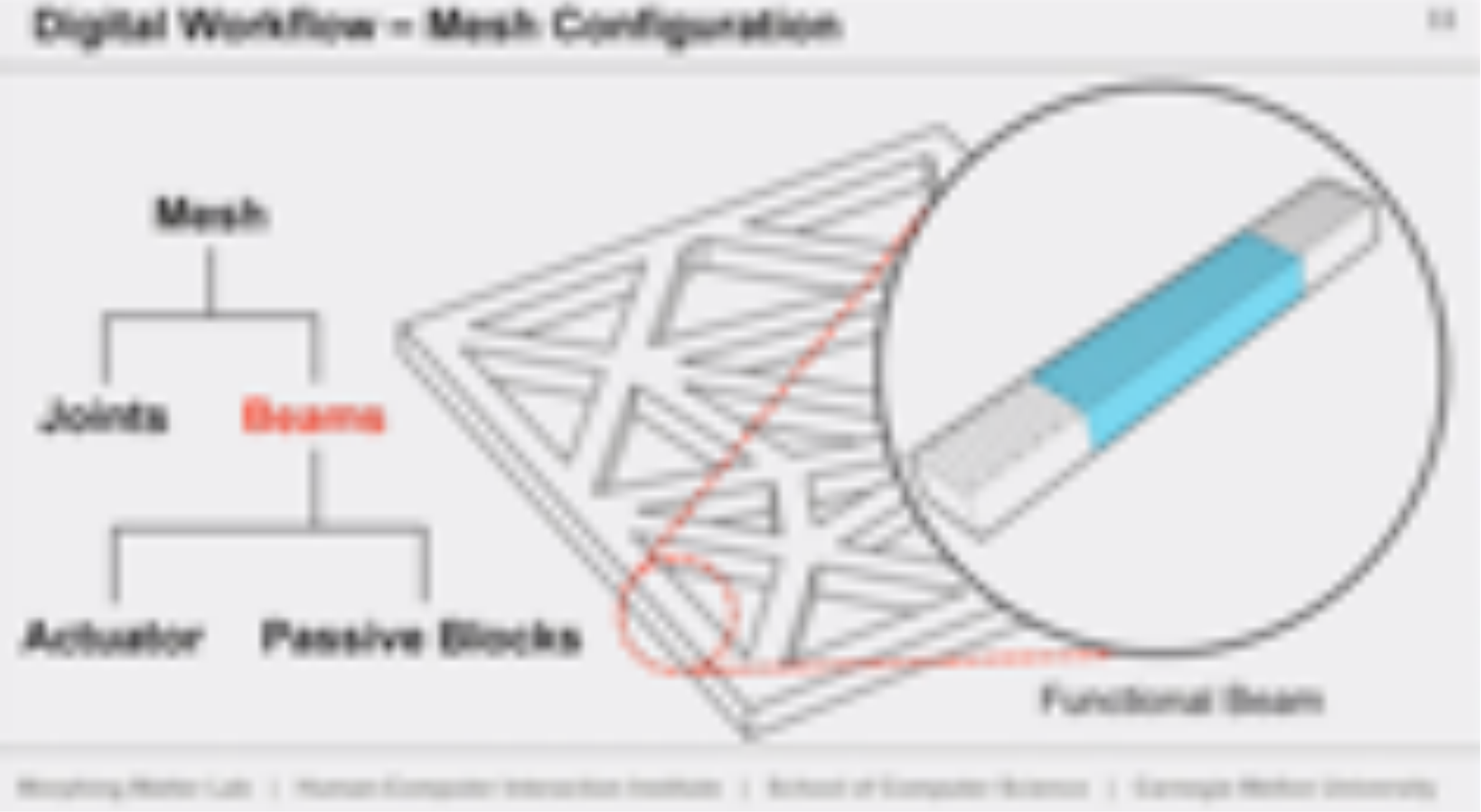
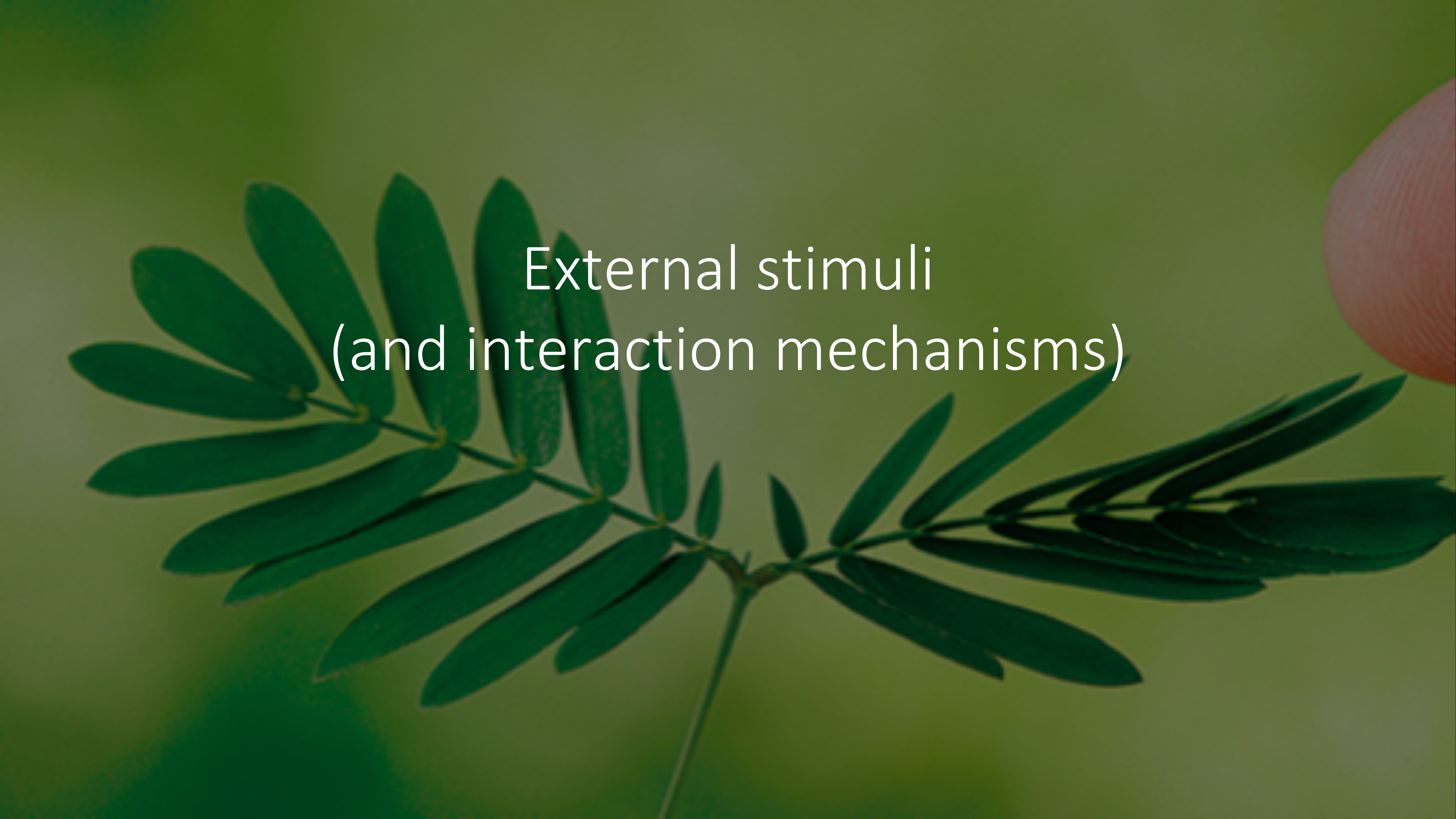
Geometries



Wang, G., Yang, H., Yan, Z., Gecer Ulu, N., Tao, Y., Gu, J., ... & Yao, L. (2018, October). 4DMesh: 4D Printing Morphing Non-Developable Mesh Surfaces. In The 31st Annual ACM Symposium on User Interface Software and Technology (pp. 623-635). ACM.

