Study on a Novel Type of Magnetic Actuated Microrobot

by

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Abstract

The capsule endoscope (CE) is used in a wide range of minimally invasive medical field. After 20 years of development, it has become a frontline established technology and be favorited by the patients. OMOM (Jinshan, China), MIRO (Intromedic, Korea), and PillCam (Given-, Israel) are popular capsule endoscopes that have been commercialized, they provide reference norms for the industry, such as ethics, theory, size, clinical, materials and some expert consensus. The novel types minirobots proposed in this research are focused on the development of the wireless magnetic actuated minirobot, which provides the feasibility of the similar wireless capsule endoscopes (WCE). The WCE have many potential applications in the medical field. For example, there are three main global medicine market, the first one is the high-end physical examination, high-income people have a great demand for emerging medical experience, and the number of physical examinations has increased year by year and for this traditional medical project, WCE is more popular than traditional endoscopy. Second, gastroenterology and cardiovascular medicine (WCEs are expected to reduce the mortality of gastrointestinal bleeding in patients with coronary heart disease after stent surgery), and form an effective complementary with traditional endoscopy to solve the limitations of traditional endoscopy. Third, the early detection of gastrointestinal disease. The WCEs has been widely used because of its painless, safe and effective, high diagnostic accuracy and easy operation. The sum of the above three types of market values will be about 4 billion dollars in 2020. This non-invasive method is more popular with the patients, they can just oral the WCEs and wait for it to move down along the stomach, duodenum, jejunum, colon and large intestine. After two decades of development, comparing with the traditional CEs, the active WCEs with advanced technology are more suitable for the narrow areas and complex environments during the GI tract. Comparing the traditional CEs, the size limitation, power supply dependence and lack of functions are the main challenges during the development of the WCEs. For the dimension design of the robots, it generally refers to the CEs which has been commercialized. For instance, the PillCam and OMOM are the bellwethers in this field, the CEs that they carried out have been certified by the US Food and Drug Administration (FDA), the relatively high-level research in the industry will follow the basic standards such as dimensional requirements, ethical and theoretical examinations proposed by these two companies. Then, the power supply of the traditional CEs is relying on the battery and the movement of them rely on the gravity and intestinal peristalsis. It is difficult for them to arrive at the desired area sometimes, meanwhile, the CEs without active locomotion will takes 8 hr to pass through the whole digestive tract. The driving mode in this thesis we used is the force transmission method actuated by the electromagnetic actuation (EMA) system. The EMA system is widely used in the advanced research in this field, the force transmission method provides the feasibility of the non-battery active locomotion CEs. The three-axis Helmholtz coils we proposed contains three pairs of electromagnetic coils that are orthogonally arranged in a spatial coordinate system, and the coils are driven by a servo amplifier, whose signal of control input is calculated by the control program on the PC controller. The generated uniform magnetic fields have the same magnitude and direction at all point inside the working space. The operators can monitor the orientation and motions via the real-time data and the information of the applied dynamic electromagnetic field, such as magnitude, direction and frequency by the control panel. The axial orientation of the rotating magnetic field can be adjusted in response to currents applied to three-axis Helmholtz coils, and the superimposed magnetic field features good uniformity and directivity. When the operator changes the electromagnetic field generated by the Helmholtz coil, the digital signal is converted to an analog signal, which is then passed and controlled to the power supply to generate the desired current.

Based on the above medical background and devices, the main challenges of this research are the size limitation, realization of the function modules and according to the pathological requirements to design the structure and realize the functions.

So this study will be divided into three steps.

The first is to develop and evaluate the novel type active magnetic actuated minirobot with screw jet motion. Then, a novel multiple functions minirobot will be carried out to complete different tasks under the same EMA system during the evaluation experiments. Finally, according to the pathological background and real environment, an in-vitro experimental environment was established to simulate the real intestine, a series of in-vitro experiments will be carried out to evaluate the different performances of the proposed minirobots in the complex environments. We also summarize the bottlenecks of the current research, prospective the application feasibility of the minirobots and in the process of commercialization, there are still a series of difficulties in customer service.

