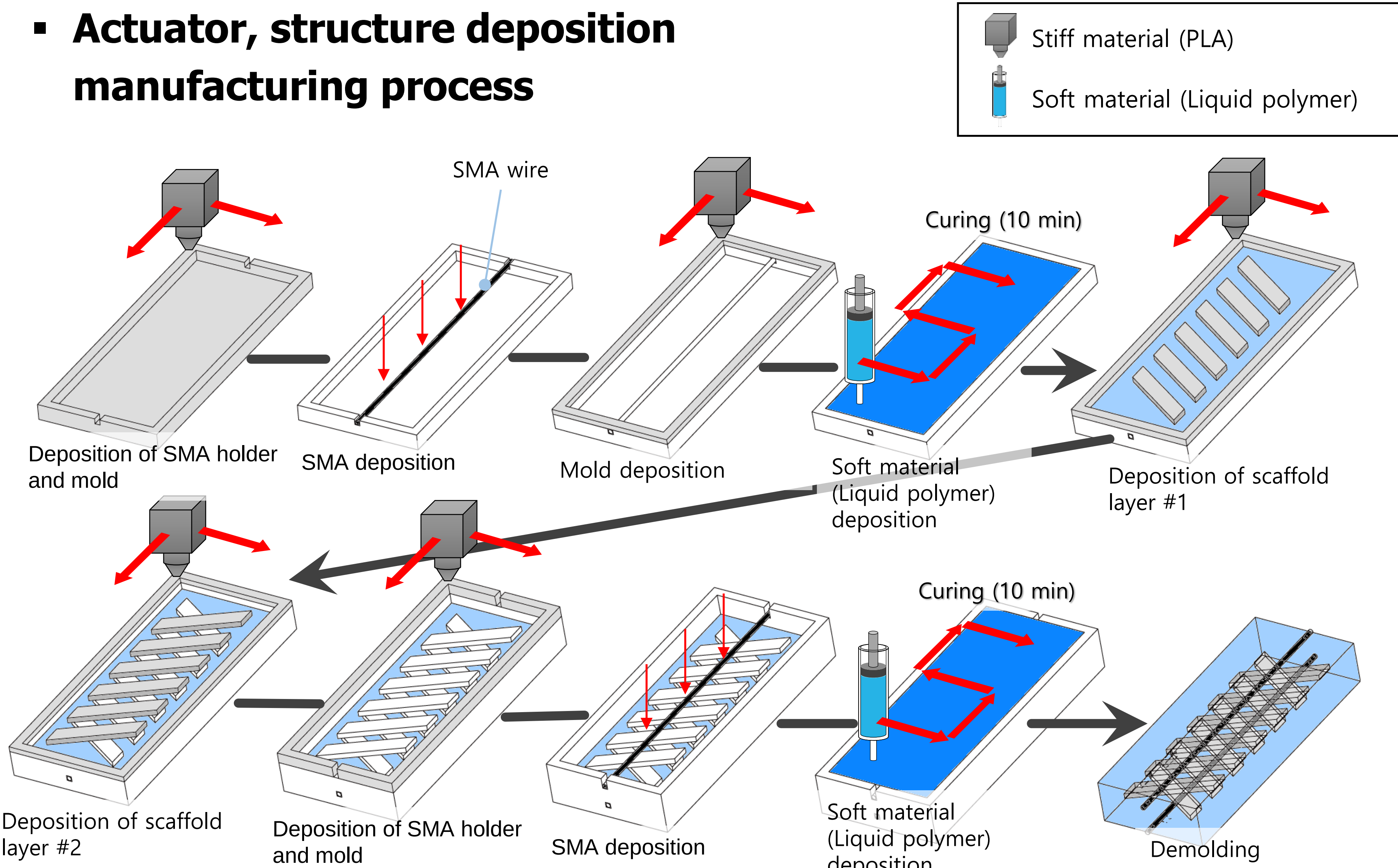


Sample parts

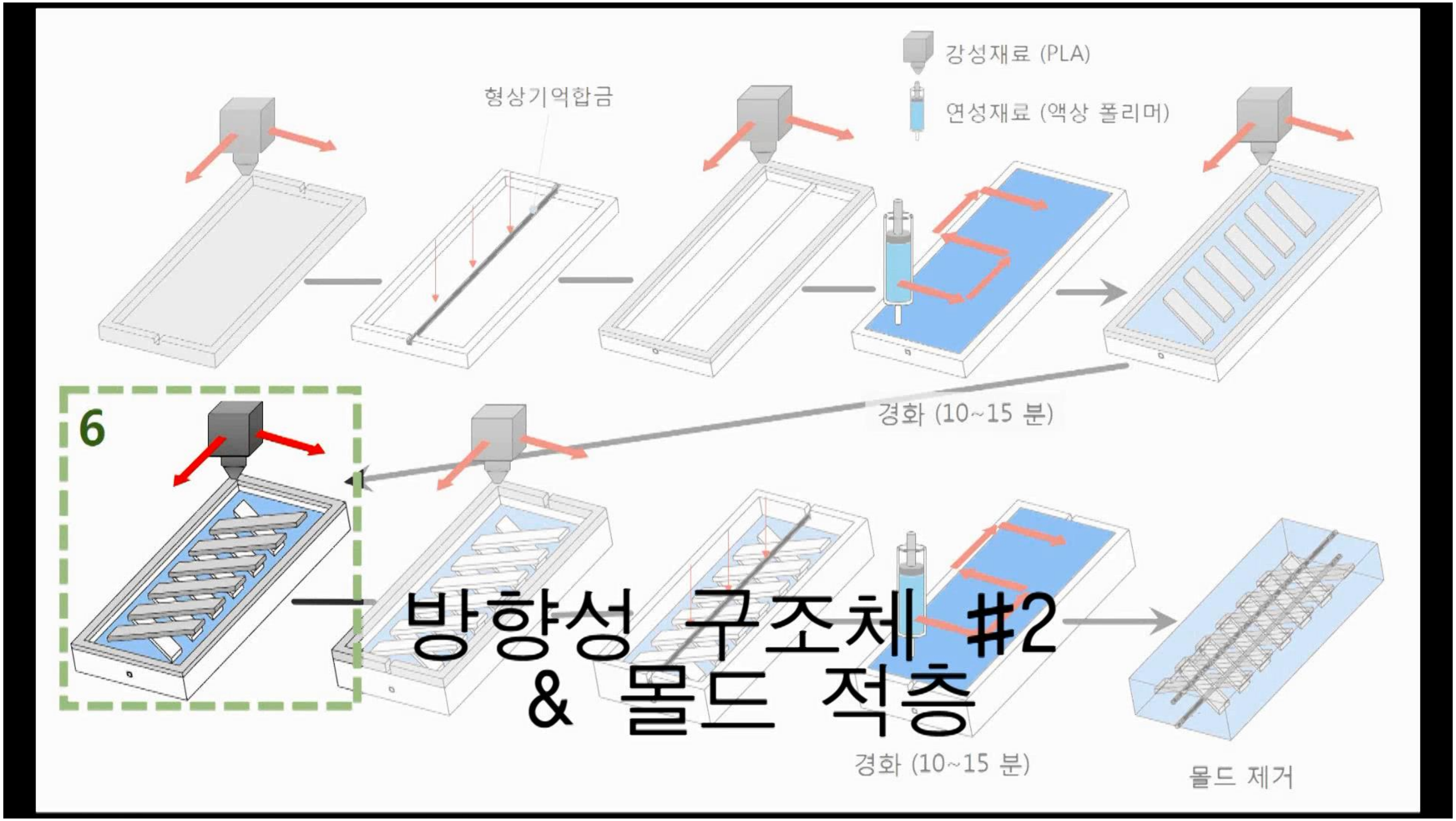
Rodrigue H. *et al.*, 3D Soft Lithography: A Fabrication Process for Thermocurable Polymers, CJournal of Materials Processing Technology (2015)

Actuator deposition manufacturing process

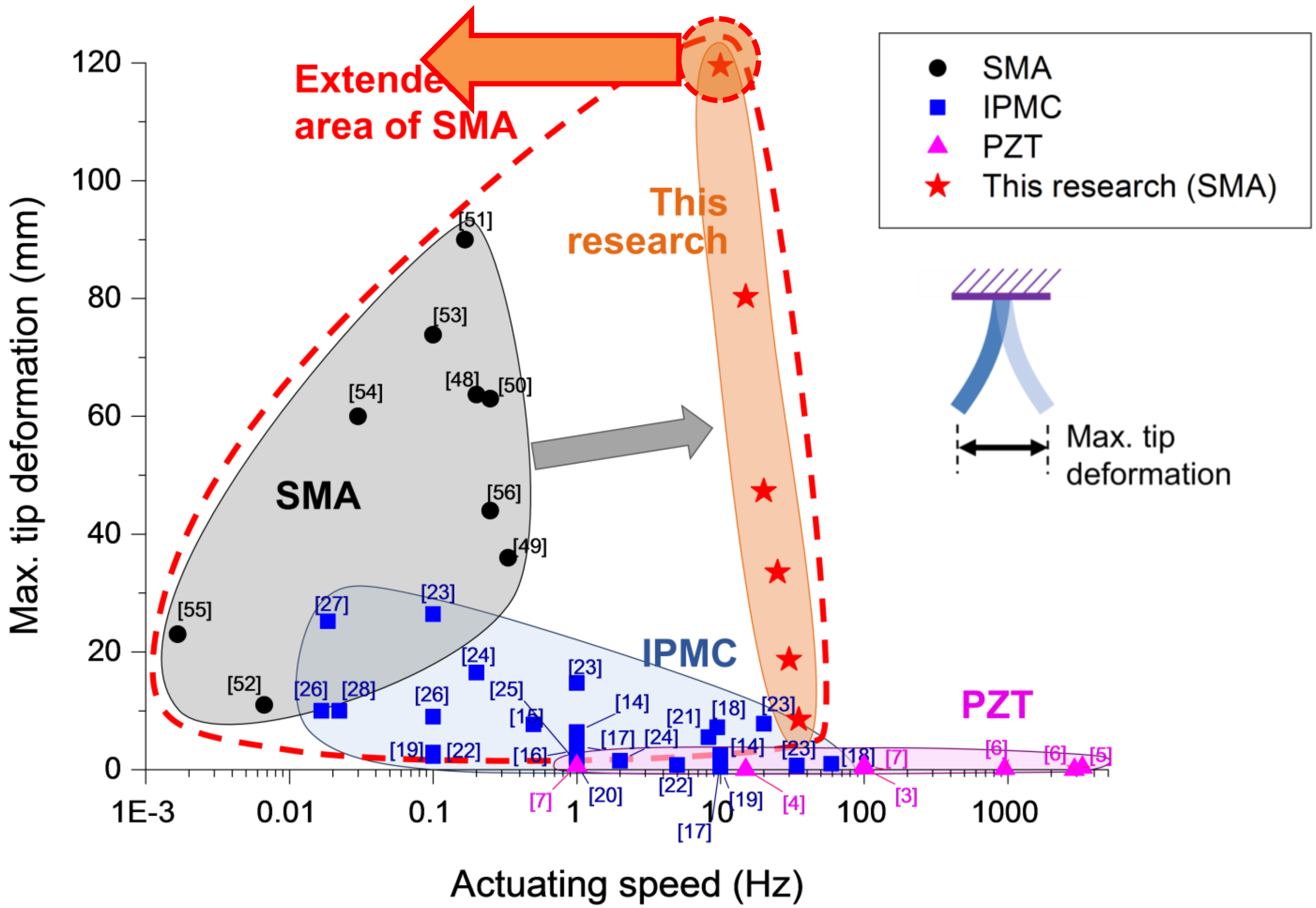
- **Actuator, structure deposition manufacturing process**