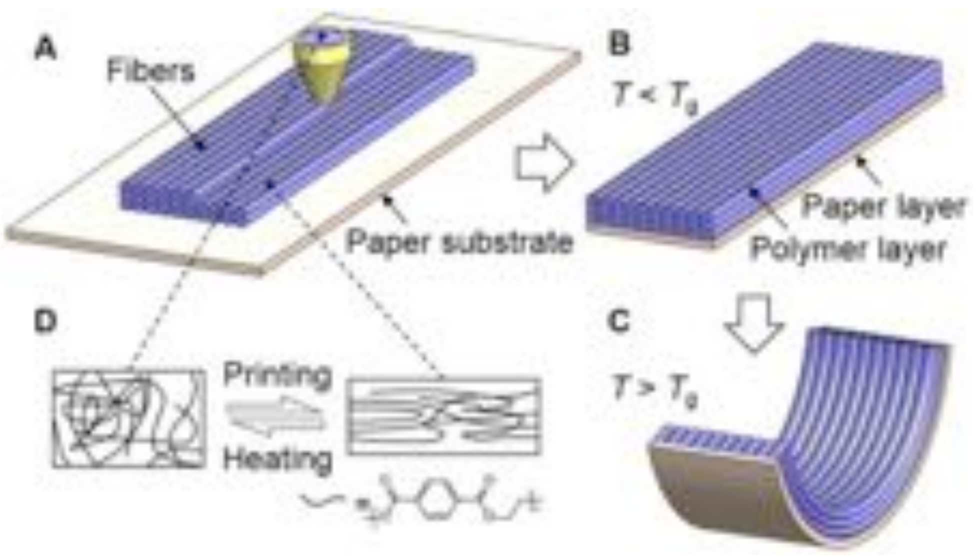
External stimuli
(and interaction mechanisms)

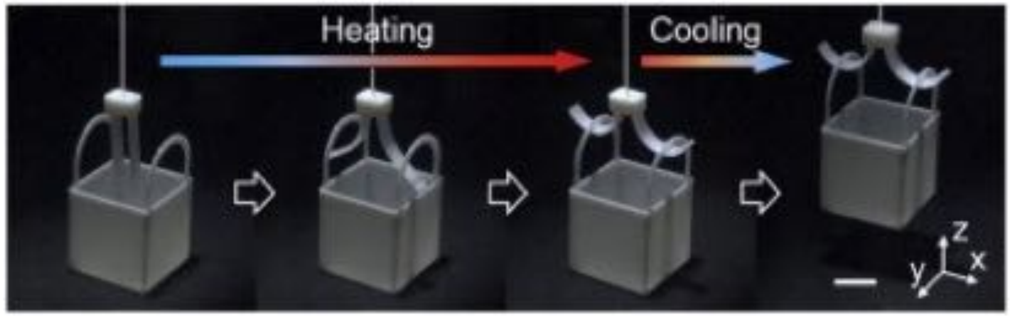


Stimulus

- ✓ Different materials inside the same structure can be actuated through multiple stimuli
  - ➢ Heat, light, water, pH, etc.
- ➢ Spatial arrangements determine the interaction mechanism

Thermal Stimulus: Grasping Mechanism

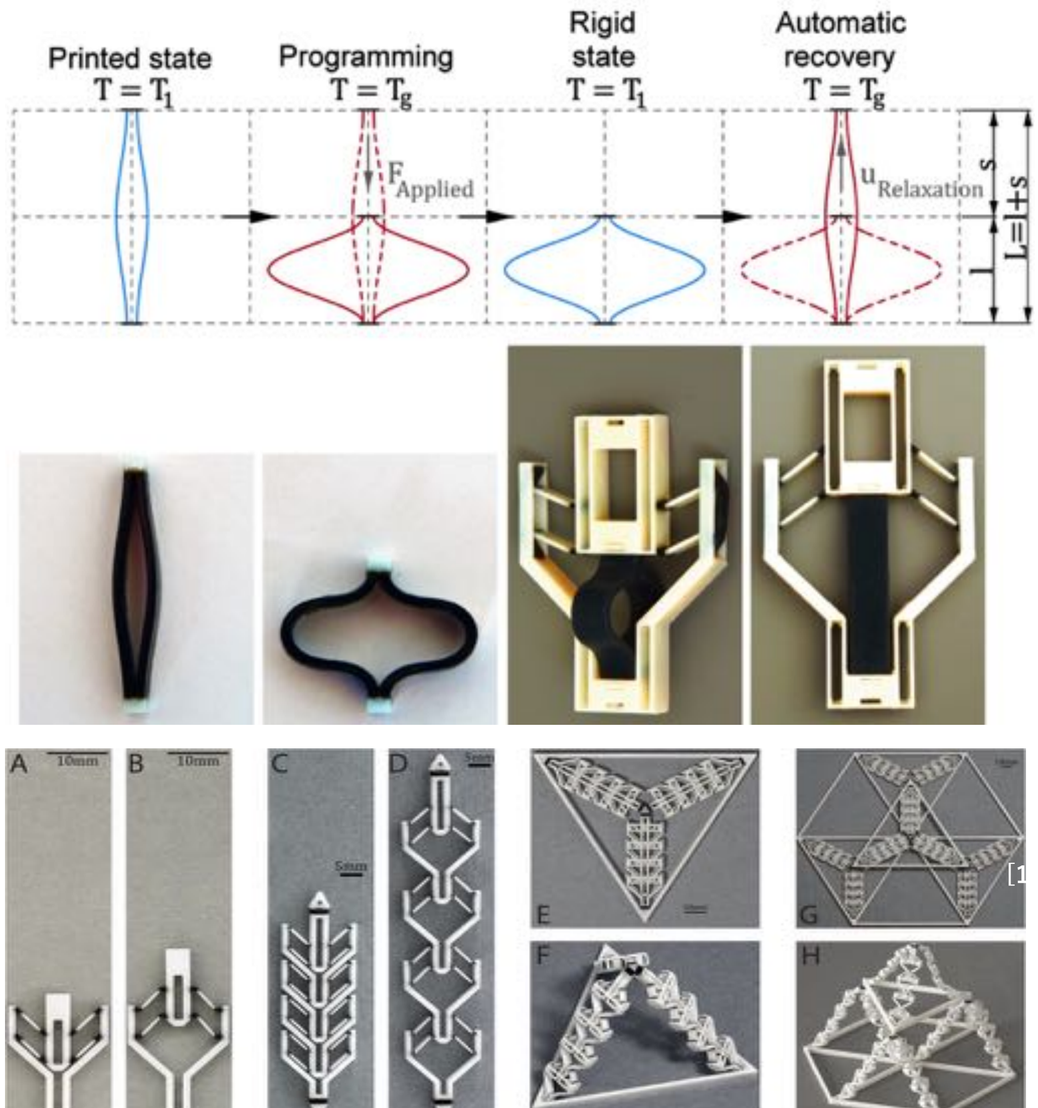




- Printing Technology :
  - Fused Deposition Modeling (FDM)
- Materials:
  - Polyester (PE)
  - copy-paper (substrate)

Wang, Wei, et al. "Soft grasping mechanisms composed of shape memory polymer based self-bending units." Composites Part B: Engineering 164 (2019): 198-204.

Thermal Stimulus: Bistable Mechanism

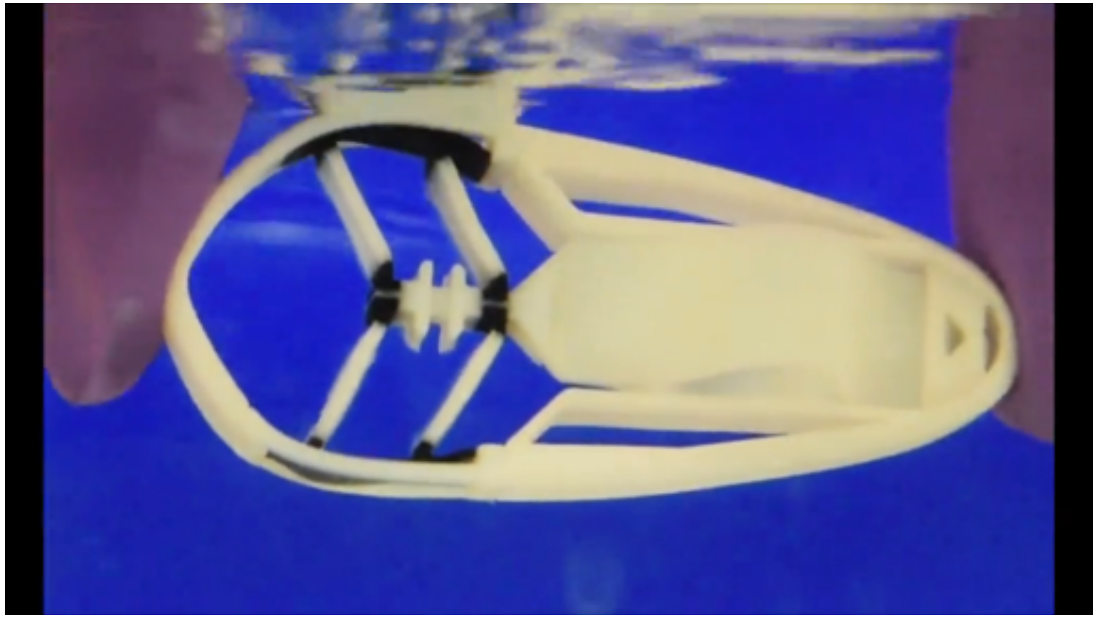


- Bistability : energy is required only to transform between two states, not to maintain them
- Printing Technology :
  - Polyjet
- Materials: liquid photopolymer
  - Agilus30 [10] / TangoBlackPlus [11]: elastomer-like materials
  - VeroWhitePlus [10] ,[11] : temperature-resistant rigid plastic
  - By jetting a mixture of an elastomer-like and a rigid-plastic liquid photopolymer at different ratios, the printer is able to provide materials of varying mechanical properties

