Proceedings of the 4th International Conference on Biological Engineering and Medical Science
DOI: 10.54254/2753-8818/49/20241306

Magnetic hexagram micro soft robot

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Abstract. This research focuses on the development of a hexagram-shaped multimodal magnetic soft robot for biomedical applications. This micro-robot utilizes principles of soft robotics and magnetic control mechanisms to achieve precise manipulation and maneuverability within biological environments at the micrometer to millimeter scale. Its advantages include precise navigation through physiological fluids via magnetic fields, enabling targeted drug delivery, diagnostic imaging enhancement, and minimally invasive surgical interventions. The hexagram shape ensures stable and controlled movements, overcoming instability seen in alternative robotic systems. However, these magnetic robots also face challenges such as size constraints, navigating turbulent flows and anatomical obstacles, sustaining operations with an efficient energy source, and biocompatibility concerns. The design of the micro-robot involves mixing silicone gel with NdFeB powder to create a soft and flexible structure with magnetic responsiveness. Through the magnetization process, the alignment of the NdFeB particles is controlled to enable precise manipulation of the robot's motions. Experimental results demonstrate that the robot can perform various modes of movement, including walking, rolling, folding into a box-like structure, and jellyfish-like swimming in fluids, exhibiting adaptability in complex biological environments.

Keywords: micro-robot, NdFeB, various modes of movement

1. Introduction

The integration of micro robots into medical applications is a transformative advancement in biomedical engineering. These miniature robotic systems operate at a scale of micrometers to millimeters, offering precision and maneuverability within biological environments [1, 8]. By harnessing principles of soft robots and using innovative control mechanisms such as magnetic fields, micro robots show promise for revolutionizing new methods of medical intervention. Their diminutive size enables a minimally invasive procedure, overcoming the limitations of conventional drug transportation and surgical techniques [2]. Furthermore, their ability to navigate complex anatomical structures enable them to perform targeted drug transportation, diagnostic imagining enhancements, microsurgical interventions, and more.

Advantages and disadvantages of magnetic soft robots, along with their movement limitations, are critical considerations in the creation of these microrobots. They offer a plethora of advantages, notably their precise navigation through physiological fluids facilitated by magnetic fields [3]. This precision can enable targeted drug transportation, diagnostic imaging enhancement, and microsurgical interventions with minimal invasiveness [4]. In addition, their adaptability and ability for real-time control during an operation and enhance their utility [1]. The hexagram shape ensures stable and controlled movements, overcoming instability seen in alternative robotic systems. However, these magnetic robots also face limitations. Size constraint can restrict their payload capacity, limiting the amount of drug materials they can carry. Additionally, navigating turbulent flows and anatomical obstacles can pose challenges in the transportation process [5]. Sustaining operations with efficient energy source still remains a hurdle, particularly in energy-requiring microrobots[6]; and biocompatibility concerns also linger, raising questions about potential reactions within the body to the materials used to fabricate the robot [7].

The research project involves the development of a hexagram shaped multimodal magnetic soft robot for biomedical applications. Using principles of soft robotics and magnetic control mechanisms, this project aims to address the limitations of conventional medical interventions through minimally invasive and highly precise robot platforms.

The field of biomedical engineering continues to evolve with technological advances aimed at enhancing medical interventions. Targeted drug transportation within the human body is a pivotal area of exploration, offering the potential for more effective treatments with reduced side effects. In this area, micro-robots have emerged as a solution, seeing the potential to revolutionize drug transportation systems.

Microrobots, operating at a microscale, have demonstrated unique capabilities in navigating complex biological environments with precision. Their size allows for a minimally invasive procedure, overcoming challenges associated with conventional drug transportation methods. The potential to reach specific anatomical targets with accuracy makes microrobots a crucial area of development for improving the precision of medical interventions.

