

The Structural Design of a Magnetic Driven Wireless Capsule Robot for Drug Delivery

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Abstract - The development of the millimeter-level wireless magnetic actuated robot has provided the possibility for the development of endoscopy. In the modern medical system, drugs enter the human body by oral administration and reach the intestinal tract through the esophagus and stomach. If the lesion is located in the gastrointestinal tract, most of the drugs have been absorbed by other parts, and the efficacy is not maximized. In this paper, a structure design of multi-capsule robotic group fixed-point drug release based on Ferro fluid is proposed. The robots group is composed of a front robot and a rear robot, each of which is composed of the robotic body, permanent magnet and Ferro fluid. Permanent magnets are fixed inside of the robot and the rotating electromagnetic field generated by the Helmholtz coils actuates the robots to move forward. Each robot is injected with Ferro fluid, and a clamping force can be generated between the two robots by applying an external magnetic field. The experimental results show that the capsule robots group can reach the designated location for drug release by rotating magnetic field and external permanent magnet.

Index Terms - capsule robots group, magnetic driven, drug release, structural design.

I. INTRODUCTION

With the frequent occurrence of gastrointestinal diseases, endoscopy has been used more and more widely. In modern medicine, the diagnosis and treatment are performed by means of a flexible fibrillar tube with a miniature electronic camera at the end, which is slowly inserted from the anus into the gastrointestinal tract. In the process of the doctor's operation, the patient has a great sense of discomfort and will also cause unnecessary trauma. Therefore, the development of capsule robot has been paid more and more attention.

Since 1999, when Israeli company Given Image developed the oral capsule M2A [1], wireless capsule endoscopy has become a means of diagnosing gastrointestinal diseases. Wireless capsule endoscopy is noninvasive, painless and easy to detect, which provides a good basis for the diagnosis and treatment of gastrointestinal diseases [2]. However, the capsule robot currently used in clinical practice can only make basic diagnosis, and does not add functions such as treatment on the basis of diagnosis [3]. In addition, the current clinical capsule robot can not achieve independent movement, can only rely on gastrointestinal peristalsis for passive movement, can not be accelerated, deceleration, stop and reverse movement. These major problems limit the possibility of a full medical treatment for the capsule robot.

In order to make the capsule robot available for clinical application, various methods have been studied in laboratories and companies to research the movement mechanism in the pipeline. In 2006, the company of Tokyo Olympus developed the EndoCapsule robot [4], which is equipped with a micro-CCD and micro-lens and can automatically control the brightness inside the human body to provide high-resolution images. Similar to M2A, their movements depend on the physiological and natural peristalsis of the digestive tract, which means that their movements are passive and random. In 2011, Koga et al. from Ritsumeikan University in Japan designed a wireless capsule endoscopic robot with the functions of fixed position and drug injection for intestinal medical diagnosis and treatment [5], which can be used for image collection. The robot has a diameter of 15mm and a length of 50mm. The disadvantage of the robot is that it is too large and can not achieve active movement.

In 2013, Yim and Sitti et al. from Carnegie Mellon university in the United States designed a flexible capsule robot driven by magnetic force [6-8]. Driven by external magnetic force, the robot can take the initiative to deform in the axial direction, so as to press the medicine capsule in the body and release the medicine it carries at a fixed point. In 2014, they designed a device to extract tissue for biopsy, using tiny claws to collect tissue samples, based on the original dosing robot. In 2016, the team designed an electromagnetic drive device for the flexible capsule robot [9], but the robot could not achieve effective active movement in the intestinal tract and its structure made it difficult for patients to swallow.