Actuator deposition manufacturing process



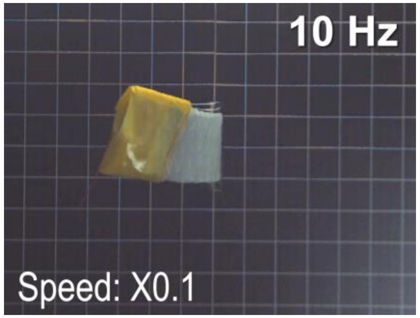
Position of high-speed actuator

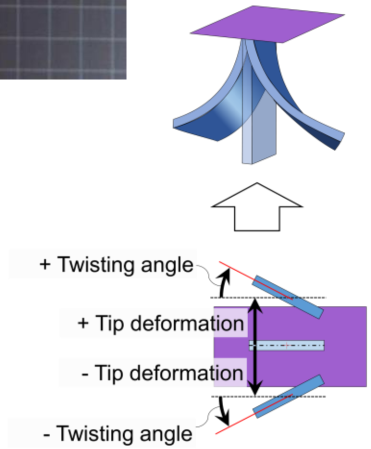


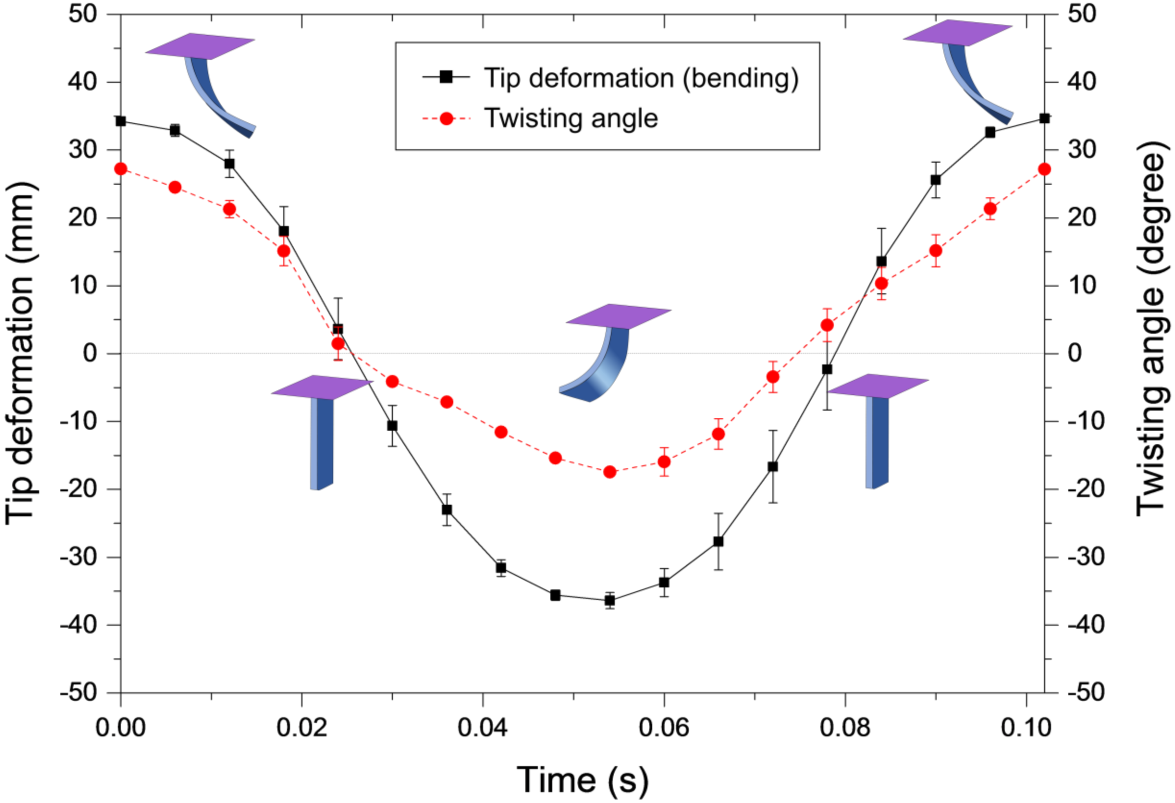
Comparison of the performance of the actuators from this research with PZT, IPMC and previous SMA-based bending actuators.

Bend-twist coupled mode design

- **Bend-twist coupled mode in 10 Hz actuating speed**
  - By using angle-ply scaffold ([30/45/30]), high speed bend-twist coupled mode can be produced.
  - In different scaffold ply combination, other motions also can be realized.



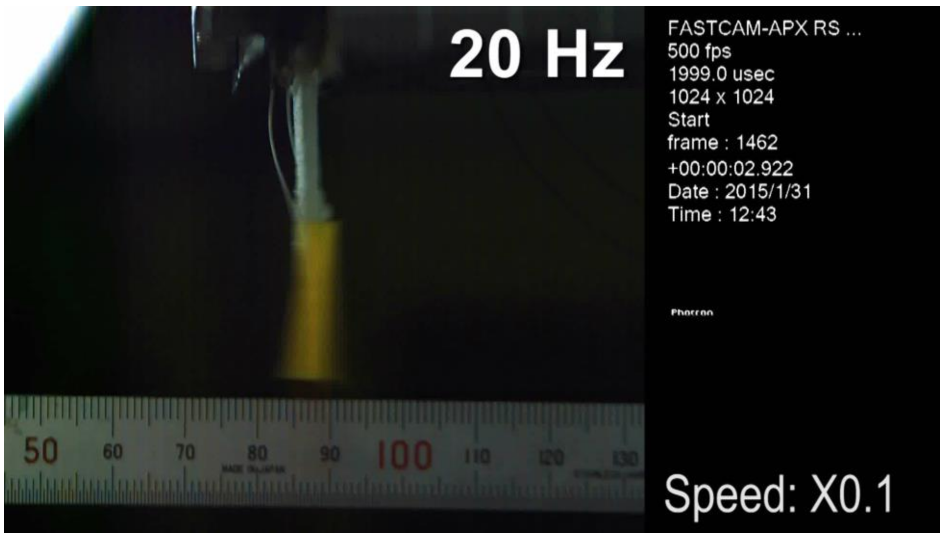


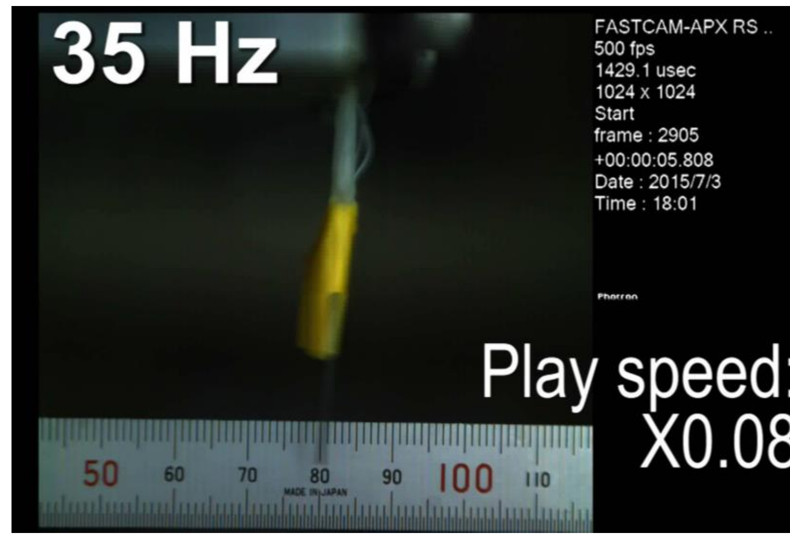


Bending-twisting coupled mode using the [30/45/30] scaffold

High speed actuator

- **Performance of high speed actuator**
  - 20, 35 Hz



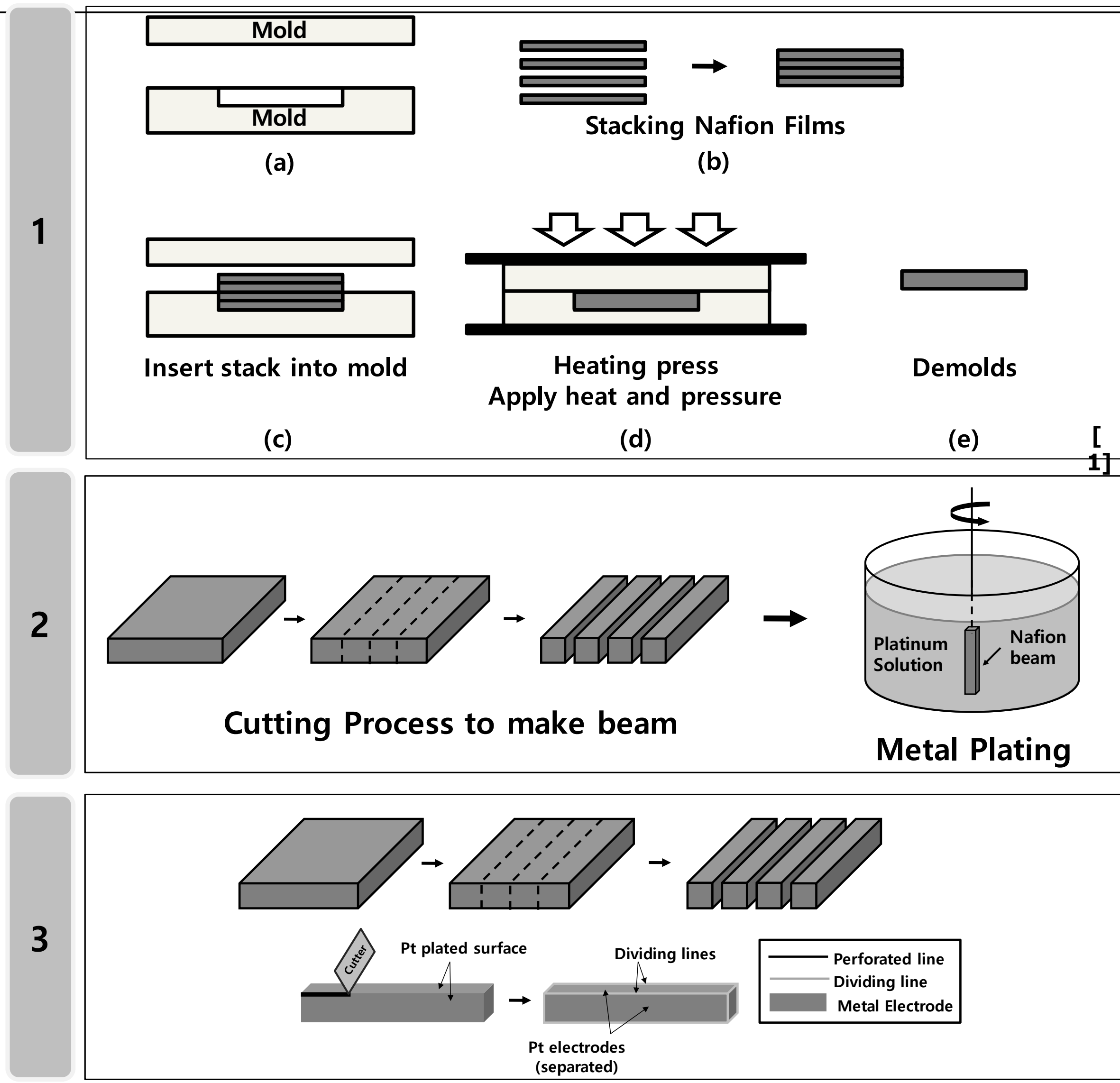


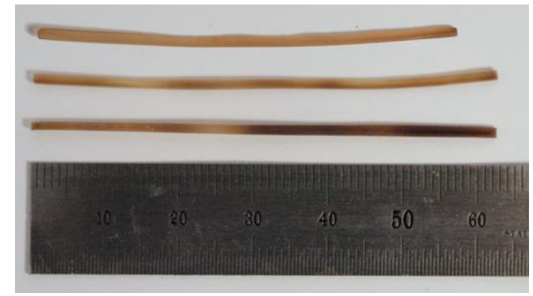
Flapping motion of high speed actuator at 20 and 35 Hz

Song S H, *et al*. *Scientific reports*, 2016, 6.

DESIGN AND FABRICATION EXAMPLE 1 : SOFT MORPHING ACTUATOR USING IPMC

Manufacturing process





(a)

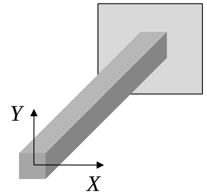
(b)

(a) Stacked and cut Nafion samples and (b) fabricated IPMC actuator sample

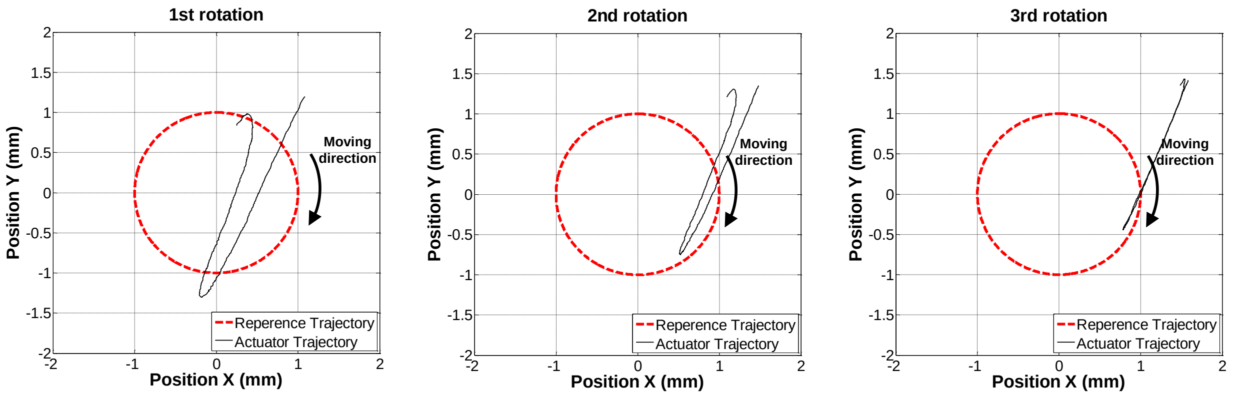
[1] A new fabrication method for IPMC actuator and application to artificial fingers, Smart Materials and Structures,Sang Jun Lee, Man Jae Han, Seong Jun Kim, Jae Young Jho, Ho Young Lee and Yong Hyup Kim, Smart Mater. Struct. 15 (2006) 1217-1224