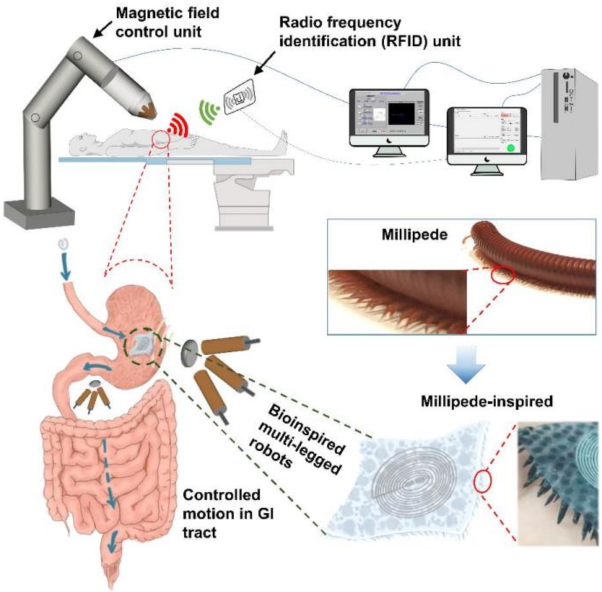

Figure 1. Application of magnetic soft microrobots in medical care

Within the realm of microrobots, our research focuses on the development of a hexagram-shaped multimodal magnetic soft robot. This design incorporates principles of soft robotics and utilizes magnetic fields for precise control at a microscale. Compared to alternative robotic systems such as wireless, chemical, light, pH, and thermal robots, magnetic microrobots offer several distinct advantages. The magnetic field allows for a high level of precision in navigating through physiological fluids, allowing the robot to reach specific targets with accuracy. Unlike some chemical or thermal-based robots, magnetic micro robots can operate in a non-invasive manner, minimalizing potential harm to surrounding tissues (Fig.1). The magnetic control allows for real-time adjustments and adaptability during the drug transportation process, an advantage that allows for external manipulation. Compared to light or chemical-based systems, the usage of magnetic fields can reduce the potential harm to the biological tissues. The chosen hexagram shape for the robot can ensure a series of stable and controlled movements, overcoming the instability seen in wireless or light-based robots.

As of current, we see a large area of development of magnetic soft microrobots, seen in the application of various biomedical domains. Its primary application is in targeted drug transportation, with the ability to navigate the bloodstream to reach specific locations within the body. Magnetic microrobots are often used in diagnostic imaging, serving as contrast agents for magnetic resonance imaging or providing a means for the detection of specific biomarkers. In microsurgery, these robots can offer a minimally invasive approach to procedures, also aiding in tissue engineering. Going beyond medical applications, magnetic microrobots have also explored remote sensing within the body of environmental exploration in challenging terrains. Though there are a multitude of advantageous applications, these robots also come with limitations. The size constraints for microrobots limit their payload capacity, restricting the amount of drug materials they can carry. The presence of turbulent flow of anatomical obstacles, it presents a challenge for the microrobots. In other forms of energy-requiring microrobots, they struggle to perform sustained operations with a reliable and efficient energy source. And though these robots perform non-invasive operations, the question of biocompatibility of materials remains, with the possibility of reactions within the body.

Our design seeks to mitigate these limitations, using a series of design choices to make up for these pre-existing limitations for microrobots. Though size constraint is a concern, our choice in the hexagram shape allows for structural folding into a box, able to secure the maximum amount of drug payload possible. Using the soft structure of the magnetic robot, it can perform a series of movements inspired by biomimicry. Using jellyfish-like motions will securely hold the drug, the robot can move in a preplanned manner under the control of magnetic fields to reach its destination despite anatomical obstacles or fluids. Through the usage of external control via magnetic fields, we can mitigate the issue of providing sustained energy form, not requiring direct energy to go to the microrobot during its operation. To create the most non-invasive and biocompatible operation using our robot, we carefully chose a silicon solution that would react to tissues within the body, hence lowering the possibility of harm to tissues surrounding the operation.

2. Methodology

2.1. Principle

Bio-inspired

Inspired by the biomechanics of a starfish, our robot takes a hexagonal shape able to bend at multiple angles (as shown in Fig.2). This shape allows the robot to execute a series of actions, one of which is the ability to fold into a box-like structure to secure drugs during transportation. This can ensure safe transportation of drugs to their targeted site. By manipulating its hinges, the robot can perform walking motions. This helps with navigation allowing the robot to travel through complex biological environments and reach its destination with accuracy. In fluid environments, the robot can carry out jellyfish-like movements. This helps the robot navigate through bodily fluids while maintaining stability and control of the drug.