In 2014, Kim and Ishiyama et al. at Tohoku University in Japan proposed an active sport-targeted drug-release capsule robot based on the rotating magnetic field control of the three-axis Helmholtz coil system [10]. The robot solved the movement and drug delivery problems of the capsule robot, but the robot has weak movement ability and small drug carrying capacity. In 2018, Guo et al., at Tianjin University of Technology, proposed a spiral capsule robot driven by external magnetic field control wireless targeted drug delivery module, the module includes two radial magnetizing magnetic ring and a simple plastic chain [11]. From 2013 to 2018, Guo Lab of Kagawa University in Japan carried out an in-depth study on the active motion capsule robot driven by triaxial Helmholtz coil [12-15], including spray rotary motion and vibrating tail pendulum motion. The laboratory has improved the robot structure and external coil system to reduce the required input

current amplitude and improve the safety of the system. The robot has not realized auxiliary functions such as detection or diagnosis and treatment.

In this paper, a magnetic fluid - based structure design of multi - capsule robotic drug delivery system is presented. The robot group is composed of two front and rear robots, each of which is composed of the main body of the robot, permanent magnet and magnetic fluid. Permanent magnets are placed inside the robot and the rotating electromagnetic field generated by the Helmholtz coil causes the robot to rotate and move forward. The two robots are injected with magnetic fluid. By applying external magnetic field, the two robots can generate clamping force to release drugs.

The structure of this article is as follow. The Section II describes the mechanical structure design, magnetic field design and working principle of the fixed-point drug delivery robot group. In Section III, the dynamic model of robot group is established. In Section IV, the fixed-point drug delivery robot group is evaluated. Finally, section V describes the conclusions and future work.

II. MODULE STRUCTURE AND MAGNETIC FIELD DESIGN

A. The Design of Capsule Robots Group Structure

In this paper, the drug fixed-point release mechanism is composed of two parts, the former robot and the rear robot. The bodies of both robots are made of resin and produced by the 3D printer. Each robot is composed of a screw structure, a Ferro fluid chamber and a medicine slot. The inner part of the screw is a hollow structure, which is used to assemble the sensor for further development and at the same time to obtain a larger buoyancy [16]. The Ferro fluid is injected into the magnetic fluid chamber. The Ferro fluid can be magnetized by the external magnetic field and generate a force, which does not rotate with the rotation of the robot. A circular groove was designed as the medicine slot at the junction of the two robot magnetic fluid Chambers to carry the drug.

The Ferro fluid can change with its liquidity in the shape of the mechanical structure and remain relatively stationary inside the rotating robot. In addition, it consists the magnetism of solid magnetic materials, and the remanence remains small enough. In the environment of magnetic field, it can be magnetized and moved with the movement of the magnetic field. When the magnetic field is removed, the remanence disappears quickly. According to the characteristics of Ferro fluid, the mechanical structure in Fig. 1 is designed.



Fig.1 Design of the capsule robots group.

In Fig. 2, it shows the mechanical structure of the capsule robots group and the direction of rotating and motion.

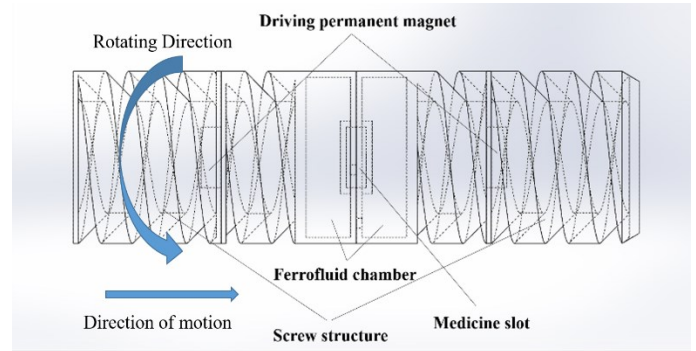


Fig.2 The mechanical structure of the capsule robots group.

The structural design parameters of the robots group are shown in Table I.