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

Chapter 1 Introduction

1.1 Background of the research

WCEs are favored in modern surgical procedures for the treatment of disease in clinical surgery and examination. The patients are willing to choose only simply swallowing a pill to do the early screening and medical examinations without anesthesia. WCE offers a promising method for precision medicine for minimally or non-invasive procedures in the gastrointestinal (GI) tract. Microrobots have the potential to revolutionize many aspects of medicine 错误!未找到引用源。. It benefits from untethered, wirelessly controlled performance and diversified powered devices, which will make existing therapeutic and diagnostic procedures less invasive that can cause new procedures possible. Moreover, most traditional CEs rely on their gravity and intestinal peristalsis to move forward passively. Generally, the time required for such a medical procedure is about 8 hr [anhan]. Further, these CEs can not achieve active locomotion may cause undesired effects, such as the risk factor for capsule retention 错误!未找到引用源。. In view of the above problems, the development of the active capsule endoscope (ACE) is required. Among them, the magnetically manipulation ACE is a method accompanying the invention of the ACE. Meanwhile, the energy supply problems, space constraints of the internal environment, operational difficulties and the size limitations always been the toughest challenges. Some current stage research to develop function module of magnetic actuated minirobot is mainly focusing on adding battery-powered function modules. Although with the progress of technology, the desire of miniaturization and integration of hardware can be realized, the problem of energy supply and security of the capsule robots is still inevitable, even in some cases, the problem of heat dissipation is also a big hidden danger 错误!未找到引用源。.

1.2 Electromagnetic actuation system

It is expected to complete the tasks of diagnosis, biopsy and drug delivery in the gastrointestinal tract by using the body fluid in the natural cavity of the human body as the medium to actively drive and control the medical microrobot, which has a broad application prospect in medical engineering. Gastrointestinal motility cannot be completely dependent on the endoscopic diagnosis of the gastrointestinal tract, and its gastrointestinal motility cannot be completely dependent on gastrointestinal motility. Therefore, it is of great significance to drive and control the capsule robot reliably and effectively, especially in the curved intestine [33]- [37].

1.3 Motivation and research purpose

We have proposed different kinds of minirobots in previous research. However, in order to meet the conditions of disease treatment, diagnosis of intestinal problems and clinical minimally invasive surgery, further structural optimization design and clinical application experiments are necessary. In addition, robots need to be able to integrate executive components (such as drug delivery module), cameras (e.g., endoscopes) and sensing elements for medical tasks. Therefore, medical safety, structural optimization potential and effective performance in specific environments are extremely important and challenging. There are several challenges in our research.

1) Minirobot structure design for active locomotion with effective propulsive creative ability on limited size requirements.
2) The selective motion control method and targeted drug delivery method to realize function module on the minirobot.
3) The method to prepare the environment to simulate the human intestine, and the minirobot will face different complex environments to complete the tasks during the in-vitro experiment.

1.4 Thesis contributions

In this thesis, a series of novel magnetically actuated minirobots based on EMA system are proposed, the force transmission and non-contact movement of these minirobots are realized by NdFeB magnet and transformed magnetic field. We have gradually completed the development of robots, step by step to achieve a number of theoretical and experimental innovation and practice in this field.

Contributions of this thesis are:

(1) Development and evaluation of the novel active locomotion minirobot with screw jet motion

The screw jet minirobot has the advantage is that comparing with the traditional active CEs, this type of minirobot has a shell outside the active device. This kind of inner driving CEs are comfort and easily to swallow by the patients, meanwhile, it can suit various complex environments inside human body and it provides the feasibility for the development of the similar active CEs to minimize the risk of perforation, the outer shell of it was smoothly fabricated to reduce the scratching of the intestinal wall.

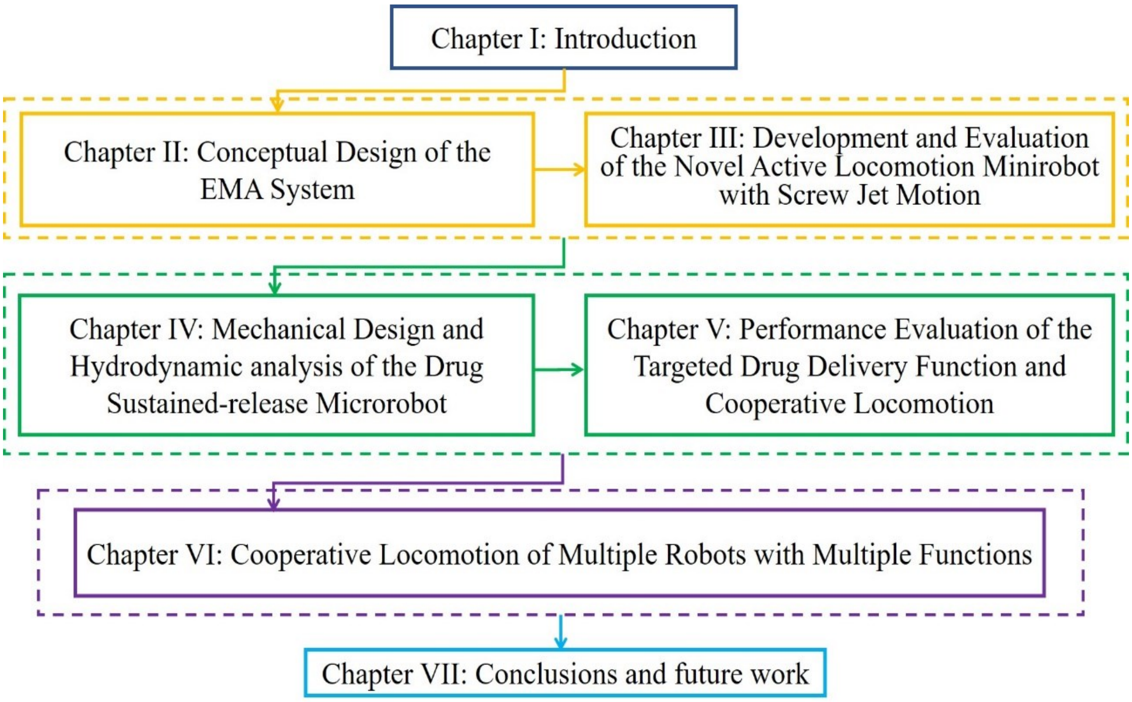
(2) Development and evaluation of the minirobot with targeted drug sustained-release function

