Reconfigurable Self-Shrinking Magnetic Soft Robot Accessible to Confined Spaces

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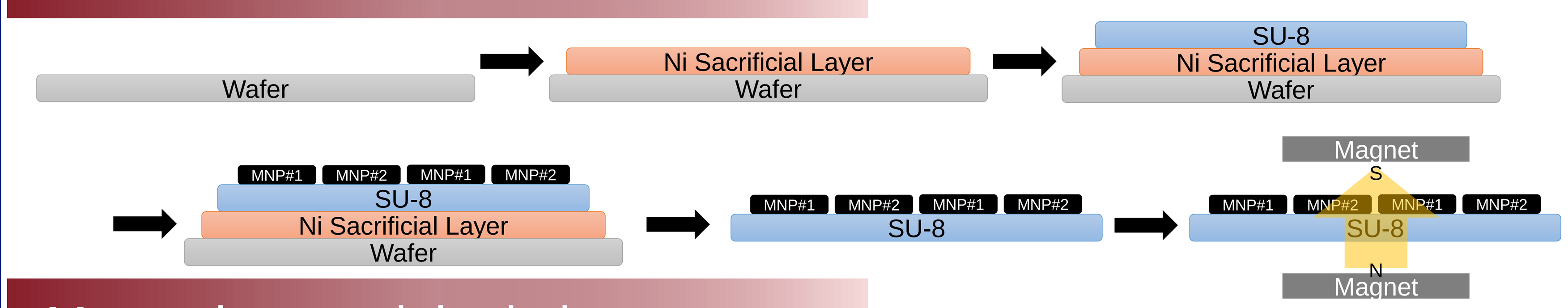
Introduction

Magnetic soft robots have highly applicable to healthcare and bio-application devices. Depending on the design, complex and small human areas are easily accessible. Furthermore, it can be controlled remotely to achieve healthcare functionality. Magnetic soft robots can be used in various applications such as drug delivery to narrow areas, targeted therapy, biopsy or catheter. So far, there have been many studies on the structure of large sizes. Bio-application requires the micro-size or smaller structures for easy access to small human areas.

This study devised a submillimeter-sized magnetic foldable soft robot. Device was fabricated using lithography, and the hinge design and magnetization conditions were optimized. A folding structure was implemented by applying an external magnetic field.

Experimental Methods

Device Fabrication Process

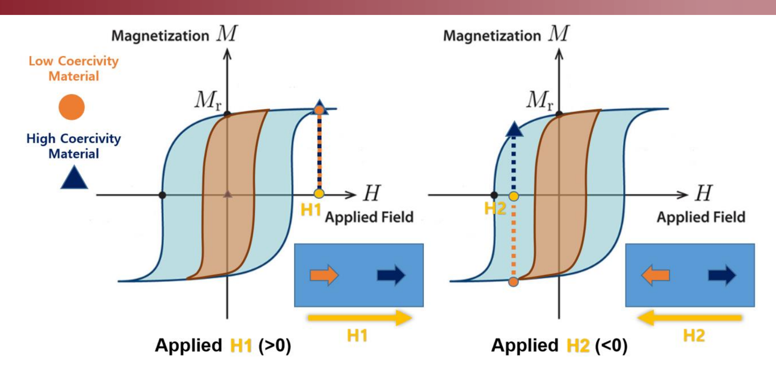


Magnetic material printing

There are several advantages of using the printing method of magnetic materials. First , it is possible to print with a high resolution of tens of micrometer scales. Second, it is possible to apply a high concentration, that is, a large amount of magnetic nano particles(MNPs). Finally, it is possible to quickly apply the MNP in a short time.