TABLE I
THE STRUCTURAL DESIGN PARAMETERS OF THE EACH ROBOT

Property	The capsule robots group
Length of the body	28mm
Diameter of the body	16mm
Diameter of the driving permanent magnet	6mm
Diameter of the medical slot	6mm
Deep of the medical slot	2mm
Material of the robots	resin material

B. Design of external magnetic field

Design of the rotational electromagnetic field. Previously, our team used a rotating magnetic field generated by two directional Helmholtz coils to separate the two robots from each other [17]. Therefore, we re-optimize the design of this rotating magnetic field. In this paper, the rotating magnetic field generated by the external three-axis Helmholtz coil drives the internal permanent magnet of the robot to rotate, so that the spiral structure converts the rotating force into the propulsion force of the capsule robot. In fact, the Helmholtz coil produces a perfectly uniform magnetic field in the central region. Therefore, in order to effectively assemble the Helmholtz coils, three pairs of Helmholtz coils should have different sizes. The specifications of the three-axis Helmholtz coils are shown in Table II.

TABLE II
SPECIFICATIONS OF THE THREE-AXIS HELMHOLTZ COILS

Property	X-axis	Y-axis	Z-axis
Length*Width(cm)	18*18	22*22	26*26
Turns	500	620	740
Magnetic field(A/m)	3880.9		
Materials	copper		
Diameter of copper wire(mm)	1.25		

Selection of the external permanent magnet. The robots gain forward momentum by rotating a magnetic field to rotate

themselves. However, there is no transverse attraction between the two robots to clamp the drug, thus an external magnetic field is needed to generate transverse clamping force between the two robots. The external magnetic field is provided by the permanent magnet, which moves along with the movement of the robot group for a certain distance above the micro pipeline, so that the joint of the robot group generates relative transverse force. Therefore, the selection of external permanent magnets is important. The parameters of the permanent magnet are shown in Table III.

TABLE III
THE PARAMETERS OF THE PERMANENT MAGNET

Model number	N38	
Intensity of magnetic remanence	1220-1250mT	12.2-12.5kGs
Coercivity	>899kA/m	>11.3kOe
Intrinsic coercive field	>955kA/m	>12kOe
The maximum magnetic energy	287-310kJ/m ³	38-39MGOe
Operating temperature	<80°C	
Size of the permanent magnet	D:12mm	H:2.5mm

III. ANALYSIS OF ROBOTS PRINCIPLE

A. Working Mechanism of Drug Delivery Robots

A multi-capsule robot group for drug delivery is presented. In a practical clinical application, the treatment procedure consists of several steps. The doctor places the drug in a medicine slot, assemble the robot, coat it with a capsule which is dissolved in acid fluid, and the patient swallows the assembled robots. Given the space limitation of the larynx, the robot should be small enough to be swallowed and passed through the internal organs. The combined robot is designed to be swallowable and could pass through the esophagus into the stomach, where the capsule coat dissolves and the external magnetic field begins to work. Doctors control the motion form of the robots group by controlling the motion of rotating magnetic field and permanent magnet. When the robot group reaches the location of the lesion, remove all external magnetic field, the transverse force at the junction of the robot group disappears and separates it, and the drugs in the medicine slot are released. After the drug was released, the external rotating magnetic field was restored to allow the robot group to move forward. Finally, the robot excretes the body through the anus. The whole process of drug delivery in the robot group of fixed-point drug delivery is shown in Fig.3.

B. Mechanical Analysis of Screw Structure

According to our previous study, The total circumferential viscous resistance f_c and torque M_c of the capsule robot are expressed as [18]:

$$f_c = n \left(\int_0^H df_{c1} + \int_0^H df_{c2} + f_{c3} + f_{c4} \right) \quad (1)$$

$$M_c = n \left(\int_0^H (R - H + h) df_{c1} + \int_0^H (R - H + h) df_{c2} + f_{c3} R + f_{c4} (R - H) \right) \quad (2)$$