Circular motion tracking

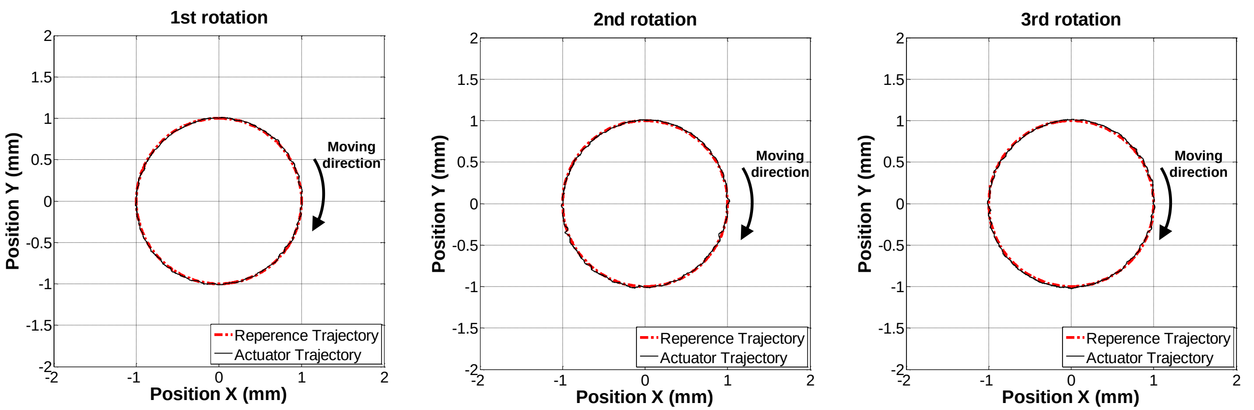
- **Comparison between open-loop/closed loop system**



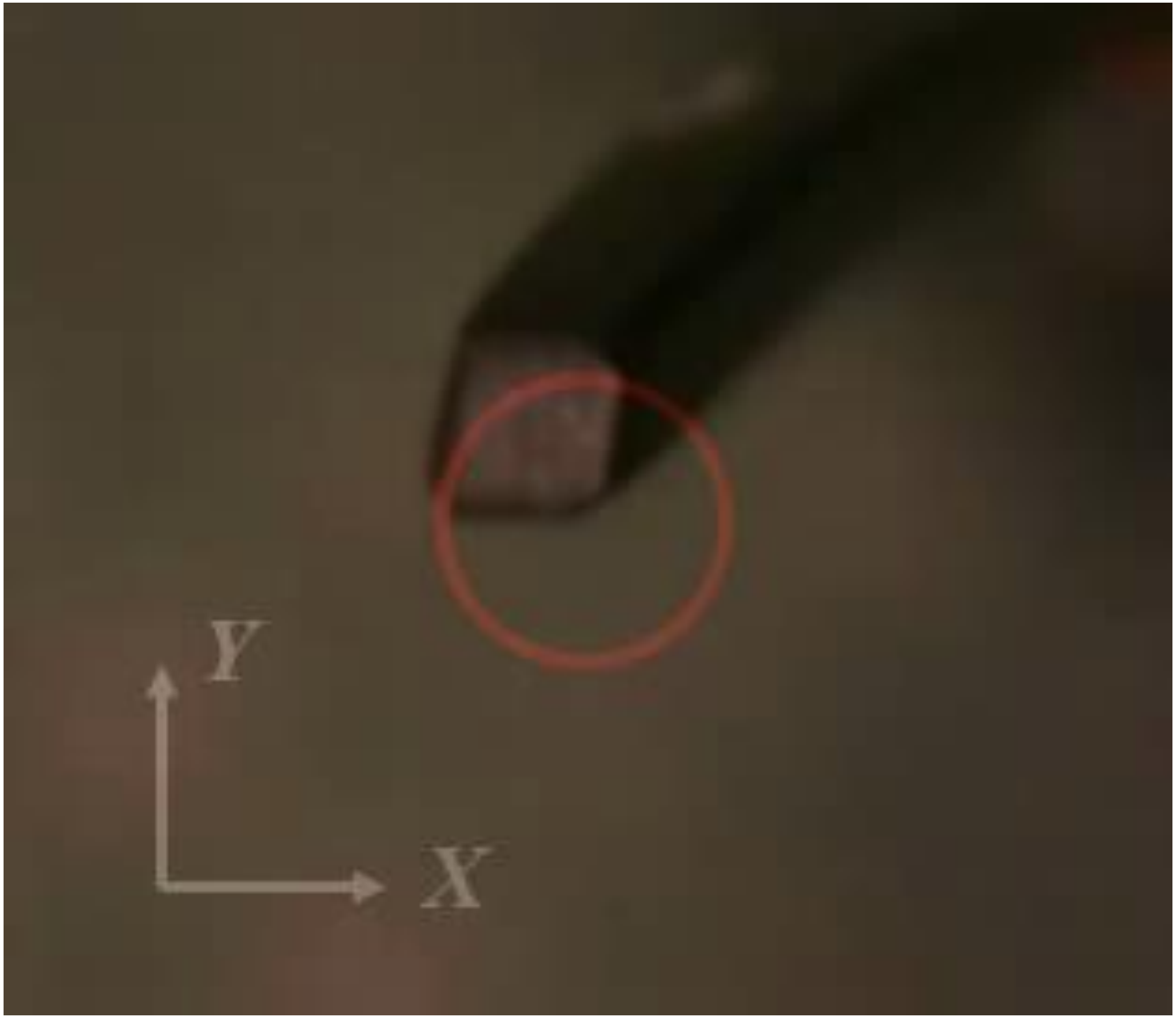
Open loop system



Closed loop system

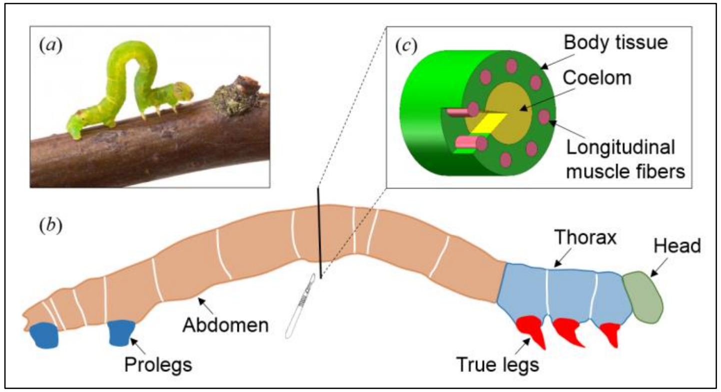


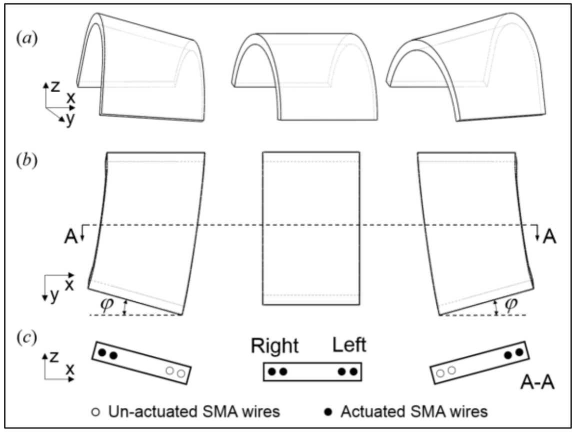
Circular motion tracking



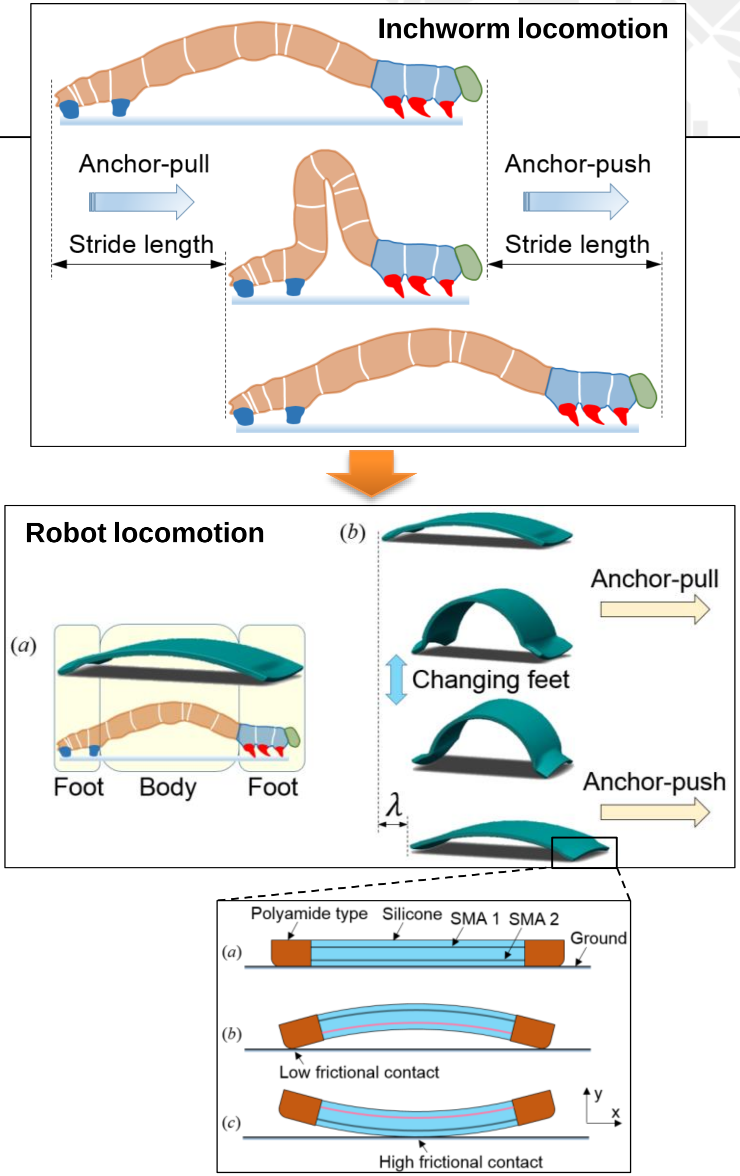
DESIGN AND FABRICATION EXAMPLE 2
: BIOMIMETIC INCHWORM ROBOT

Inchworm robot design





Design of inchworm robot

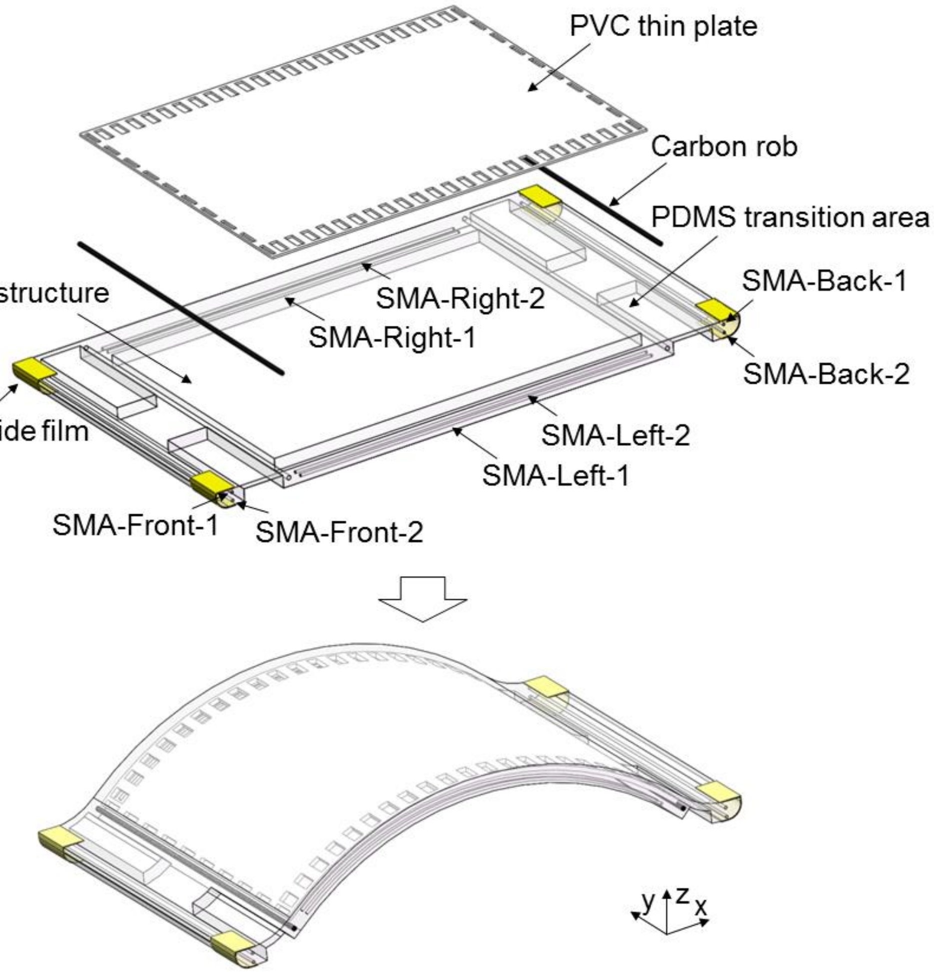


Locomotion mechanism of inchworm robot

W. Wang *et al.*, *Bioinspiration & Biomimetics*, 2014

Inchworm robot fabrication

- **Robot structure**



Overall robot structure and its components

Table 1. Parameters of robot structure.