Main Idea

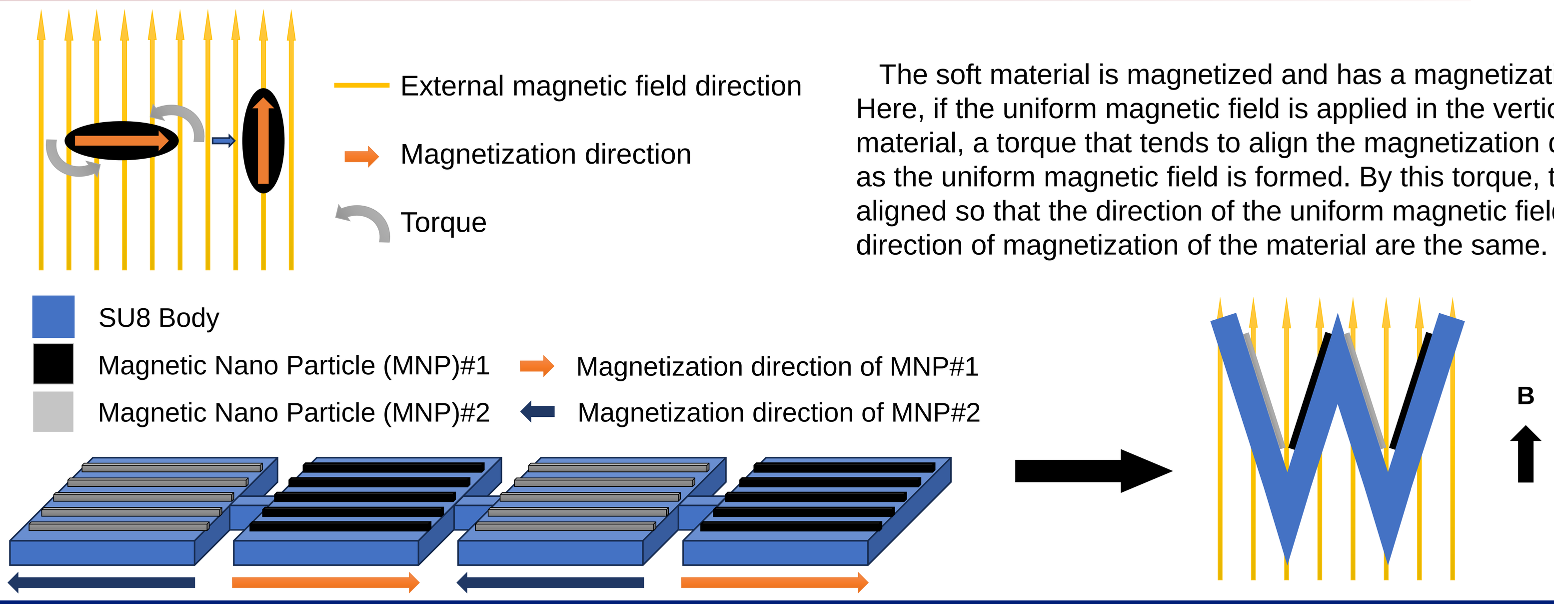
Coercivity Engineering



Two kinds of magnetic nanoparticles are used, and the magnetization direction can be controlled by the applied magnetic field according to the different characteristics of their magnetization curves.

Two particles have different values of coercivity. When the particles are magnetized in a magnetic field that is much higher than the coercivity of two particles, the two particles are magnetized in the same direction. And if the particles are magnetized in the opposite direction by the magnetic field of the value between the coercivity of two particles, only the lower coercivity particles will change their magnetization direction.