Magnetic particles

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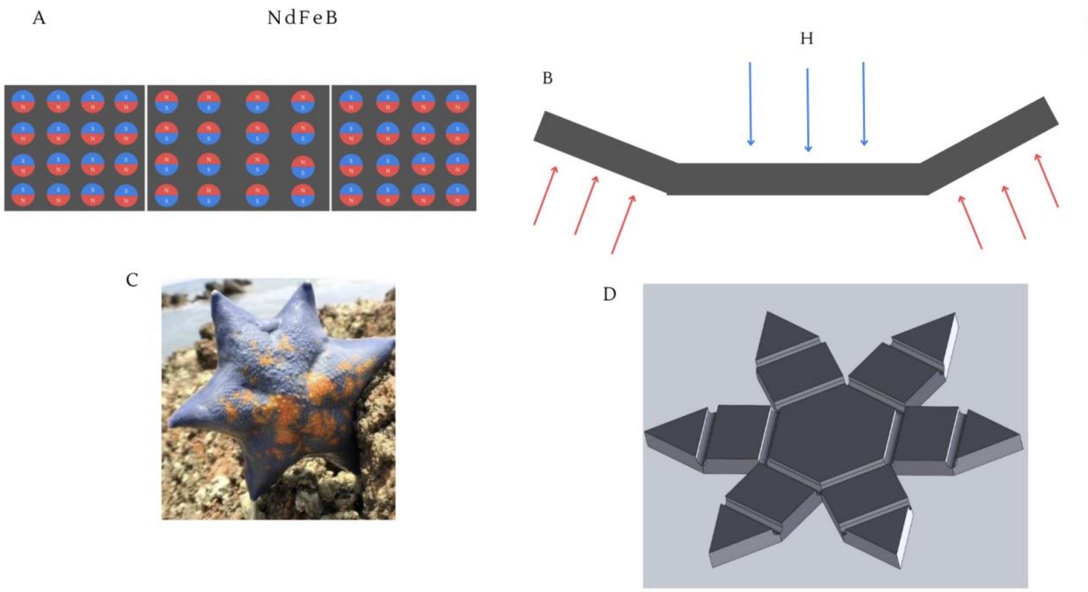

Figure 2. Robot Design

Our magnetic soft microrobot can carry out a remarkable range of functionalities beyond its primary role in drug transportation. As given in Fig.3, to achieve this versatility, we integrated flexible hinge-like structures at the intersection of each surface point. A design feature commonly employed to enhance flexibility in robotics.

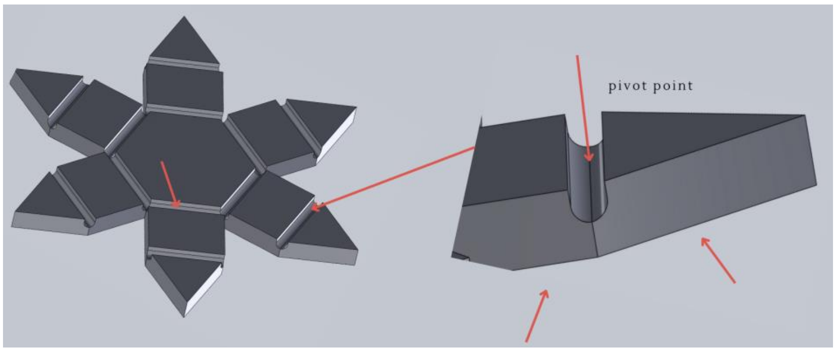

Figure 3. Hinge structure of the robots

These hinge-like structures serve as pivot points, allowing the robot to bend and deform in response to magnetic stimuli. These little structures work because it concentrates the force stressed on the targeted surface, rather than distributing force evenly across the structure. This ensures that our design bends, deforming into its designated design. This design contributes to the robot's ability to adapt to different environmental conditions and perform a diverse range of motions.

2.2. Material and fabrication

To create this soft-robot, we mixed silicon gel and NdFeB powder to be molded into the shape of the robot (Fig.4). Our choice in silicon gel is due to its biocompatibility and flexibility, which serves as a great foundational material to construct the microrobot. This material is also widely used in medical applications, showing minimal risk of side effects or harm on biological tissues. It is soft and flexible, allowing the robot to navigate complex environments without causing damage to its surrounding structures. For the magnetic responsiveness of the microrobot, we incorporated NdFeB power to the

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silicon gel mixture. Neodymium Iron Boron is a commonly used magnetic material, allowing for interaction with external magnetic fields. With both materials chosen in consideration for its biocompatibility, there is very minimal risks of reactions occurring with the body. Over time, the soft nature of the silicon gel allows for natural expulsion of the microrobot from the patient's system.