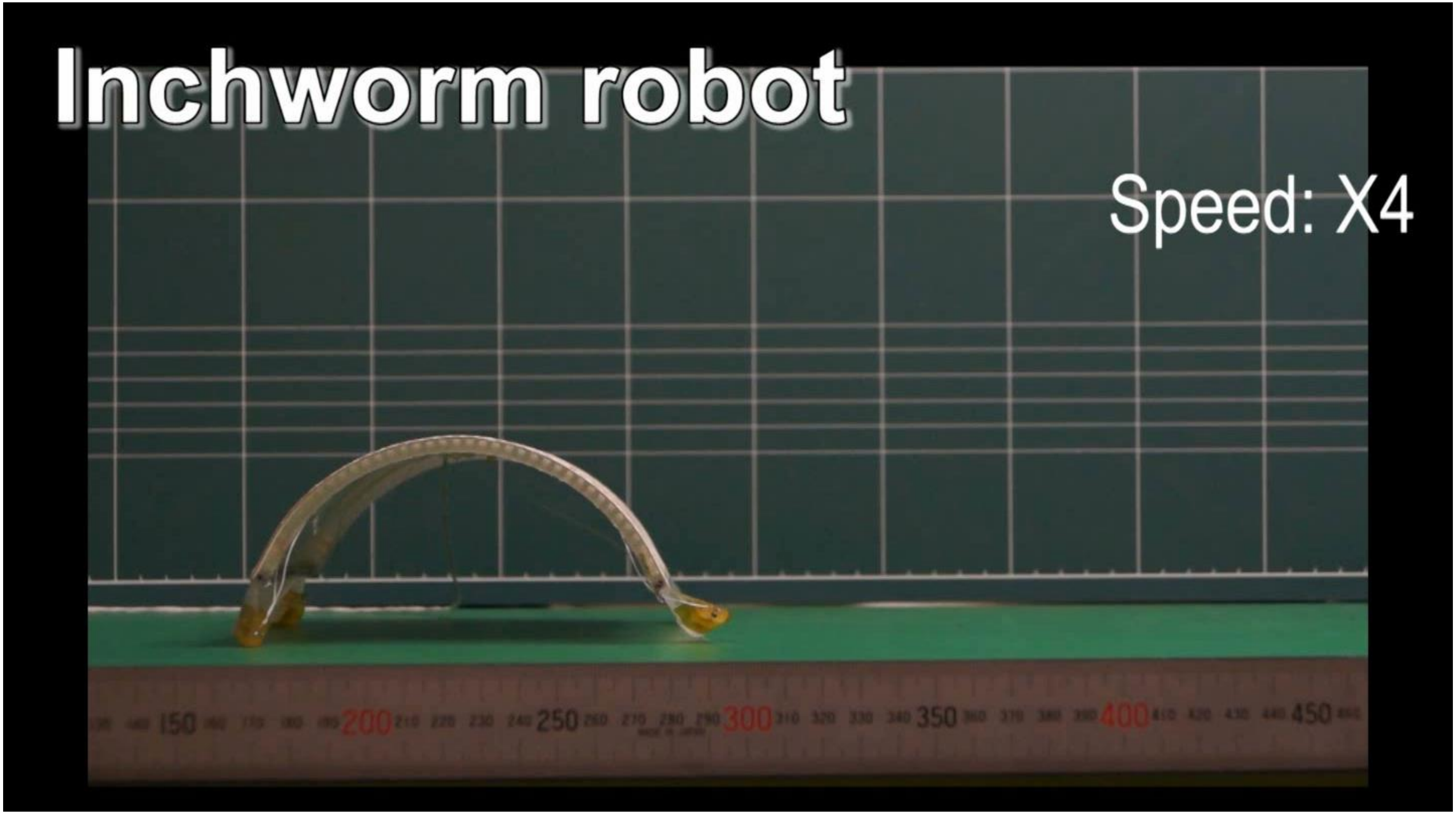
Robot parameter	Value
Robot structure dimension (mm)	196 L × 140 W × 4 T
Body structure dimension (mm)	158 L × 140 W × 4 T
Feet structure dimension (mm)	140 L × 8 W × 4 T
Robot structure weight (g)	63.0

L, W, and T: length, width, and thickness.

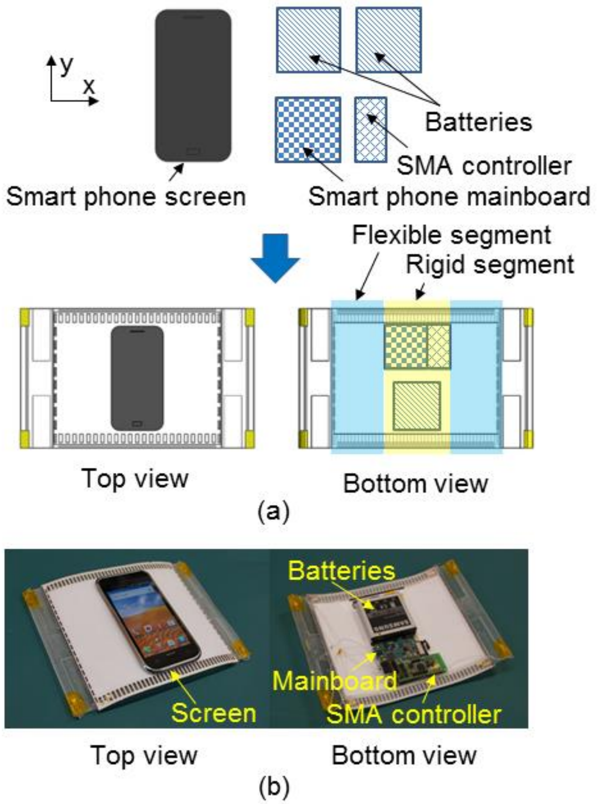
SMA: Shape memory alloy
PDMS: Polydimethylsiloxane
PVC: Polyvinyl chloride polymer

W. Wang *et al.*, *Bioinspiration & Biomimetics*, 2014

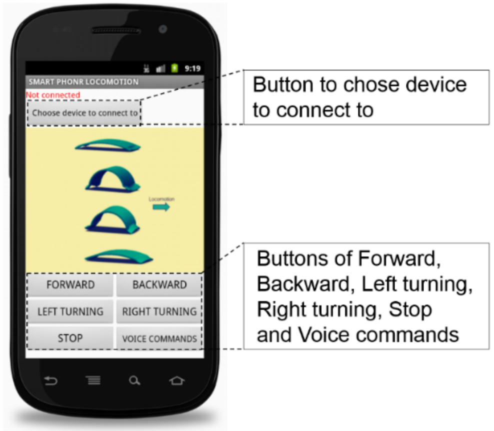
Locomotion of inchworm robot



Crawling cellphone robot



(a) All components and CAD model of integrated smart phone robot.
(b) Fabricated smart phone robot.



Interface of phone app for smart phone robot locomotion.

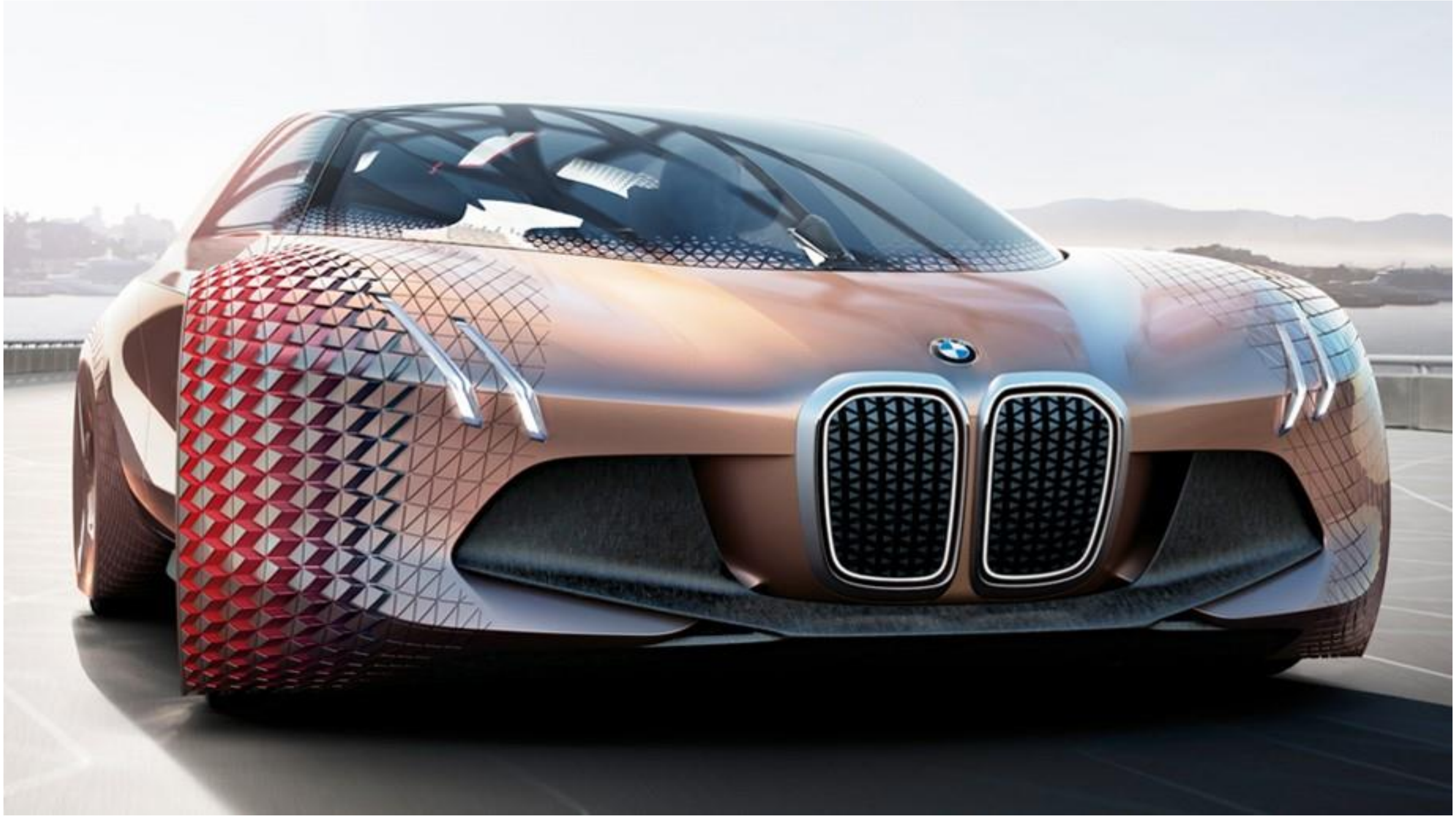
W. Wang *et al.*, "Smart Phone Robot made of Smart Soft Composite (SSC)," Composites Research, 2015.

Crawling cellphone robot

DESIGN AND FABRICATION EXAMPLE 3
: SOFT MORPHING SPOILER

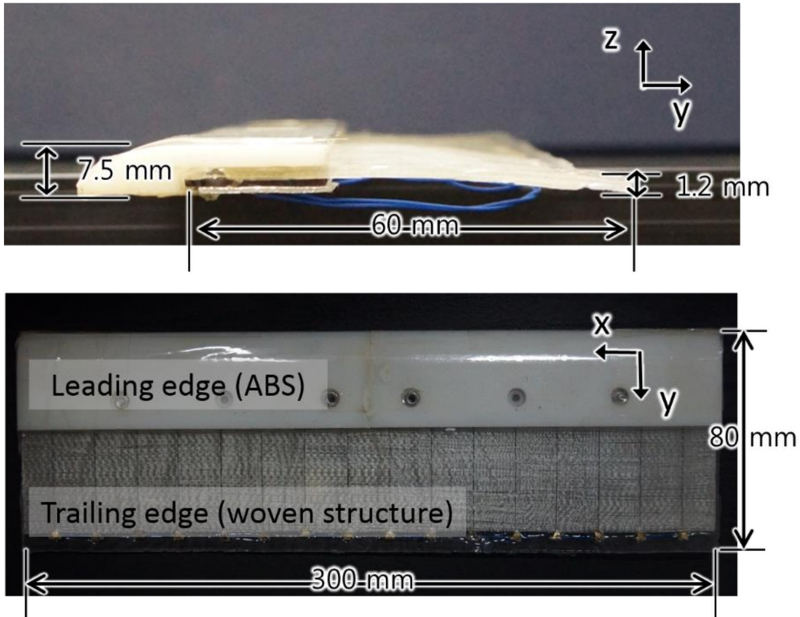
Shape-Morphing Cars

BMW Predicts Shape-Morphing Cars With AI Companions

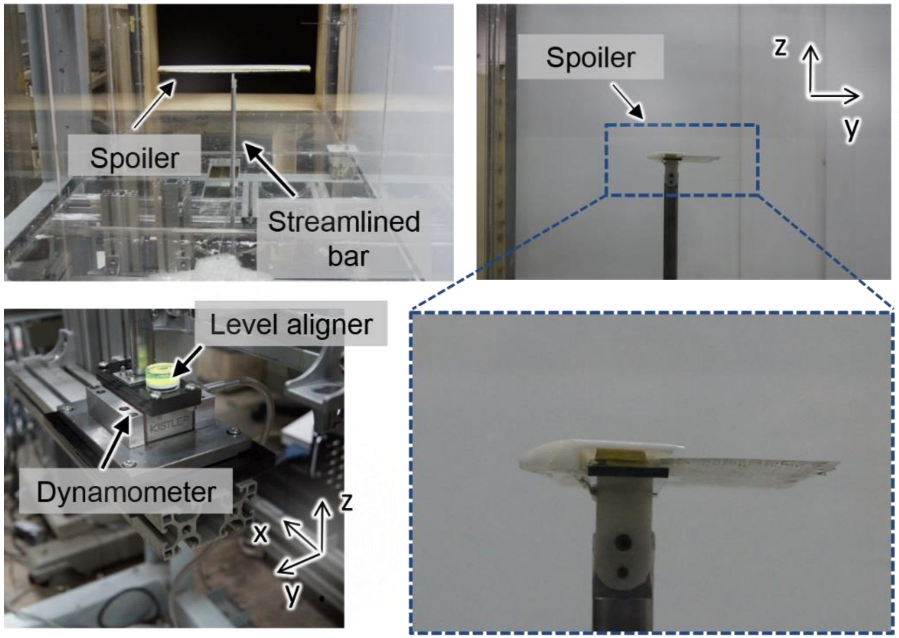


http://www.psfk.com/2016/03/bmw-predicts-shape-morphing-cars-in-the-future.html
https://www.youtube.com/watch?v=ztfVoGqW5VU&nohtml5=False