A novel type of magnetically actuation minirobot with targeted drug sustained-release function is proposed. The structure of the Drug sustained-release Minirobot (DSM) is mainly divided into three parts, a shell, an internal propeller and a drug chamber. The shell can effectively protect the intestinal tract and reduce the various resistance during the work, the built-in propeller not only realizes active locomotion but also saved internal space, which provides the feasibility for the development of functional modules of the robot. The drug chamber pushes the carried drugs out of the chamber is similar to a syringe. a series of simulations and experiments to evaluate DSM's motion performance, drug delivery function, and dose control during drug delivery. In the experiment, two different drug delivery points were set up to make DSM spray the drug on the fester areas twice respectively.

(3) Cooperative locomotion of minirobots based on the clinical applications.

Based on previous research, the EMA system is developed to allow a doctor to remotely control a wireless capsule minirobot through a master device. After realized the development of the active locomotion and function module, multiple CEs with multiple functions become the trend in the field combining with the commercial demand such as reducing hospitalization time and enhancing recovery. Besides, in order to get closer to the real environments inside the human body, we simulated the pig large intestine pipe as the motion environment based on the practical applications, a series of the in-vitro experiments have been carried out in the third topic.

1.5 Structure of the thesis



Chapter 2 Conceptual Design of the Electromagnetic Actuation System

2.1 Conceptual design of the electromagnetic actuation system

In recent years, power supplied by the external electromagnetic field has been proposed so that the capsule minirobot manipulating method by force transmission could be achieved. In this research, three-axis Helmholtz coils are utilized to manipulate the multi-module minirobot's multi-directional motion, posture and high precision drug delivery function.

There are three pairs of symmetric coils on the three-axis Helmholtz coils, with flowing identical electric currents in each pair coil. This operation system is to provide a rotational dynamic electromagnetic field for the movement of the robots and the operating environment. It generates uniform electromagnetic fields, which can be utilized to manipulate the different driving methods and directions of multi robots in the experimental area. Figure 2.1.2 is the illustration of the experimental operating system [38]-[41].

2.2 Electromagnetic actuation system

The three-axis Helmholtz coils contain three pairs of electromagnetic coils that are orthogonally arranged in a spatial coordinate system, and the coils are driven by a servo amplifier, whose signal of control input is calculated by the control program on the PC controller. The pairs of X and Y axis coils form a cubic shaped horizontal direction working space with a width of 370 mm, length of 400 mm and height of 300mm, meanwhile, the generated uniform magnetic fields have the same magnitude and direction at all point inside the working space [42]. The operators can monitor the orientation and motions via the real-time data and the information of the applied dynamic electromagnetic field, such as magnitude, direction and frequency by the control panel. When the operator changes the electromagnetic field generated by the Helmholtz coil, the digital signal is converted to an analog signal, which is then passed and controlled to the power supply to generate the desired current. Through the above processes, the operators can manipulate the motions and directions of the electromagnetic field according to real-time data and conditions via using this open-loop controlling method.

Table 2.1 Specification of Three-axes Helmholtz coils

	Turns (n)	r (mm)	d (mm)	Resistance(Ω)
x-axis coils	125	142	150	2.4
y-axis coils	150	175	175	3.3
z-axis coils	180	200	200	4.5

According to the Biot-Savart law, the magnetic flux density was generated by this coil. It is defined as following equation (2-1):

$$\mathrm{B} = \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \begin{bmatrix} a\cos(\omega t)\cos\alpha & 0 & 0 \\ 0 & b\cos(\omega t)\cos\gamma & 0 \\ 0 & 0 & c\cos(\omega t)\cos\beta \end{bmatrix} \begin{bmatrix} I_x \\ I_y \\ I_z \end{bmatrix} \quad (2\text{-}1)$$

where B_x(t), B_y(t), and B_z(t) denote the magnetic flux densities of the x-, y- and z-axes, respectively; α, β, and γ denote the angles between the moving direction of the minirobot and the x-, y-, and z-axes, respectively; and a, b, and c are constants of the three Helmholtz coils [43]-[47].