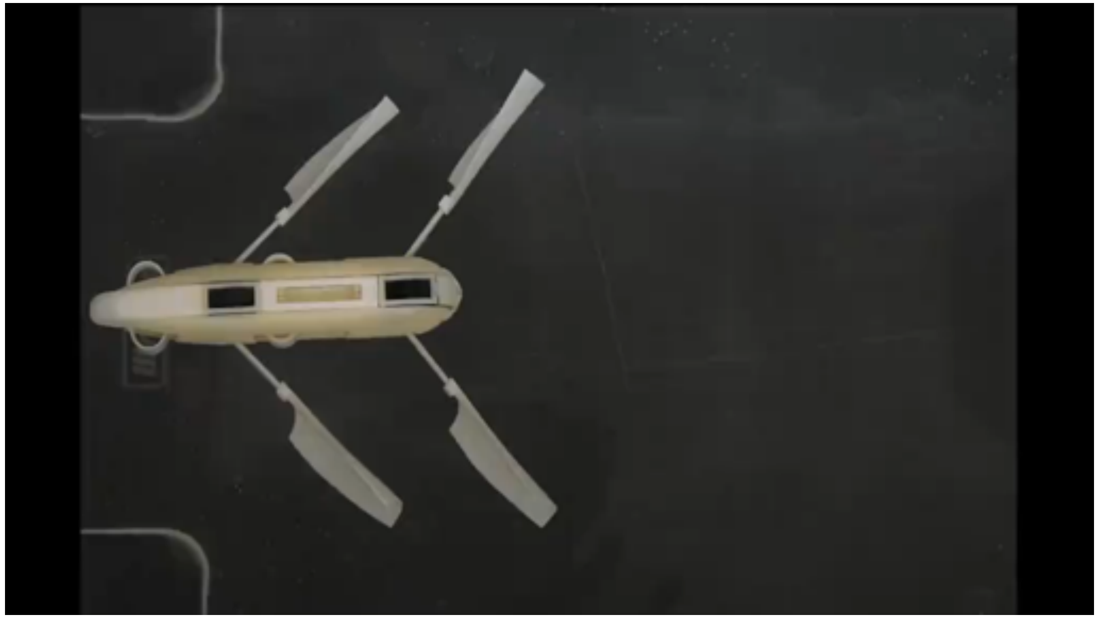
Chen, Tian, and Kristina Shea. "An autonomous programmable actuator and shape reconfigurable structures using bistability and shape memory polymers." 3D Printing and Additive Manufacturing 5.2 (2018): 91-101.
Chen, Tian, Jochen Mueller, and Kristina Shea. "Integrated design and simulation of tunable, multi-state structures fabricated monolithically with multi-material 3D printing." Scientific reports 7 (2017): 45671.

Bistable Mechanism: Propulsion of soft, untethered robots

✓Internal Bistable Mechanism



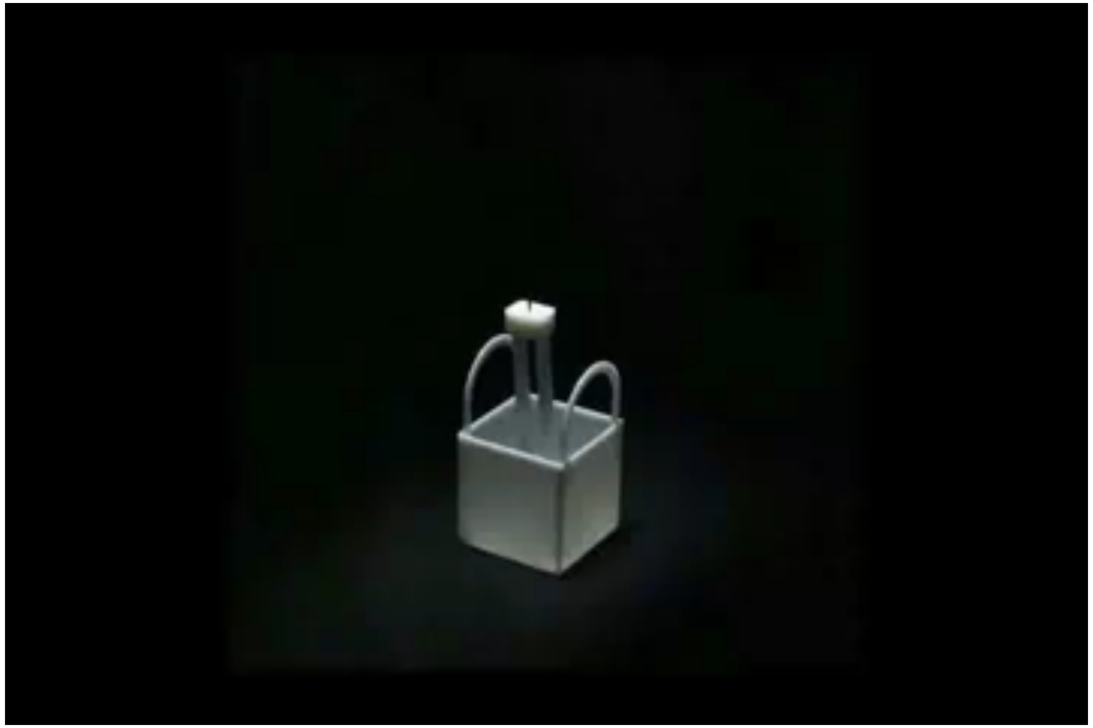
✓Propulsion of a two-stroke swimmer



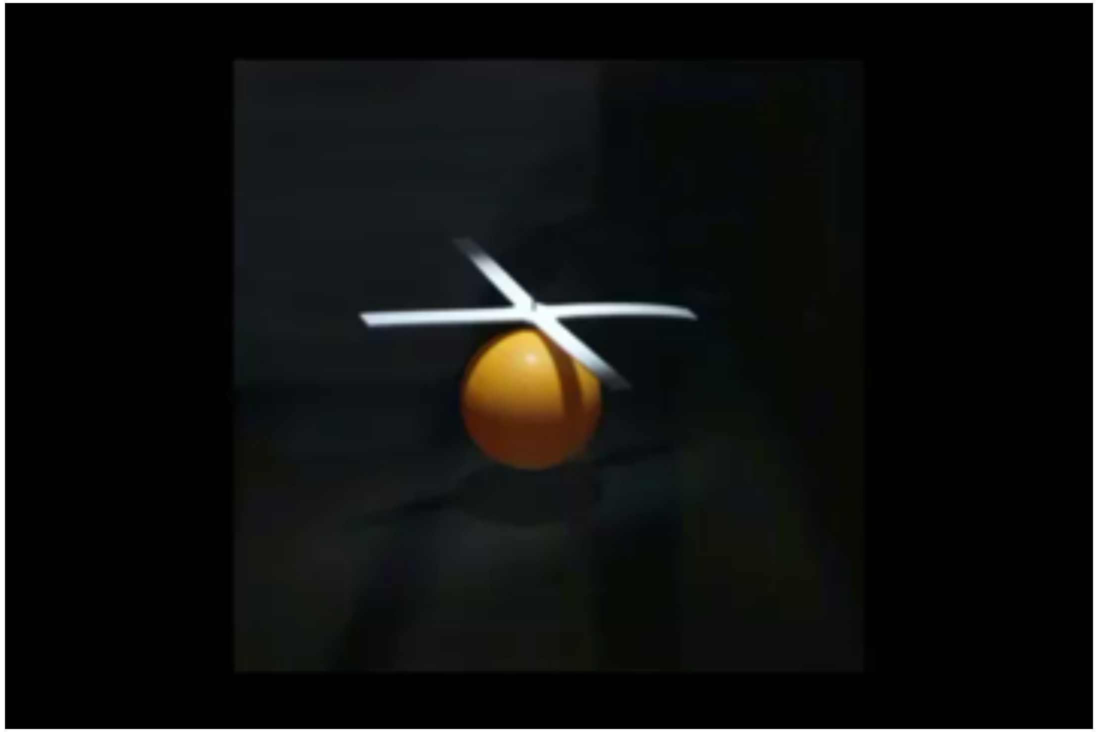
[12] Chen, Tian, et al. "Harnessing bistability for directional propulsion of soft, untethered robots." Proceedings of the National Academy of Sciences 115.22 (2018): 5698-5702.