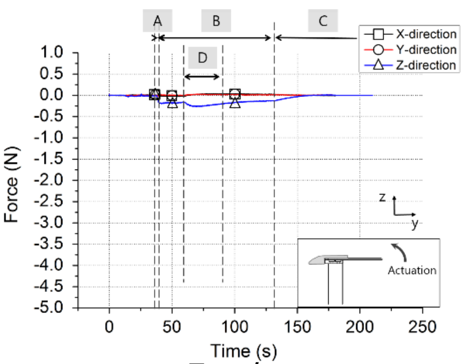
Soft morphing spoiler design



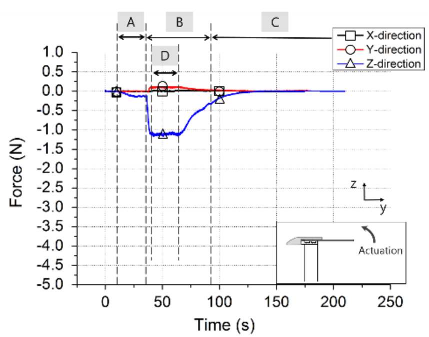
Soft morphing spoiler



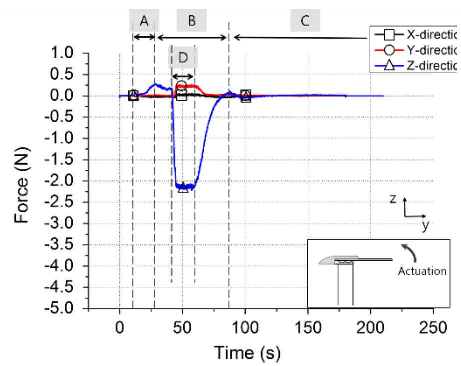
Wind tunnel test of soft morphing spoiler



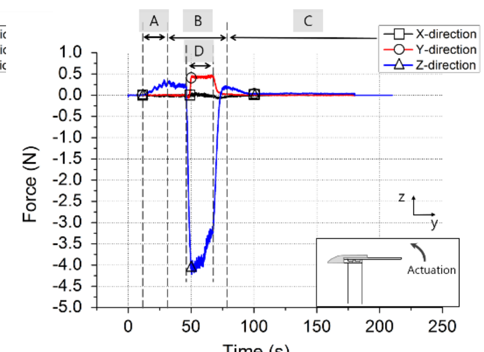
5 m/s



10 m/s



15 m/s



23 m/s

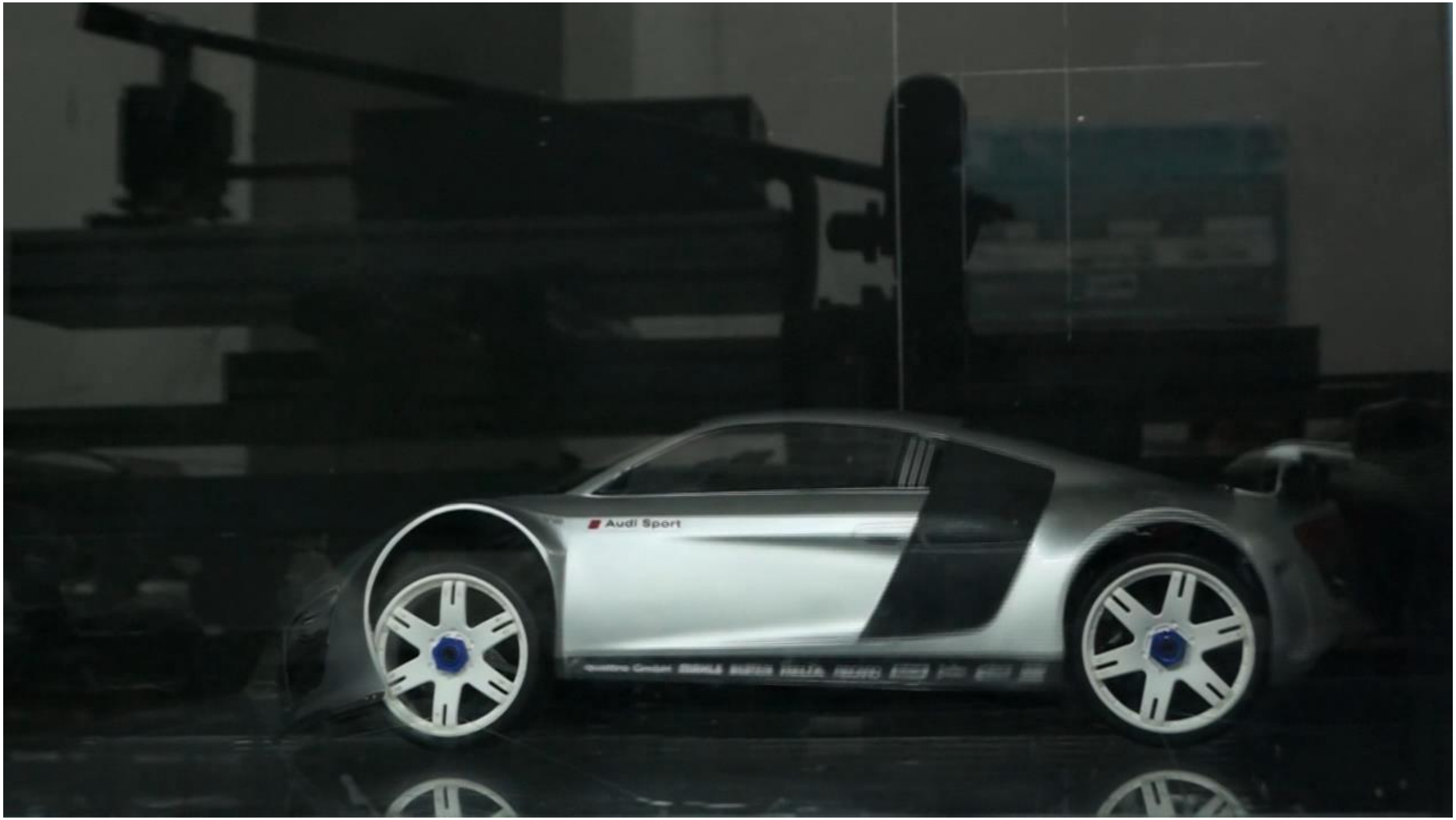
Wind tunnel test result

Han M W, et al. Woven type smart soft composite for soft morphing car spoiler. Composites Part B: Engineering, 2016, 86: 285-298.

Soft morphing spoiler

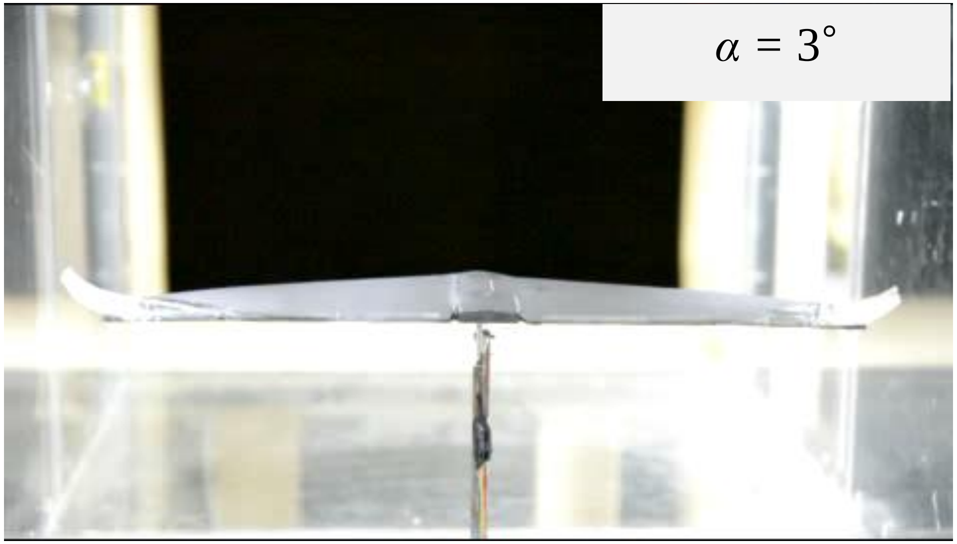
Han M W, et al. Woven type smart soft composite for soft morphing car spoiler. Composites Part B: Engineering, 2016, 86: 285-298.

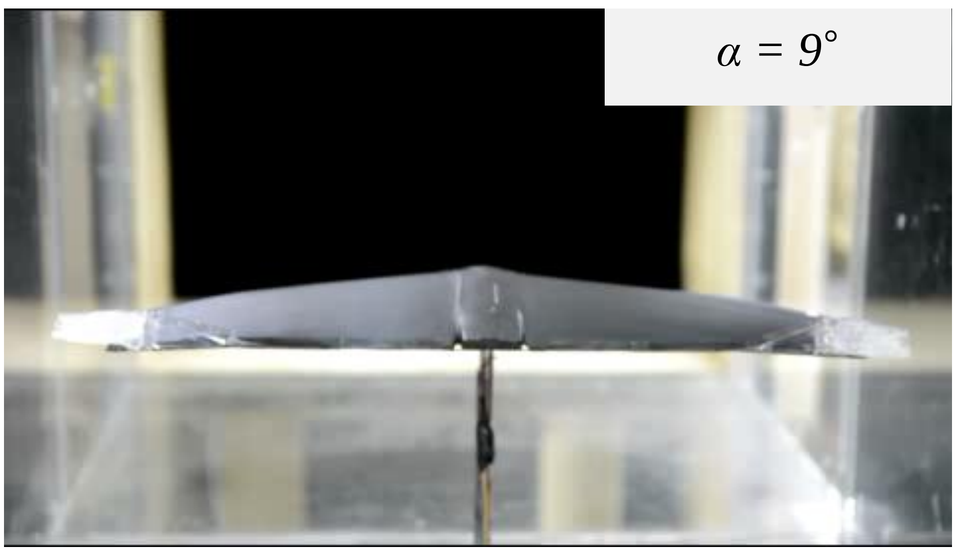
Soft morphing spoiler

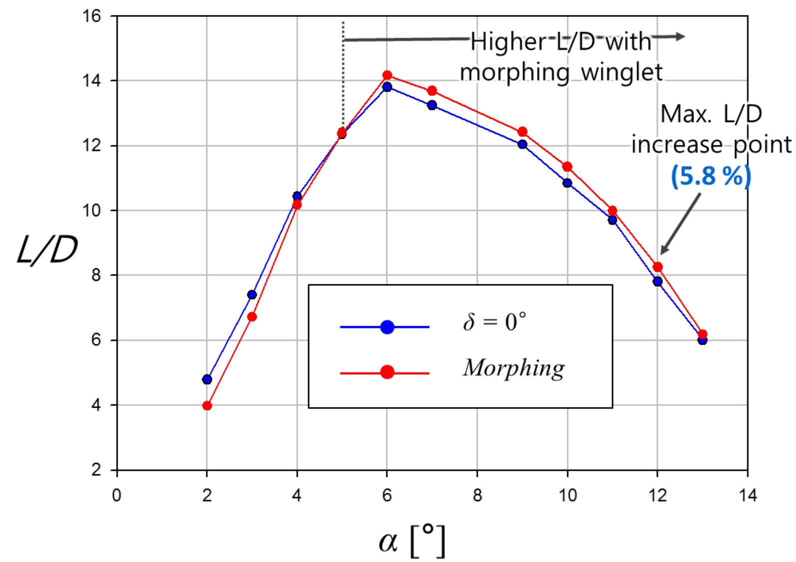


Han M W, et al. Woven type smart soft composite for soft morphing car spoiler. Composites Part B: Engineering, 2016, 86: 285-298.