Principle of shrinking via folding motion



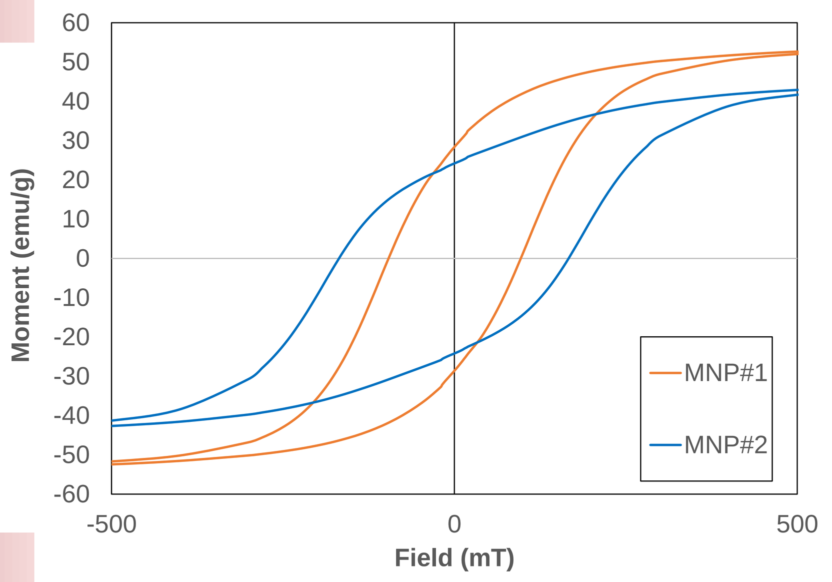
The soft material is magnetized and has a magnetization direction. Here, if the uniform magnetic field is applied in the vertical direction of the material, a torque that tends to align the magnetization direction the same as the uniform magnetic field is formed. By this torque, the material is aligned so that the direction of the uniform magnetic field and the direction of magnetization of the material are the same.

Results

1. Material

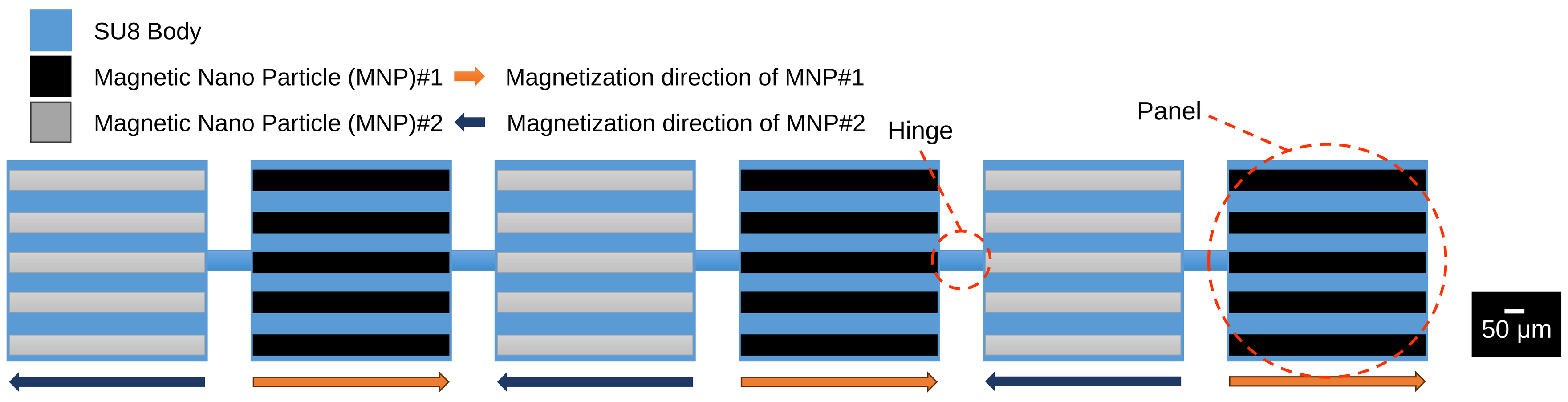
Magnetic nanoparticles (MNPs) are used for magnetic material. MNPs consist of $Zn_{0.4}Fe_{2.6}O_4@CoFe_2O_4$, and are octahedron shaped with size of 30 nm (MNP#1) and 40 nm (MNP#2), respectively.

Material	Coercivity (Hc) [mT]	Moment under 20 mT [emu/g]
MNP#1	96	32.54
MNP#2	168	25.89

