ICCES 2024 The International Conference on Computational & Experimental Engineering and Sciences
Singapore ✦ August 3-6, 2024

SUSTech Southern University of Science and Technology

Miura-origami Soft Robots with Proprioceptive and Interactive Sensing via Embedded Optical Sensors

Introduction---Soft robots

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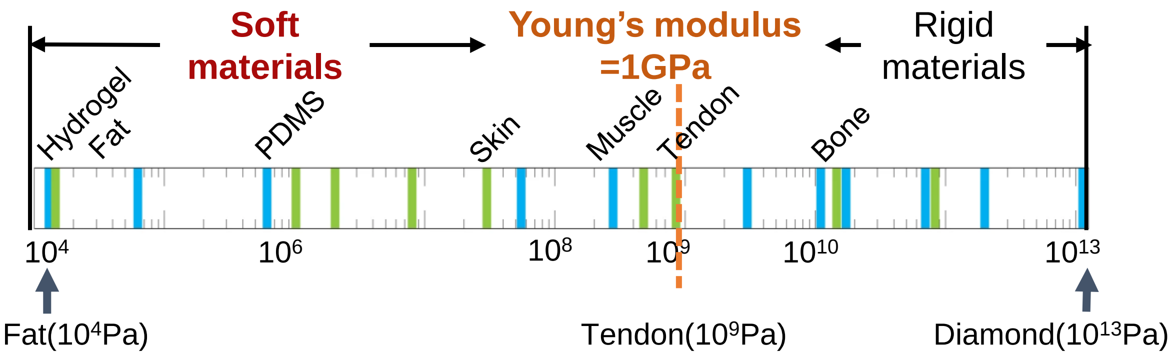
Soft robots

Robots whose core components (structure, actuation, sensing, etc.) are made of **soft materials**

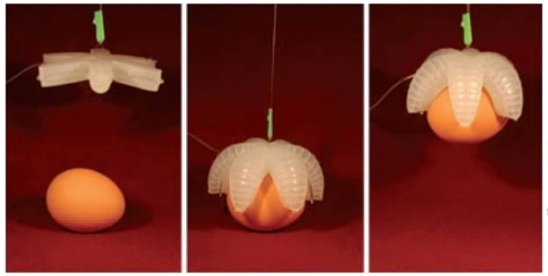


Young's modulus(Pa)

Rus., et al. Nature. 2015

Researches & applications

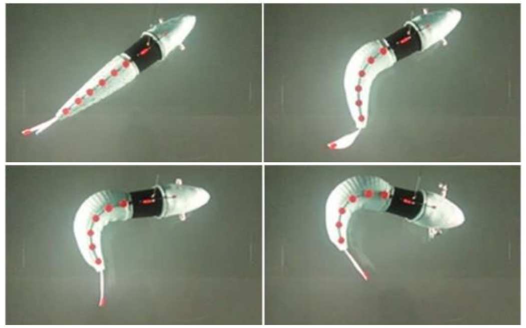
Due to the advantages, soft robots have been widely used in intelligent grasping, assisted rehabilitation, underwater detective and other fields



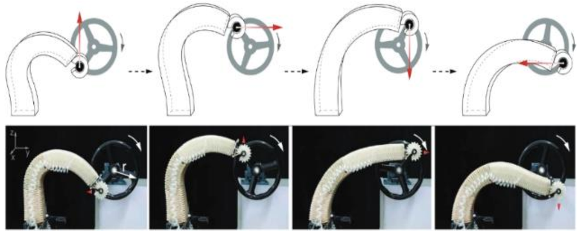
Ilievski., et al. Angew. Chem. 2011

Polygerinos., et al. Robot. Auton. Syst. 2015

Baines., et al. Nature. 2022

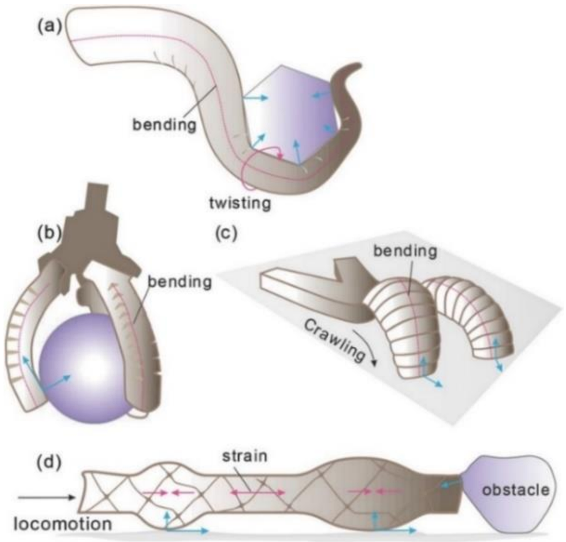


Marchese., et al. Soft Robot.2014



Jiang., et al. Int. J. Robot. Res. 2021

Our research

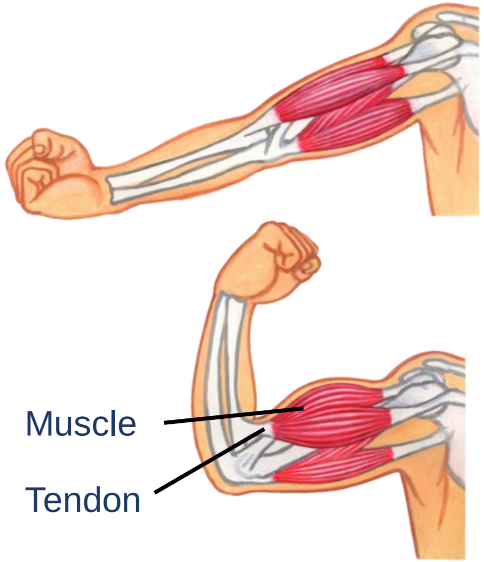


Wang., et al. Adv. Sci. 2018

In the face of complex tasks or unstructured environments, soft robots require **self-shape perception** to execute tasks smoothly like biological systems

Introduction---Proprioception

Proprioception



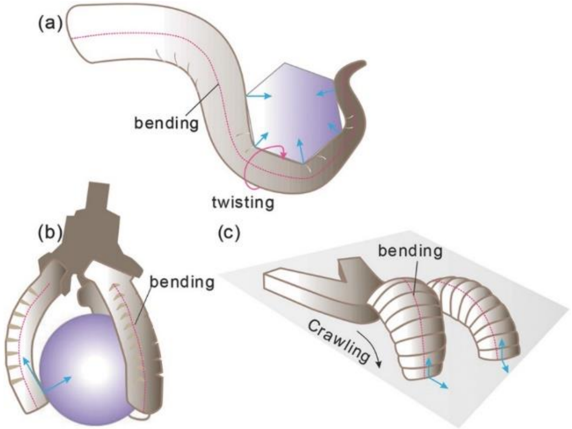
The concept of **Proprioception** was first proposed by British neurophysiologist Charles Sherrington in 1906.
It represents sensory information from nerve receptors such as joints, muscles and tendons in the human body

Rigid robots

The development of perception technology for rigid robots has a long history, and there are now more mature solutions.

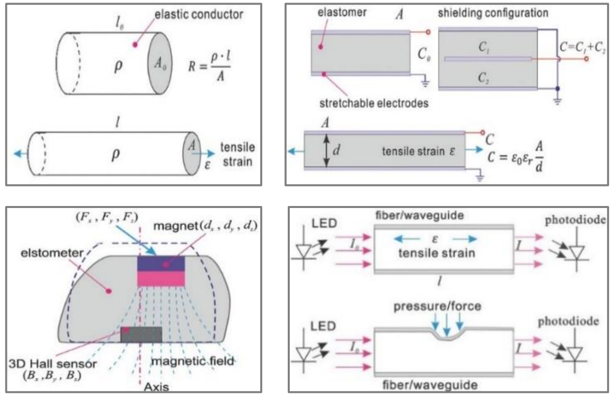
Usually, the information obtained by the encoder, such as the angle of the motor, is the proprioceptive information.