Thermal Stimulus: Grasping Mechanism

✓Outward Bending

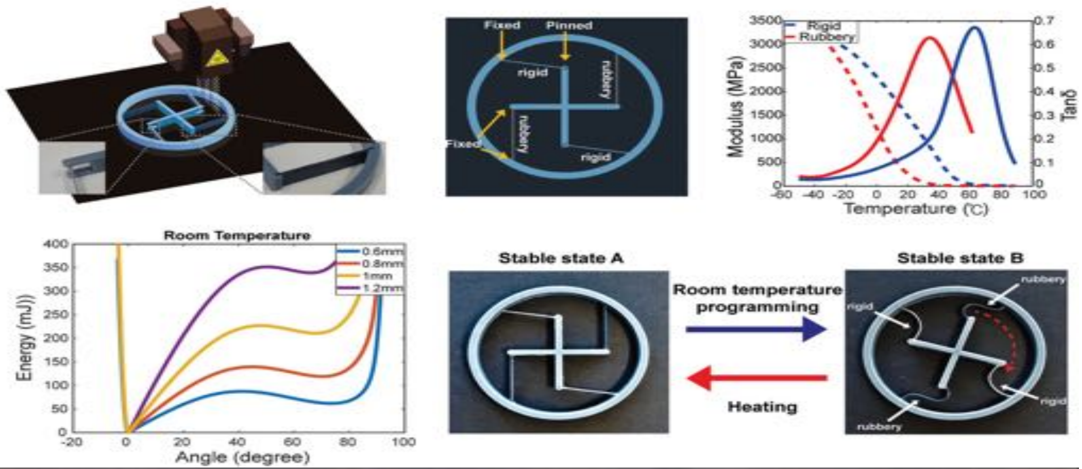


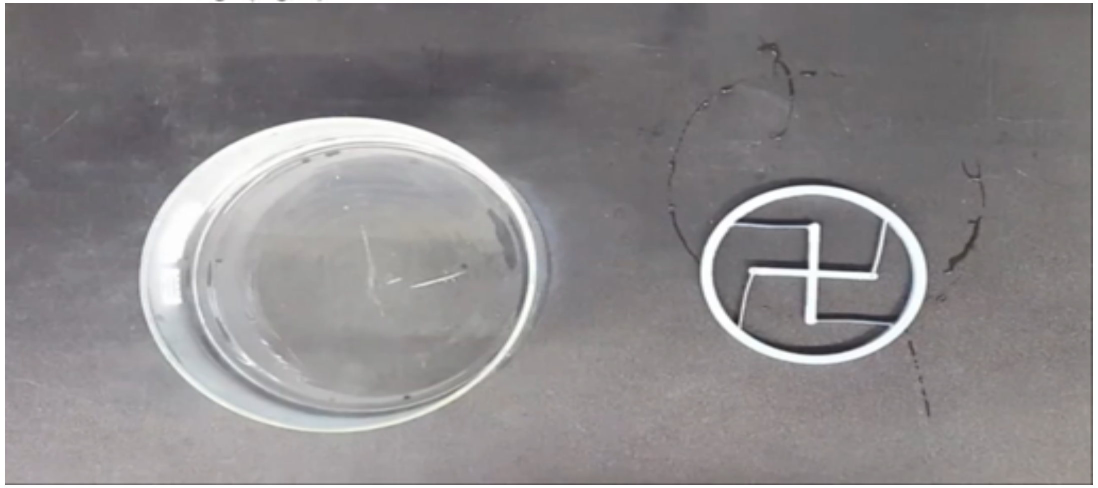
✓Inward Bending



[13] Wang, Wei, et al. "Soft grasping mechanisms composed of shape memory polymer based self-bending units." Composites Part B: Engineering

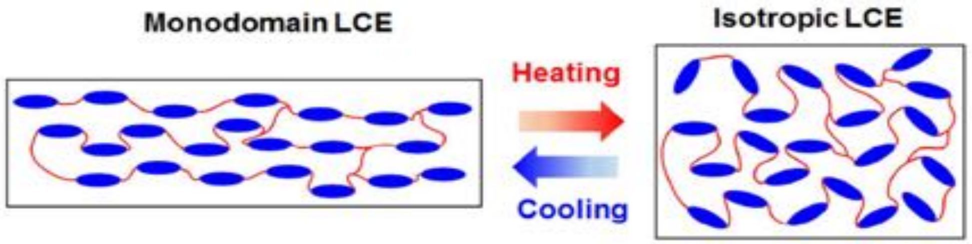
Thermal Stimulus: Cold Programming

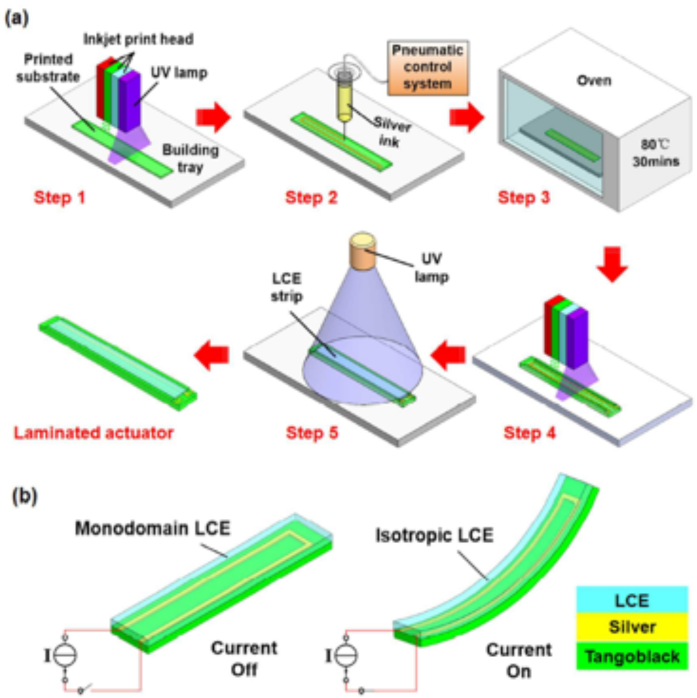




- ***Printing Technology*** :
  - Inkjet
- ***Materials:*** liquid photopolymer
  - *TangoBlackPlus:* elastomer-like materials
  - *VeroWhitePlus:* temperature-resistant rigid plastic
  - By jetting a mixture of an elastomer-like and a rigid-plastic liquid photopolymer at different ratios, the printer is able to provide materials of varying mechanical properties

Electro-Thermal Stimulus: Joule Heating





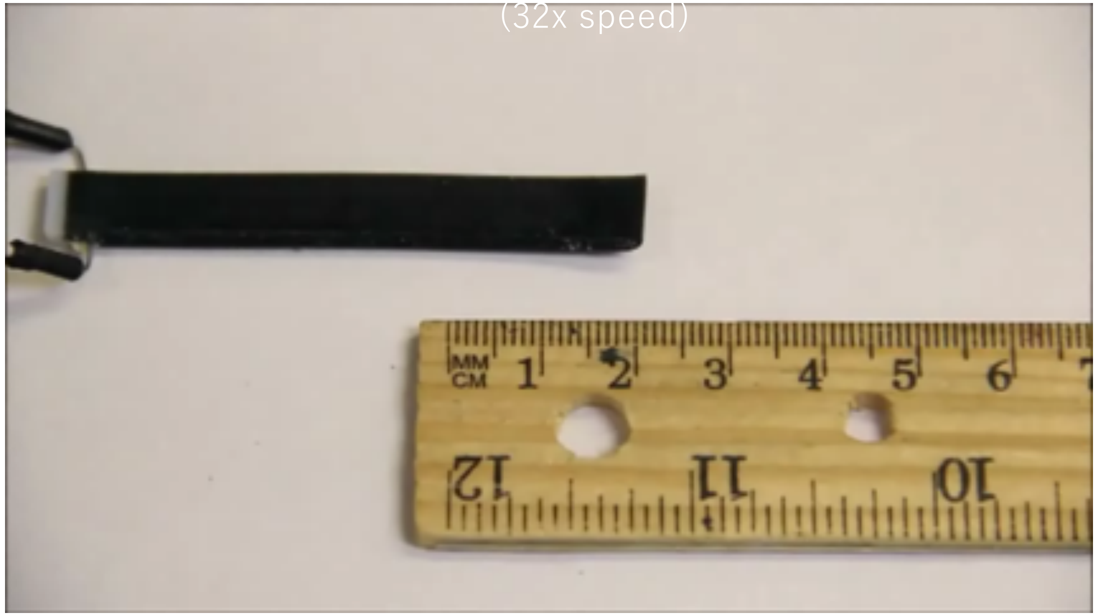
- Liquid crystal elastomers (LCEs)
  - Synthesized
- Silver ink:
  - Direct Ink Writing (DIW)
- Actuator Frame:
  - Polyjet
    - Tangoblack to construct the substrate of the hinge
    - Verowhite to construct the rigid panel of the hinge.