Where n is the number of screws. R is the radius of the

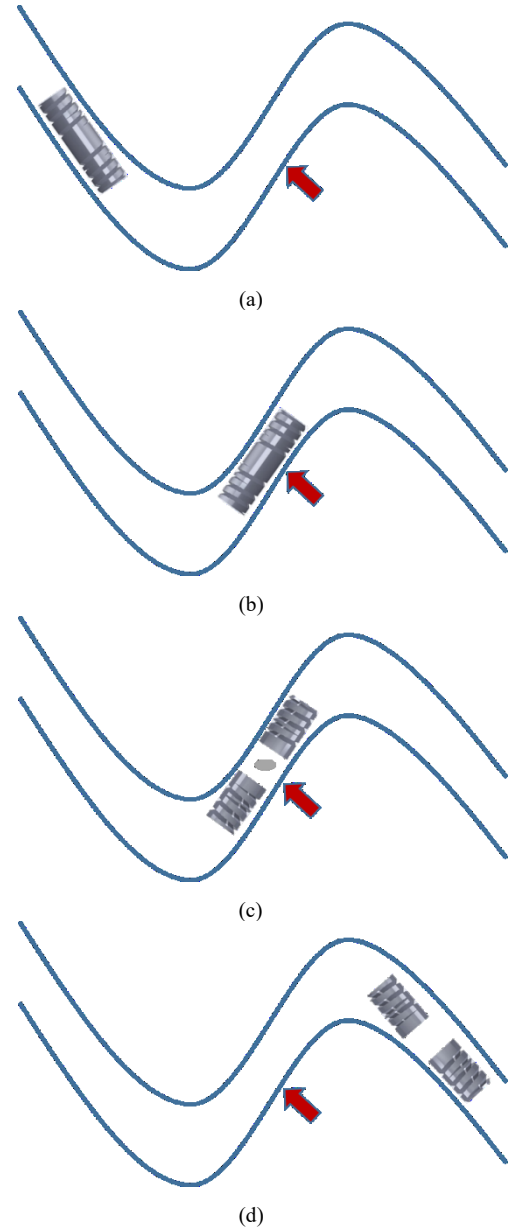


Fig. 3 The whole work process of the capsule robots group. (a) The robots group enters the gastrointestinal tract. (b) The robots group reaches the lesion. (c) The robots group releases drugs. (d) The robot moved away from the body.

robot and H is the depth of the screw. h is the radial distance between the infinitesimal element and the root of the screw. f_{c1} and f_{c2} are circumferential viscous resistance of left and right screw blade respectively. f_{c3} and f_{c4} are the circumferential viscous resistances acting on the crest and root of the screw.

The dynamic model is related to geometrical parameters of the screw. The geometrical model of the screw is established in Fig.4. a is the width of the screw. c is the distance between pipe and the robot. λ is the pitch of the screw. θ and δ are the blade angle and lead angle separately.

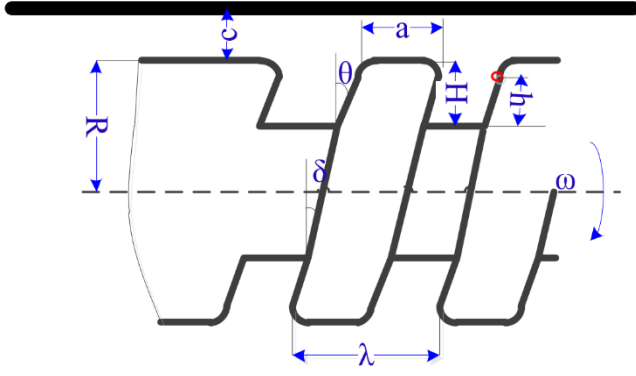


Fig. 4 Geometrical parameters of the screw structure.

In Fig. 4, the circumferential viscous resistance of screw blade f_{c12} perpendicular to the paper is expressed as:

$$f_{c12} = n \left(\int_0^H df_{c1} + \int_0^H df_{c2} \right) \quad (3)$$

which can also be expressed as:

$$f_{c12} = \frac{f_a}{\tan \delta} \quad (4)$$

where f_a is the propulsion along the axis. At low frequencies, the robots try to rotate synchronously with rotational electromagnetic field. Rotating at a certain velocity, the capsule robot obtains an axial force while the water flows backward. The capsule robot begins to move axially only when it can overcome friction force between the pipe and the robot. For laminar flow, friction force can be calculated as:

$$F_f = \eta(G - F_b) \quad (5)$$

where G and F_b are the gravity and buoyancy of the robot, η is the friction coefficient, and F_b is given as:

$$F_b = \rho V g \quad (6)$$

where V is the volume of the capsule robot. Once the capsule robot moves forward, the drag force increases as the axial speed increases. The drag force of a cylinder is defined as:

$$F_d = \frac{1}{2} \rho C_d S v^2 \quad (7)$$

where S is the maximum cross area that is vertical to the flow of fluid and C_d is the resistance coefficient.

C. Mechanical analysis of the joint of robots group

The clamping force mentioned in the Section II. As shown in the Fig.5, a permanent magnet is placed above the joint. It is assumed that its attraction to the Ferro fluid in the front robot and the rear robot is F_{mag} , then the transverse force F_n generated at the joint is as followed:

$$F_n = F_{mag} \cos \gamma \quad (8)$$

where γ is the angle between F_{mag} and the horizontal line.

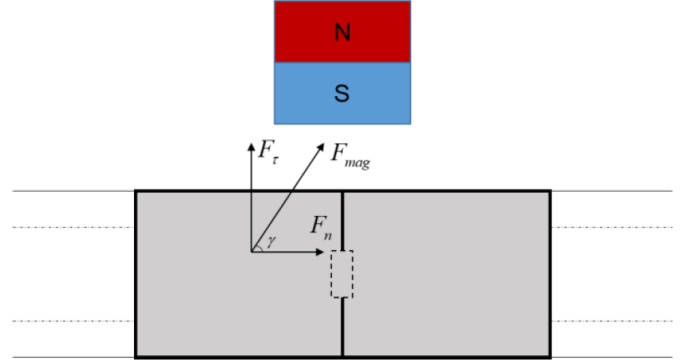


Fig. 5 Mechanical analysis of the joint of robots group.

IV. EXPERIMENTS AND RESULTS

In order to verify the ability of fixed-point drug delivery robots group, an experimental platform was established. The experiments included a set of delivery robots injected with Ferro fluid, permanent magnets, gaussian magnetometer, mechanical arm and a polyvinyl chloride (PVC) pipe with a diameter of 19mm. The robots were placed in pipe filled with water and exposed to external magnetic field. The entire experimental platform is shown in Fig. 6.

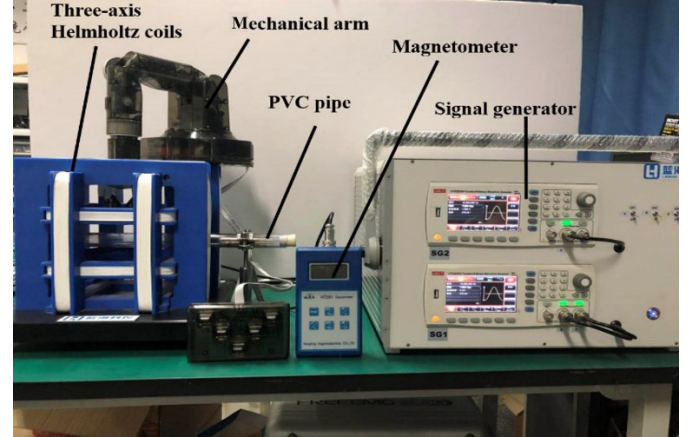


Fig. 6 The picture of the entire experimental platform.

Based on the theoretical analysis of the capsule robot designed in this section, the geometric parameters of the front and rear robots are given in Table IV. The group of robots perform basic movements in the pipeline, such as starting, stopping, assembling and releasing drugs.

