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A Novel Spiral Capsule Robot with Liquid Drug Releasing Functions

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***Abstract* - In the field of gastrointestinal and gastrointestinal diseases, the most common detection method is to use a digestive endoscope, but because the gastroscope passes through the human pharynx, it causes irritation to the pharynx, and patients will have discomfort such as nausea; after the colonoscopy enters the intestinal cavity, the patient will feel abdominal pain. To solve these problems, researchers invented capsule endoscopes. At present, after the capsule endoscope used in the clinic is swallowed by the human body, it is moved by the peristalsis of the intestine, and the internal image is transmitted to the outside world through wireless communication for diagnosis by the doctor, and finally discharged from the human anus, with low efficiency and controllability. In this paper, a liquid drug release module device that can be assembled on a micro-robot drive module is proposed, which uses a rotating magnetic field to push the internal spiral rotation structure, and pushes the piston at the bottom of the drug warehouse to squeeze the internal space of the drug warehouse, to achieve the purpose of releasing liquid drugs at a fixed point in the digestive tract.**

Index Terms - Spiral capsule robot, Drive module, Magnetic field drive, Liquid drug release.

I. INTRODUCTION

In the field of gastrointestinal and gastrointestinal diseases, the most common detection method is to use a digestive endoscope, but because the gastroscope passes through the human pharynx, it causes irritation to the pharynx, and patients will have discomfort such as nausea; after the colonoscopy enters the intestinal cavity, the patient will feel abdominal pain. Capsule endoscopy greatly alleviates the discomfort of patients during gastroscopy. However, due to the randomness of its motility, a comprehensive examination may not be possible at some folded intestines; at the same time, its working time is severely limited due to battery limitations, and most patients cannot tolerate the long hours of lying in a fixed transmitting coil during diagnosis. [1]. In addition, individual capsule endoscopes cannot carry enough medical devices, and tiny bodies lead to fewer functions [2].

The miniature pipe robot that will be studied in this article is a small, maneuverable device that can operate in the human body. These small-size devices allow the use of much less invasive procedures in place of surgery as well as non-targeted chemical and radiation therapies [3]. With the gradual improvement of people's pursuit of quality of life, the combination of robotics and medical technology is becoming closer, and the research and development of micro-robots that can enter the human cavity have important significance and research value to complete the medical tasks of low-aggression, low-invasive or even non-invasive diagnosis and treatment [4].

Considering the safety and biocompatibility of in vivo or tissue engineering environments, cableless is an inevitable trend in the development of micro-robots. The external magnetic field drive method is more suitable for the drive and control of cableless microrobots. Operating with magnetic fields has advantages in biomedicine because they have minimal interaction with tissues with magnetic field strengths below 3 Tesla (T) [5]. Guo et al. designed a multifunctional capsule robot (MCR) with active locomotion, dual-drug load, and selective drug release. Simulated experiments were done with pig intestines, and no noticeable damages to the pig intestine were observed to the naked eyes [6]. Recent developments involve the use of magnetic torque, rotating and oscillating magnetic fields, among other methods to actuate miniature robots, causing them to make spiral movements that propel them forward and allow these devices to perform more precise 2D and 3D navigation. Many propulsion methods of these devices have been adapted from nature, such as spiral flagella found in certain bacteria, caudal flagella found in sperm, and designs that mimic the movement of fish in water.

Rotating structures can generate more driving forces than other structures. In terms of drive mode, due to the limited size and load of the microrobot, the built-in drive device is not suitable as a power unit, and the external drive mode can avoid the increase in robot size and load [7]. The advantage of using a magnetic field drive is that it is fast in response, flexible in control, and less restrictive [8]. Liu et al. designed a bacteriologically-like spiral propulsion robot. The propulsion power of the robot comes from the four spiral rigid materials in the tail, and the motor provides kinetic energy to control the speed of the four spirals and then control the axial and circumferential movement of the robot. Guo et al. designed a tiny fish-shaped tubular robot that is wirelessly driven by a magnetic field. The robot can control the movement of the robot by changing the amplitude and frequency of the tail by changing the magnetic field [9], [10]. The spiral structure and liquid on the surface of the capsule produce an axial thrust due to relative rotation, allowing it to move through the intestines [11], [12].