2.3 Positioning system

The monitoring of the microrobot in interesting region of human organ, e.g. gastrointestinal tract and blood vessels, is essential to guarantee the availability of the diagnosis, therapy and minimally invasive surgery. The 3-D ultrasound imaging, nuclear medicine imaging technology, fluorescence imaging and X-ray monitoring have been extensive in the clinical application. However, these monitoring methods not only need the lager and expensive monitoring equipment, but also are harmful to the patient or doctor to a certain extent [49]- [51].

2.3.1 Analysis of the magnetic field

The magnetic flux density of the magnet inside microrobot is analyzed. The magnetic dipole model is shown in Figure 2.3.1. The relationship between the distance and magnetic field as follows:

$$U = \frac{ml\cos\theta}{4\pi\mu_0 r^2} \tag{2-4}$$

$$H_r = -\frac{\partial U}{\partial r} = \frac{ml}{2\pi\mu_0 r^3}\cos\theta \tag{2-5}$$

$$H_\theta = -\frac{\partial U}{r\partial\theta} = \frac{ml}{4\pi\mu_0 r^3}\sin\theta \tag{2-6}$$

$$H_X = \frac{X}{\sqrt{X^2+Y^2}}\left(\frac{3ml}{4\pi\mu_0 r_1^3}\sin\theta_1\cos\theta_1 + \frac{3ml}{4\pi\mu_0 r_2^3}\sin\theta_2\cos\theta_2\right) \tag{2-7}$$

$$H_Y = \frac{Y}{\sqrt{X^2+Y^2}}\left(\frac{3ml}{4\pi\mu_0 r_1^3}\sin\theta_1\cos\theta_1 + \frac{3ml}{4\pi\mu_0 r_2^3}\sin\theta_2\cos\theta_2\right) \tag{2-8}$$

$$H_Z = \frac{ml}{4\pi\mu_0 r_1^3}(2\cos^2\theta_1 - \sin^2\theta_1) + \frac{ml}{4\pi\mu_0 r_2^3}(2\cos^2\theta_2 - \sin^2\theta_2) \tag{2-9}$$

2.3.2 Simulation results

We analyzed the magnetic field density by the COMSOL software. Figure 2.3.2 shows the simulation results. This result indicated that the magnet having multi magnetic potentials is higher magnetic field area than one magnetic potential type. The magnetic field intensity in the center of the sphere is uniform, the parameters set up in each step during the simulation are according to the real experimental device.

2.4 Summary

In this chapter, we propose and evaluate an electromagnetic driven minirobot system. It is composed of electromagnetic manipulation system and positioning system. The electromagnetic manipulation system is used to generate uniform magnetic field in any direction in the center part of the workspace. We use our proposed control system to control the minirobot to realize the flexible and non-contact motion. The proposed system can be controlled locally and remotely.

Chapter 3 Development and Evaluation of Novel Active Locomotion Screw Jet Minirobot

3.1 Internally driven minirobot with active locomotion

3.1.1 Structure of the screw jet minirobot

The whole system consists of three main parts, the power supply section, three-axes Helmholtz coils are to provide a uniform controllable rotating magnetic field; the simulated intestinal part, a transparent plastic pipe; a screw jet microrobot, it consists a radially magnetized O-ring type neodymium magnet and a rotating screw jet structure. The internal structure of our microrobot is shown in the Figure 3. 1. Each part of the robot has been identified. Comparing to the previously developed screw microrobot, we added a shell outside the new type SJM, its usefulness is avoiding the direct friction in human intestine when the microrobot is rotating. Certainly, the addition of the shell will take a lot of impact on the movement. That's the reason we have to experiment and re-evaluate the effects of changes in some of the parameters in the experimental section.

3.1.2 Propulsion force on screw jet microrobot

The propulsion force of magnetic screw micro robot is along the central axis. In the low Reynolds number region, the total non fluid torque and force are linearly related to axial velocity and angular velocity. The following symmetric propulsion matrix equation is used to describe the propulsion force and torque of the magnetic screw micro robot:

$$\begin{bmatrix} F \\ T \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} v \\ \varpi \end{bmatrix} \tag{3-1}$$

where F is the non-fluidic applied force, T is the non-fluidic applied torque, v is the axial speed, and ω is the angular speed [59]-[63].