Soft robots



The methods and technologies for proprioception in soft robots have a relatively short history of development and are currently still under extensive exploration.

Currently, the widely explored methods are primarily categorized into four types: resistive, capacitive, magnetic, and optical.



Wang., et al. Adv. Sci. 2018

Introduction---Traditional TIR optical sensor

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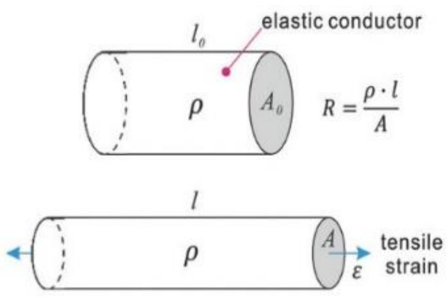
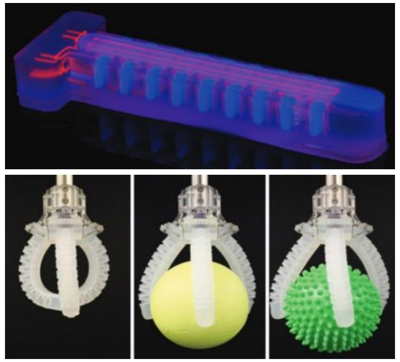
Resistive

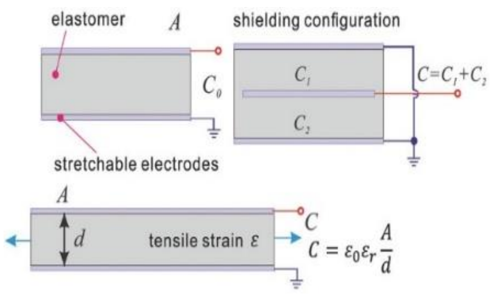


Resistance variations caused by changes in geometry or resistivity of conductive materials



Truby., et al. Adv. Mater. 2018

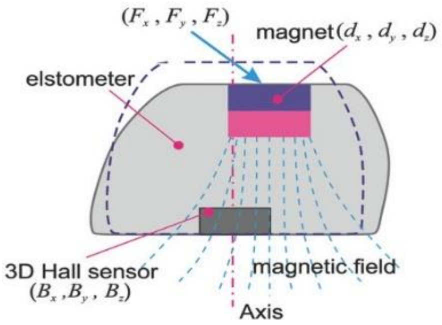
Capacitive



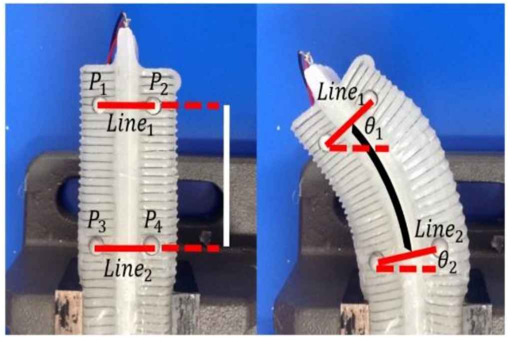
capacitance variations caused by geometry changes when the elastic body is deformed

Atalay., et al. Adv. Mater. Technol. 2017

Magnetic

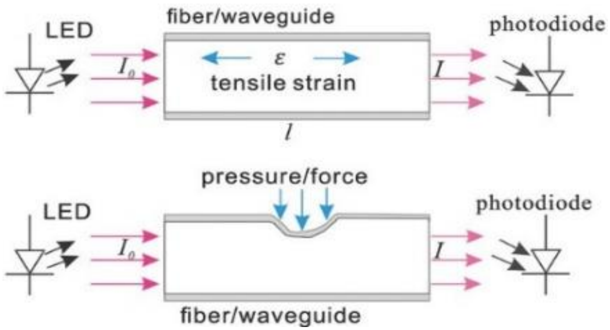


The relative position and orientation of the Hall-effect sensor for the permanent magnet

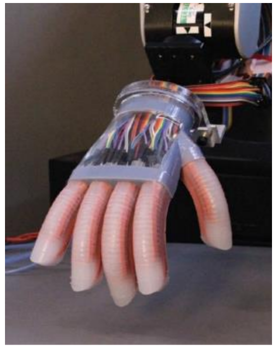


Ozel., et al. Compos. Part B. 2016

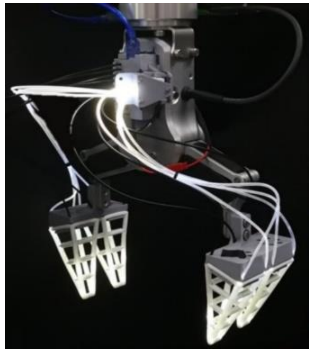
Optical



Light variations (intensity, frequency, or phase) caused by strain or pressure applied to the light transmission medium



Zhao., et al. Sci. Robot. 2016



Yang., et al., RoboSoft. 2020

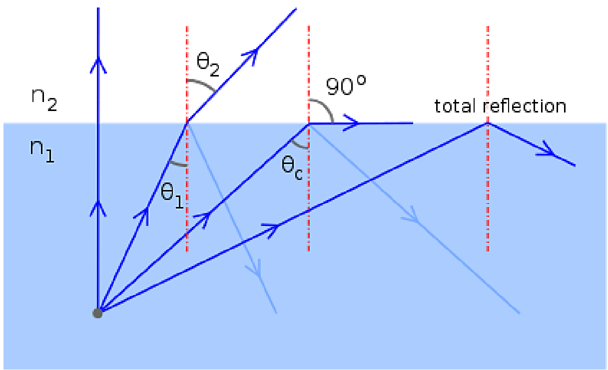
Sensing Technologies for Soft Robots ⇨

1. Soft robots equipped with **proprioception** capabilities show **stable** and **accurate** performance in task execution

2. Optical waveguide method are widely studied due to its advantages such as fast response, high sensitivity, and strong anti-interference

Introduction---Traditional TIR optical sensor

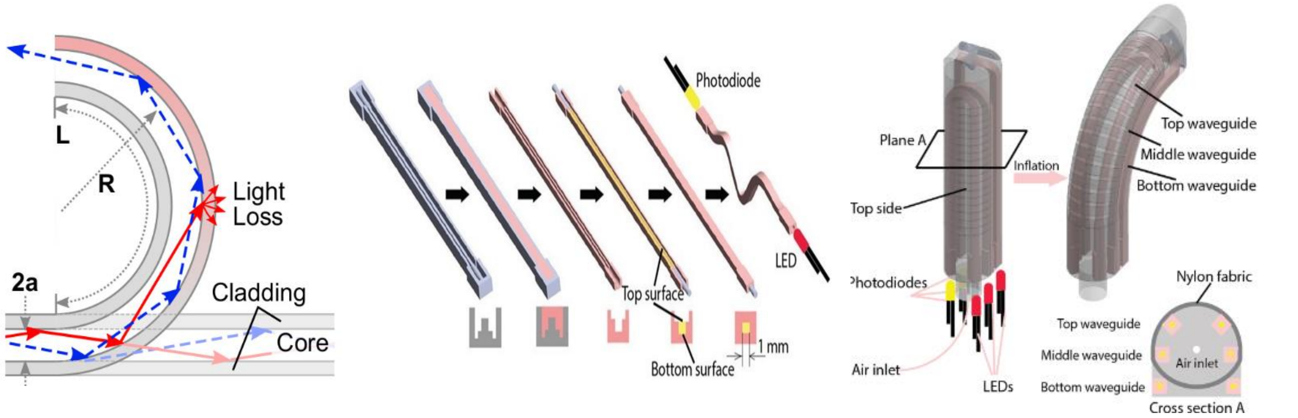
Total internal reflection



In physics, **total internal reflection** (**TIR**) is the phenomenon where light is not refracted into the second medium but is completely **reflected back** into the first medium

