Magic paper： programmable magnetic origami robot for medical applications

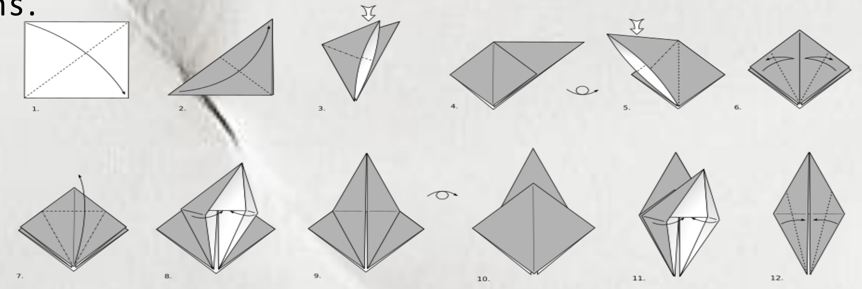
Introduction

1.Background & Inspiration

Magnetic microrobots help in medical tasks like imaging, drug delivery, and painless exams. They are wireless, battery-free, and safe for the body.

However, current microrobots have limits:

- **Simple Shapes** – Hard to make complex or flexible designs.
- **Fixed Functions** – Cannot change movement or shape after making.
- **Manufacturing Limits** – Methods like 3D printing restrict designs.



Origami is an art form that showcases immense creativity. It begins with a simple piece of paper and, through folding, transforms into beautiful and intricate shapes.

2.Engineering Goal

- **New Fabrication Method** – Create a standard way to make microrobots.
- **More Flexibility** – Use the same design for different tasks and environments.
- **Origami & Pixel Design** – Use tiny magnetic "pixels" to shape and move better.
- **Better Medical Use** – Make a ver[...]ile microro[...]

Figure.1 Prototype made by folding paper

Robot Design

1.Principle

The magnetic robot uses pixel pieces' structure design allows flexible movement in different directions.

As shown in the figure, the robot's cross-section has:

- **Bottom Layer** – Made of paper, providing a flexible base.
- **Active Layer** – A mix of liquid metal and NdFeB magnets in a silica gel matrix.
  - **Liquid Metal** – Adds electrical conductivity and flexibility.
  - **NdFeB Magnets** – Improve magnetic control and m[...]

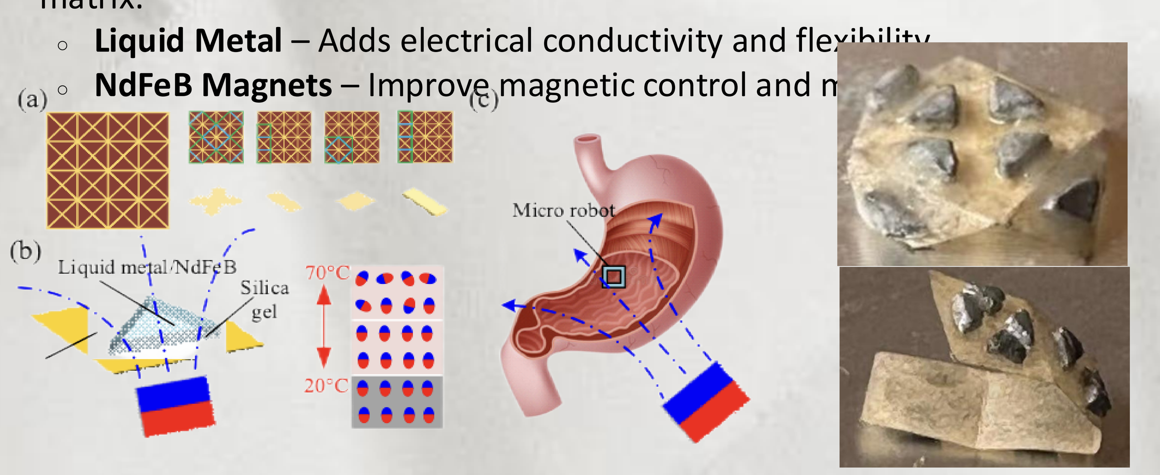


Figure.2 Principle of the magnetic origami robot:(a) ,(b), (c)