Islam S.M. Khalil et al. proposed a method for positioning and controlling a spiral robot during the removal of superficial blood clots in vitro and ex vivo models. This method is used to locate the spiral robot in the rabbit aorta (ex vivo model), and the localization accuracy is verified using ultrasonic feedback

[13]. Jang et al. studied the motion of a magnetic three-stranded nanorobot that creates undulating motion under an oscillating magnetic field superimposed by two sinusoidal magnetic fields on the x and y axes [14]. Guo et al. designed a new type of magnetically driven micro-robot selective motion control with targeted drug sustained release function based on the capsule robot of the multifunctional module for controlling the robot's movement in the intestine [15], [16]. The findings in this paper suggest that the problem of using magnetic nanorobots in highly viscous fluid environments commonly found in living organisms can be overcome. The use of fish swimming motion mode to make bionic robots is not unfamiliar, most of them are driven by motors, the use of strong magnetic field drive examples are relatively rare, Li et al. made magnetic propulsion of fish-like artificial nanoswitch, under the oscillating magnetic field, push nickel rod periodically bend the body and tail fin, to produce a traveling wave movement of more than 30 μm/s, is the use of planar oscillation magnetic field to propel artificial nanofish [17]. Applying an oscillating magnetic field in the z-direction causes the nanorobot to freestyle, in which two nanobs swing, creating a driving force in the x-y plane [18]. Driven by an electromagnetic field, the driving torque is related to the volume of the robot body, and deformation is generated at the same time, and the continuous deformation is used to produce propulsion in the fluid, such as the propulsion in countercurrent [19].

In this paper, a liquid drug release module structure design based on a multifunctional capsule robot is proposed. The robot consists of two drive robot modules in front and rear and a function module in the middle, and the rotating electromagnetic field generated by the Helmholtz coil rotates the permanent magnet inside the drug release robot and pushes the liquid drug release. The structure of this article is as follows. The second section introduces the mechanical structure design and magnetic field driving principle of the drug release function module. The third section establishes a dynamic model of the robot swarm. The fourth section conducts an experimental evaluation of the drug release function module. Finally, Part V presents the conclusions of this article and future work.

II. Magnetic Field And Structure Design

A. Magnetic Field Generation Device

The magnetic field control in this experiment is mainly based on a signal generator connected to the three-dimensional Helmholtz coil, and the current signal in the control coil generates a uniformly changing magnetic field in the middle of the coil, and then controls the miniature pipe robot with a permanent magnet located in the center of the coil to rotate, combined with the water in the pipeline to generate a forward motion thrust. The three-dimensional Helmholtz coil used in the experiment is a square coil that is used to generate the robot's peripheral drive magnetic field. In this study, a rotating magnetic field generated by two pairs of Helmholtz coils perpendicular to each other was used to drive the spiral robot [20]. The position of the two pairs of Helmholtz coils perpendicular to each other is marked in blue, and the central axis of the pipe is perpendicular to the plane where the two pairs of Helmholtz coil axes are located, as shown in Fig.1.

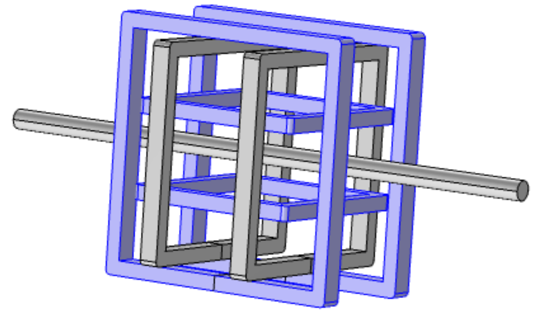


Fig. 1 Schematic diagram of the position of a three-dimensional Helmholtz coil relative to the pipe

The parameters of the triaxial Helmholtz coil designed in the experiment are shown in Table I.