Yuan, Chao, et al. "3D printed reversible shape changing soft actuators assisted by liquid crystal elastomers." Soft Matter 13.33 (2017): 5558-5568.

Electro-Thermal Stimulus: Joule Heating

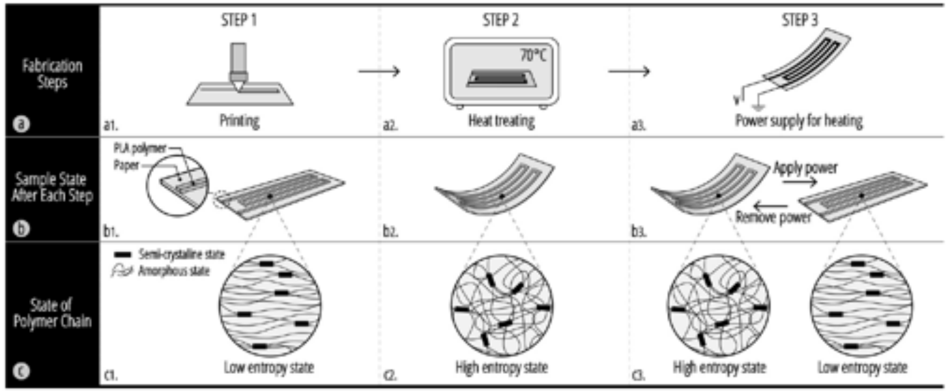
✓Soft Actuator

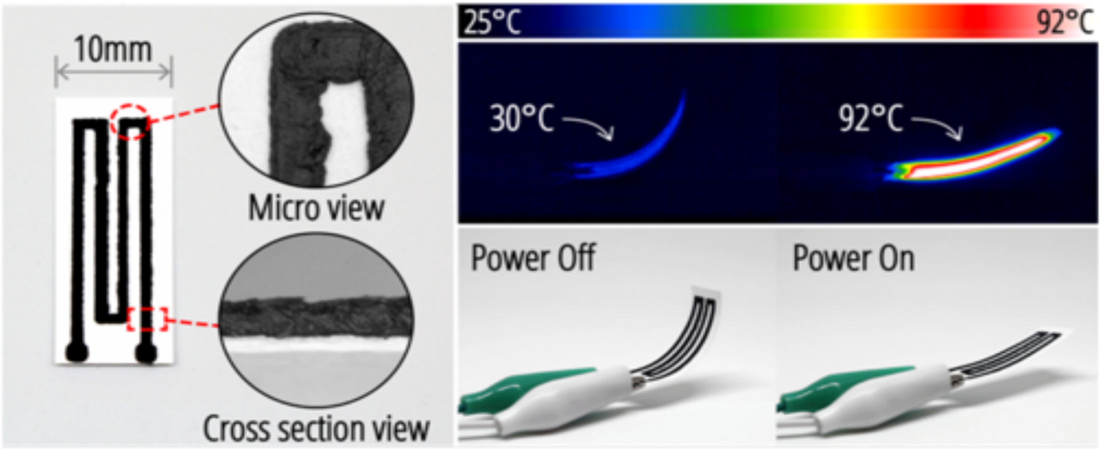
✓Deployable Structure



[15] Yuan, Chao, et al. "3D printed reversible shape changing soft actuators assisted by liquid crystal elastomers." Soft Matter 13.33 (2017): 5558-5568.

Electro-Thermal Stimulus: Joule Heating cSMP

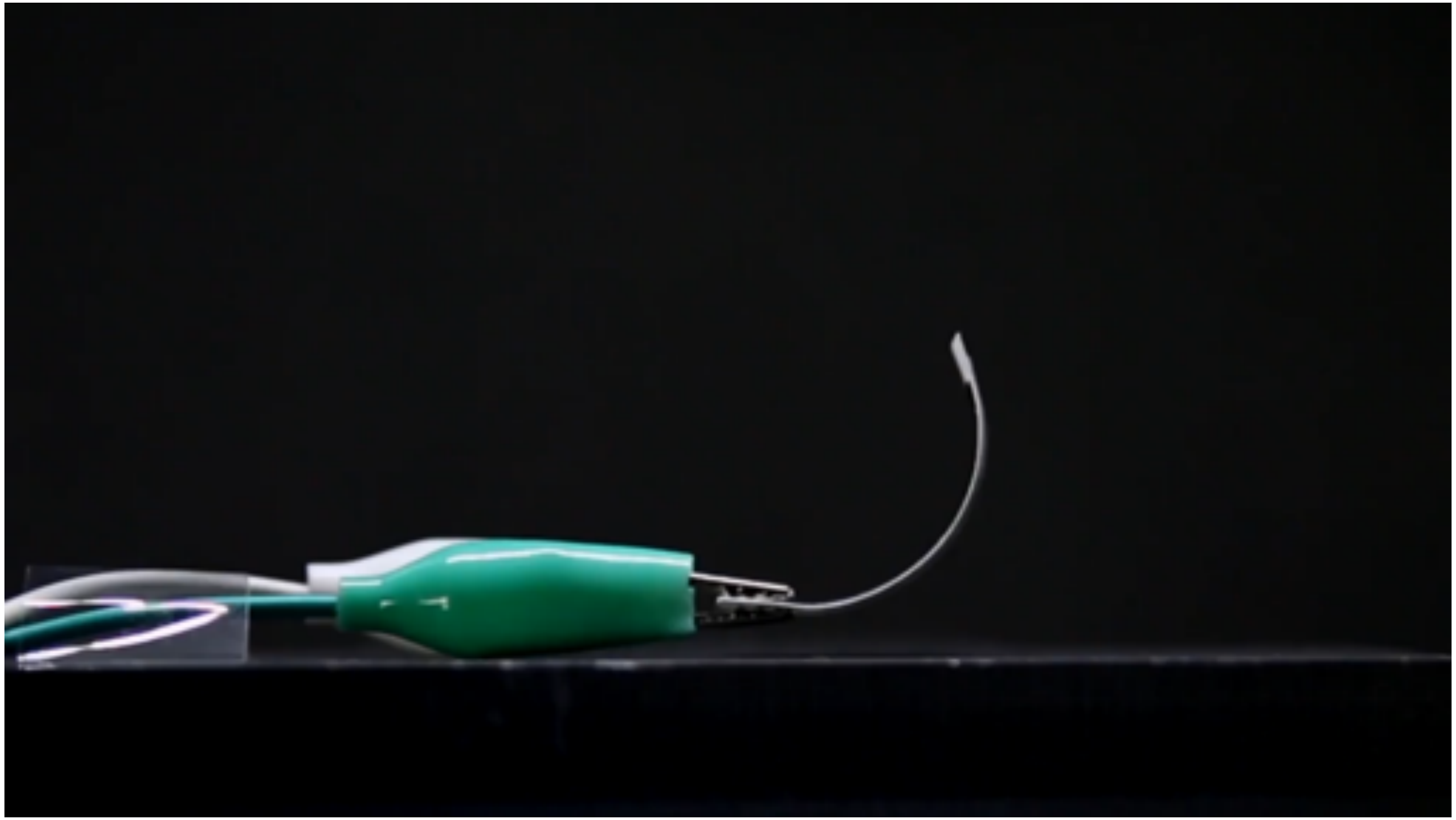




- Printing Technology :
  - Fused Deposition Modeling (FDM)
- Materials:
  - Conductive Shape Memory Polymer (cSMP)
    - Conductive Graphene PLA Filament

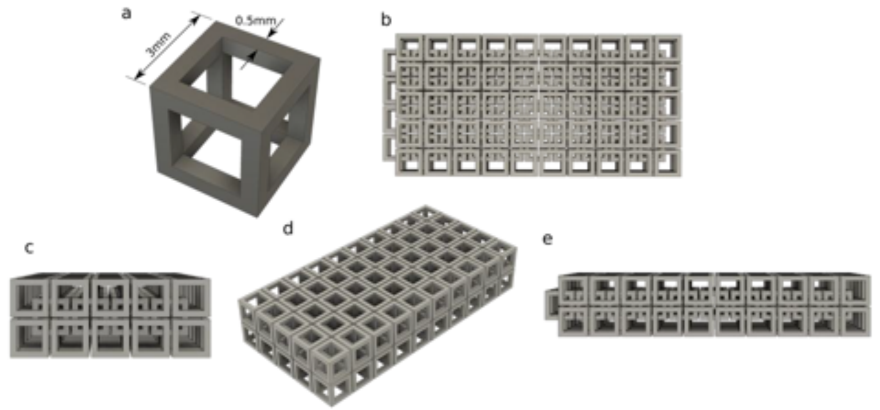
Wang, Guanyun, et al. "Printed Paper Actuator: A Low-cost Reversible Actuation and Sensing Method for Shape Changing Interfaces." Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. ACM, 2018.