2.Materials

Figure.3 Materials: (a) liquid-metal ,(b)NdFeB powders, (c) silica gel, (d) paper

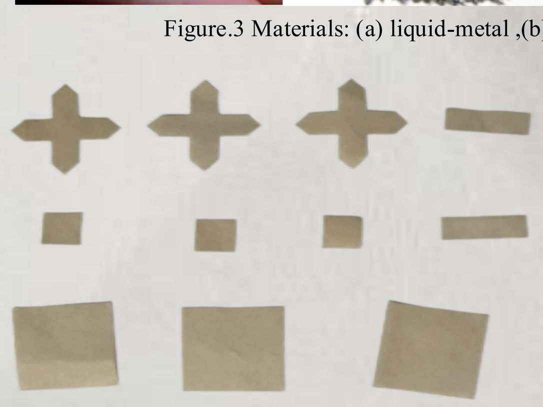


Figure. 4: Kraft paper cut by laser cutter of the shape of structures

Figure. 5: The finished magnetic robot after putting in magnetic clay

As shown in Fig.4, 4 type of robot substrate are cut by a UV Laser. These substrates are used to manufacture centimeter-scale robots.

We filled the paper with small pixel to allow the robot move more freely and complex.

Fabrication procedure

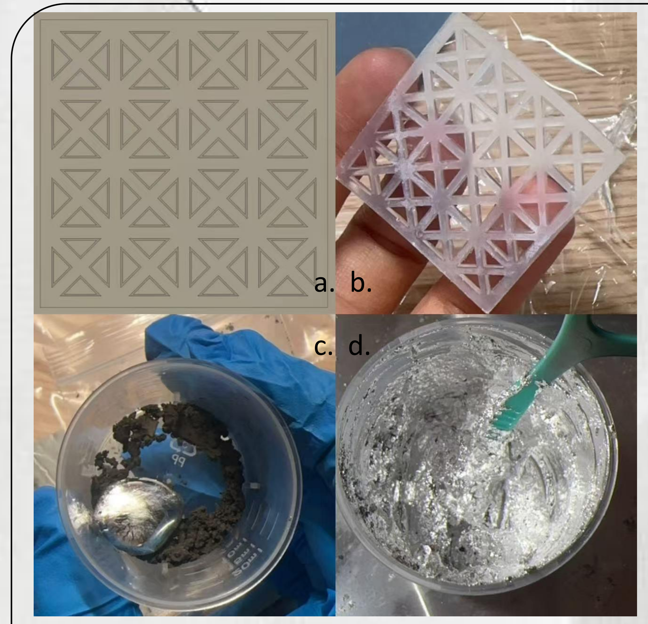


Figure.6 Materials: (a) CAD ,(b)Silicone soft mold, (c) NdFeB and Gallium, (d) magnetic mixture

Step 1: Materials

a. Use SolidWorks draw 3d model for mirror mold. Use SLA print out the model
b. Pure silicone in the model to make a soft mold
c. Mix the Gallium and NdFeB together with a ratio around 1:1
d. Step 4: Stir evenly until the mixture is close to the texture of plasticine

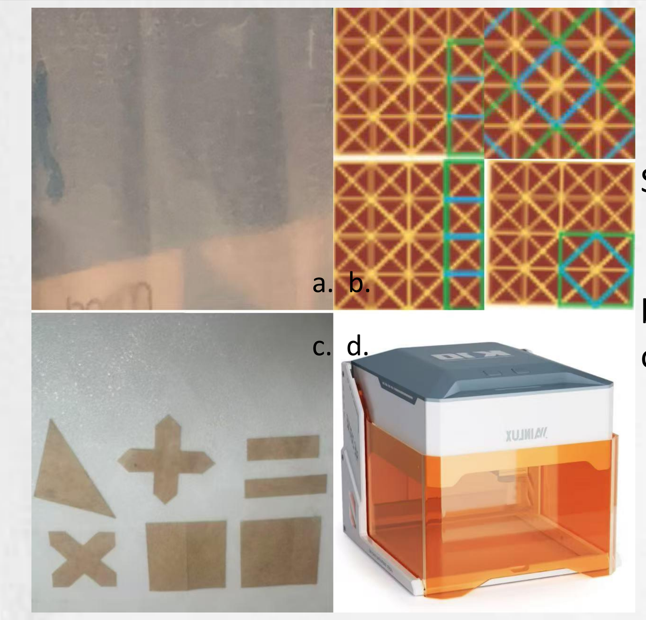


Figure. 7: (a) Silicone on paper ,(b) previous design shape, (c) paper after cutting, (d) laser cutter