3.1.3 Fluid drag force on screw jet microrobot

The total drag force depends on the Reynolds number and the shape of the magnetic spiral microrobot. In a pipe, the Reynolds number is generally defined as:

$$Re = \frac{\rho v d}{\mu} \tag{3-3}$$

3.1.4 Evaluation performance of the screw jet microrobot

Different pitch microrobots have shown in Figure 3.1.2. We kept the length of the robot in the case of the same and made four different pitch microrobots. Pitch is the distance of two screw center points, the pitch (P) is 14 mm, 9.3 mm and 7 mm respectively while keeping the overall length (L) of the internal part is 28 mm.

3.2 Hydrodynamic simulation of the characteristic design

During the simulation we set a plane on the outlet part, and carried out the data of outlet velocity for each setting, from the simulation results, the velocity is showing an increasing trend, but the 6–6.5 mm's radius velocity begins to decrease. The 5.5 mm inner radius has the peak velocity, however, there are some limitations of our 3D printer such as the accuracy, finally we chose 5 mm inner radius using on robot's shell.

3.3 Experiment and results of the motion performance

This section introduces the development of the shell part. The gap on the shell is used for the water that flows into the interior of the robot, then the size of the inlet will affect the robot's speed and other parameters.

3.4 Summary

The published papers have analyzed the driving device, principle and movement characteristics, discussed the effect on different flow (by changing the height). And this paper introduced a wireless capsule Screw Jet Motion microrobot and its working principle based on previous system. The main work in this paper is to evaluate the motion performance of robots with different pitch with different motion characteristics, first part is about the evaluation of the inlet size on the shell module, then we have chosen the fastest solution for the average flow rate at the inlet. Although the simulation part is an ideal state, we did not consider the friction generated by the internal rotation of the robot itself, because this force has a negligible impact on propulsion force. As for different pitch internal structure experiments, the experimental data shows that the 2 pitch microrobot has the highest speed and it performs better than the other two at start frequency and stop frequency, the experimental results also become a linear, and its speed is more stable at low frequencies it has played a positive role in evaluating our athletic characteristics, the difficulty of this experiment is to control the other variables when replacing the robot. We also evaluated the effect of outlet size of the shell on velocity, the first part is about the relative research in recent years and listed some shortcomings of them, as for the second section, we showed the design of SJM and the research purpose in this paper is to evaluate the evaluation of the outlet size on the shell module, then we have chosen the fastest solution for the average flow rate at the inlet. Although the simulation part is an ideal state, we did not consider the friction generated by the internal rotation of the robot itself, because this force has a negligible impact on propulsion force. In the simulation progress of experiment, we evaluated the effect on inner radius of the shell, according to the Eqs. (3), (4), we explained the increase and decrease of the velocity, and this simulation verifies our previous theory that speed will not infinitely be increasing, because the variable flow is inversely proportional to the cross-sectional area. In the second progress of experiment, we evaluated the effect on drag coefficient, this experiment verifies our previous theory that speed will not infinitely be increasing, because the propulsion force will be decreased with the increasing of hydraulic resistance.

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Chapter 4 Mechanical and Hydrodynamic Analysis of the Drug Sustained-release Minirobot

4.1 Concept of the DSM

Capsule drugs were originally developed to mask the special odor or irritation of certain drugs and the most important effect is the drugs can be sustained-release. On this basis, many researchers designed the capsule minirobots to decrease the pain experienced by the patients during the surgery or medical examination, and this research is focused on the development of drugs sustained-release function of the capsule minirobot.

4.2 Structure design and working principle

4.2.1 Structure design of DSM

The viscosity and relative motion of fluid will hinder itself flow around the object. Then for the purpose to reduce the outflow phenomenon and pressure difference between the top and tail of the object, we need to design a streamlined structure that can force the fluid to better fit the surface of the robot. Finally, the capsule-shaped shell was carried out to reduce undesired resistance at the highest accuracy that we can achieve.**4.2.2 Working principle of different motions**

During the rotation, the blades generate lift force L and drag force D when the water flows through the device. The lift force and drag force of the blade per unit length are:

$$L = C_L \cdot \frac{1}{2}\rho U^2 C \tag{4-2}$$

$$D = C_D \cdot \frac{1}{2}\rho U^2 C \tag{4-3}$$

4.2.3 Functions of DSM

The shape of the drug chamber is a hollow cylinder, the inner and outer diameters of it are 10 mm and 11mm, respectively. Its front end is inserted into a bearing, and the center of the bearing is inserted into the magnet that drives the fan. The drug chamber's tail is fixed by the support part at the end of the robot shell to ensure that the structure of the robot is on the same central axis.

4.3 Hydrodynamic analysis

4.3.1 Geometry model setup

Hydrodynamic characteristics are the key parameter that determines the efficiency and accuracy of the process control algorithms for capsule robots in the flow environment [72]-[77]. Moreover, to optimize the structure of the capsule robot, taking into consideration that the hydrodynamic characteristics of a capsule robot are different for each motion, a unique propulsion system is required for the capsule robot created by 3D resin printing. A series of vital hydrodynamic parameters of the motions can be obtained through the analysis of the simulations.