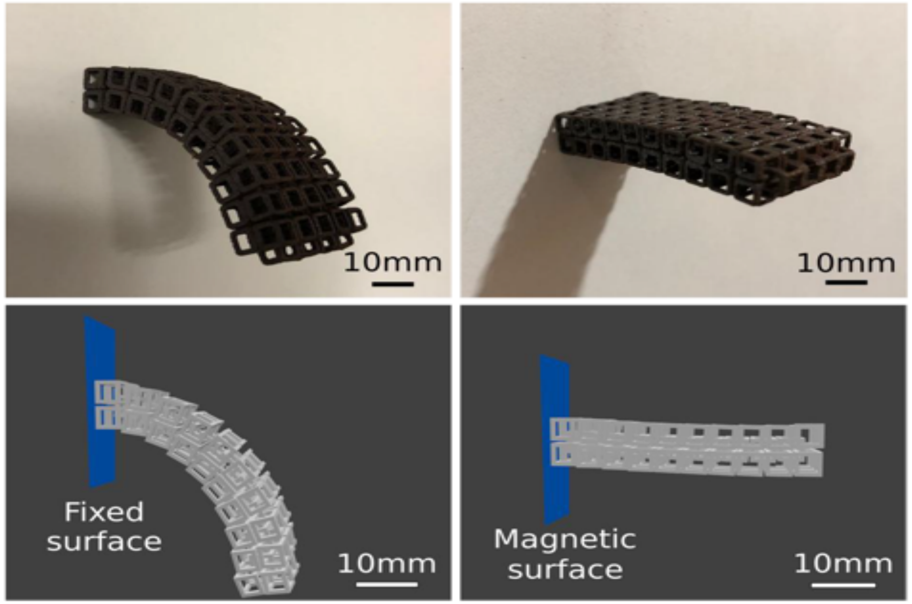
Electro-Thermal Stimulus:
Joule Heating cSMP

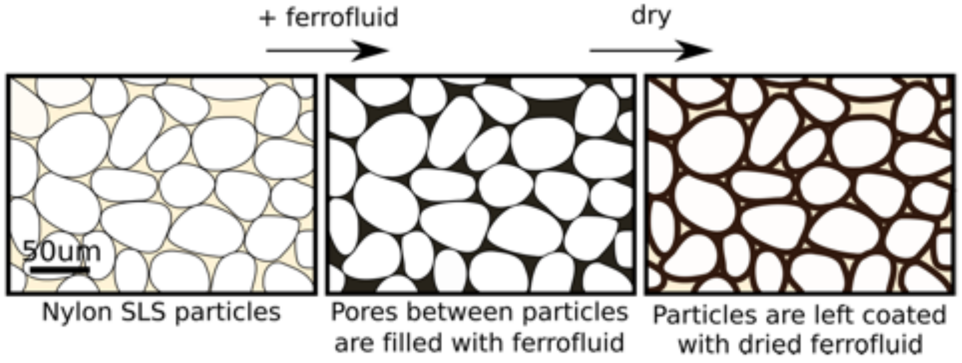


Wang, Guanyun, et al. "Printed Paper Actuator: A Low-cost Reversible Actuation and Sensing Method for Shape Changing Interfaces." Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. ACM, 2018.