Step 2: Cutting paper

a. Pure and spread the Silicone evenly on a piece of kraft paper
b - d. Design and draw the shape, cut it out with laser cutter.

Figure. 8: assemble Gallium and NdFeB mixture on the paper using silicone, (a), (b), (c), (d)

Step 3: Assemble

a. Put silicone mold on the silicone paper, apply the magnetic mixture evenly in the holes
b. Put it on the hot plate to allow the magnetic mixture melt a bot and spread it more evenly.
c. Let it cool and take away the silicone mold
d. Sealing the magnetic block with silicone.

Figure. 9: Magnetization (a), (b), (c), (d)

Step 4: Magnetization

a - d. Put the micro robot on the hot plate, and keep it in the shape we wanted, use magnetic to help it magnetization.

Model

1. Model of a magnetic dipole

Magnetic source:

$$\mathbf{B} = \frac{\mu_0 \mu_r M_t}{4\pi}\left(\frac{3(\mathbf{P}\cdot\mathbf{H})\mathbf{P} - R^2\mathbf{H}}{R^5}\right) \quad (3.1)$$

μ0: permeability of air,
μr: relative permeability of the medium,
Mt: magnetization intensity,
P = position difference vector from magnet to point

R = distance from the magnet to **P**

$$P = (x_0 - x_d, y_0 - y_d, z_0 - z_d)$$

$$R = \sqrt{(x_0 - x_d)^2 + (y_0 - y_d)^2 + (z_0 - z_d)^2}$$

$$B_x = \frac{3B_t}{R^5}\left((x_0 - x_d)(m(x_0 - x_d) - p(y_0 - y_d) + n(z_0 - z_d)) - \frac{R^2 m}{3}\right)$$

$$B_y = \frac{3B_t}{R^5}\left((y_0 - y_d)(m(x_0 - x_d) + p(y_0 - y_d) + n(z_0 - z_d)) - \frac{R^2 p}{3}\right) \quad (3.2)$$

$$B_z = \frac{3B_t}{R^5}\left((z_0 - z_d)(m(x_0 - x_d) - p(y_0 - y_d) + n(z_0 - z_d)) - \frac{R^2 n}{3}\right)$$

2. Magnetic actuation

Magnetic force:

$$\mathbf{m} = V_m\mathbf{M} = V_m\frac{\chi_m}{(1+\chi_m)\mu_0}\mathbf{B} \quad (3.3)$$

Vm is the volume of the magnetic material ;Xm is the magnetic susceptibility; μ0: is the permeability of free space

Magnetic force & Torque:

$$F = (m\cdot\nabla)B \quad \text{and} \quad \tau = m \times B = \begin{bmatrix} 0 & -m_z & m_y \\ m_z & 0 & -m_x \\ -m_y & m_x & 0 \end{bmatrix}\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \quad (3.4)$$

B is magnetic field , F the force determined by the gradient interaction with m; and τ is the results from the cross product of m and B

Experimental Results

1 Fundamental test

We use a 3D hall sensor to measure the surface magnetization of the pixels. As given in Fig.10 the diamond shape robot has 8 pixels. And the surface magnetization of each pixel are given in Tab.1.