TABLE I
EXPERIMENTAL DESIGN OF THREE-AXIS HELMHOLTZ COIL PARAMETERS

Property	X-axis	Y-axis	Z-axis
The length of side (cm)	18*18	22*22	26*26
turns per coil	500	620	740
The magnetic field intensity	3899.9A/m		
The diameter of the wire (mm)	1.25		
The material of the conductor	copper		
The direct-current resistance	4.8Ω	3.5Ω	2.4Ω
The Magnetic field uniformity	3%	5%	9%
The Maximum current	5A		
The Magnetic field uniform region	60mm*60mm*60mm		

Because the external rotating magnetic field needs to be provided, and the rotation plane is perpendicular to the direction of the robot's axial motion. Therefore, two pairs of Helmholtz coils perpendicular must produce a stable rotating magnetic field in the two-dimensional plane, the input amplitude and frequency are the same in the two coils, and the phase difference is π/2 of the sinusoidal signal, and the rotating magnetic field in the two-dimensional plane can be generated in the plane perpendicular to the axial motion direction of the miniature robot after the superposition of the two signals.

B. Liquid Drug Release Device

The liquid release device of this design is embedded in a radial magnetized drive permanent magnet, and the rotating piston base is driven to rotate in the magnetic field. The exterior of the base is designed with three grooves 0.2 (mm) deep, and the cylindrical structure with a diameter of 5 (mm) and a height of 2.5 (mm) above the rotating piston base connects the piston structure. The rotating piston base is nested on the outside of the fixed shell, embedded in the groove with a diameter of 1mm steel ball, its function is mainly to reduce the friction of the base when it spirals up, the fixed shell is fixed in the groove of the release module shell, when the external rotational magnetic field perpendicular to the axis plane of the base, the internal radial magnetized permanent magnet rotates to drive the external piston base to rotate, due to the presence of grooves and steel balls, the rotating piston base does a spiral upward movement. This translates into a straight upward movement of the piston. The piston is embedded in the shell of the liquid pharmacy, which is the liquid drug storage area between the two, which can hold 0.2 (ml) of the liquid and inject the liquid into the tissue by pushing the piston through the rotation of the base. The entire release device is embedded in the release module housing, and the release device structure diagram is shown in Fig. 2.

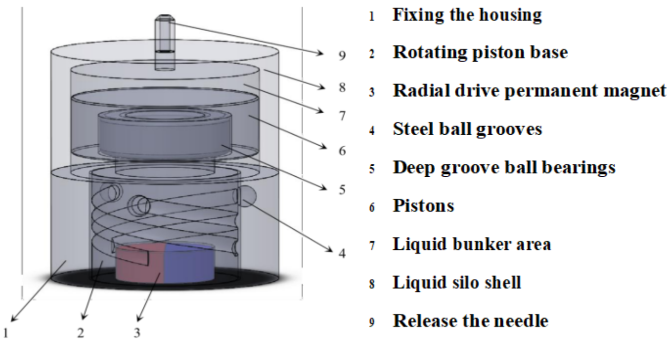


Fig. 2 Schematic diagram of the internal device structure of the liquid drug release module.