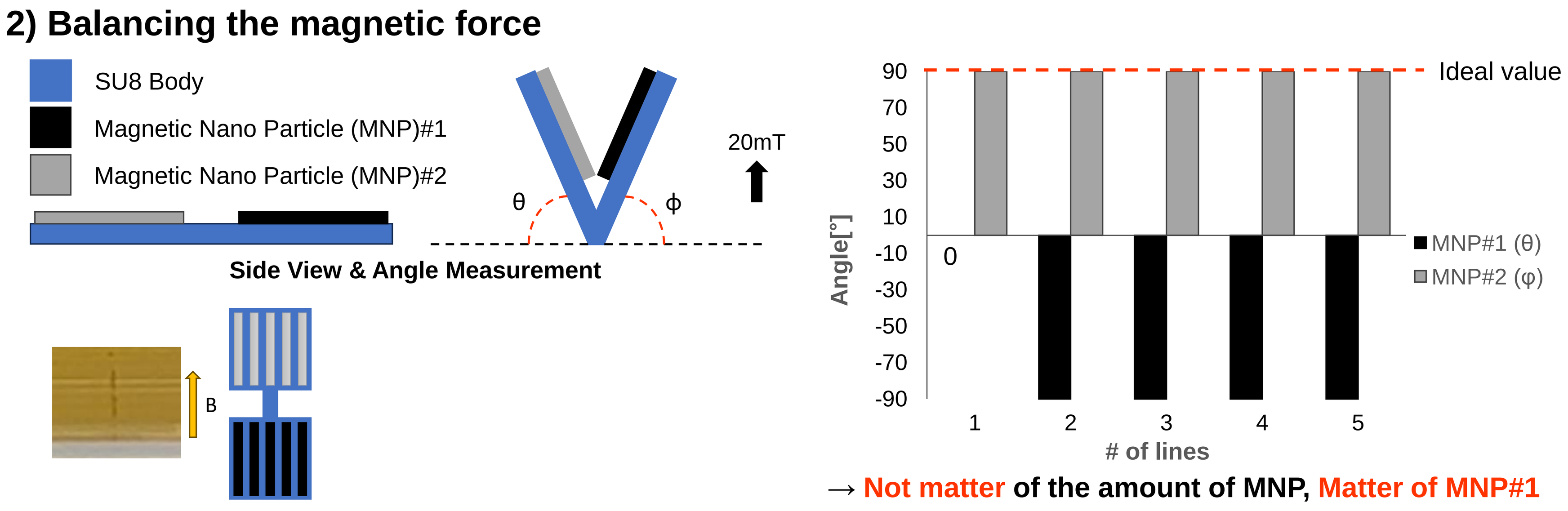


2. Folding test

1) Design

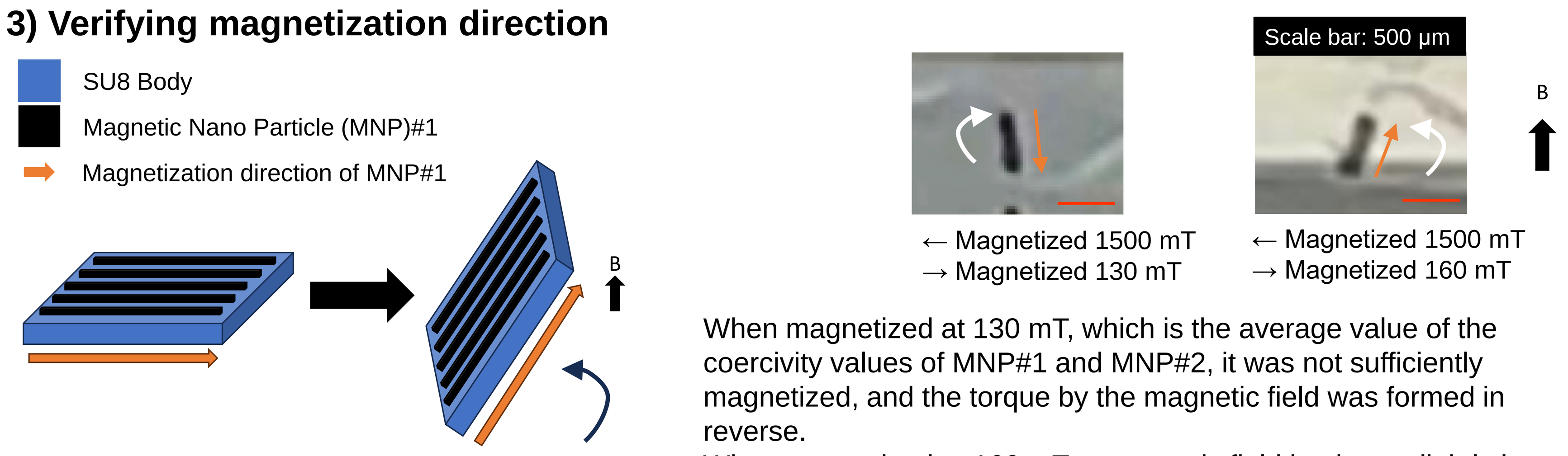


2) Balancing the magnetic force



→ **Not matter** of the amount of MNP, **Matter of MNP#1**

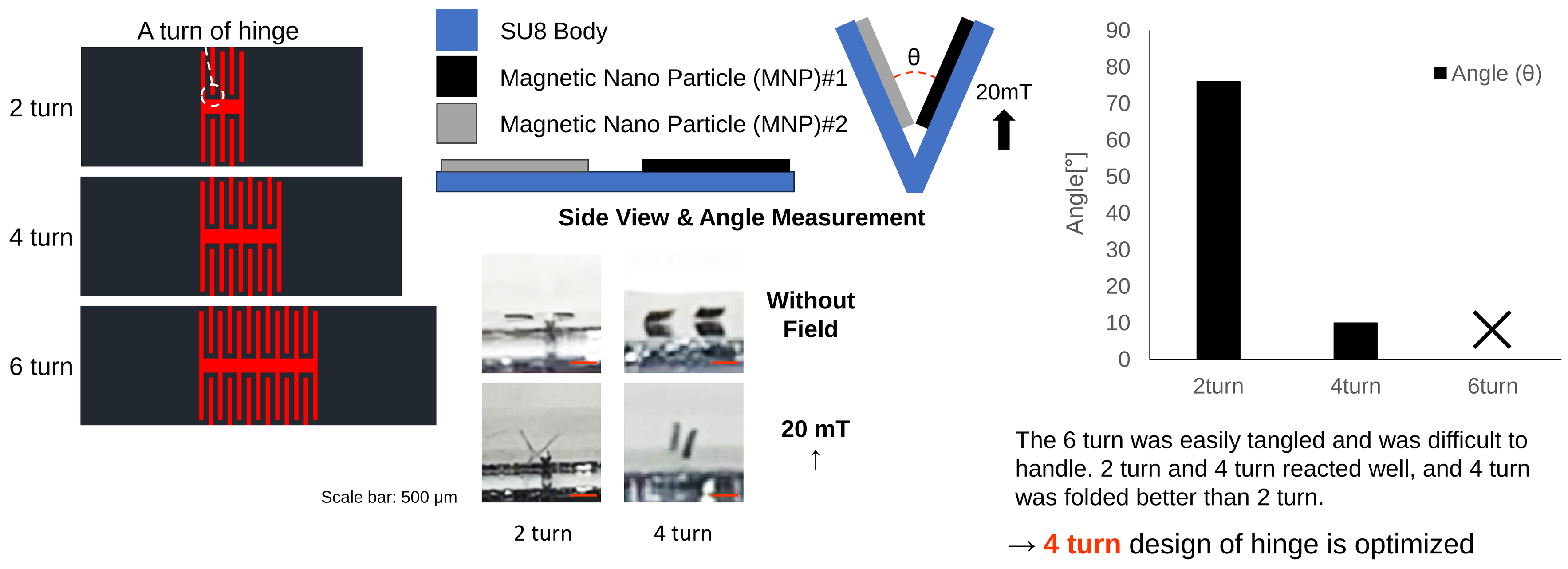
3) Verifying magnetization direction



When magnetized at 130 mT, which is the average value of the coercivity values of MNP#1 and MNP#2, it was not sufficiently magnetized, and the torque by the magnetic field was formed in reverse.

When magnetized at 160 mT, a magnetic field having a slightly larger value than that, a magnetization direction was formed in a set direction.

4) Number of hinge turns



The 6 turn was easily tangled and was difficult to handle. 2 turn and 4 turn reacted well, and 4 turn was folded better than 2 turn.