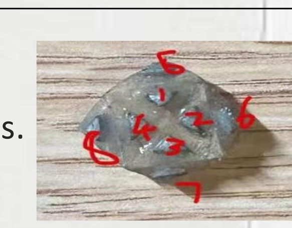


Figure.10 Number of diamond shape robot magnetic pixels

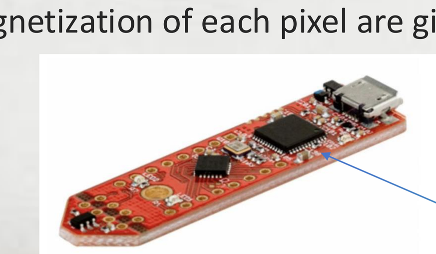


Figure.11 3D Hall sensor

Figure. 11 Vertical displacement table (40*40 mm)

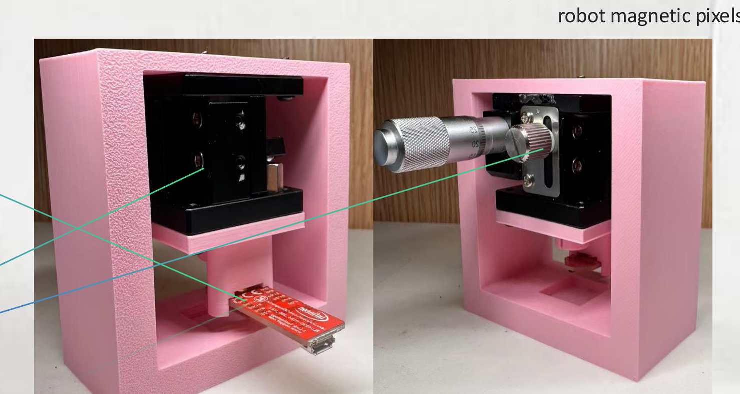


Figure. 12 Self-design 3d printed instrument for measuring magnetization

Table.1 Surface magnetization of the pixels

No. of pixel	Bx	By	Bz
1	x=3.72	y= 0.20	z= -1.76
2	x = -1.08	y= -1.27	z= 1.37
3	x= -0.69	y= 1.27	z= 0.20
4	x= 0.69	y = -0.49	z= 0.98
5	x= -3.23	y = 3.72	z = 4.9
6	x = -5.39	y = 1.76	z= -1.76
7	x= -2.84	y= 0.78	z= 1.67
8	x= 6.27	y = 2.84	z = 2.94

Experimental Results

2.Deformation

Fig.13 shows 4 kind of robots, i.g., diamond, 12-pixels rectangular, 16-pixels rectangular and cross-shape robot. As shown in Figs.12a to 12c, each robot performed two different deformation actions, such as, standing, folding and walking. Fig.13d exhibits a cross shape magnetic robot with folding into a box shape.

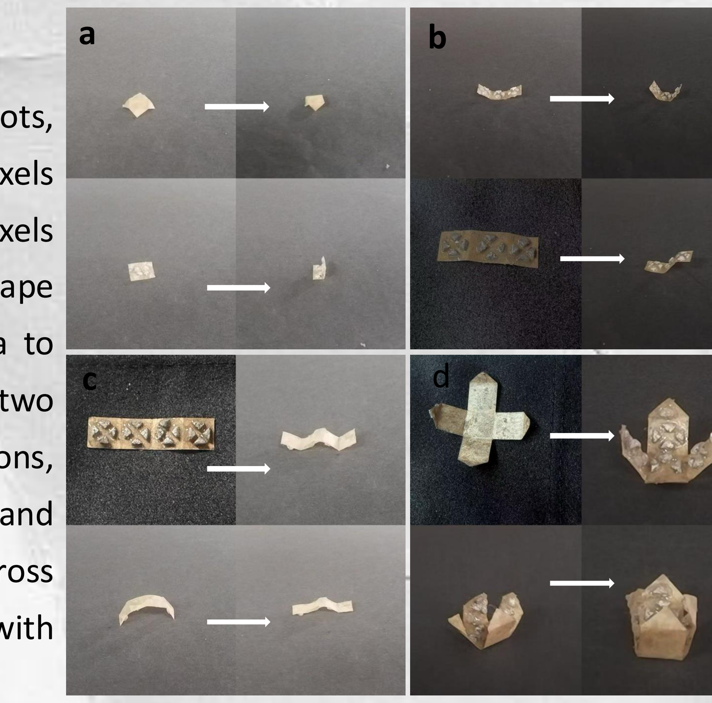


Figure. 13 Robot deformation:(a) diamond robot, (b)12-pixels rectangular robot, (c)16-pixels rectangular robot, (d) cross-shape robot

3. Motion performance

The motion control of the robot is achieved through a magnetic field source composite drive device.As shown in Fig.13, The modified device utilizes a permanent magnet, a stepper motor, and a reciprocating linear motor to generate a magnetic field with sinusoidal and sawtooth wave variations.