4.3.2 Mesh independence study

It is necessary to evaluate the effect of the mesh on the accuracy of the solution based on the study of mesh independence [78]-[83]. The most basic requirement is to ensure that the residual value after each iteration is less than 0.0001. Then, we compared the monitoring values in the simulation results with different mesh sizes until the monitor points for the values of interest have reached a steady solution. Figure 4.3.4 shows the comparison of the influence of five different mesh size on the monitoring value, in which the mesh size increases by 20% in each group. From the monitoring value, the variation error value of different mesh size is between 1.9% - 0.4%. From the above evaluation, within the above mesh accuracy range, the simulation results will not produce excessive error due to the mesh accuracy. Under those settings will provide a mesh independence solution. Considering the need to reduce computational saving of computing resources, the total number of elements is maintained between 300000 to 400000 in the following simulations. According to the above mesh independence study, the total number of nodes was 640043, and the total number of elements was 3334106.

4.3.3 Simulation results

After hydrodynamic analysis simulations, in the case of the static flow field, by the rotation of the propeller, the liquid passed through the propeller and generates the power of the forward movement. The samples of velocity vector results are shown in Figure 4.3.5, the samples given here are cross-section image at the highest driving frequency. The models used in Figure 4.3.5 are 4 blades, 3 blades and 2 blades in Figure 4.3.5 (a), (b) and (c) respectively. The water inlet can well let the water flow in when the propeller is rotating. The aisle between the drug chamber and shell can effectively pressurize and discharge the liquid. Combining with the initial tests, the

DSM achieved the highest velocity at 10 Hz. So we simulated the case of less than 10 Hz in the fluid-structure coupling simulation, in which the ideal forward velocity reached about 7 mm/s. The rest of the simulation results will be given in the experiment part and be compared with the experimental results.

4.4 Experiments and results

4.4.1 Evaluation of the motion stability

In this section, the evaluation of the motion performance of DSM in different flow environments will be proposed. The first preparation work for the performance experiment is the stability test. We fixed a custom 6-DOF inertial measurement unit behind DSM to make their coordinate systems are consistent so that the measured real-time angular velocity can be used as a reference for the steady state of DSM movement in liquid. During the test, the DSM performed linear motion in rigid and flexible pipe respectively.

4.4.2 Motion performance evaluation on horizontal direction

In this part, several experiments in different environments were carried out for the static flow and resistance flow separately in the pipe. The robot model used in the experiment will be different, that is, the number of blades of propeller is the variable parameter in this the horizontal motion experiments, and the different blades propellers are shown in Figure 4.4.1. The velocity of the DSM in a pulsatile flow environment was measured in a PVC pipe of diameter 20 mm, the pulsatile flow was generated by a peristaltic pump (EYELA RP-1000) at 60 RPM rotation rate, which is similar to the flow rate in an intestinal fluid environment and some cardiovascular environment of the human body. The experiment results of velocity have been shown in Figure 4.4.2. As expected, the velocity of the three experimental objects grow linearly, and the experimental results demonstrated that when DSM at low rotational frequencies, it was at lower axial velocity. Furthermore, its starting frequency is 3 Hz without the influence of water flow. However, when it is in the environment of the water flow opposite to its direction of motion, the low-frequency rotating propeller-driven water flow is subject to the disorder of the reverse water flow, causing its start frequency to be changed, DSM was tended to fall into stop motion at lower rotational frequencies as well. Under the influence of the resistance flow, the propulsive force would increase as the rotational frequencies increased, the axial velocity of the DSM began to increase significantly before the maximum frequency at 10 Hz for DSM. The steep increase of velocity shows at 7 Hz, this phenomenon is reflected in the results before 10 Hz, and combining with the deflection angle results, as the velocity of DSM increased, its motion stability will also be affected, due to the existence of high-speed propeller, DSM no longer moves close to the pipe wall, but floats in the pipe and occasionally has a very light collision. This is the reason why the speed of DSM becomes faster and higher than 7 Hz, the stability decreases. But this level of vibration was still within the controllable range. Finally, the velocity would drop sharply to 0 at 11 Hz, which is the step-out frequency of DSM.

4.4.2 Motion performance evaluation on vertical direction

The results of the velocity have been shown in Figure 4.4.4. This experiment started at 0 Hz, at this time, the DSM sunk freely in the water, and the forces acting on the robot are only gravity, buoyancy and hydraulic resistance. Then we manipulated the program to generate a 1 Hz rotational magnetic field, the propeller began to produce a downward propulsive force to drive the DSM up. With the rotation of the propeller, the velocity at which the robot falls in the water at 1-2 Hz was significantly slowed down. After that, when the rotational frequency reached 3 Hz, DSM stayed suspended in the water. Then, the DSM started a significant upward movement from 4Hz to 10 Hz, and reached the highest speed of 15.125 mm/s at 10 Hz. Finally, when the DSM reached step-out frequency, it stopped and began to gradually sink.

