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Magnetic Paper: Programmable Magnetic Origami Robot for Medical Applications

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Abstract: This research introduces a micro-magnetic robot that uses the delicate art of traditional paper cutting and folding as its design inspiration, allowing it to change its shape and move smoothly in a tiny environment. This robot uses small magnetic fields to navigate and perform tasks like delivering medicine directly to where it's needed, making treatments less invasive. We improved shape and the movement reacting to magnetic fields, by creating a new shape. These changes help us steer the robot more accurately inside the body and ensure it can deliver medicine exactly where it's needed. Our tests show that this new approach works well, making it a promising tool for delivering treatments right to specific parts of the body. This could lead to better ways of giving medicine and performing other medical tasks with less impact on the patient.

Keywords: Magnetic micro robot, Origami, Liquid metal.

1. Introduction

Magnetic microrobots represent a class of robots controlled by magnetic fields, with sizes ranging from micrometers to centimeters [1]. Recently, they have demonstrated tremendous application prospects in the medical field. Compared to micro-robots driven by heat[2-4], light[5-7], chemicals [8,9], and electric fields [10,11], magnetic microrobots offer significant advantages, including wireless operation, no need for batteries, and enhanced safety.

However, current magnetic soft robots are often limited by their structures and functions. For instance, H. Shum presented a helical micro-robot for micro cargo delivery [12], and Z. Peng developed a bio-inspired micro-robot using NdFeB material [13]. These robots typically have fixed structures and singular functions, with varying materials and fabrication methods, leading to a lack of a unified design framework.

To address these limitations, we have developed a new magnetic microrobot with a dynamic structure that adapts to various medical tasks and environments, significantly improving flexibility and control. This innovative robot can navigate complex areas within the human body, making it a versatile tool for both delivering medication and performing intricate medical procedures. This advancement represents a significant step forward in creating responsive, minimally invasive medical devices.

Inspired by the traditional art of paper cutting, our groundbreaking robot is uniquely designed to navigate complex environments inside the human body using precise magnetic fields. It focuses on delivering medications directly to targeted areas, making treatments less invasive and more effective. This paper explores the development and fine-tuning of our micro-magnetic robot, addressing the

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challenges of accurate control within the unpredictable magnetic fields of human tissues. We have significantly enhanced the robot's functionality through extensive testing and advanced modeling techniques.

By integrating traditional art with modern robotics, we are creating more adaptable and efficient robots, pushing the boundaries of targeted medical treatments in clinical settings. Magnetic microrobots represent a transformative advancement in medical technology, offering a wire-free, precise, and targeted approach to treatment. This introduction sets the stage for a detailed examination of their development, functionality, and potential impacts on healthcare, which will be explored in the subsequent sections of this paper.

2. Methodology

2.1. Principle

The foundational principle of our magnetic origami robot is illustrated in Figure 1. The robot is designed with a flexible, paper-based substrate integrated with programmable magnetic pixels composed of liquid metal and NdFeB. This design allows the robot to navigate and adapt its shape dynamically under the influence of magnetic fields.

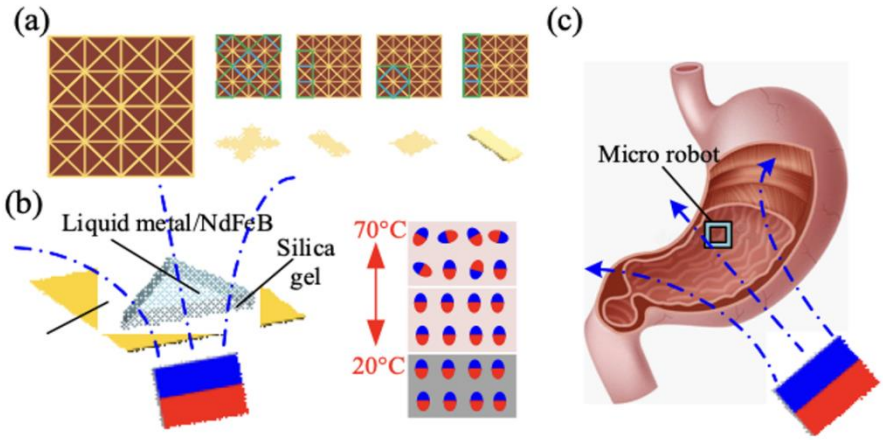

Figure 1: Principle of the magnetic origami robot: (a) structure of the paper based magnetic robot, (b) programming a magnetic pixel and, (c) application

2.2. Structural design

The magnetic robot's structural design facilitates flexible movement in various directions, enhancing its operational versatility. As depicted in Figure 1(b), the robot features a dual-layered construction:

a. Bottom Layer, Comprised of paper, it provides a flexible foundation.

b. Active Layer, A composite of liquid metal and NdFeB magnets set in a silica gel matrix, which serves as the primary mechanism for actuation and control via magnetic fields. The inclusion of liquid metal boosts electrical conductivity and flexibility, while the NdFeB enhances the magnetic responsiveness of the robot.