C. Design of The Liquid Drug Release Structure

A liquid drug release module apparatus may be assembled in a micro-robot drive module is proposed, and the working schematic diagram of the functional module and the driver module after assembly is shown in Fig. 3. When the miniature robot carrying the liquid drug release function module enters the pipeline after assembly, the external Helmholtz coil group begins to work, and the incoming current generates a rotating magnetic field in a plane perpendicular to the axial direction of motion, due to the different magnetic induction lines of the permanent magnet in the drive module and the liquid drug release module, the magnetic field does not affect the driving permanent magnet in the release module. When the drug release point is reached, the magnetic field of the drive module stops working, at this time the external anchoring device equipped with a permanent magnet is used in the outside world to act on the permanent magnet inside the micro-machine human drive module, so that it is anchored in the position of the lesion and the use of the folding environment in the intestine will release the module The drug release port is close to the lesion tissue, the external magnetic field continues to work, and the direction of the rotating magnetic field generated by the outside world at this time is perpendicular to the plane of the release needle, and the drug is released into the intestinal tissue using the internal spiral rotation structure, After the release work is completed, the existing rotating magnetic field is stopped, and the rotating magnetic field is generated in the direction of the axial motion of the microrobot so that the robot continues to move inside the pipeline. The structure after combining the liquid release function module with the drive module is shown in Fig. 3.

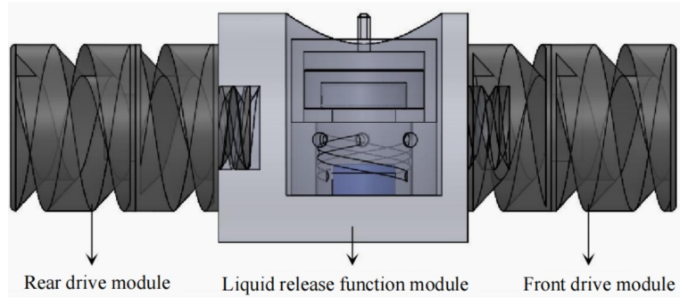


Fig. 3 Schematic diagram of the combined structure of the liquid drug release module and the drive module.

The liquid drug release device is mainly composed of an external release module shell and a release device installed in its internal groove, which is mainly composed of a fixed housing, a rotating piston base, a radial drive permanent magnet, steel balls, ball bearings, pistons, a medicine chamber, a drug chamber shell, and a release needle.

III. Simulation And Force Analysis

A. The Simulation Drives the Magnetic Field

Using the simulation software COMSOL Multiphysics 5.6, the magnetic field of the energized Helmholtz coil was simulated to explore the principle of a uniformly changing magnetic field generated by the energized three-dimensional Helmholtz coil. First, the square uniaxial Helmholtz coil is simulated.

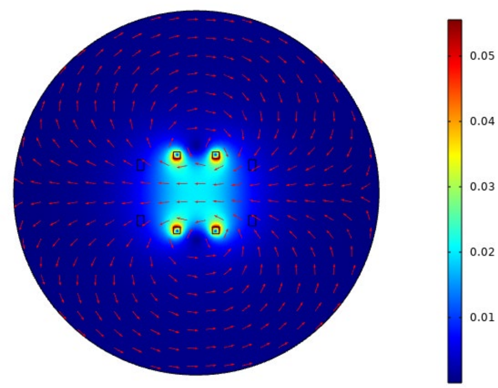


Fig. 4 The coil generates a magnetic flux density distribution map within the xoz plane

At the 0th moment, only the innermost large coil Y-axis coil has a current, and the current size is 4A, and the X and Z axis coils are in a state of no current. Simulation calculations can obtain a magnetic flux density distribution of the magnetic field generated by the Y-axis uniaxial square Helmholtz coil, which is shown in Fig. 4. It can be seen that a uniform and stable uniform magnetic field can be generated in the two coils, and the magnetic field size of the uniform area is 25mT.