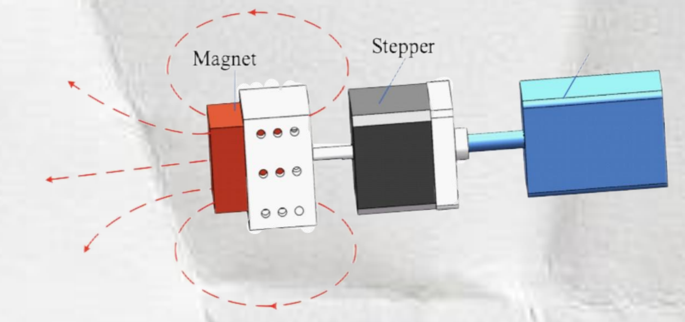


Figure. 16 Driven magnetic field

Figure. 15 Micromagnetic robot driven magnetic field

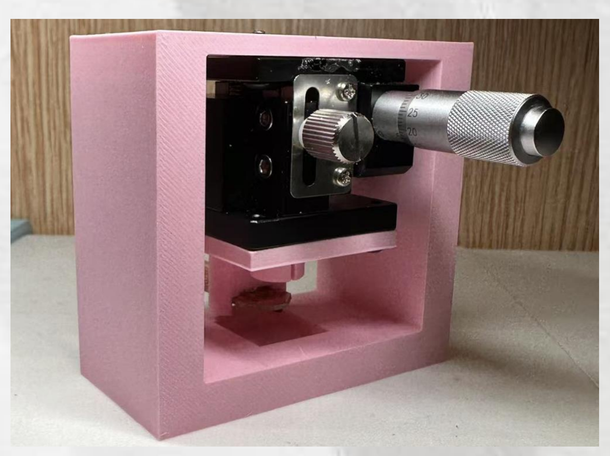


Figure. 17 self design 3d printed machine to measure surface magnetic

Conclusion

1.Discussion

In this work, we developed a magnetic origami micro robot. The main contributions are given as follows:

a. A new method for robot manufacturing has been proposed.

b. Implemented repeatable programming and multimodal motion of magnetic robots.

2.Future work

- More flexible structures with enhanced functionality
- Applications in the medical field
- Development of a system using robotic arms/instruments for automated control of robot movement

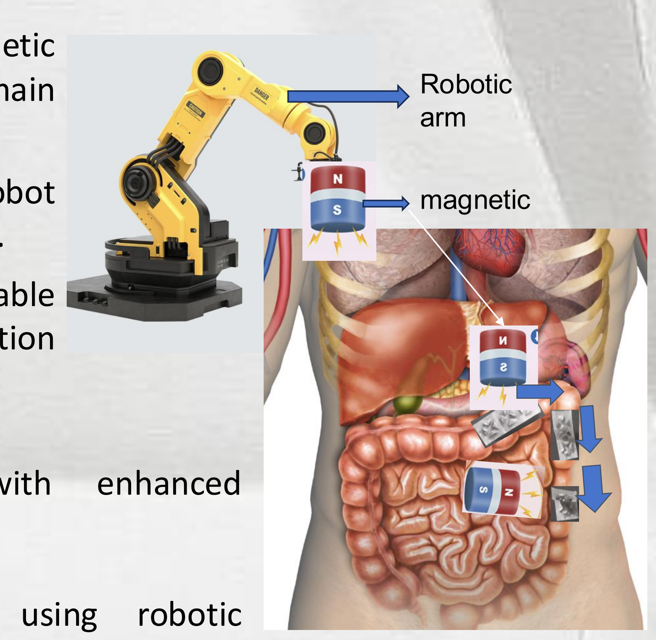


Figure. 18 Future work prototype

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