The structure design of the magnetic robot, this design allows its structure to move flexibly in different ways and directions.

As shown in Figure1 (b), the diagram shows a cross-section of the soft magnetic robot, where the bottom layer consists of paper, suggesting a flexible base. Above it, a combination of liquid metal and NdFeB (Neodymium Iron Boron) magnets interspersed in a silica gel matrix form the active layer. This layer is responsible for the robot's actuation and control through magnetic fields. The liquid

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metal could provide electrical conductivity and flexibility, while NdFeB enhances magnetic responsiveness.

3. Materials and fabrication

3.1. Materials

The proposed robot is made of gallium (liquid metal), NdFeB, Silicone and Kraft paper(as shown in Figure 2), the parameters of these materials is given in Tab.1. The chosen materials for the robot—gallium, NdFeB powders, silicone, and Kraft paper—are tailored to its needs. Gallium is used for its low melting point, allowing the robot to change shape easily. NdFeB powders provide strong magnetic fields necessary for controlling the robot's movements. Silicone offers protection and flexibility, safeguarding the robot's internal components. Kraft paper is light and easy to handle, ideal for temporary structures during assembly. Each material plays a critical role in enhancing the robot's performance and adaptability.



Figure 2: Materials: (a) liquid-metal, (b)NdFeB powders, (c) silica gel, (d) paper

Table 1: Data for Gallium, Silicone, NdFeB and kraftpaper

Materials	Density	Melting point	Shore Hardness	Curing period	Thickness
Gallium	5.04g/cm^2	29.74 C	-		-
Silicone	1.1g/cm^3	>200 C	30	1h	-
NdFeB	7.5g/cm^3	-			-
Kraft paper		-	-	-	0.1mm

3.2. Fabrication

The fabrication procedure for the robot involves a meticulous multi-step process, as outlined below. This process begins with the creation of a 3D model and a silicone mold to shape the robot's structure. Following this, specific materials such as gallium and NdFeB are combined and placed within the mold to integrate the robot's essential magnetic functionalities. The next steps include cutting the necessary shapes from Kraft paper, using a laser cutter for precision, and assembling these components with the silicone mold. Finally, the assembled parts are magnetized to activate the robot's movement capabilities. This sequence ensures that each part of the robot is crafted with precision and integrates seamlessly to produce a functional and effective robotic system.

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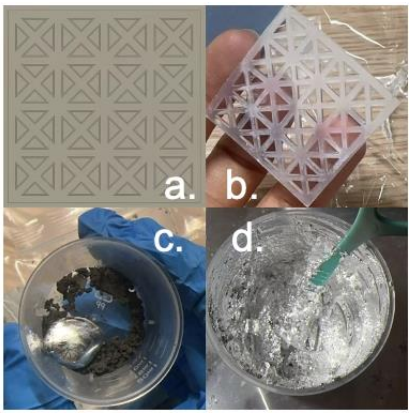

Figure 3: Materials: (a) CAD, (b)Silicone soft mold, (c) NdFeB and Gallium, (d) magnetic mixture

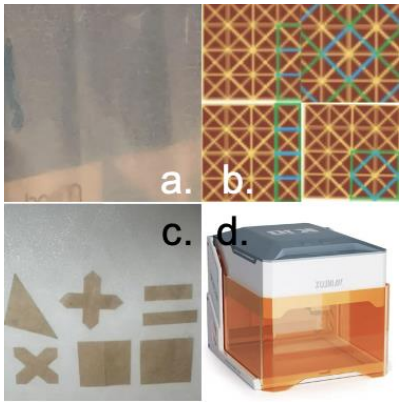

Figure 4: (a) Silicone on paper, (b) previous design shape, (c) paper after cutting, (d) laser cutter



Figure 5: Assemble Gallium and NdFeB mixture on the paper using silicone, (a)Put the mixture on, (b)heat the mixture, (c)cool and take off the mixture, (d) seal with silicone