Take the Y-axis and Z-axis square Helmholtz coils generate a rotating magnetic field in the yoz plane for example. To generate a clockwise rotating magnetic field in the yoz plane, a current is introduced in the Z-axis square Helmholtz coil and a sinusoidal current in the Y-axis square Helmholtz coil, as follows:

$$\begin{cases} I_Z = I_0 \sin 2\pi f \\ I_Y = I_0 \sin\left(2\pi f t - \frac{\pi}{2}\right) \end{cases} \tag{1}$$

The above current is injected into the coil, where the amplitude of the current is 4A and the frequency is 10Hz, which is simulated. Select the square area in the middle of the yoz plane to establish a parametric plane and use arrows to indicate the direction and magnitude of the magnetic field strength. Observe its change over a period, and the results are shown in Fig. 5:

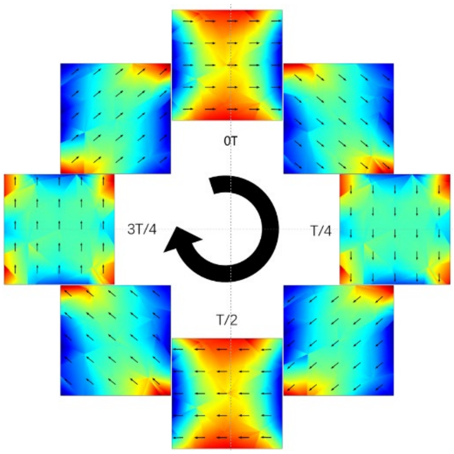


Fig. 5 Parametric plan of changes in the magnetic field over one period

B. *Mechanical Analysis of the Liquid Drug Release Module*

When the micro-robot liquid drug release module works, a rotating magnetic field is generated within the xoy plane. In the active operating area of the magnetic field, the expressions for the torque τ and force F_1 generated by the external magnetic field acting on the driving permanent magnet within the drug release module are:

$$\tau = \mu_0 V M \times H \tag{2}$$

$$F_1 = \mu_0 V (M \cdot \nabla) B = \mu_0 V \left[\frac{\partial H}{\partial x} \quad \frac{\partial H}{\partial y} \quad \frac{\partial H}{\partial z}\right]^T M \tag{3}$$

Where the vacuum permeability is $\mu_0 = 4\pi \times 10^{-7} N \cdot A^{-2}$, V is the driving permanent magnet volume, M is the magnetization vector of the permanent magnet, and H is the generated magnetic field vector.

Referring to the theoretical expression of the relationship between bolt tightening force and axial force in mechanical principles, the relationship between the torque of the piston base in the drug release module and the axial thrust in this topic can be obtained, and the expression is:

$$M = \left[\frac{2\xi(L^3 - l^3)}{3(L^2 - l^2)} + \frac{R\tan\delta}{2}\right] P \tag{4}$$

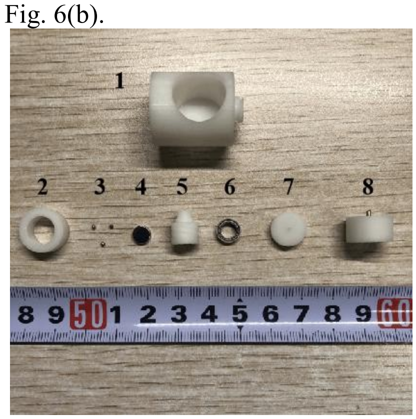
Where P is the axial thrust of the piston base upwards, L is the outer radius of the outer shell ball groove of the rotating piston base, l is the inner radius of the shell ball groove, ξ is the friction coefficient between the piston base and the outer plane, R is the middle diameter of the piston base groove thread, and δ is the rising angle of the piston base groove thread. The expression for the axial thrust P up the piston base is evaluated as:

$$P = \frac{6\tau(L^2 - l^2)}{4\xi(L^3 - l^3) + 3R\tan\delta(L^2 - l^2)} \tag{5}$$

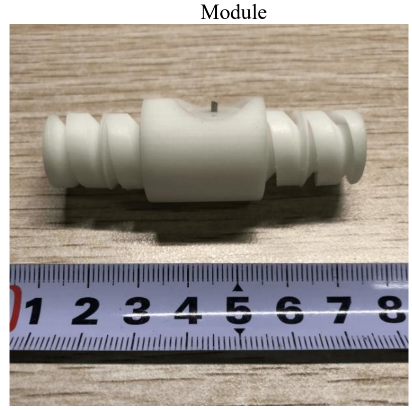
Therefore, the thrust F of the liquid in the propeller bunker can be calculated as $F = P - f$, where f is the sliding friction between the piston and the inner wall.