$$n_1 \geq n_2, \theta \geq \theta_c$$

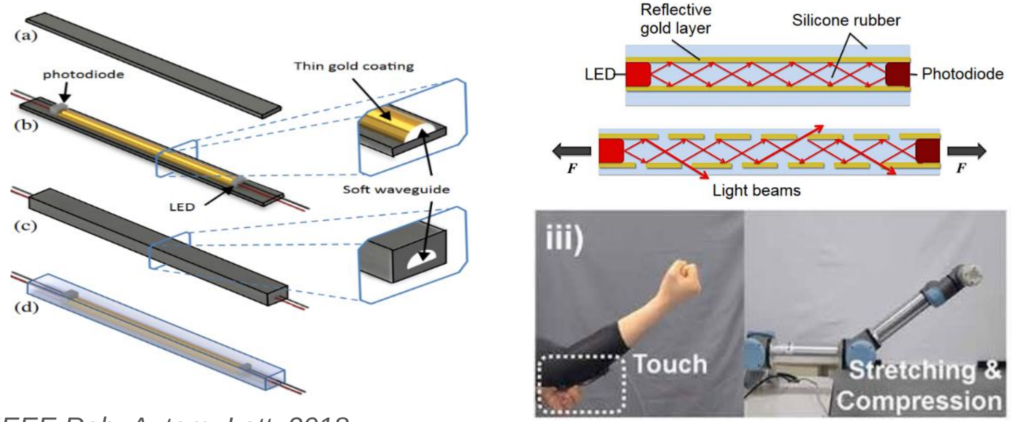
TIR optical waveguide sensor



Zhao, et al. Sci. Robot. 2016

Limitations or difficulties

- Composed of **two or more materials** with different refractive indexes
- Manually produced, the fabrication process is **cumbersome** and has **poor repeatability**
- Sensors are integrated with the robot body through **post-assembly**



Celeste, et al. IEEE Rob. Autom. Lett. 2018

Traditional optical sensor: complex fabrication, poor repeatability and scalability

3D-printed optical sensor

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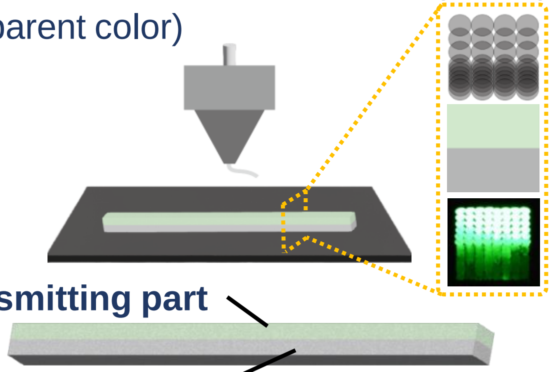
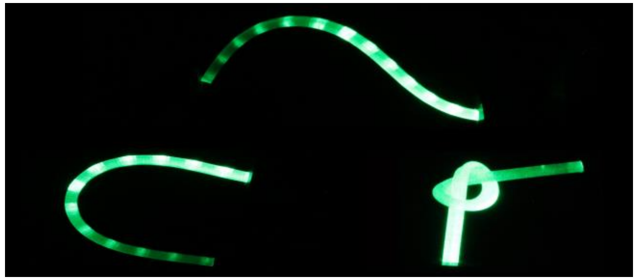
Method & material

The **light attenuation** of waveguides can be adjusted by setting the printing structures

Common **FDM** method
Single TPU material
(transparent color)

Differential optical waveguide (**DOW**)





3D-printed, flexible, light-conducting waveguides

Key structures

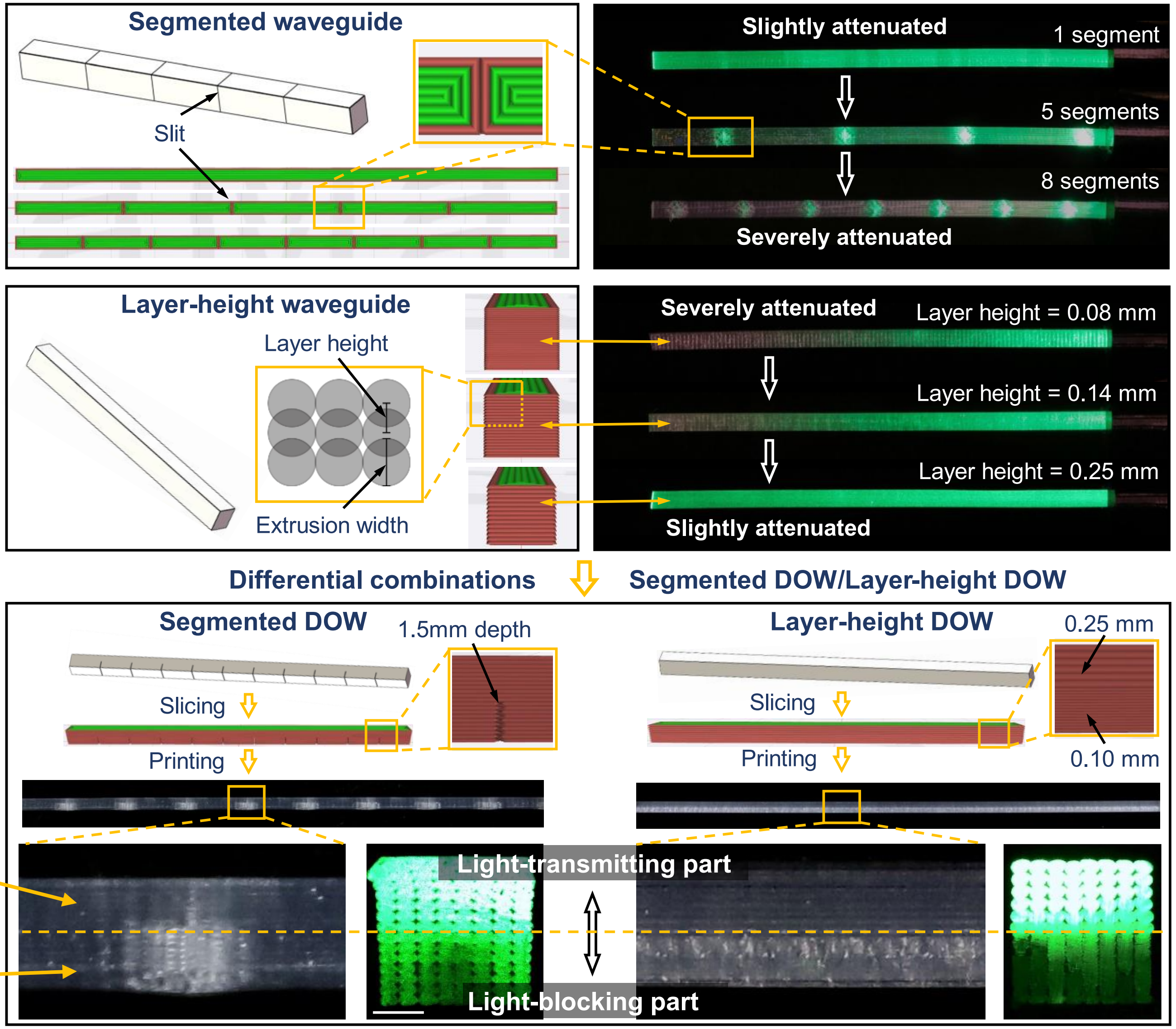
1. segments

2. layer-height

Construct and integrally print optical waveguides with differential optical attenuation structures