Magnetic Stimulus



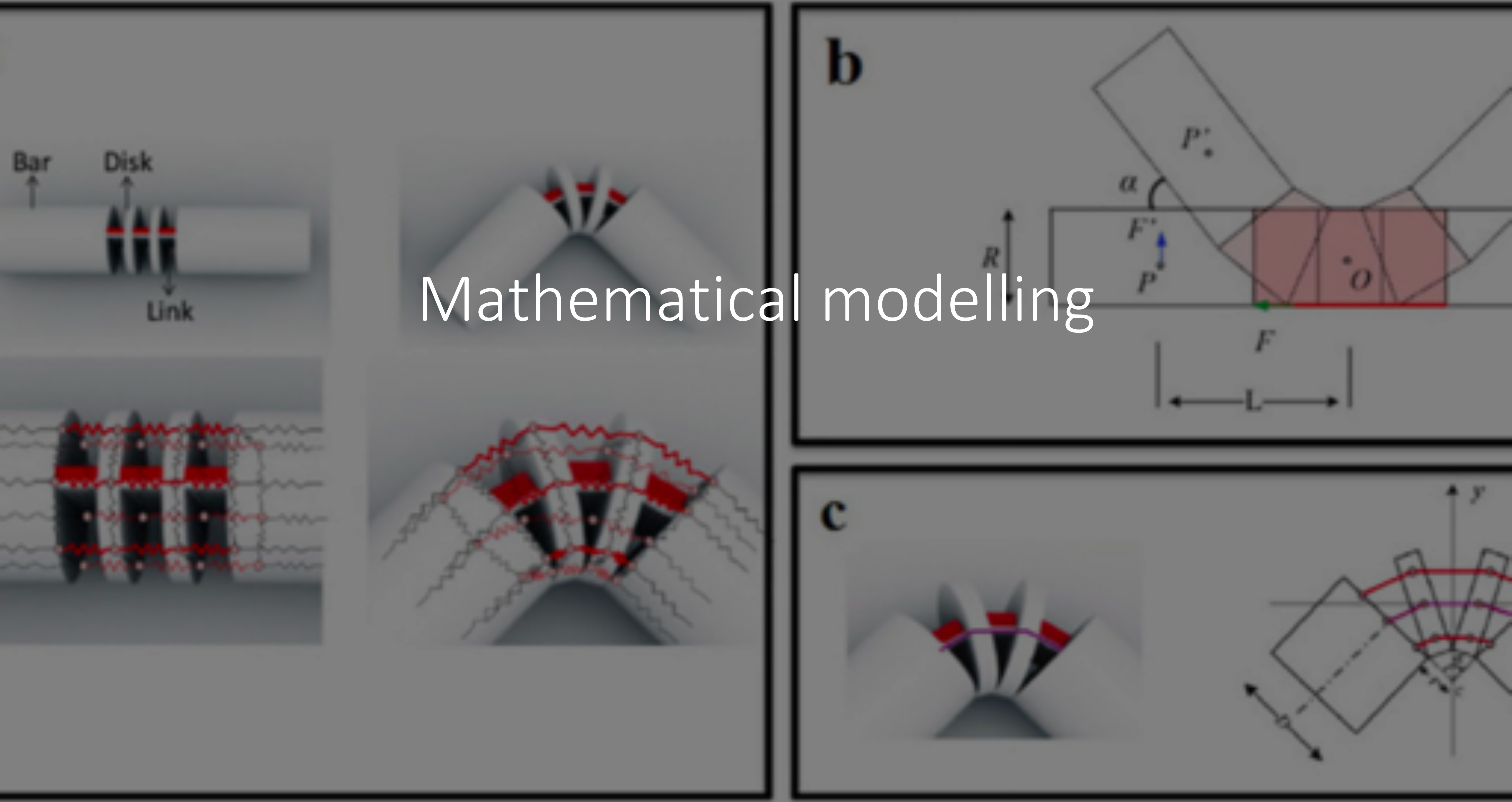




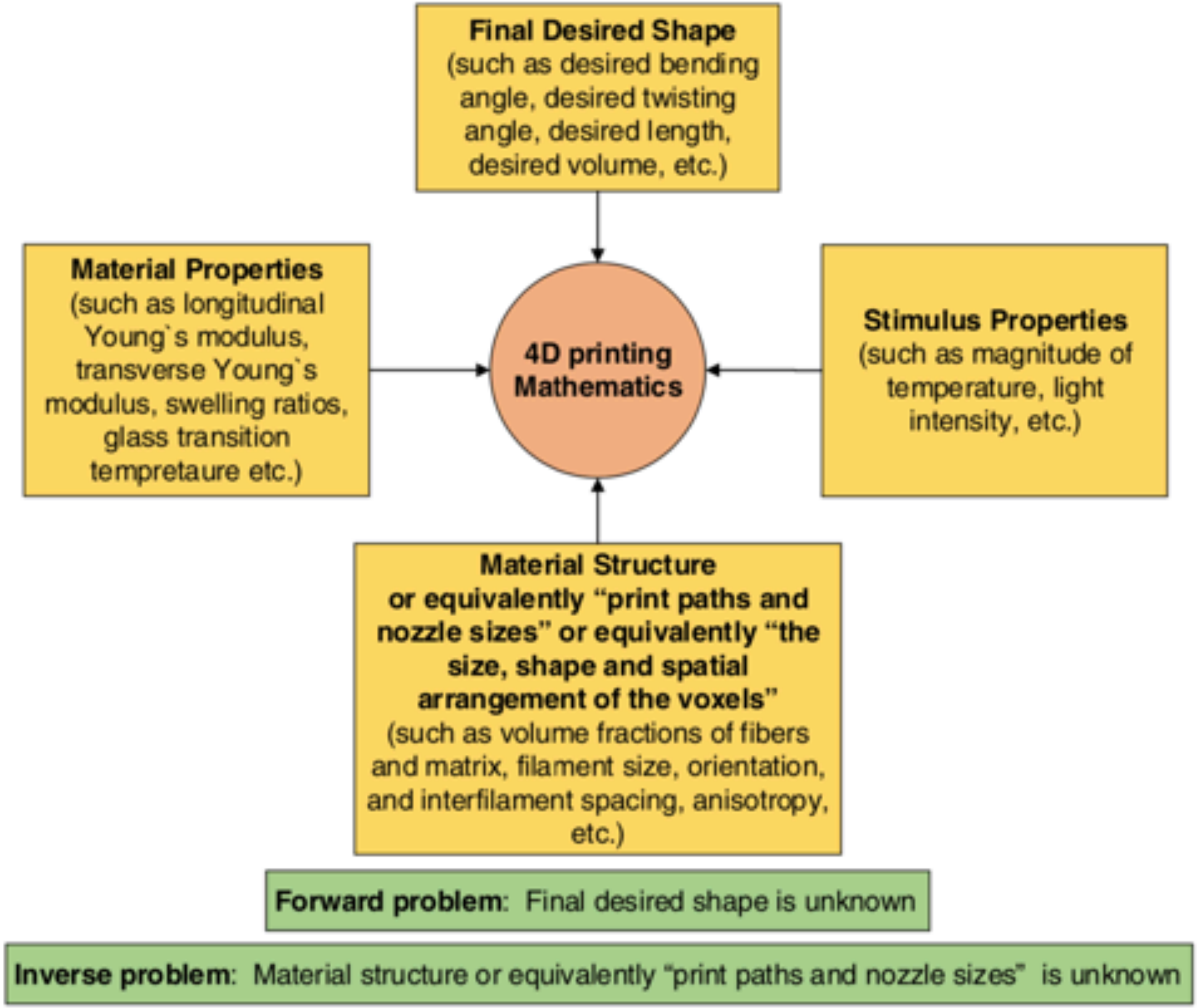
- Printing Technology :
  - Selective Laser Sintering (SLS)
- Materials:
  - Nylon 12 – PA 2200
- Post-Processing:
  - submerging a nylon print in ferrofluid, rest for 30 minutes and dried for 48 hours at 90° C

[18] Ploszajski, Anna R., et al. "4D Printing of Magnetically Functionalized Chainmail for Exoskeletal Biomedical Applications." MRS Advances 4.23 (2019): 1361-1366.

Mathematical modelling

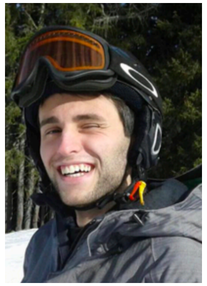


4D printing – Modelling

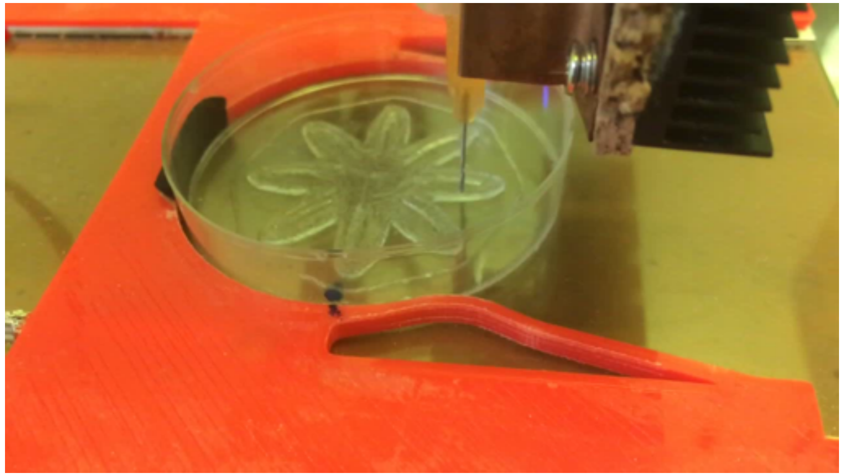


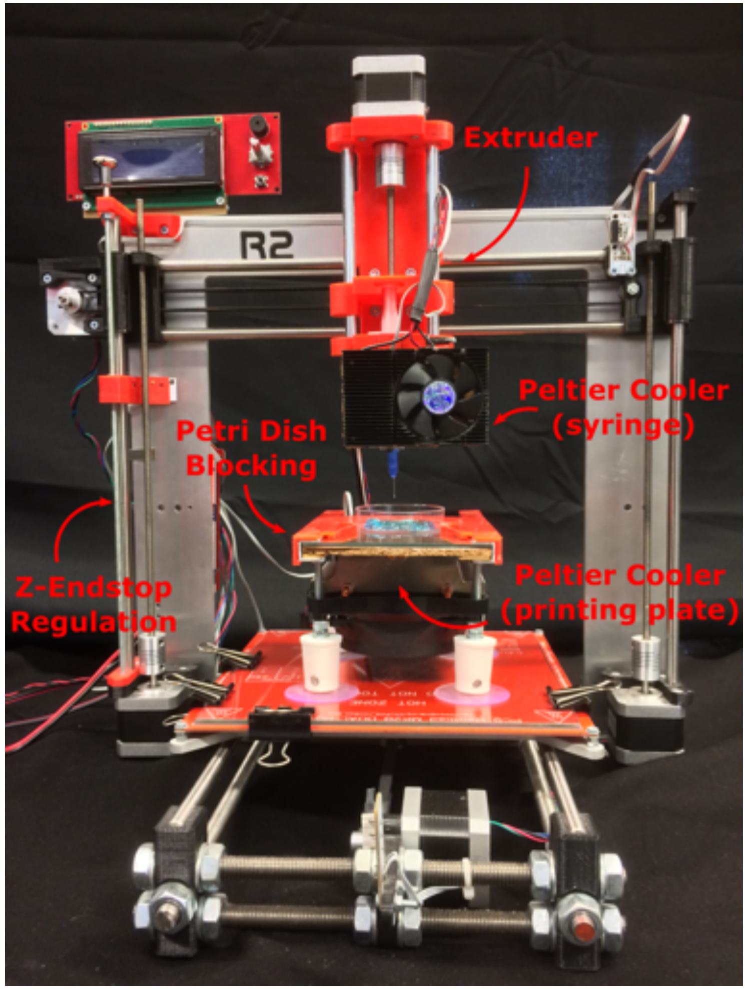
4D Printing of Bioinspired Actuators

4D Printing of Bioinspired Actuators



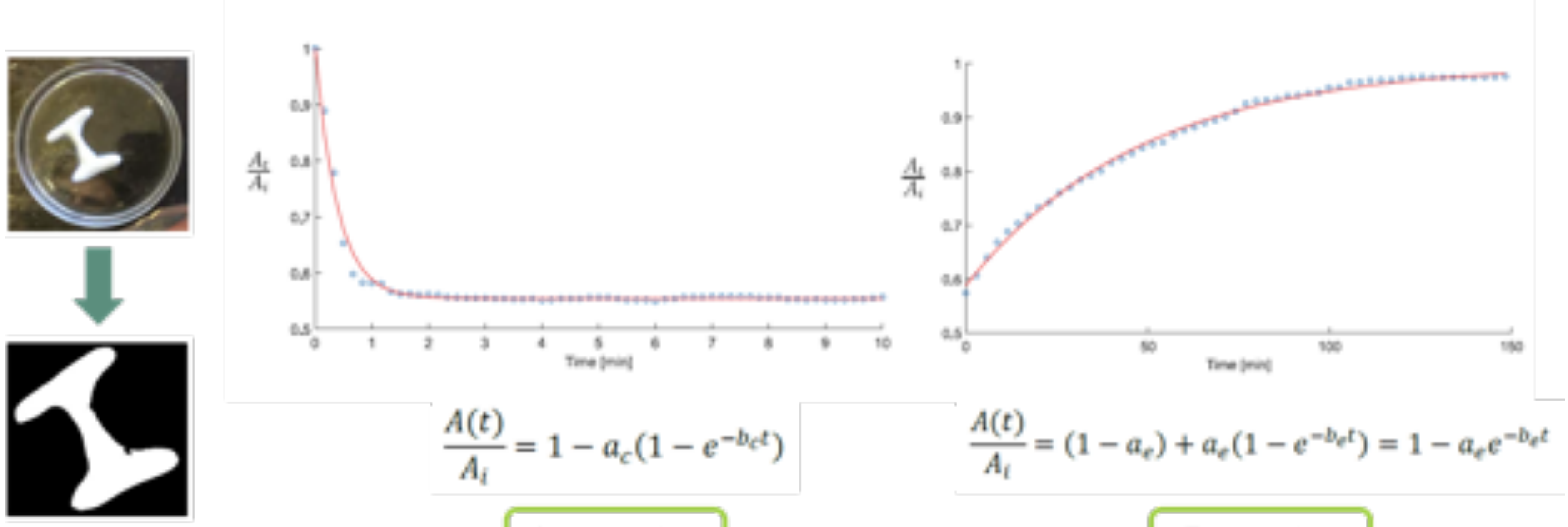
- ✓ Extrusion based 3D printer
- ✓ Temperature control to extrude Poly-*N*-isopropylacrylamide (PNIPAAm)