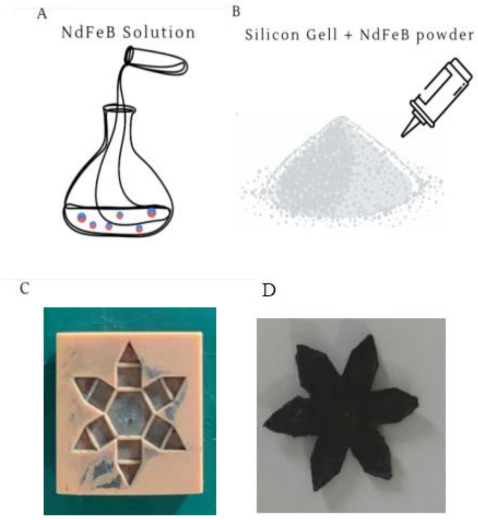

Figure 4. Fabrication of magnetic robot

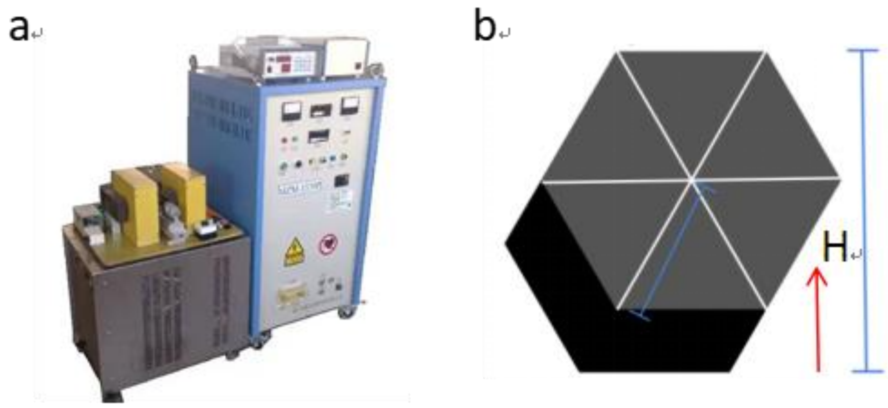

Figure 5. Magnetization of the magnetic soft robot: (a)Magnetizing machine, (b) Magnetizing direction

The first steps of the creation of the robot involve the preliminary design and sketches showing a detailed magnetization profile and mapping the magnetic fields across different segments. This guides the folding motion, ensuring the robot's magnetically controlled motions.

The process begins with the preparation of the unmagnetized NdFeB particles and silicon gel. The particles are mixed with the silicon gel to form a homogeneous solution. The mixing helps ensure the even distribution of the magnetic elements within the gel solution for the robot's magnetic responsiveness. The blended solution is then poured into a miniature 3D printed mold, designed to shape the microrobot into its hexagonal shape. Following this, the solution undergoes a curing process, allowing the silicon gel to solidify around the NdFeB particles and create the cohesive structure of the microrobot. After curing, the robot undergoes the magnetization process. During this, the cured structure is wrapped around a hexagonal box designed to magnetize the particles into their chosen profiles. The magnetization process is crucial to the fabrication process(Fig.5), by carefully wrapping the cured

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structure during magnetization, we can control the alignment of the NdFeB particles to allow for specific manipulation of targeted motions later on.

3. Model

3.1. Magnetic field model

During the magnetization, we incorporated principles of magnetic dipole to measure the magnetization at any given point in space. The application of the magnetic dipole principles is crucial in understanding the magnetic field generated by the micro robot [10]. The magnetic dipole formula, expressed as

$$B = \frac{\mu_0}{4\pi}\frac{3(p\cdot n)n - p}{r^3} \tag{1}$$

Provides a quantitative representation of the magnetic field strength and direction at different spatial locations around the magnetic dipole.

In the magnetization process, we used the magnetic dipole formula to measure the magnetization strength at specific points within the microrobot. Through the use of instruments and sensors, we were able to gather data on the magnetic dipole moment generated during the process, this data allows us to map the special distribution of the magnetic strength to ensure a uniform magnetization and alignment of the NdFeB particles.