Lower light attenuation

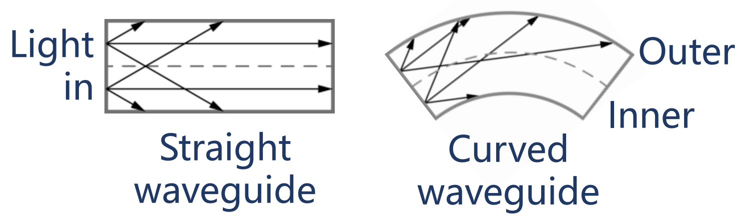
Higher light attenuation



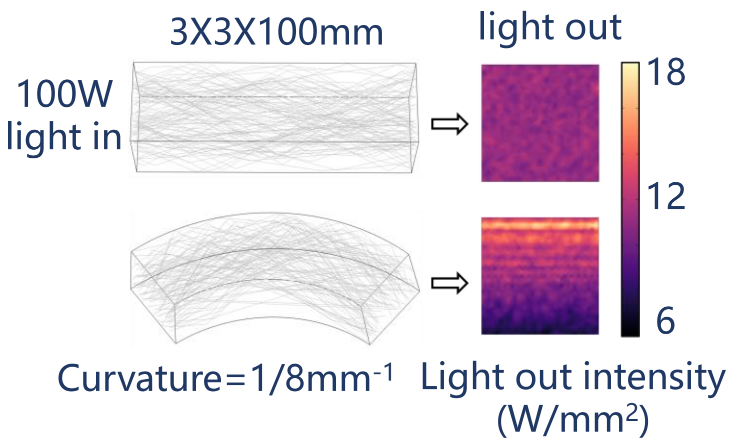
3D-printed optical sensor

light propagation + Adjustable light attenuation = 3D-printed DOWs

Analysis:

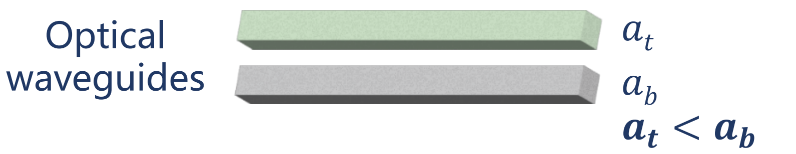


Simulation:

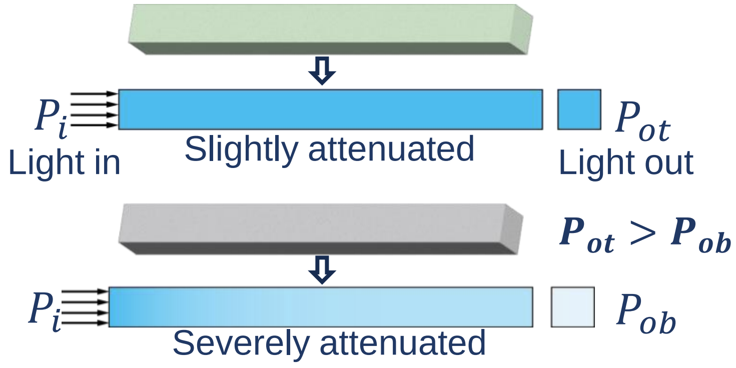


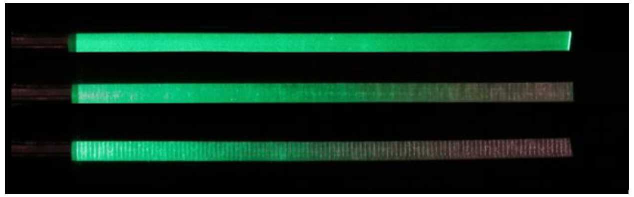
Attenuation coefficient:

$$a = \frac{10\lg(P_i/P_o)}{l}$$

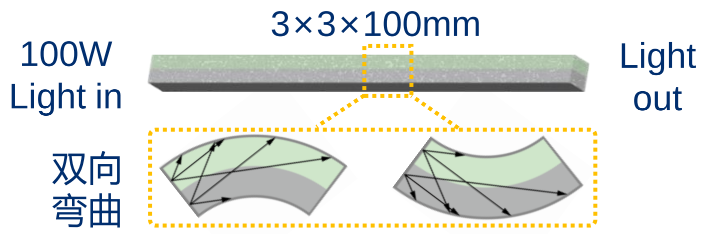


Light attenuation:

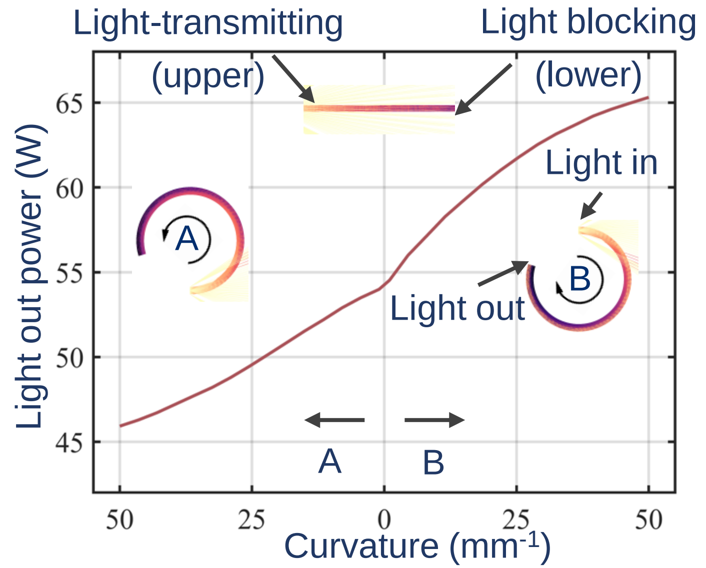




Structural principle:

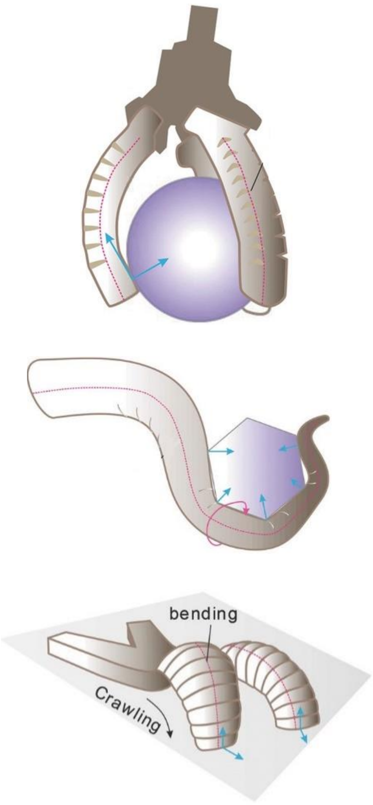


Simulation:

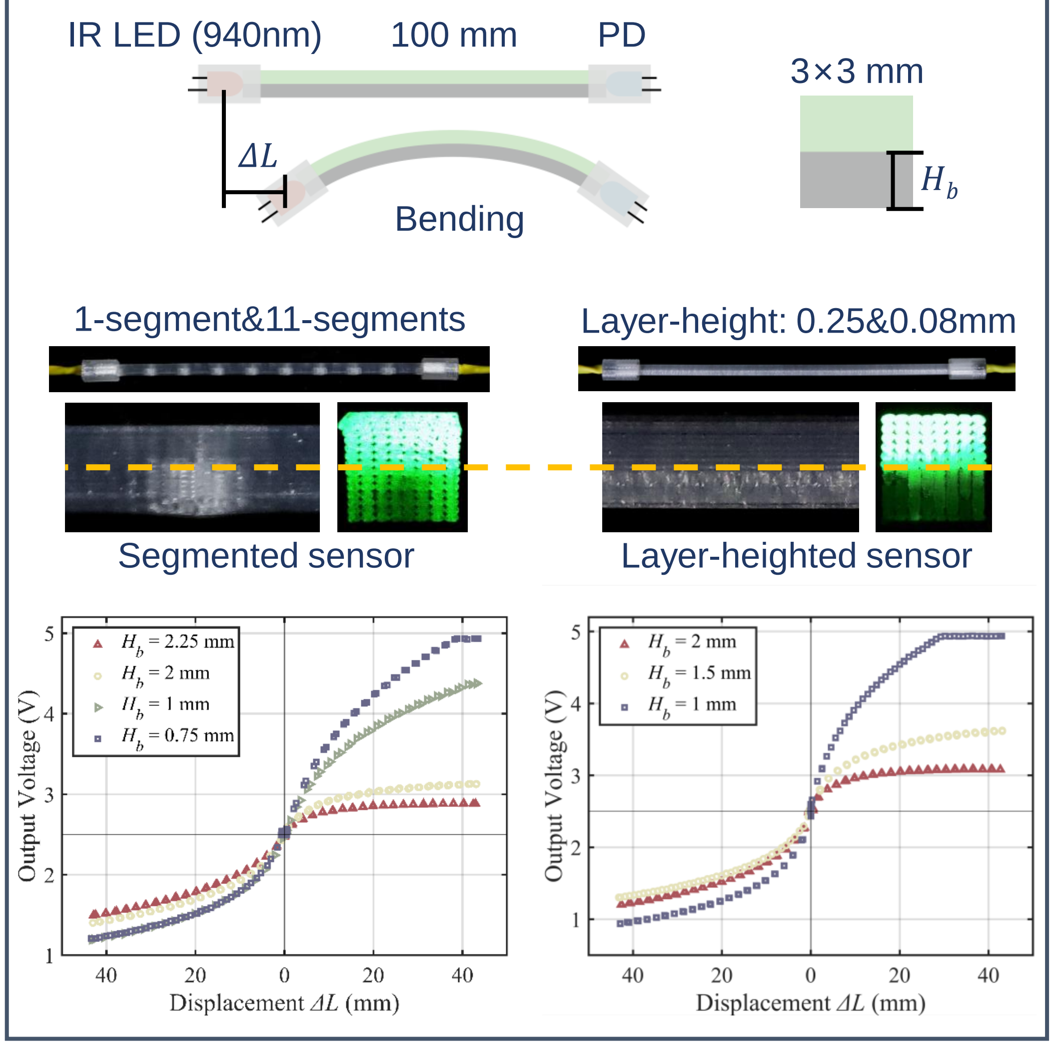


3D-printed optical sensor

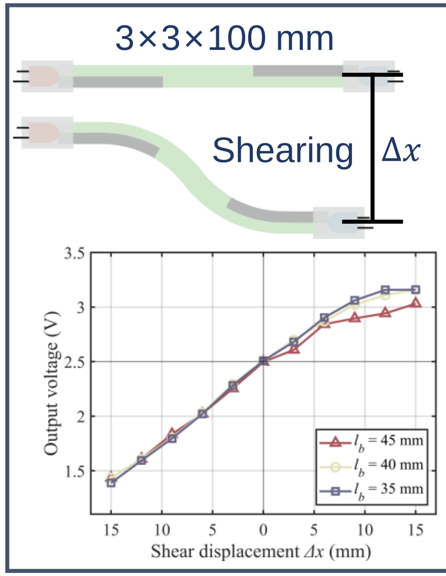
For the perception needs of soft robots, three types of deformation sensors were designed and verified.



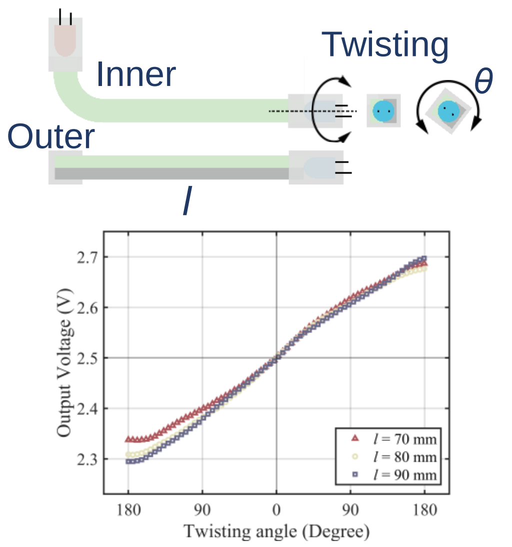
Bending sensor

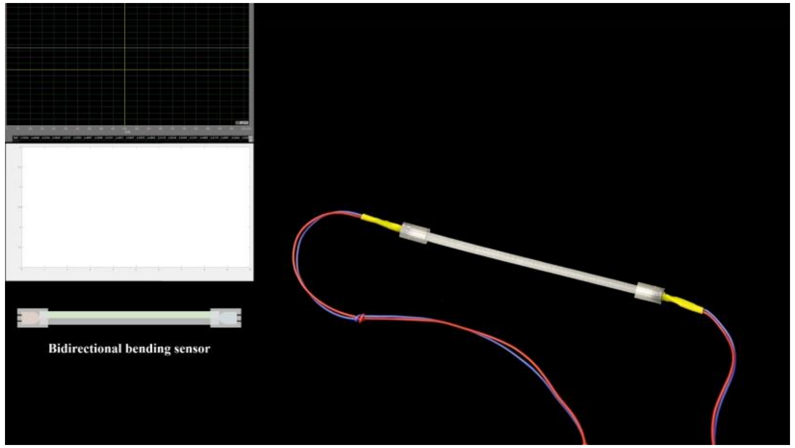


Shearing sensor



Twisting sensor





Bidirectional deformation sensing

3D-printed optical sensor

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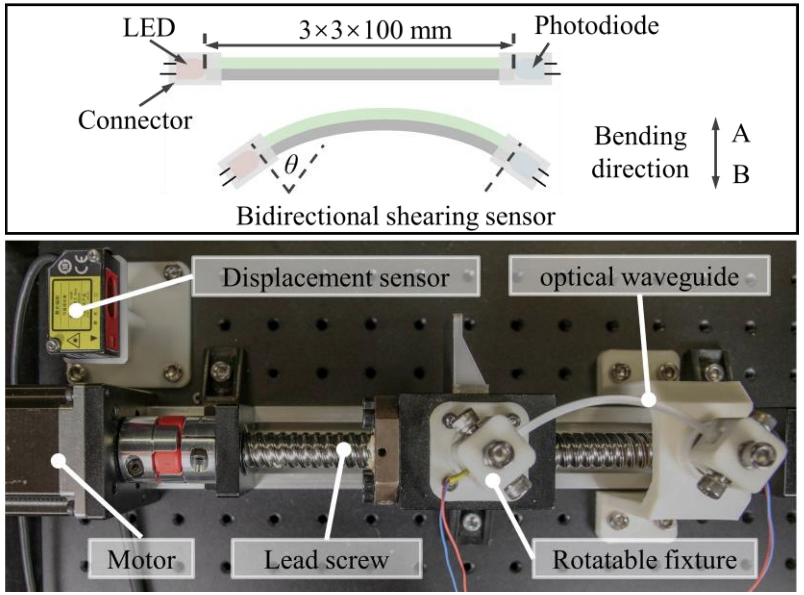
Experimental setup