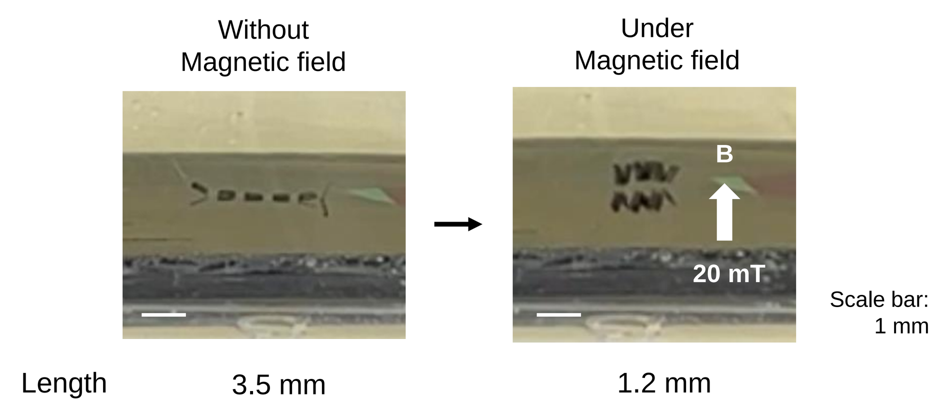
→ **4 turn** design of hinge is optimized

3. Magnetic actuation of shrinking soft robot

1) Multi-panel magnetic actuated soft robot

Multi-panel soft robot is actuated under magnetic field to quantify shrinkage. Here, six-panel soft robot is analyzed.

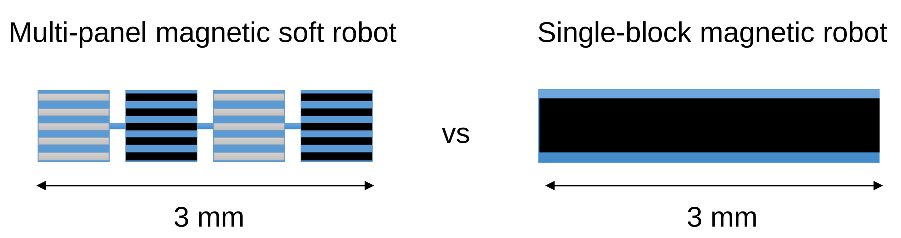
Under 20 mT uniform magnetic field, the six-panel soft robot is folded and **shrunk about three times**. We expect the greater number of panel, the shrinkage will be greater.



→ ~3 times shrinkage

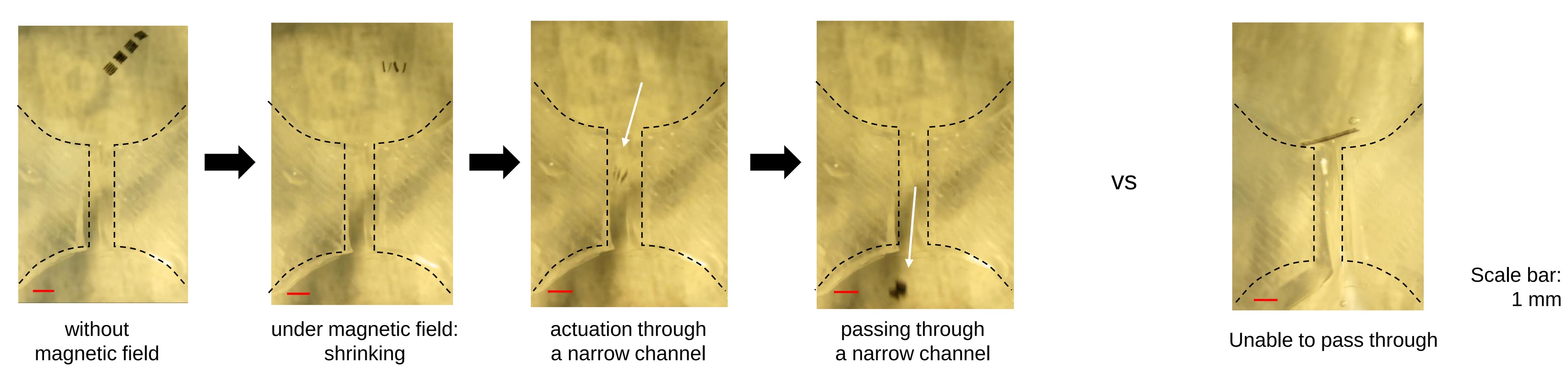
2) Magnetic actuation in confined spaces