IV. Experiments And Results

The structures used in this experiment are the front and rear drive modules of the miniature pipe robot, the liquid drug release module, the external magnetic field generation device, and the external anchoring device. The liquid drug release module internal parts after the installation of the liquid drug release module after the completion of the liquid drug release module model, it and the drive module can be assembled to obtain a micro pipeline robot for liquid drug release, the microrobot model before assembly is shown in Fig. 6(a), the part structure is in turn the module shell, liquid release device shell, steel ball, radial magnetized permanent magnet, rotating piston base, bearing, piston, liquid cartridge and release needle. The assembled liquid release module is connected to the drive module by a threaded structure to obtain a complete robot. This is shown in Fig. 6(b).



(a) Schematic diagram of the components of the Liquid Drug Release Module



(b) Miniature robot model of liquid drug release after assembly

Fig. 6 The coil generates a magnetic flux density distribution map within the xoz plane

Since the slightest change in the external structure of the micro-pipe robot can change the starting frequency, cut-off frequency, and optimal working frequency of the robot in this state, the motion characteristics of the micro-robot after assembly are measured before the experiment. The assembled micro-robot is put into a pipe filled with water, the initial current into the coil is the sine current with the same amplitude frequency and the same phase difference, the current frequency is increasing from zero, and the external magnetic field rotation frequency of the assembled robot model is obtained and its axial average motion speed data and the relationship between the external magnetic field rotation frequency and the axial average motion speed of the micro-pipeline robot liquid drug release module is shown in Fig. 7. When the external magnetic field rotates at frequencies in the 3Hz and 5Hz ranges, the microbot has a certain axial motion speed, corresponding to which the frequency interval is the operating frequency of the liquid drug release module.

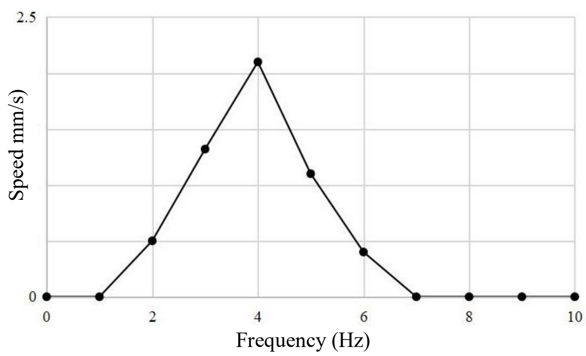
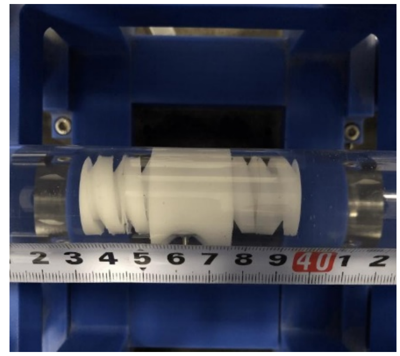
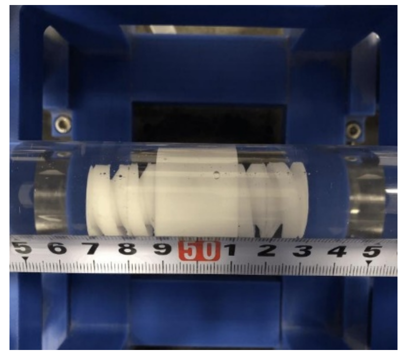


Fig. 7 Graph of the relationship between the rotation frequency of the magnetic field and the axial average motion speed of the liquid drug release module of the microrobot