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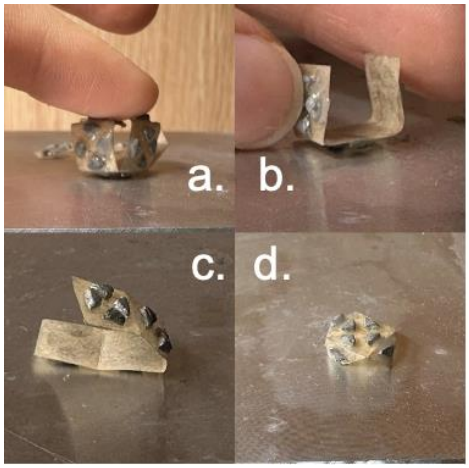

Figure 6: Magnetizing the robots

Step 1: Materials

Use SolidWorks draw 3d model for mirror mold. Use SLA print out the model

Pure silicone in the model to make a soft mold

Mix the Gallium and NdFeB together with a ratio around 1:1

Step 4: Stir evenly until the mixture is close to the texture of plasticine

Step 2: Cutting paper

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.

Step 3: Assemble

Put silicone mold on the silicone paper, apply the magnetic mixture evenly in the holes

Put it on the hot plate to allow the magnetic mixture melt a bot and spread it more evenly.

Let it cool and take away the silicone mold

Sealing the magnetic block with silicone.

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.

The structural integrity and design flexibility of our magnetic origami micro robot are crucial for its functionality in medical applications. As depicted in Figures 8 and 9, the fabrication process begins with the precise shaping of kraft paper using a UV laser cutter. This step produces four distinct substrate shapes, including crosses and squares, which are essential for the assembly of centimeter-scale robots.

Following the initial cutting, these paper substrates are embedded with a gallium and NdFeB magnetic composite. This embedding process, shown in Figure 9, involves filling the substrates with small, pixel-like magnetic units. These units enhance the robot's magnetic responsiveness and allow for intricate movements and configurations. This design strategy not only increases the robot's operational flexibility but also improves its ability to perform precise tasks within complex internal environments. The integration of advanced materials and precise fabrication techniques underscores the potential of this technology in transforming robotic-assisted medical therapies.

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Figure 7: The prepared robots

4. Model

4.1. Magnetic source

We use the magnetic dipole model to describe the behavior and control of micro-robots in magnetic fields. These formulas elaborate on the interactions between the magnetic dipole moment and the external magnetic field, and how these interactions influence the robot's motion and orientation. The primary model formula calculates the magnetic field B, taking into account the relative permeability of the medium and the magnetization intensity of the material.

$$\mathbf{B} = \frac{\mu_0 \mu_r M_t}{4\pi}\left(\frac{3(\mathbf{P}\cdot\mathbf{H})\mathbf{P} - R^2\mathbf{H}}{R^5}\right) \tag{1}$$

μ_0: permeability of air,
μ_r: relative permeability of the medium,
M_{tt}: magnetization intensity,
P: the position difference vector from magnet to point
R: the distance from the magnet to **P.**

And when the location **P** is given as,

$$P = (x_0 - x_d, y_0 - y_d, z_0 - z_d) \tag{2}$$

The distance R is,

$$\mathrm{R} = \sqrt{(x_0 - x_d)^2 + (y_0 - y_d)^2 + (z_0 - z_d)^2} \tag{3}$$

According to Equation (1)-(3), The 3-axis magnetic field component can be expressed as,

$$\begin{aligned} B_x &= \frac{3B_t}{R^5}\left((x_0 - x_d)(m(x_0 - x_d) + p(y_0 - y_d) + n(z_0 - z_d)) - \frac{R^2 m}{3}\right) \\ B_y &= \frac{3B_t}{R^5}\left((y_0 - y_d)(m(x_0 - x_d) + p(y_0 - y_d) + n(z_0 - z_d)) - \frac{R^2 p}{3}\right) \\ B_z &= \frac{3B_t}{R^5}\left((z_0 - z_d)(m(x_0 - x_d) + p(y_0 - y_d) + n(z_0 - z_d)) - \frac{R^2 n}{3}\right) \end{aligned} \tag{4}$$

4.2. Magnetic actuation

This section outlines the magnetic actuation mechanism that governs the behavior of the micro-robot within magnetic fields. It describes the relationship between the magnetic properties of the material used in the robot and the external magnetic fields that influence its movement and orientation. The

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interaction of these properties to produce force and torque is critical for the precise control and functioning of the robot in its intended applications.