The magnetization action model is formulated based on principles of the magnetic dipole formula. It involves wrapping the cured microrobot structure around the hexagonal box during magnetization, this action aligns the NdFeb particles in a controlled manner. The magnetization action model supports real-time monitoring of the magnetization strength at different points within the micro robot. This allows for adjustments during the fabrication process, ensuring that the robot fits the desired specifications and archives the necessary magnetic properties in order for motions of targeted drug transportation to function.

3.2. Magnetic actuation model

The magnetic torque τ of the controlled magnetron microrobot in the magnetic field can be expressed as [9]:

$$\tau = \mathrm{VM} \times \mathrm{B} \tag{2}$$

where V is the volume of the microrobot, M is the magnetization, and B is the external magnetic field. This mathematical model explains the fundamental principles governing the interaction between the magnetic soft robot and its surrounding magnetic field. By quantifying the torque exerted on the microrobot, the equation serves as a foundation for further analysis and optimization of magnetic control strategies. These insights are necessary for enhancing the precision, maneuverability, and efficacy of the microrobot in various medical applications, ranging from targeted drug transportation to microsurgical interventions. Additionally, this model provides a theoretical framework for designing and implementing advanced magnetic actuation systems.

3.3. Motion model

3.3.1. Deformation equation. The rotational deflection along the robot θ(s) can be described by the Euler-Bernoulli equation as,

$$\tau_m A(s) = -EI\frac{\partial^2\theta}{\partial s^2} \tag{3}$$

where *EI* represents the flexural rigidity of the robot, *mA(s)* represents the bending moment distribution along the robot's length *s*, and *θ(s)* is the rotational deflection.

This is a fundamental principle that governs the bending behavior of slender structures. This equation provides a comprehensive understanding of the crawling motions exhibited by the magnetic soft robot as it navigates through its biological environments. By quantifying the rotational deflection as a function of special position *s*, the equations shows how the robot's flexible structure deforms in response to external stimuli of the magnetic fields. This deformation equation is crucial for analyzing and optimizing crawling motions of the robot, enabling the fine-tuning of parameters to enhance its maneuverability.

3.3.2. Rotation equation. Starting from the center of the circle $r < r1 < r2$, the subtle radius difference in reciprocating rotation will cause the mode a forklift movement. from (a)to (d), under the condition of B; the radius is getting smaller and smaller r2−> r1−> r, so when the robot rotates, the CTM does not reach the ground and rotates in the air. The motion from (a) to (d) is an empty rotation around a fixed axis without friction with the ground. The robot settles down to the ground in the moment (e) to complete the step one. Ignoring the slight difference in radius, r is the radius of rotation.

$$\mathbf{B_3} = \mathrm{B}[|\cos(2\pi ft)|\tilde{u} + |\sin(2\pi ft)|\tilde{v}] \tag{4}$$

$$\tau = \mathbf{M}_{\mathrm{net}} \times \mathbf{B_3} \tag{5}$$

$$\mathbf{M}_{net}(\emptyset\mathrm{R}) = \mathrm{M}_{net}(\cos(\emptyset\mathrm{R})\ \sin(\emptyset\mathrm{R})\ 0)^T \tag{6}$$

where τ, $\mathbf{M}_{net}$, $\mathbf{B_3}$ are magnetic torque, net magnetic force and magnetic field, respectively. B is the magnitude and f is the magnetic field frequency. $\vec{u}$ and $\vec{v}$ are the base vectors in the rotating plane. From (a) to (d), the microrobot rotates around the fixed axis and stretches out its feet can be expressed as:

$$\tau_u - C_u\dot{\emptyset}_u = J\ddot{\emptyset}_u \tag{7}$$

τ_u represents the magnetic moment received by rotation. $C_u\dot{\emptyset}_u$,J are the rotational damping coefficient, the rotation angle and moment of inertia of wheel, respectively. Ignoring the lag, the angular velocity eventually tends to the following formula:

$$\dot{\emptyset}_u = 2\pi f \tag{8}$$

The rotation equation for the magnetic soft robot is essential for understanding its locomotion patterns. Expressed as

$$\mathbf{B_3} = \mathrm{B}[|\cos(2\pi ft)|\tilde{u} + |\sin(2\pi ft)|\tilde{v}] \tag{9}$$

where B represents the magnetic field magnitude, f represents the magnetic field frequency, and u and v are the base vectors in the rotating plane, this equation explains the robot's rotational motion. As the microrobot rotates around a fixed axis, stretching out is feet, the equation captures the magnetic movement received from the rotation, expressed as $\tau_u - C_u\dot{\emptyset}_u = J\ddot{\emptyset}_u$ where $C_u\dot{\emptyset}_u$ represents the rotational damping coefficient. By disregarding lag effects, the equation predicts the angular velocity, eventually approaching $\dot{\emptyset}_u = 2\pi f$.