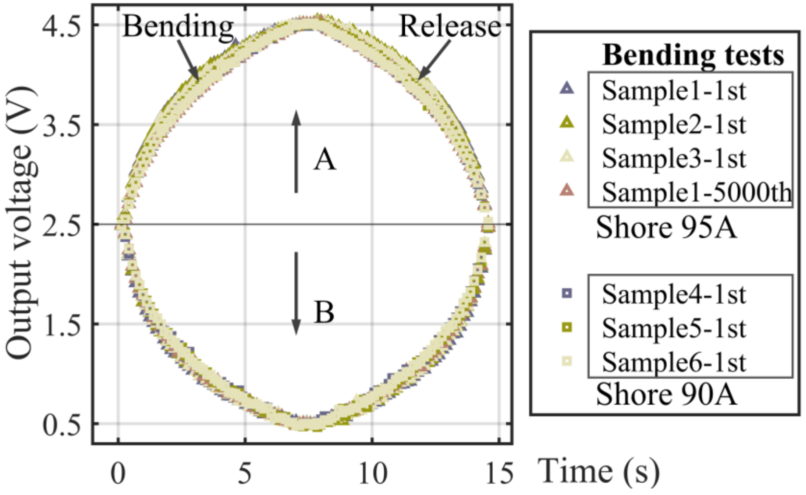
The **bending angle** of the waveguide and the **voltage** generated by the photodiode and circuit were recorded.



Repeatability & consistency

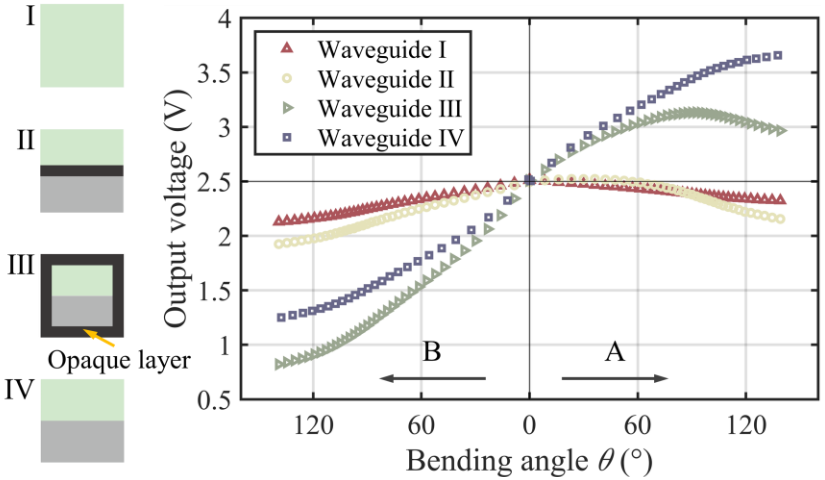
5000-replicate tests of 6-samples

The maximum RMSE is **0.104V**



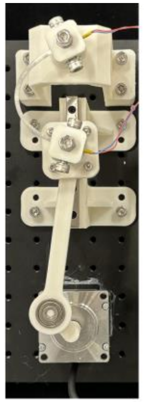
Structural comparison

The proposed DOW design can detect bidirectional bending deformation



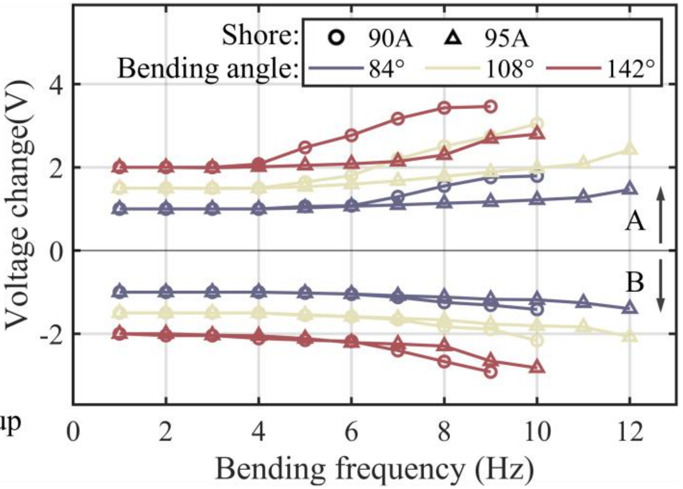
Response bandwidth

The maximum response bandwidth is about **9Hz**



Crank-slider setup

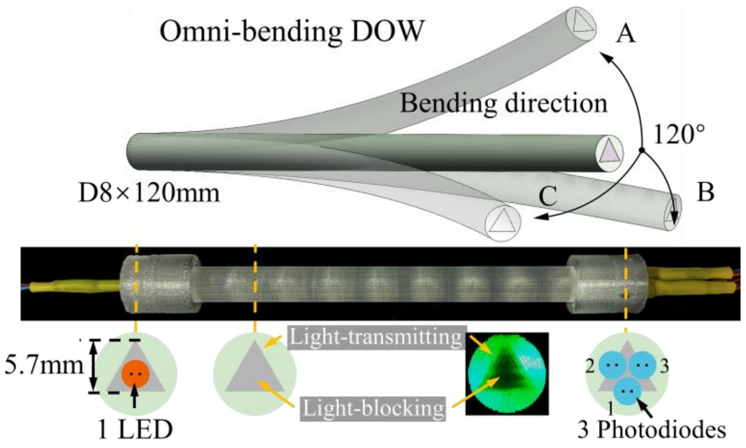
(Max: 12Hz)



3D-printed optical sensor

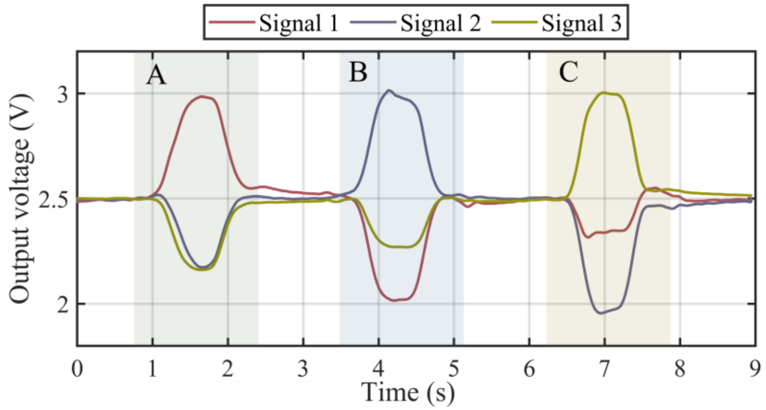
Omnidirectional bending sensor

The omnidirectional bending sensor designed based on the proposed method



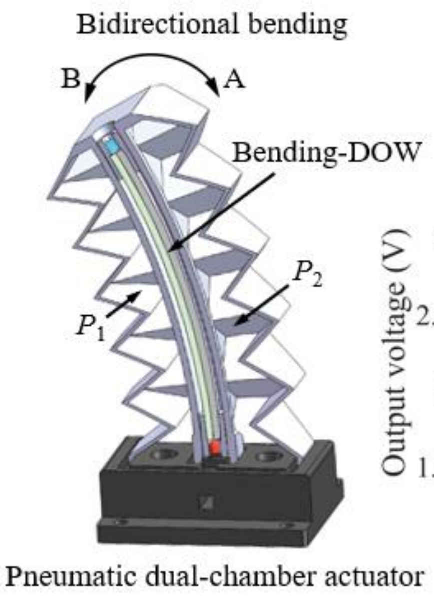
It consists of a waveguide, an LED and three PDs