Soft morphing winglet design





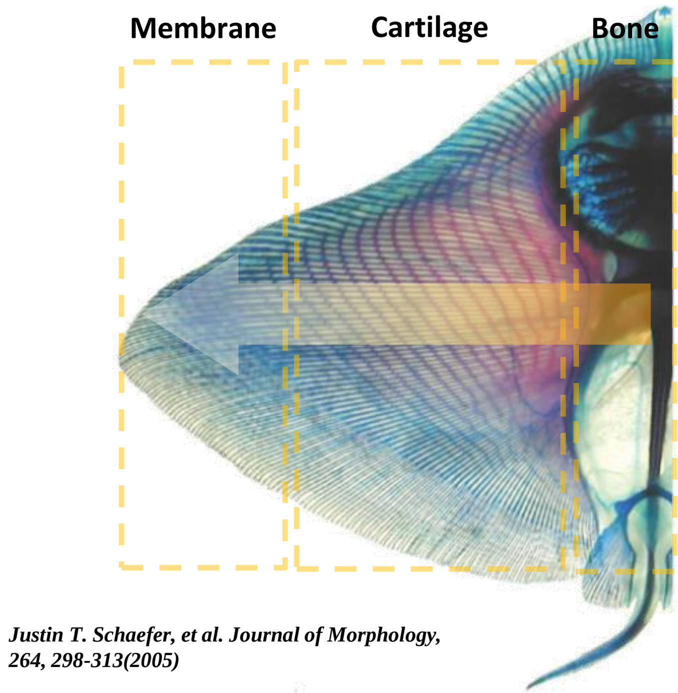


Wind tunnel test of morphing winglet ($Re = 9 \times 10^4$, $U_\infty = 15$ m/s)

DESIGN AND FABRICATION EXAMPLE 4
: BIOMIMETIC RAY ROBOT

Locomotion of Ray

- **Swimming method of rays**
  - Thrust via pectoral fins' movement
  - Stiffness variation in the skeleton structure of ray

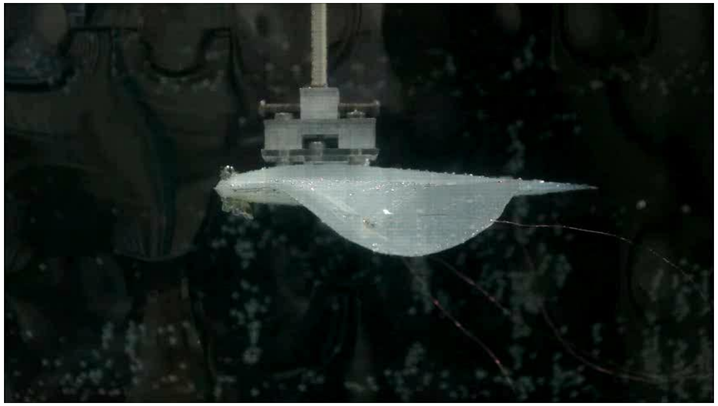


Skeleton structure of Ray (Gymnura micrura)

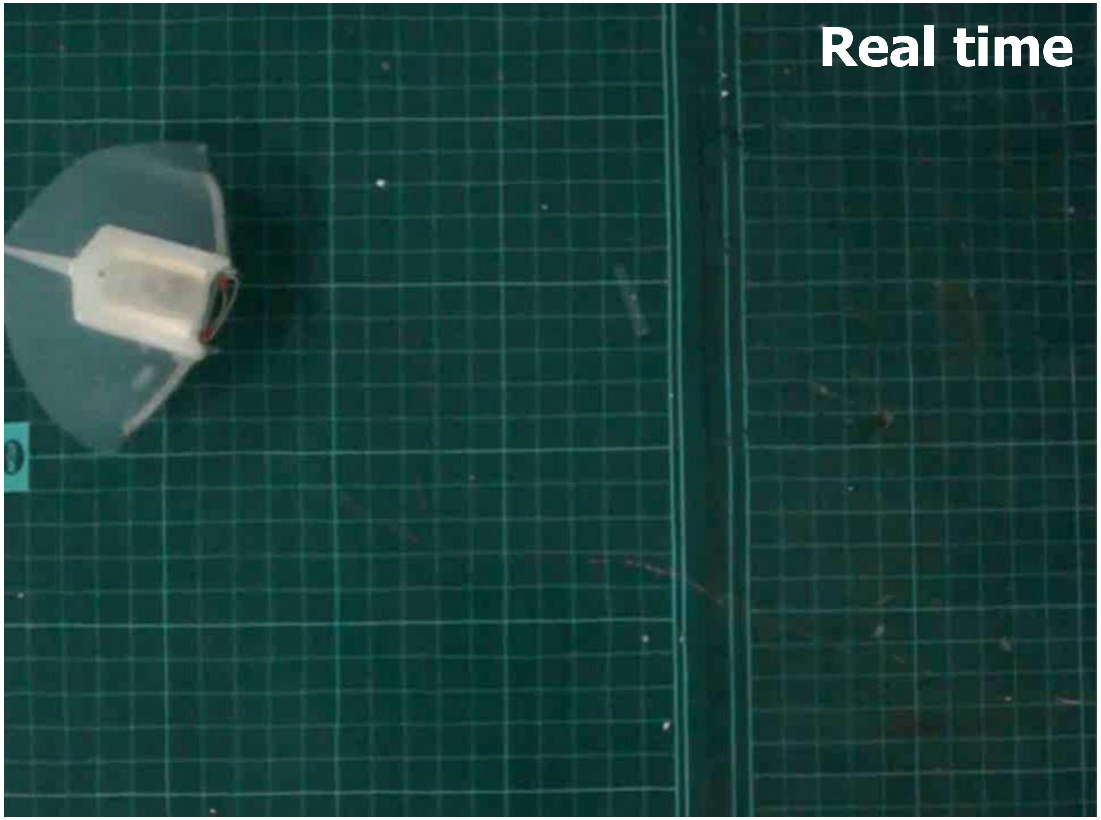
Undulating Locomotion of Ray

Evaluation of prototype

- **Ray robot locomotion**
  - Ray robot fabrication using anisotropic material
  - Undulating motion of the ray was realized at robot



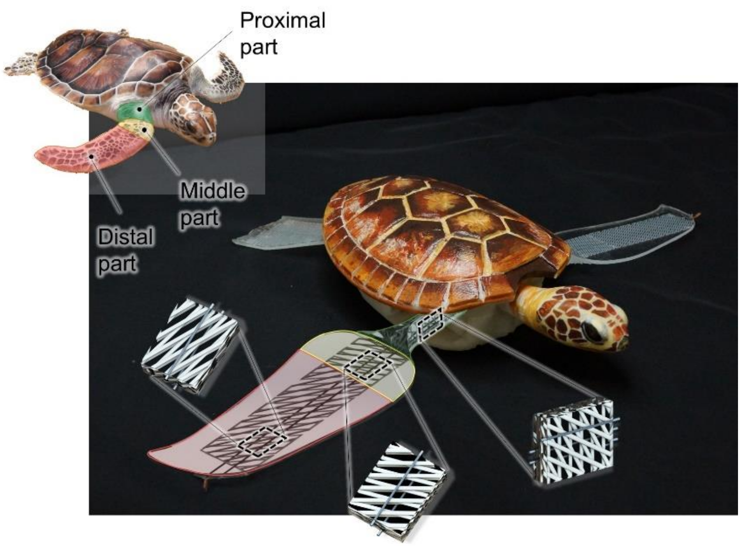
Fabricated ray robot and undulating motion of robot



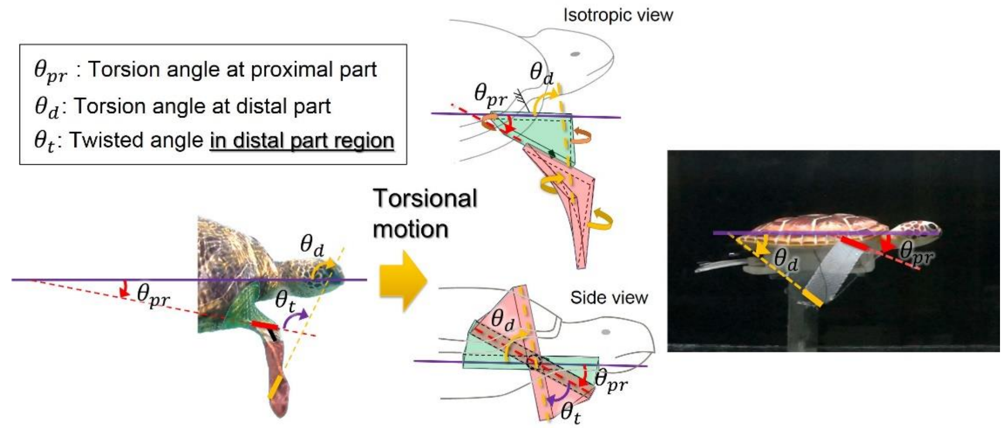
Locomotion of biomimetic ray robot

DESIGN AND FABRICATION EXAMPLE 5
: BIOMIMETIC TURTLE ROBOT

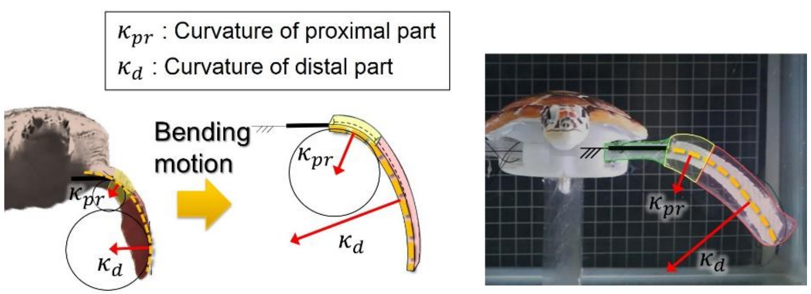
Turtle robot design



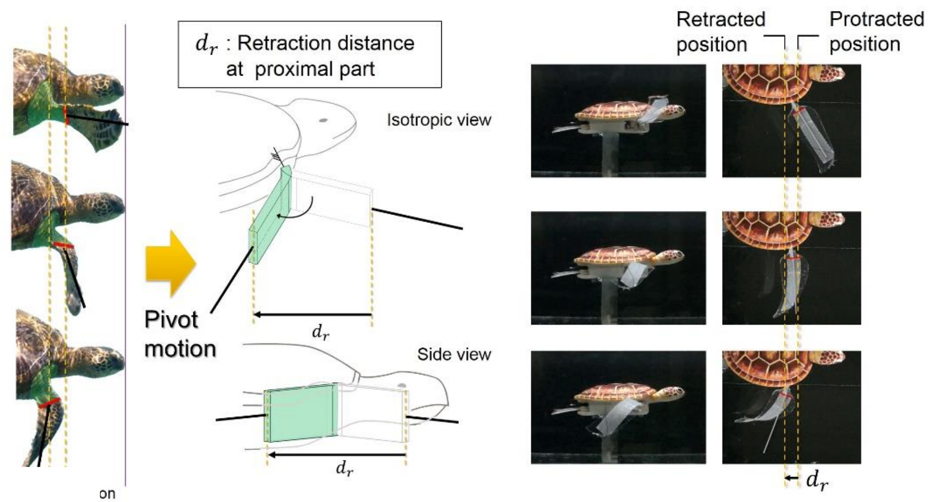
Soft morphing turtle robot



Side view of turtle motion and robot locomotion



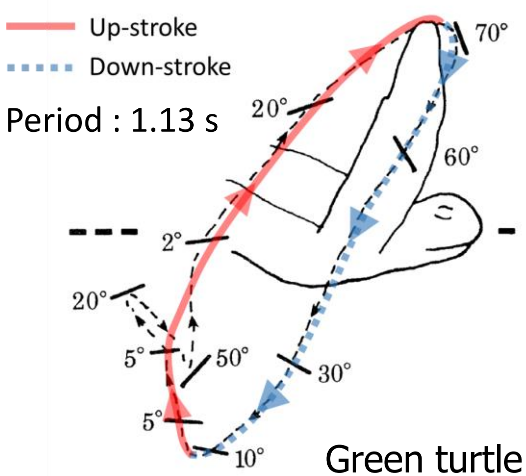
Front view of turtle motion and robot locomotion



Side view of turtle motion and robot locomotion

Song, S.H., et al., **Turtle mimetic soft robot with two swimming gait**," *Bioinspiration & Biomimetic*, 2016