3.3.3. Swimming equation. The swimming equation for the magnetic soft robot explains its propulsion mechanisms and fluid dynamics interactions. Expressed as

$$T_x + f = D_x + G_x + F_x \tag{10}$$

where *I* represent fluid s propulsion, *f* represents friction, *D* represents resistance, *G* is the acceleration of the reaction force, and *F* is the inertia force, this equation shows the balance of forces governing the robot's swimming motion.

In the horizontal direction, the projections of *Tr, Da, G,* and *F* on the X-axis are described. According to Daniel's theoretical model, the final inference can be expressed as

$$\left(\frac{\rho}{A}\right) \cdot \left(\frac{dV}{dt}\right)^2 \cos\theta + f = 0.5\rho SC_d v^2 \cos\theta + (1+a)\rho V\left(\frac{dV}{dt}\right)\cos\theta \tag{11}$$

4. Results and discussion

4.1. Magnetization profiles

This research project has yielded promising results in the development of a hexagram-shaped multimodal magnetic soft robot for biomedical applications (Fig.6). The utilization of soft robotics principles combined with magnetic control mechanisms has enabled precise and adaptable movements at the microscale. The design choices, including the hexagram shape and soft structure, have addressed key limitations associated with conventional microrobots, such as payload capacity and maneuverability in physiological fluids. Through experimentation and analysis, we have demonstrated the potential of our robot in targeted drug transportation, diagnostic imaging, microsurgery, and environmental sensing within the body.

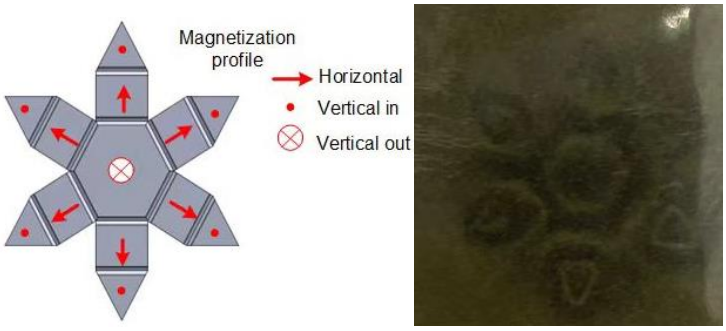

Figure 6. The magnetization profile for the hexagram-shaped multimodal magnetic soft robot.

The horizontal line, vertical in, and vertical out components depicted in the diagram correspond to distinct regions of magnetization observed in the image of the robot under a magnetization sheet (Fig.7). This visualization shows the distribution and alignment of the magnetic domains within the robot's structure. By analyzing the magnetization profile, we can better understand the magnetic properties of the robot and optimize its response to external magnetic fields to alter its range of motions.

Figure 7. Effect of magnetic field on angle of bending in robot

To record the magnitude of the magnetic field and capture different deformation postures of the robot, we implemented a simple experimental setup. A magnetic sensor was securely attached to the bottom of the platform holding the microrobot(Fig.7). By manipulating a magnet under this platform along the z-axis, we induced bending in the robot to various angles. At the same time, the magnetic sensor recorded the input of the magnetic fields in real-time. This sensor data was then transmitted to a laptop for analysis. To capture the deformation postures at different magnetic field strengths, we took photos of the robot at various angles during the bending process. These images served as visual references for the corresponding magnetic field strengths. By correlating the recorded sensor input with observed angles, we generated a dataset paring angle measurements with corresponding magnetic field strengths. Subsequently, this data was plotted on a chart, with angle represented on the y-axis and magnetic field strength on the x-axis. This experimental procedure allowed us to quantitatively analyze the relationship between magnetic field magnitude and robot deformation, providing valuable insights into the behavior and responsiveness of the magnetic soft robot to external magnetic stimuli.