The defination the magnetic moment *m* of the robot is given as,

$$\boldsymbol{m} = V_m \boldsymbol{M} = V_m \frac{\chi_m}{(1+\chi_m)\mu_0} \boldsymbol{B} \tag{5}$$

where V_m is the volume of the magnetic material, χ_m is the magnetic susceptibility, and μ0 is the permeability of free space.

This equation represents the force F exerted on a magnetic object with magnetic dipole moment m in a magnetic field B. The operator $(m \cdot \nabla)$ denotes the dot product of m with the gradient of B, indicating how spatial variations in the magnetic field influence the force applied to the object.the magnetic torque τ generated by a microrobot when subjected to a magnetic field B. Here, V represents the volume of the microrobot and M is its magnetization. The cross-product of M and B yields the torque exerted on the robot, which dictates its rotational movement within the field.

$$F = (m \cdot \nabla) B and \tau = m \times B = \begin{bmatrix} 0 & -m_z & m_y \\ m_z & 0 & -m_x \\ -m_y & m_x & 0 \end{bmatrix} \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \tag{6}$$

These formulas describe the interactions of a magnetic dipole moment m within a magnetic field B. The force F is determined by the gradient interaction with m, affecting how the object moves in response to changes in the field. The torque τ results from the cross product of m and B, calculated using the skew-symmetric matrix of m, which dictates the object's rotational behavior.

5. Experiment

5.1. Experimental setup

To accurately measure the surface magnetization of the magnetic pixels in the robot, we utilized a comprehensive experimental setup featuring a 3D Hall sensor, as shown in Figure 10. This sensor is critical for detecting the magnetic field intensity and orientation emitted by the robot's pixels. Additionally, the experimental apparatus includes a vertical displacement table (Figure 11), which allows for precise adjustment of the sensor's position relative to the robot. A custom-designed 3D printed instrument, depicted in Figure 12, was specifically created to hold the Hall sensor and facilitate its interaction with the magnetic components of the robot. This setup ensures that measurements are consistent and repeatable, which is essential for the accuracy of our data.

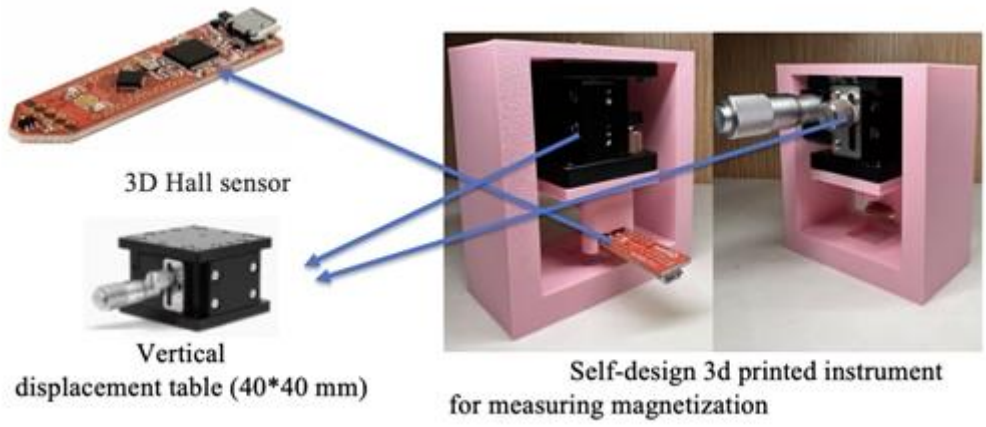

Figure 8: Testing device for surface magnetization

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5.2. Fundamental test

In the testing phase, particular attention was given to the diamond-shaped robot, which features eight uniquely positioned magnetic pixels. Figure 13 illustrates the numbering and arrangement of these pixels. Surface magnetization data for each pixel were meticulously gathered and are presented in Tab.2. This data provides insight into the magnetic profile of each pixel, which is crucial for understanding the robot's overall magnetic behavior and its ability to respond to external magnetic fields. This specific collection of magnetization values helps in refining the robot's design and enhancing its functional capabilities in navigational and actuation tasks within medical applications.