Flipper motion of turtle robot



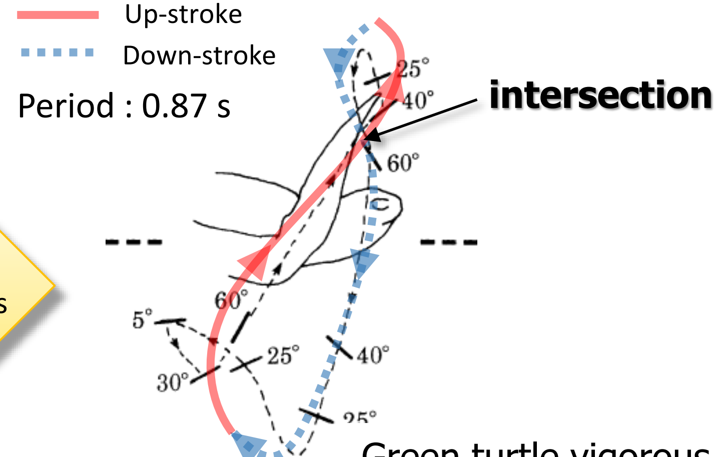
Green turtle routine mode

Period ratio

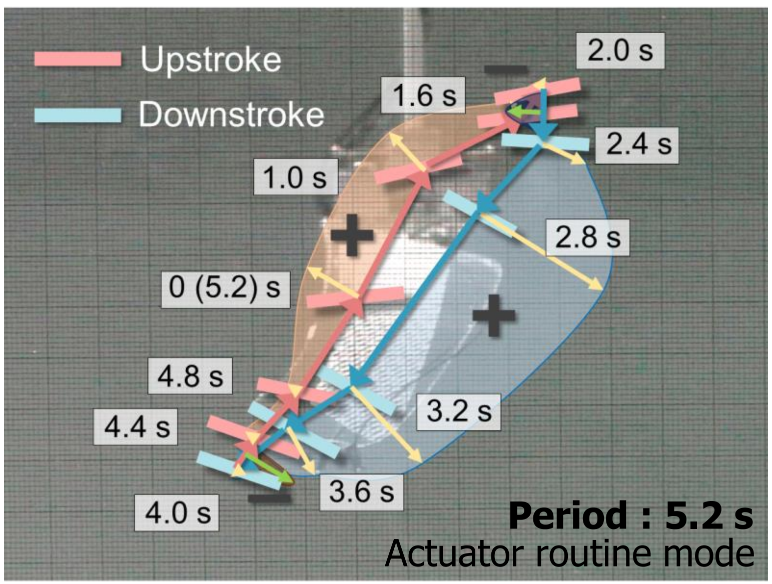
1.3 : 1

Routine mode

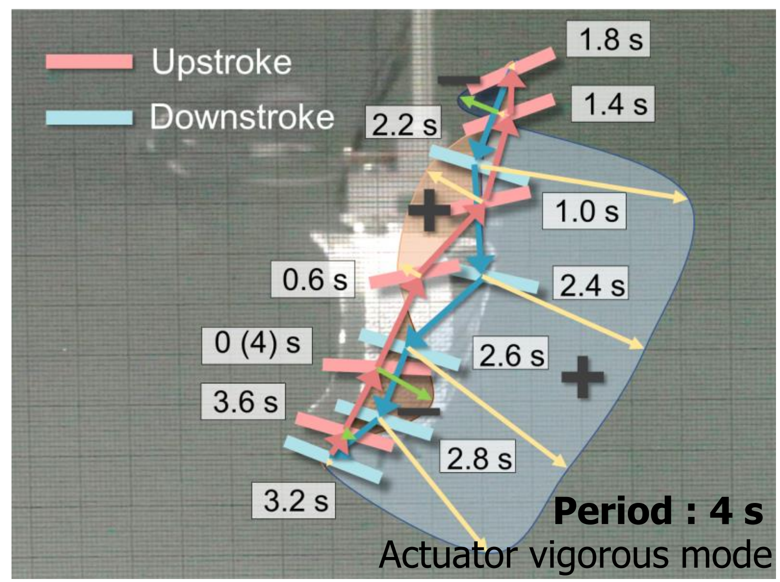
Vigorous mode



Green turtle vigorous mode



"Routine mode" flapping sequence



"Vigorous mode" flapping sequence

Song, S.H., et al., **Turtle mimetic soft robot with two swimming gait**," *Bioinspiration & Biomimetic*, 2016

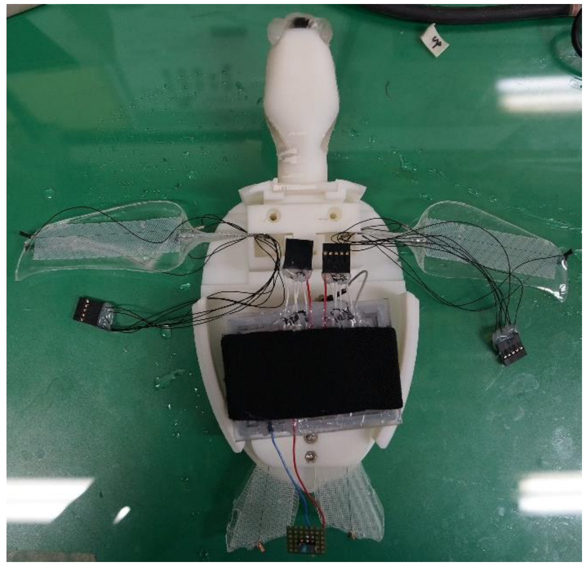
Turtle robot locomotion

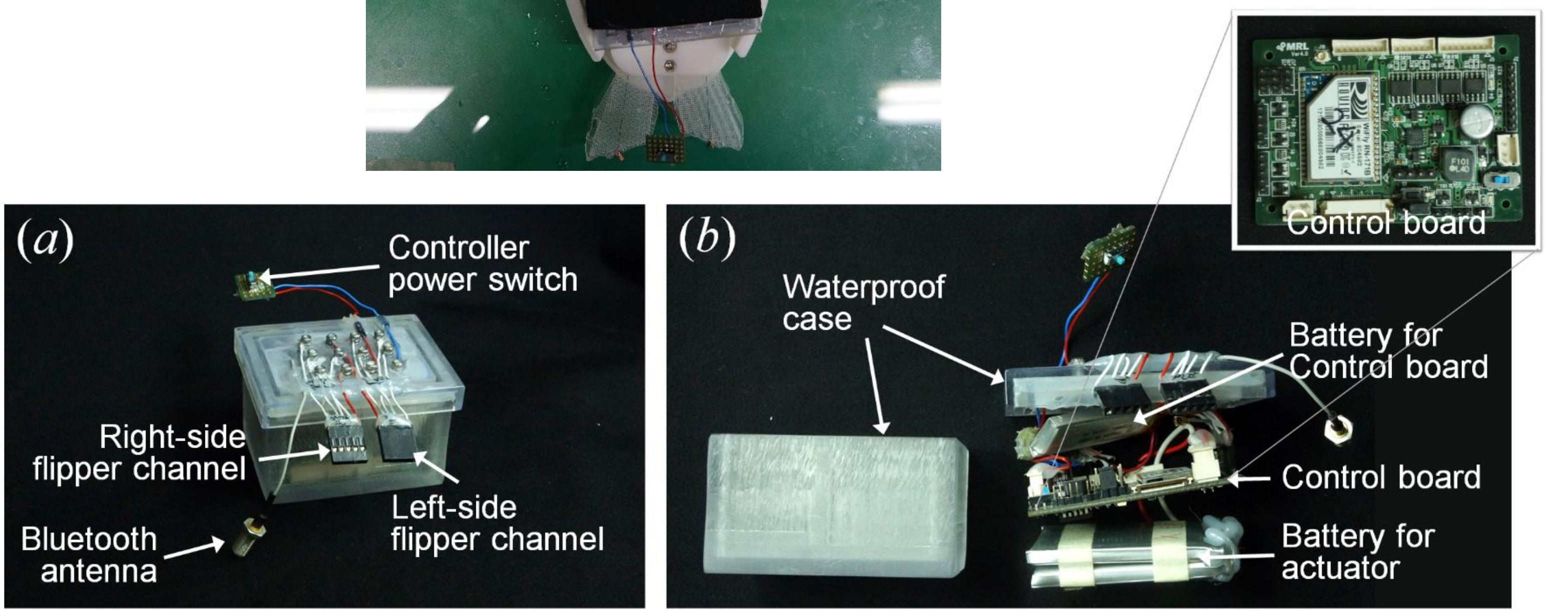
Routine mode locomotion
(speed : 7.4 mm/s)

Vigorous mode locomotion
(speed : 11.5 mm/s)

Song, S.H., et al., **Turtle mimetic soft robot with two swimming gait**," *Bioinspiration & Biomimetic*, 2016