Planar Contraction Analysis

- ✓ Simple planar shapes, e.g. ‘H’ shaped structure
- ✓ Measure the contraction and reversible expansion magnitude through image segmentation in Matlab™



$$\frac{A(t)}{A_i} = 1 - a_c(1 - e^{-b_c t})$$

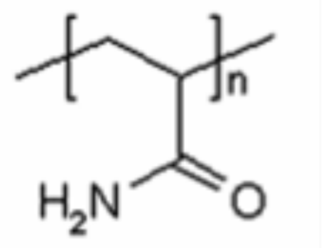
Contraction

$$\frac{A(t)}{A_i} = (1 - a_e) + a_e(1 - e^{-b_e t}) = 1 - a_e e^{-b_e t}$$

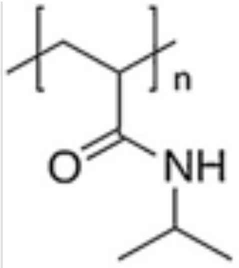
Expansion

Bending Actuation Analysis

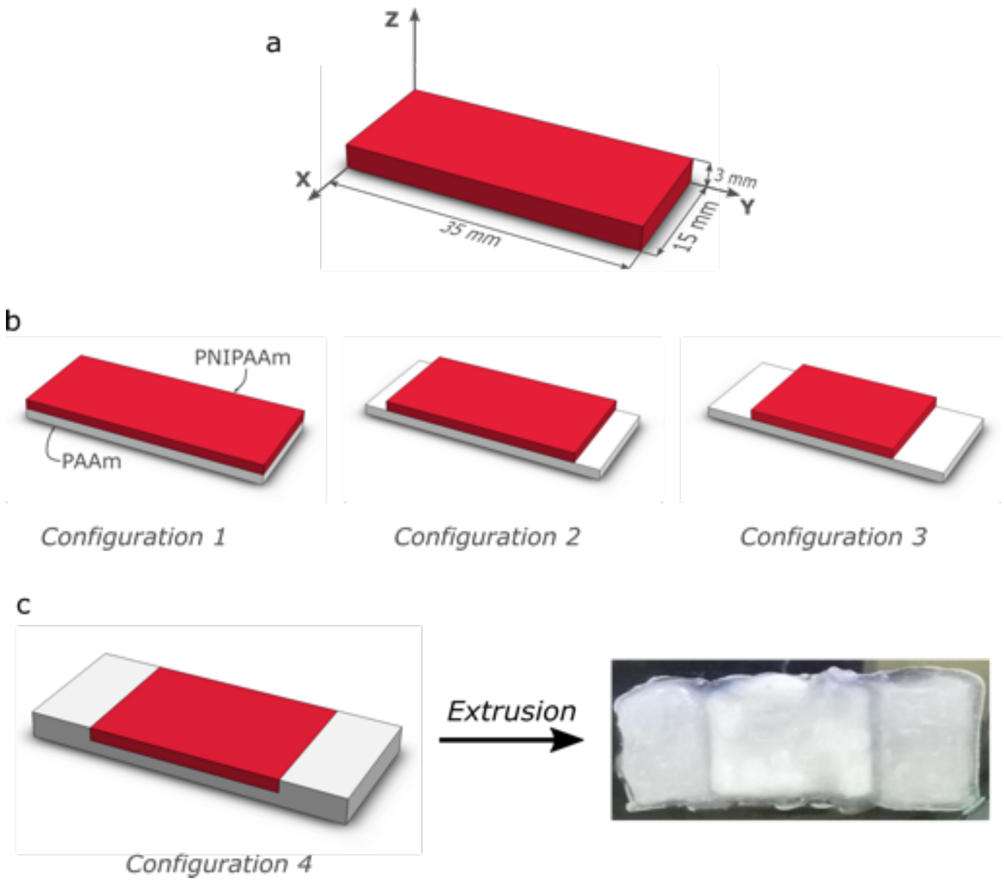
- ✓ Different bi-layer configurations that yield a bending movement
- ✓ PNIPAAm as active material, Polyacrylamide (PAAm) as passive one



PAAm

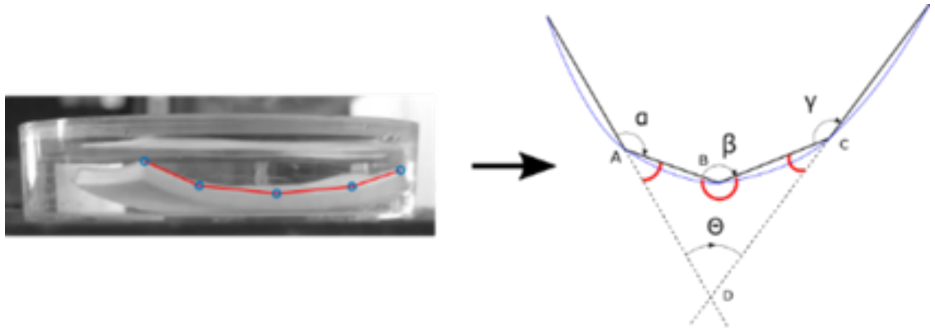


PNIPAAm

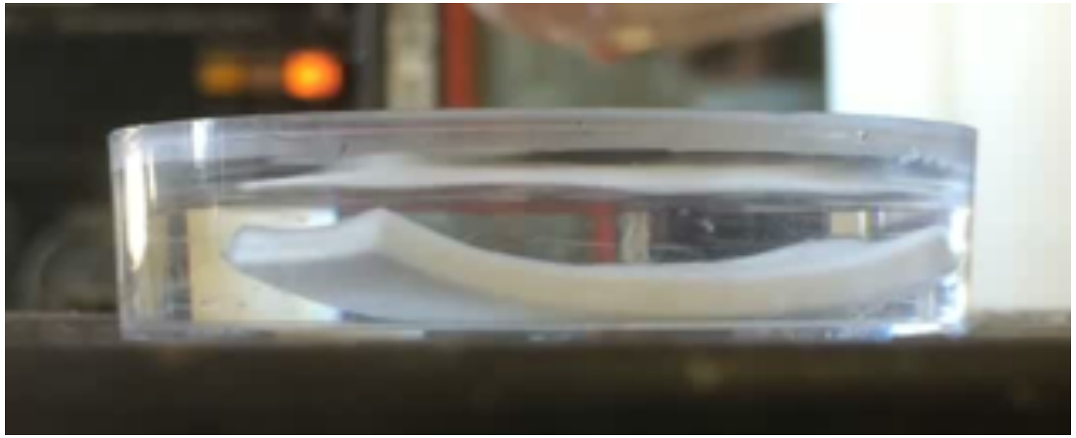


Bending Actuation Analysis

- ✓ Analysis of the bending angle
- ✓ Contraction in water at 60°C and expansion in water at room temperature

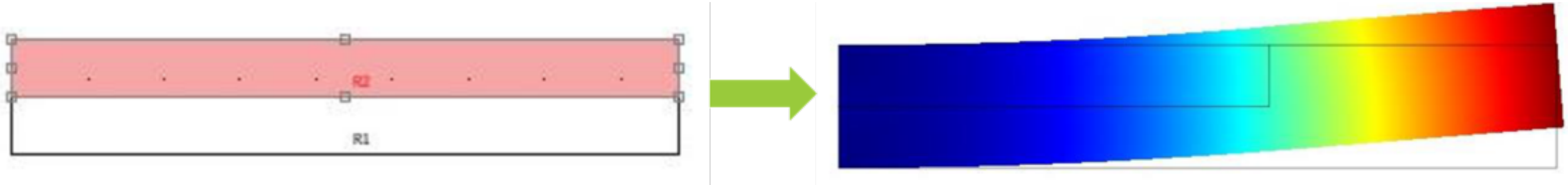


Cycle:	Θ at the end of contraction [°]	Θ at the end of relaxation [°]
First Cycle	-120	134
Second Cycle	-119	129
Third Cycle	-110	137



Modelling Bending Actuation

- ✓ Optimization of the active hydrogel distribution through Finite Element (FE) models in Comsol Multiphysics™
- ✓ 2D symmetric geometry, Plain Strain Module



Bioinspired Actuation

✓ Bioinspired crab claw model with an open-and-close movement