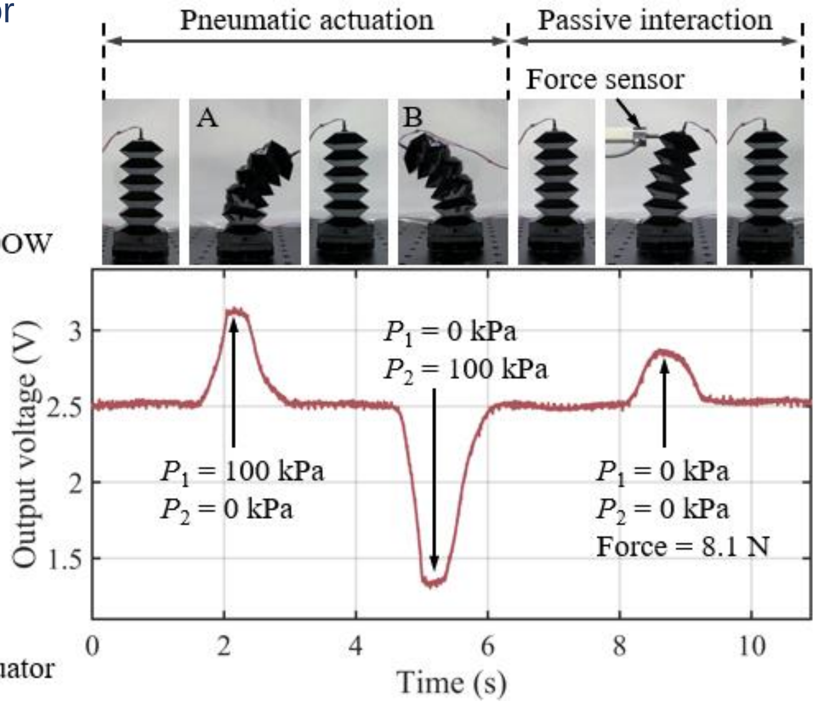
From the test data, the sensor has the potential to detect omnidirectional bending



Proprioception of a soft actuator

Soft actuator with embodied optical sensor



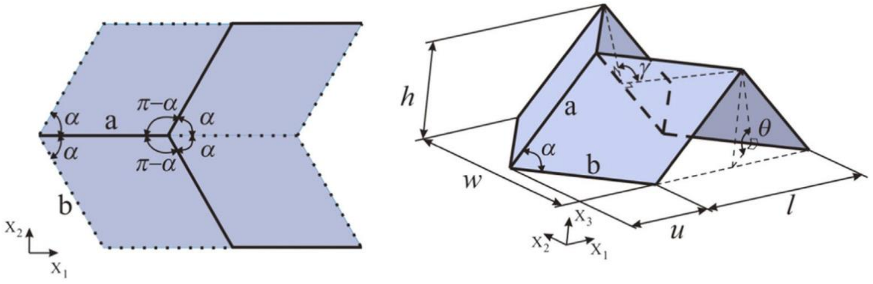


The results show that the embedded optical waveguide can detect the **active actuation** and **passive interaction** states of the soft actuator

3D-printed Miura-origami metamaterial

Miura-origami unit

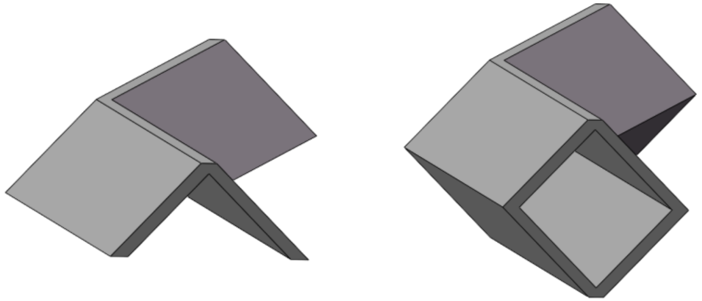
Design parameters: a, b, α, θ



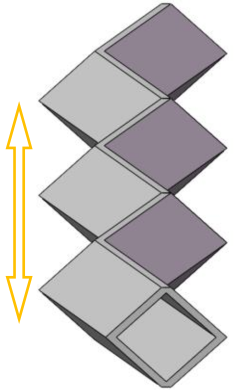
Basic geometry model:

$$\begin{cases} h = a \sin\theta \sin\alpha & g = 2a \sin\alpha \cos\theta \\ u = \dfrac{2ab\cos\alpha}{l} & w = 2b \dfrac{\cos\theta \tan\alpha}{\sqrt{1+\cos^2\theta \tan^2\alpha}} \\ l = 2a\sqrt{1-\sin^2\theta \sin^2\alpha} & \end{cases}$$