4.2. Multimodal motion

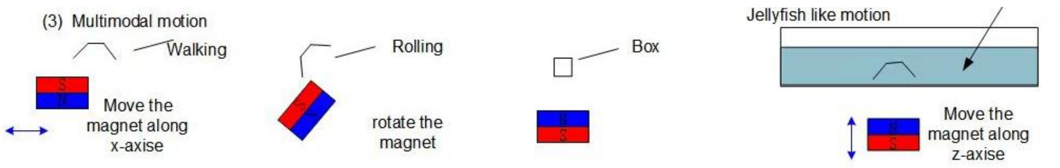

Figure 8. Multimodal motion range experimentation

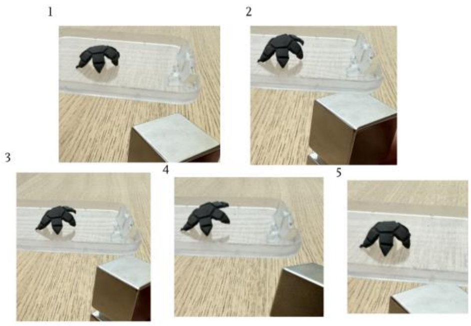

Figure 9. Robot displaying walking motions

The magnetic soft robot exhibits a range of motions (Figs.8 and 9). Firstly, the robot demonstrates walking-like motions by manipulating the magnet along the x-axis underneath the platform. This movement resembles a starfish, as the robot's "legs" flex and extend in a coordinated manner, allowing it to traverse surfaces with precision. Secondly, the robot is capable of rolling motions achieved by rotating the magnet to reposition the robot.

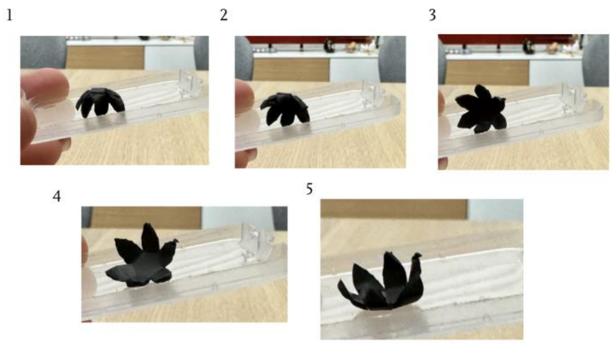

Figure 10. Robot displaying rolling motions

This rolling capability allows for efficient navigation through confined spaces or irregular terrains, showing the robots adaptability in dynamic environments (Fig.10). Thirdly, the hexagram shape of the robot facilitates its transformation into a box-like structure when faced with the north side of the magnet directly underneath.

Figure 11. Robot folded into box-like structure

This motion is particularly useful for securely folding drugs during transportation, ensuring controlled and safe transportation to targeted sites within the body (Fig.11). Lastly, the robot exhibits jellyfish-like motions when placed in water, achieved by moving the magnet along the z-axis under the water tank.

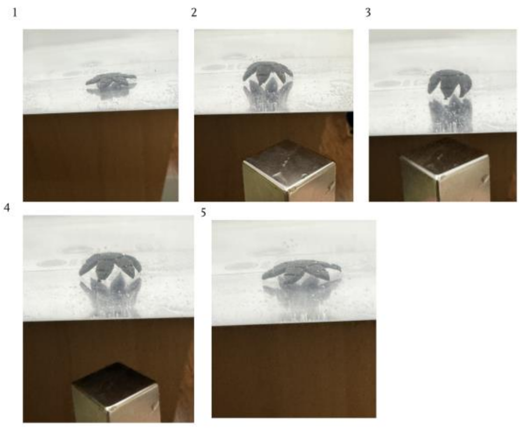

Figure 12. Robot displaying jellyfish-like motions within fluid

This fluid, undulating movement allows the robot to navigate through aqueous environments with ease, making it well-suited for tasks such as environmental sensing or microsurgery within bodily fluids(Fig.12).

5. Conclusion

In conclusion, the development of magnetic soft robots represent a promising advancement for medical interventions. By harnessing principles of soft robotics and magnetic control, these miniature robot systems offer precision, maneuverability, and adaptability within biological environments. Despite facing challenges such as size constraints, navigation difficulties, and energy sustainability, magnetic soft robots show potential in revolutionizing targeted drug transportation, diagnostic imaging, microsurgery, and other applications. Through research and experimentation, our work has contributed to the understanding and optimization of magnetic soft robots, improving the developments medical interventions with reduced invasiveness and improved efficacy.

DOI: 10.54254/2753-8818/49/20241306

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