Put the front and rear robots into the pipeline respectively. Since the structural parameters of the front and rear robots are consistent, the characteristics of a single robot are verified here. The experimental results are shown in Fig 7. Based on the experiment in our previous study [17], during the experiment, as shown in Fig. 8, the frequency of the input current was gradually increased from 0 Hz to 15 Hz, and the amplitude of the input voltage was fixed at 7v to measure the average speed of the robot. The starting frequency of the robot is 2 Hz, and the speed increases with the increase of frequency. The peak speed of the robot is 5.8mm/s. Based on the above experiments, we

set the frequency of the input current as 7 Hz, the amplitude of the input voltage as fixed at 7v, and the robot speed as 4.3 mm/s.

TABLE IV THE PARAMETERS OF THE PERMANENT MAGNET	
Item	The former(rear) robot
Cutting shape	Parallelogram
Screw pitch	5.5mm
Helix angle	$\pi/4$
Number of turns	3.8

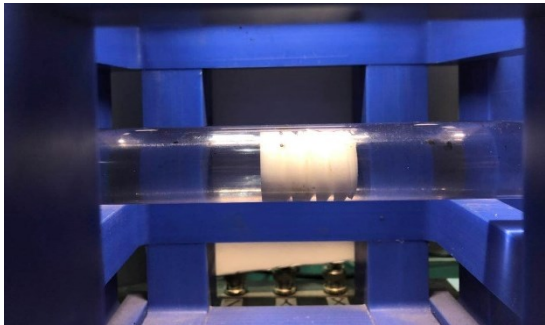


Fig. 7 The experiment of the single robot in the pipe.

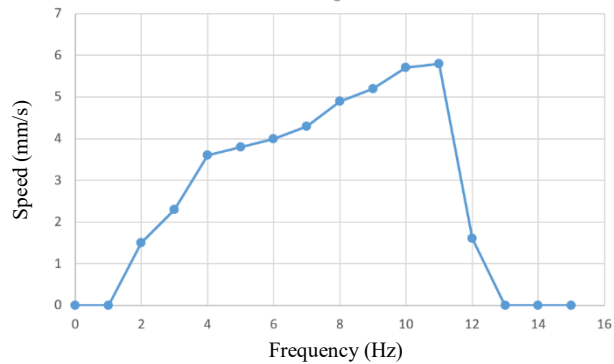
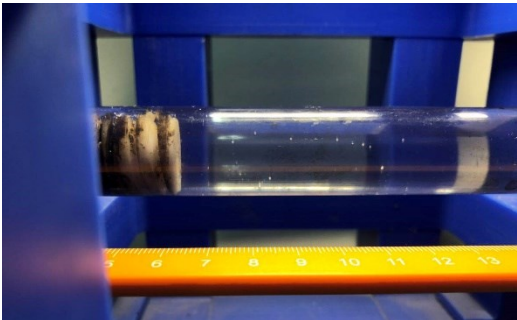


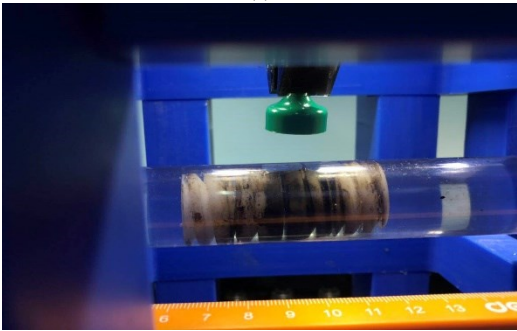
Fig. 8 The result of the image in frequency and velocity.

When the front and rear robots enter the pipeline, the rotating magnetic field and the external applied magnetic field start to work, in which the external applied magnetic field is provided by the permanent magnet. A permanent magnet is clamped at the front of the robot arm, which moves at the same speed with the direction of the robot group at a certain distance above the pipe. When the robots group reaches the designated place, the rotating magnetic field is turned off and the mechanical arm is clamping the permanent magnet to move upward, so that the control without magnetic field of the robot group is disconnected and the drug is released. After the drug is released, the Helmholtz coil is electrified to generate a rotating magnetic field, allowing the robot to continue moving forward. The experimental process is shown in Fig. 9.