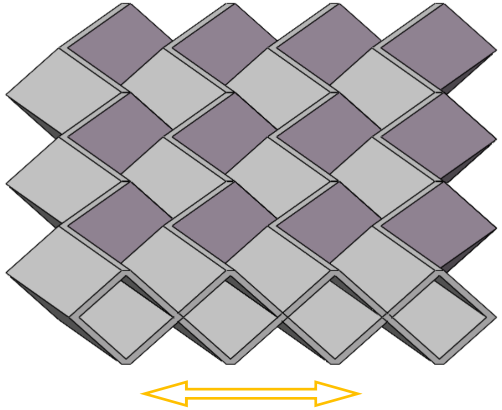
1-DoF Miura-origami unit



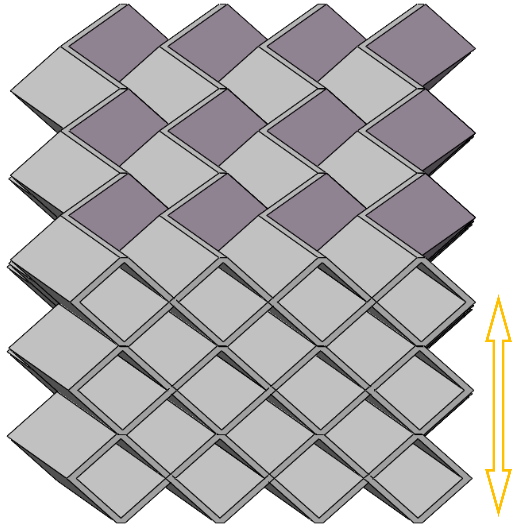
Miura-ori metamaterial



One-dimensional array

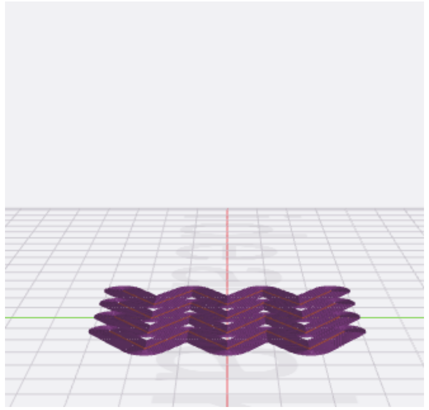


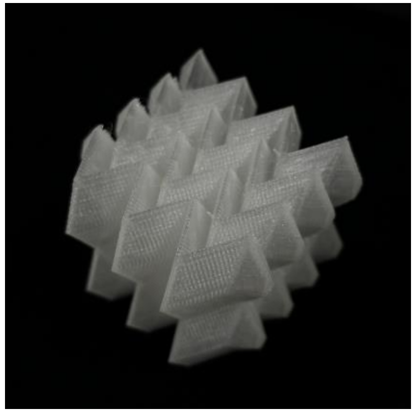
Two-dimensional array



Three-dimensional array

3D-Printed Miura-ori metamaterial

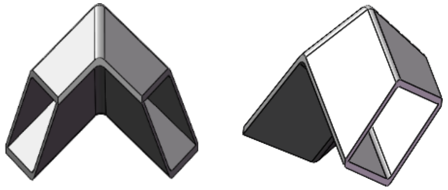




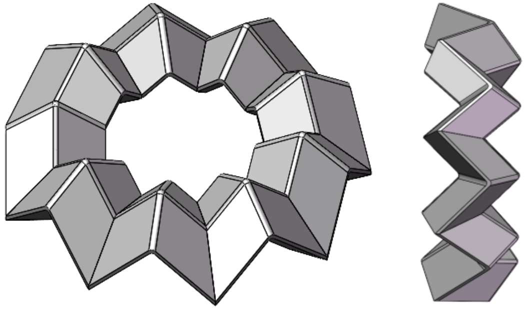
3D-printed soft actuators

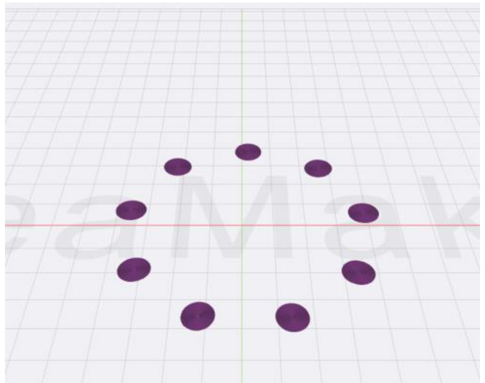
Ring-shaped gripper

40° Miura-origami unit



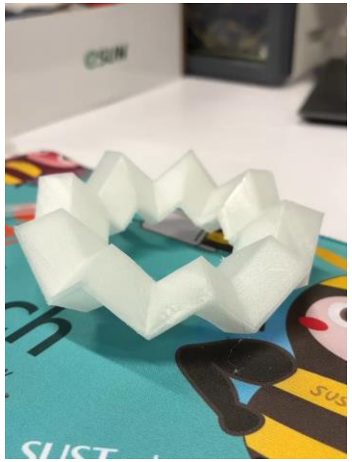
Ring-shaped gripper

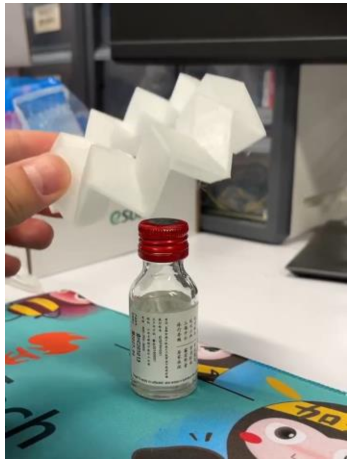




Actuation & Grasping

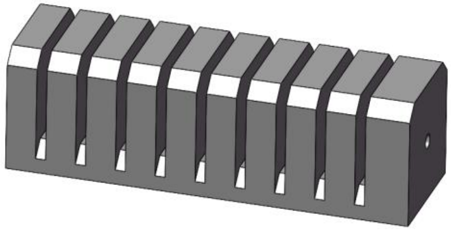
Single chamber, 1-DoF

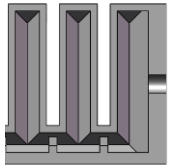


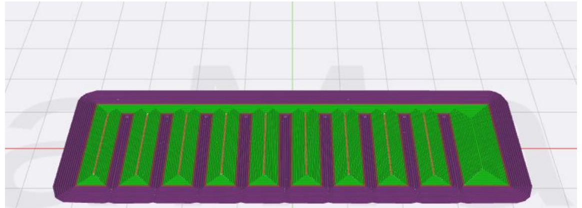


PneuNet actuator

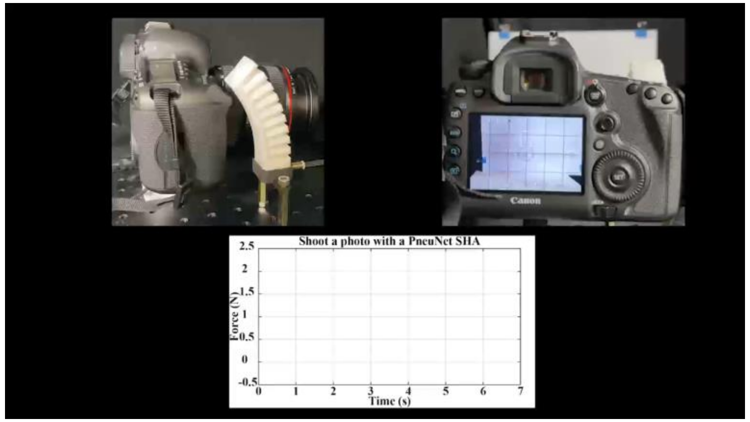
Bending actuator





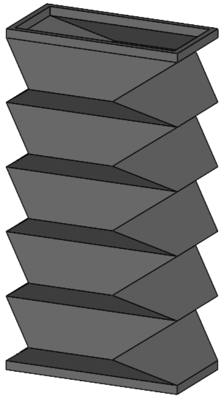


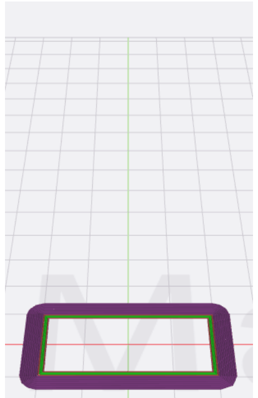
Shooting Demo



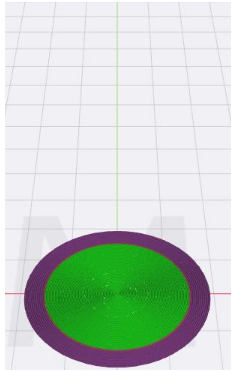
Linear actuator

Origami-based actuator





Bellow-based actuator



Conclusion and Future work

Southern University of Science and Technology

Conclusion:

- **Proprioception in soft robots:**

This presentation introduces the proprioception of soft robots and four common sensing methods, emphasizing the advantages of the optical approach.

- **3D-printed optical waveguide sensor:**

A novel differential optical waveguide design method is introduced and rapidly fabricated using 3D-printing. Experimental validation confirms the excellent performance of the proposed sensor, demonstrating potential for proprioception in soft robots.

- **3D-printed Miura-metamaterials and actuators:**

Additionally, the application of 3D-printing in fabricating Miura-origami metamaterials and various types of actuators is introduced, highlighting the significant role of 3D-printing technology in the development of soft robots.

Future work:

- **The mechanism of optical waveguide sensor:**

Referring to geometric optics and statistical optics, we will further study the propagation mechanism of optical waveguide sensors to investigate a universal sensing model.

- **Integrated printing of actuator and sensor:**

Designing of various types of actuators with embedded optical waveguide sensors, which would be fabricated integrally by using the common FDM 3D-printing technique.

- **Multimodal sensing metamaterials:**

Developing Miura-origami metamaterials with multimodal sensing capabilities.

Thanks for Listening!