4.5 Summary

In this chapter, a novel type of magnetically actuated hybrid microrobot (MAHM) based on a rotational magnetic field is proposed. The hybrid microrobot with screw jet motion and fin motion has a small scale with a wireless power supply, can be propelled by low voltage, and has a quick response. And also the hybrid microrobot can work for a long time in human. It can convert its two motions (screw jet motion and fin motion) through the proposed structure of the microrobot with rotational magnetic field, so that it realizes the movement in the different environment. The body of the microrobot with a screw jet motion can obtain a stable motion and high propulsive force. The fin motion can improve the dynamic characteristic and reduce the shake which caused by the axial propulsive force of the screw jet motion. Screw jet motion and fin motion can be controlled separated without any interference, due to the hybrid microrobot has only use one actuator to realize the screw jet motion and fin motion.

Chapter 5 Performance Evaluation of the Targeted Drug Delivery Function and Cooperative Locomotion

5.1 Performance evaluation of the drug delivery function

The DSM can self-deliver quantitative doses after advancing to the desired location, and it can continue to move advance to the next location for drug delivery several times before the drug is used up. Before the experiment of multi-module operation, we used a dosing gun to measure the velocity of which the robot actually discharged the drug under different frequencies of the rotating magnetic field. The actual discharge of the drug has some uncontrollable error compared with the calculated value in the case of the rapid rotation of the O-ring magnet. We gave a relatively stable experimental result of 1-5 Hz. The experimental results show that the drug discharge can be better controlled when the drug is discharged at a low velocity. Also, we prefer using a low frequency, because the magnet driving the propeller will also rotate at the same frequency at the same time, which means if the rotating frequency of propeller reaches a high velocity, it may lead to an undesirable error in the stability of the DSM and predetermined position.

5.2 Experiment of cooperative locomotion

In the experiment of cooperative locomotion in the pipe, the flowchart of each step is shown in Figure 5.1, in which the -1 and -2 Hz indicate the frequency of the anti-clockwise rotational magnetic field. Then the relationship between time, displacement and frequency has shown in Figure 5.1(b). We manipulated the DSM to achieve the mission: it starts to deliver the drug after advancing to the desired position and can continue to move forward and loop this process at different frequencies.

5.3 In-vitro experiment of cooperative locomotion

In vitro experiment usually uses components of the organism that have been isolated from the biological surroundings, it can analyze the sample in a specific and simple method by evaluating the manually processed organism samples [91]-[98]. An in-vitro experiment was carried out to provide the effectiveness of the cooperative locomotion of the DSM. A curved manually processed pig large intestine pipe with different liquid level was used as the operation environment [99]-[103]. The overview of the pig intestine pipe is shown in Figure 5.2, during the process of the experiment, both ends of the pipe are sealed with the membrane and the pipe contains half of the volume of liquid. Meanwhile, the irregular folds on the intestine will make the DSM operate at different liquid levels. DSM's embedded cylinder permanent magnet which is controlled by the external electronic magnetic field could provide the propulsive force to support DSM achieve multi-direction movement in the pipe, then the O-ring type magnet inside the drug chamber will be activated if the DSM arrives at the desired position.

The three steps of in-vitro experiment are shown in Figure 5.2:

1) DSM moves towards the desired position;

2) DSM stops at lesion I (P_1) and lesion II (P_2) to release the drug under different frequencies respectively;

3) Finish the task and keep moving to the end.

5.4 Summary

Through the in-vitro experiment, we demonstrated the feasibility of this novel type capsule robot can be considered a potential tool for the future development of invasive surgery. However, comparing with the in-vivo experiment in living organisms, the in vitro experiment still has some limitations. First, since the size of the screw and nut inside the drug chamber can not be further reduced at this stage, which causes the diameter of the prototype is larger than that of US Food and Drug Administration (FDA) approved and applied CE size (12mm×33mm). In further works, the developed DSM prototype will correspond with the criteria. Second, for the commercialized CEs, a single type robot still can not cope with all the operating environments. For the gastric body, colon, small intestine and big intestine, manufacturers have launched robots of different designs that suit more special purposes and environments, PillCam and OMOM have proposed different models of types CEs used in clinical to make them adapt to different environments and patients. Moreover, preoperative preparation and intraoperative patient cooperation, such as exhaust, posture change and fluid supplements are also important steps. These steps are important steps to eliminate some adverse conditions in clinical examination. So that, to quantify and build the model of the effect of the living organisms and the pressure of internal organs on the intestinal environment is necessary. In clinical examination, the methods of intestinal expansion are generally divided into liquid expansion and gas expansion. As one of the developing applications of magnetic control technology, most of the proposed internal driven CEs are developed in the liquid environment. However, the reasons of the internal driven CEs have not been commercialized, such as high operating environment requirements, quantification of the intestinal parameters, ethical and theoretical examination are also the main challenges we encountered in this study. The DSM was assumed to operate in the liquid environment and verified that DSM can complete the drug delivery task efficiently and stably in a certain amount of liquid. We will also base the works on application-oriented integration and feedback module development, such as micro camera with the silver oxide battery to the identified correct position and advanced high accuracy and stability positioning algorithm and technology. For further research, the developed DSM will be analyzed for more complex environments such as in-vivo experiment with the pressure of internal organs on the wall of the intestine. Besides, in minimally invasive surgery, the surgeons need to customize treatment with different types of functions robots, several multi-module capsule robots with different functions or different drugs will be the trend and direction of our research. These CEs can be swallowed in sequence and form new structures characteristics inside the body via docking to solve more complex and changeable inspection requirements.