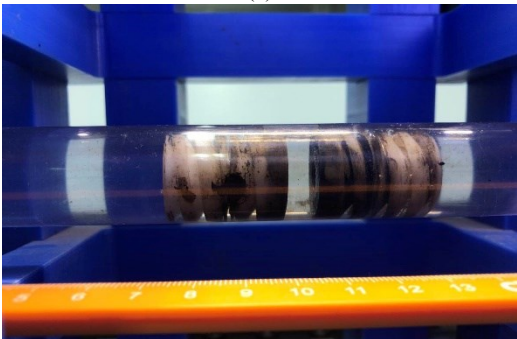
Error analysis was made on the accuracy of fixed-point drug release in the experiment. The marked points in the figure were set as focal points (the ruler scale was 10mm), and the range of about 5mm of focal points was set as focal area. The experiment was carried out according to the experimental



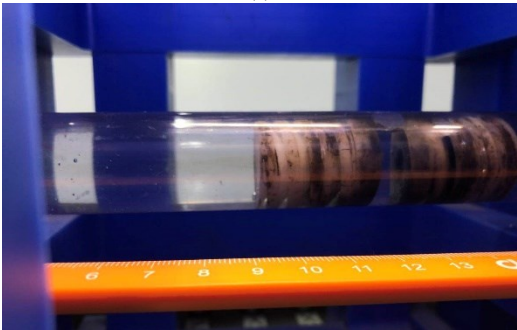
(a)



(b)



(c)



(d)

Fig. 9 The experiment of the drug delivery capsule robots group. (a) The robots group enters the PVC pipe full of water. (b) The robots group reaches the fixed point. (c) The robots group separate and releases drugs. (d) The robots move away from the pipe.

process shown in Fig. 8, to measure and calculate whether the drug release position was in the lesion area and the error distance between the drug release point and the lesion point. A total of 10 sets of the same experiment were done, and the error distance between the actual release point and the set release

point was measured. According to the above data, the drawing error accuracy analysis image is shown in Fig 10. The rectangle in the figure represents the lesion area, and the 0 scale represents the lesion location. According to the error analysis images, the following conclusions can be drawn. The drug targeted release location meets the requirements and always falls in the lesion area.

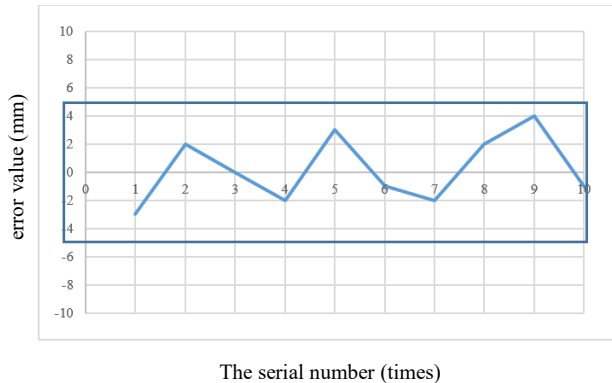


Fig. 10 The result of the image of the error analysis.

V. CONCLUSIONS AND FUTURE WORK

In this paper, a structure design of multi-capsule robotic drug delivery system based on the Ferro fluid is presented. The robot model is designed by SolidWorks software and produced by a 3D printer. Then the design of the robots group is introduced, including structure design, external magnetic field design and working mechanism. The rotating magnetic field is provided by the three-axis Helmholtz coil system, and the external magnetic field is provided by the permanent magnet. Then, the validity of the method is verified by experiments in a pipeline filled with water. The experimental results show that the rotating magnetic field drives the robot to rotate forward, and the external permanent magnet exerts external magnetic field to generate transverse clamping force at the junction of the robots group. Finally, error analysis was made on the accuracy of drug release at fixed points, and the conclusion was that the drug release at fixed points met the requirements and always fell in the focus area. However, in the future work, sensors should be added inside the robot to reserve part of the volume. In the following design, the size of the robot is appropriately reduced without affecting its function, so that the robot can move freely in the gastrointestinal tract.

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