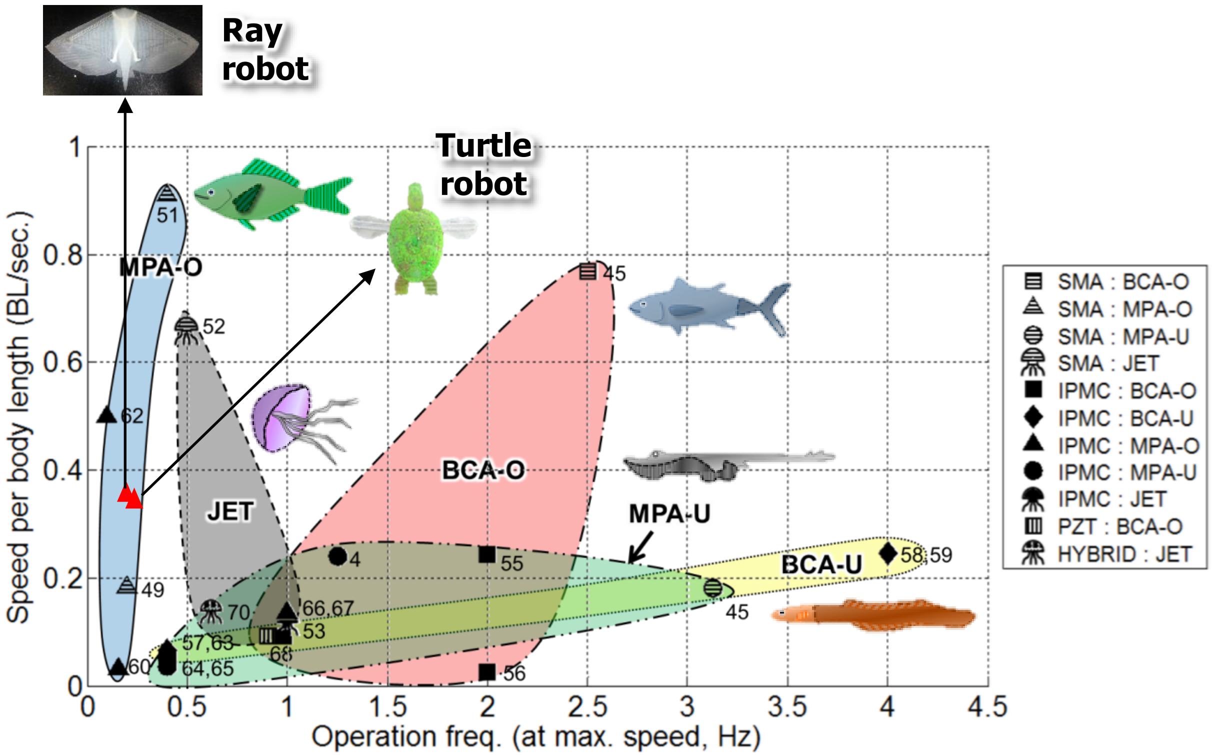
Turtle robot Controller

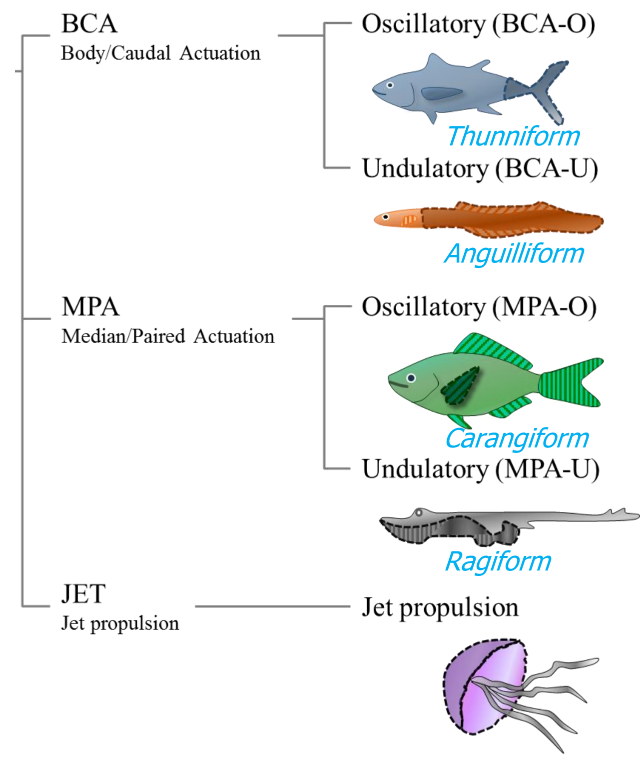




Control system of turtle robot

Underwater robots made of smart materials



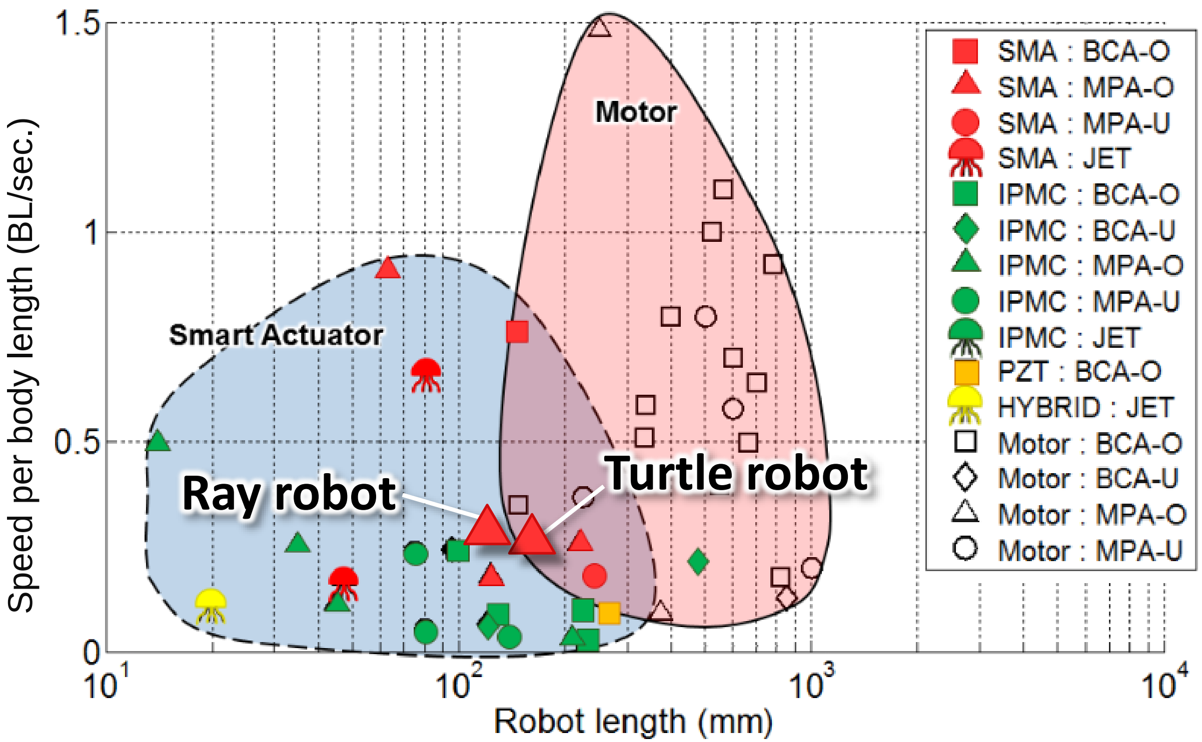


***Turtle robot and ray robot: 0.25 Hz**

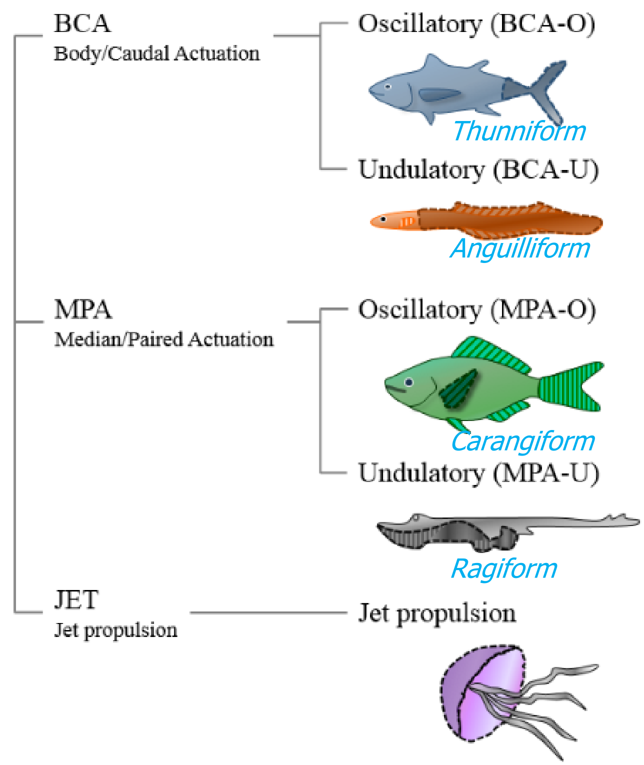
Comparison of robots operating in different swimming modes (speed per body length vs. operation frequency (at maximum speed)) [1]

[1] Won-Shik Chu, *et. al.*, “Review of Biomimetic Underwater Robots Using Smart Actuators” (2012)

Comparison with motor-based underwater robots



Robot length and speed per body length of biomimetic underwater robot [1]



Classification of swimming modes of biomimetic underwater robots [1]

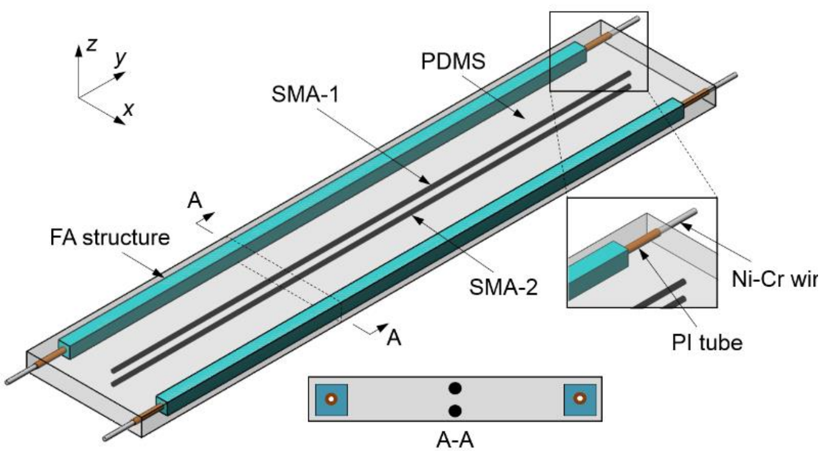
[1] Won-Shik Chu, *et. al.*, "Review of Biomimetic Underwater Robots Using Smart Actuators" (2012)

DESIGN AND FABRICATION EXAMPLE 6
: SHAPE RETENTION ACTUATOR

Shape Retention Actuator (1)

- **Shape memory alloy (SMA) based composite actuators that can retain its shape by changing locally between a high-stiffness and a low-stiffness state.**
  - Low-stiffness state: soft morphing capability (to produce a smooth continuous deformation)
  - High-stiffness state: working configuration (without continuous energy consumption)

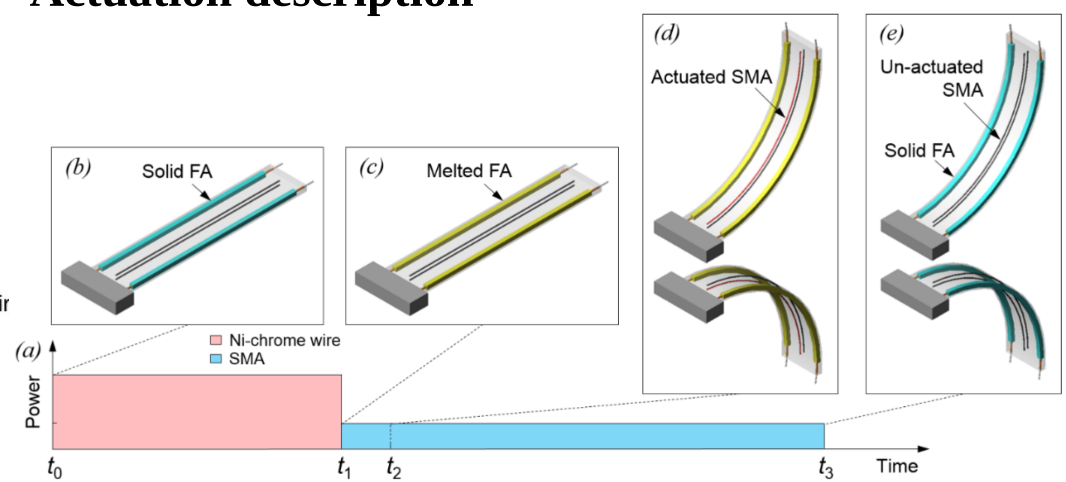
Actuator design



The actuator configuration and its components

FA materials: low melting materials such as fusible alloy, thermoplastics, wax.

Actuation description

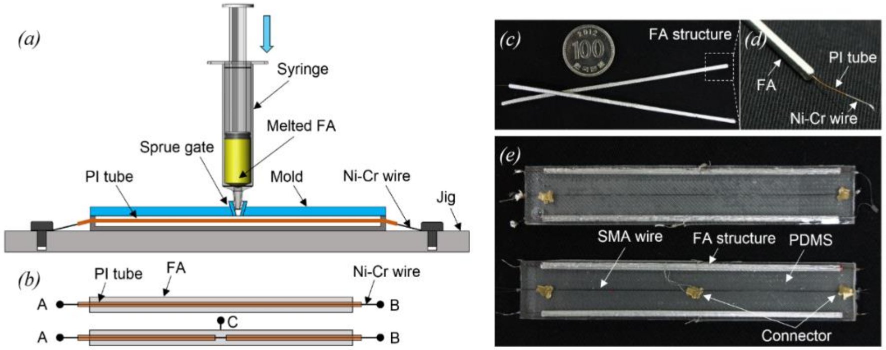


The shape retention process. *(a)* The actuation pattern. *(b)* to *(e)* are the different states of the actuator at time t_1, t_2, t_3 and t_4.

W. Wang *et al.*, Smart Soft Composite Actuator with Shape Retention Capability using Embedded Fusible Alloy Structures, Composites Part B: Engineering (2015)

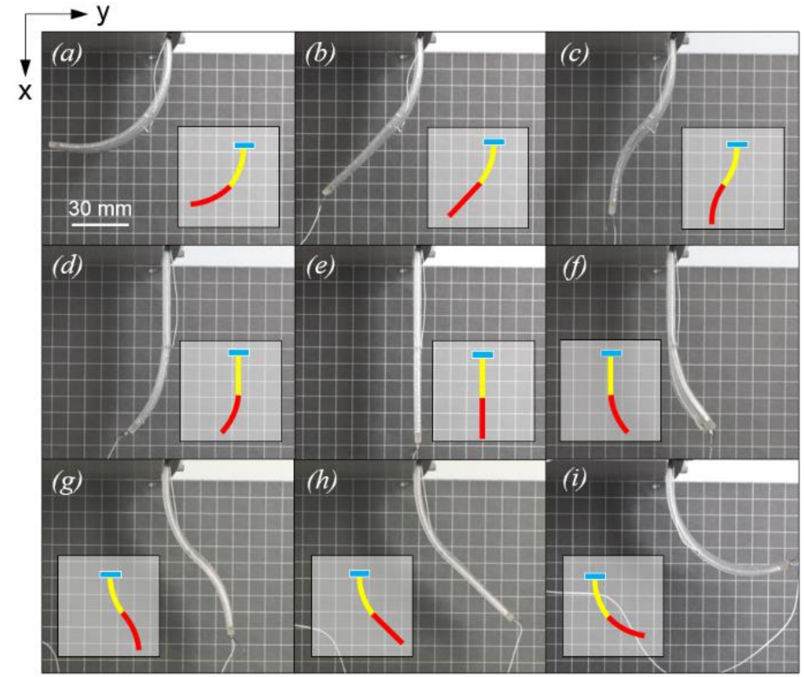
Shape Retention Actuator (2)

Fabrication process



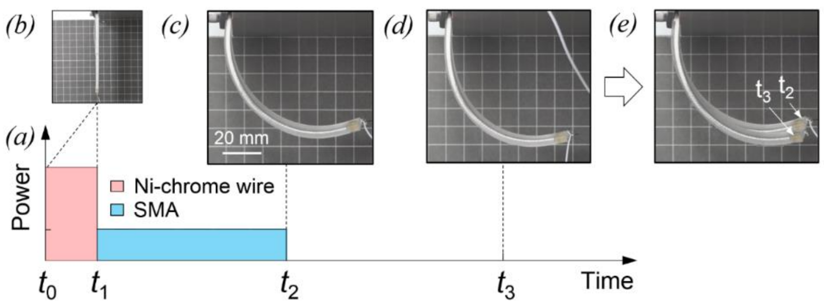
Fabrication process of the actuator. *(a)* FA structure fabrication setup. *(b)* to *(d)* Fabricated FA structure. *(e)* Fabricated shape retention actuator.

Actuation process for two-segment actuator



Nine different configurations of the two-segmented actuator, (a) to (i).

Actuation process for one-segment actuator



Shape retention sequence diagram. *(a)* Current sequence for actuating and cooling. *(b)* Actuator configuration before actuation of SMA wire. *(c)* to *(d)* The left-bending shape at time t_2 and t_3, and *(e)* juxtaposed.

W. Wang *et al.*, Smart Soft Composite Actuator with Shape Retention Capability using Embedded Fusible Alloy Structures, Composites Part B: Engineering (2015)