In order to demonstrate advantages of shrinking upon magnetic actuation, we compared magnetic actuation of two different robots, a multi-panel magnetic soft robot and single-block magnetic robot.

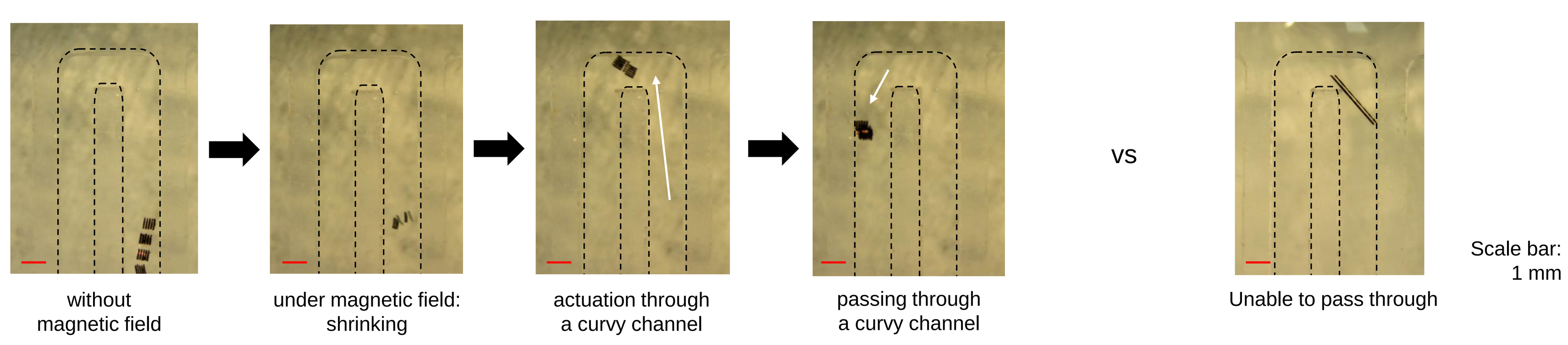


(a) Narrow channel

Size of the narrow channel: 1 mm



(b) Curvy channel



Single-block magnetic robot was difficult to pass through the channels due to the size of the narrow channel larger than the robot size. On the other hand, the multi-panel magnetic soft robot could pass through the channels even smaller than its size due to its shrinking motion.

Conclusion & Further Study

Conclusion

I carried out experiments by two different kinds of magnetic materials, three kinds of hinge designs, and two kinds of magnetization conditions. As a result, I found optimal condition for our magnetic foldable soft robot consist of multiple panels. Our robot had the best folding actuation when connected by a hinge of 4 turn design and magnetized at 1500 mT in the MNP#2 direction and 160 mT in the opposite direction. It had to be magnetized with a magnetic field greater than the average of the coercivity of the two MNPs. And it shrank ~3 times by folding and could be applied to passing through narrow channels.

Further Study

Our robot has made highly applicable motion under the external magnetic field. Therefore, our experimental model is expected to be applicable to sensing techniques by integrating recording electrodes. Also, it is expected that it can be used for organ-on-chip system by allowing it to pass through the complex microfluidic channel of the human body.

Reference

[1] Yoonho Kim and Xuanhe Zhao, Chemical Reviews, 2022, Magnetic Soft Materials and Robots
[2] Schmauch, M. M.; Mishra, S. R.; Evans, B. A.; Velev, O. D.; Tracy, J. B. Chained Iron Microparticles for Directionally Controlled Actuation of Soft Robots. *ACS Appl. Mater. Interfaces* **2017**, *9*, 11895– 11901