Figure 9: Number of diamond shape robot magnetic pixels

Table 2: Surface magnetization of the robot

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

5.3. Deformation

Figure 14 shows 4 kind of robots, i.g., diamond, 12-pixels rectangular, 16-pixels rectangular and cross-shape robot. As shown in Figs.14a to 14c, each robot performed two different deformation actions, such as, standing, folding and walking. Figure 14d exhibits a cross shape magnetic robot with folding into a box shape.

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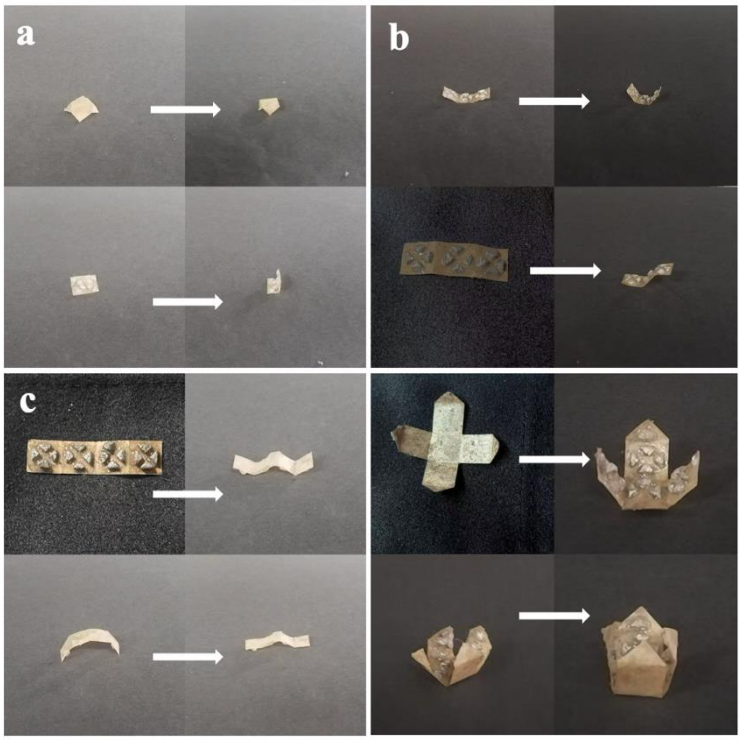

Figure 10: Robot deformation:(a) diamond robot, (b)12-pixels rectangular robot, (c)16-pixels rectangular robot, (d) cross-shape robot

5.4. Motion performance

The motion control of the robot is achieved through a magnetic field source composite drive device. As shown in Figure 15, 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.



Figure11: Micromagnetic robot driven magnetic field

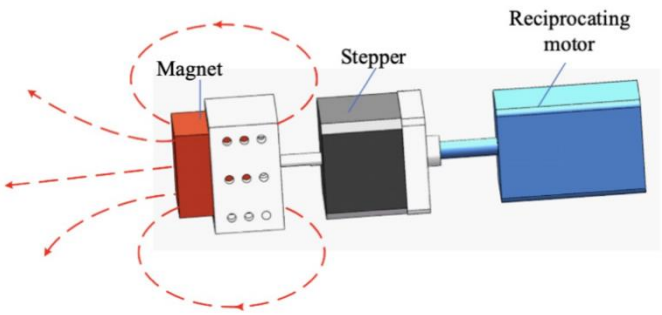

Figure 12: Driven magnetic field

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The motion control of the robot is achieved through a magnetic field source composite drive device. As shown in Figure 16, 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.

6. Conclusion

In conclusion, this research project has successfully developed a magnetic origami micro-robot, demonstrating a novel method for creating micro-robots that are both programmable and capable of multimodal motion. Through the application of origami techniques combined with magnetic actuation, the researchers have introduced a versatile approach to robot design that allows for complex, flexible structures ideally suited for medical applications such as targeted drug delivery, minimally invasive surgery, and diagnostic procedures. The integration of liquid metals and NdFeB magnets into a silicone matrix has proven to be particularly effective in enhancing the robot's responsiveness to magnetic fields, thereby improving control and functionality.

7. Future Work

Looking forward, the potential for these robots to be adapted for broader medical applications is immense. Future developments will focus on refining the fabrication process to enhance the robots' functional capabilities and operational reliability. There is also a significant opportunity to explore the integration of these robots with robotic arms and automated control systems, which could lead to more sophisticated deployments in medical environments. By continuing to advance the technology of magnetic origami robots, the researchers aim to open new pathways for patient care that offer greater precision, less invasiveness, and enhanced outcomes.

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