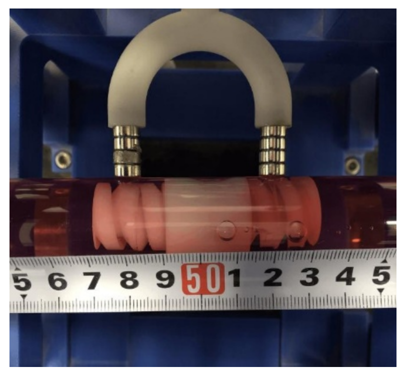
Experiments were performed on the liquid drug release module model, and the front and rear drive modules were assembled onto the liquid drug release module before the experiment, and the liquid drug was injected into the drug tank instead of a red dye and placed into a pipe filled with water. The X-axis and Z-axis coils pass through a current at a frequency of 4Hz, causing the miniature robot to rotate for axial motion. When the specified position is reached, the 50cm tick point is shown in the figure, and the current in the X and Z axis coils is adjusted to zero, at which point the external anchoring device begins to work, and the experiment is completed in the pipeline. The external anchoring device intervenes above the release point, and the permanent magnet driven inside the drive module generates magnetic force to fix the miniature robot at the release point. The Y-axis and Z-axis coils are channeled with a current frequency of 5Hz so that the micro-robot liquid drug release module is activated, and the piston moves upward when the internal permanent magnet rotates to release the drug to the outside of the robot. After completing the task, the current in the Y-axis and Z-axis coils is adjusted to zero, the current in the X-axis and Z-axis coils is restored, and the axial movement continues along the pipe. The above experimental process is shown in Fig. 8.



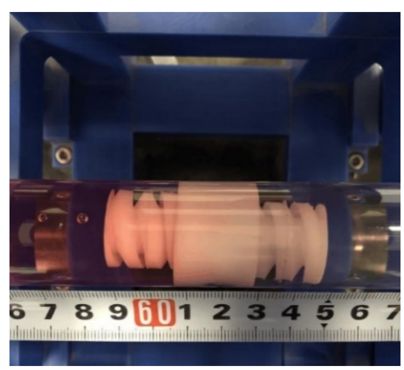
(a) Micro-robots moving inside the pipe



(b) Mic-robots arrives at the liquid drug injection point



(c) Micro-robots perform liquid drug releases



(d) Micro-robots continue to move

Fig. 8 Flowchart of the liquid drug release module experiment

In this experiment, the liquid drug release module was validated. The 3D printed drive module model is put into the pipeline for verification, and the startup frequency and cutoff frequency of the drive module model can be obtained through the relationship diagram of frequency and axial speed. The model is placed in the no-load state in the pipeline for verification to obtain the optimal operating frequency of the robot. For a robotic model assembled with a liquid drug release module, experiments are performed at its optimal operating frequency, and feasibility analysis of the liquid drug release module is performed.

V. Conclusions And Future Work

In this paper, a liquid drug release module structure design based on a multi-module capsule robot is proposed. The modules of the robot are designed with SolidWorks software and manufactured with 3D printing of white resin. The magnetic field drive principle of the robot was introduced and simulated, the effectiveness of generating a rotating magnetic field to drive the rotational motion of the radial magnetized permanent magnet with a three-axis Helmholtz coil was verified, and then its liquid drug release function was tested in a water pipe that simulated the gastrointestinal environment. Experimental results show that the rotating magnetic field in the axial perpendicular plane with the water pipe can drive the robot to travel back and forth in the pipe. After reaching the specified position, another set of coils can be used to generate a rotating magnetic field in the plane perpendicular to the injection direction, driving the radial magnetized permanent magnet inside the base of the rotating piston to push the piston so that the drug in the liquid cartridge flows out of the release port. It was concluded that the module was capable of releasing liquid drugs at a fixed point. In future research, space should be reserved inside the capsule robot, adding miniature cameras and other functional modules that can be used for medical detection. And can be transmitted wirelessly to the outside world to observe the patient's internal conditions in real-time.

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