Chapter 6 Concluding Remarks

6.1 Thesis summary

Wireless capsule endoscopes are favored in modern surgical procedures for the treatment of disease in clinical surgery and examination. The patients are willing to choose only simply swallowing a pill to do the early screening and medical examinations without anesthesia. WCE offers a promising method for precision medicine for minimally or non-invasive procedures in the gastrointestinal tract. In the minimally invasive procedures, due to its reliability and flexibility, the capsule endoscopes are both safe and convenient for most of the patients to use. Among the WCEs, the magnetically manipulation ACE is a method accompanying the invention of the ACE. Meanwhile, the energy supply problems, space constraints of the internal environment, operational difficulties and the size limitations always been the toughest challenges. Some current stage research to develop function module of magnetic actuated minirobot is mainly focusing on adding battery-powered function modules. Although with the progress of technology, the desire of miniaturization and integration of hardware can be realized, the problem of energy supply and security of the capsule robots is still inevitable, even in some cases, the problem of heat dissipation is also a big hidden danger. As for the wireless magnetic actuated minirobots, stable performance, fewer power supply problems and better security are the benefits of this type of capsule minirobot.

6.2 Research achievement

1. Development and evaluation of the novel active locomotion minirobot with screw jet motion
2. Development and evaluation of the minirobot with targeted drug sustained-release function
3. Cooperative locomotion of multiple functions minirobot

6.3 Recommendations for the future

In minimally invasive surgery, the surgeons need to customize treatment with different types of functions robots, several multi-module capsule robots with different functions or different drugs will be the trend and the next target of our research. The developing prototype minirobots will be analyzed for more complex environments such as in-vivo experiment with pressure of internal organs on the wall of intestine. In general, the development of the internally driven minirobots is always the direction of our research, wo will also focus on the improvement of the performance of it. Finally, the proposed minirobots will provide the feasibility of similar commercial WCEs.

Publication List

International Journal Papers

1. **Zixu Wang**, Shuxiang Guo, Qiang Fu and Jian Guo, "Characteristic evaluation of a magnetic actuated microrobot in pipe with screw jet motion", *Microsystem Technologies,* Vol.25, no.2, pp. 719-727, 2018. Impact Factor (IF): 1.513
2. **Zixu Wang**, Shuxiang Guo, Jian Guo, Qiang Fu, Lingling Zheng and Takashi Tamiya, "Selective Motion Control of a Novel Magnetic Driven Minirobot with Targeted Drug Sustained-release Function", *IEEE/ASME Transactions on Mechatronics* (Resubmitted). Impact Factor (IF): 5.673

International Conference Papers

1. **Zixu Wang**, Shuxiang Guo and Wei Wei, "Characteristic Evaluation of the Shell Outlet Mechanism for a Magnetic-actuated Screw Jet Microrobot in pipe", *Proceedings of 2018 IEEE International Conference on Mechatronics and Automation*, pp.1688-1692, August 5-8, Changchun, China, 2018.
2. **Zixu Wang**, Shuxiang Guo and Wei Wei, "Motion Performance of a Novel Fan Type Magnetic Microrobot in Pipe", *Proceedings of 2019 IEEE International Conference on Mechatronics and Automation*, pp.1409-1413, August 4-7, Tianjin，China, 2019.
3. **Zixu Wang**, Shuxiang Guo and Wei Wei, "Modeling and Simulation of

the Drug Delivery Function for a Magnetic Driven Capsule Robot", *Proceedings of 2020 IEEE International Conference on Mechatronics and Automation*, pp.1384-1388, Beijing, China, 2020.

Reference Papers

1. Shuxiang Guo, **Zixu Wang** and Qiang Fu, "Motion Performance Evaluation of a Magnetic Actuated Screw Jet Microrobot", *Proceedings of 2017 IEEE International Conference on Mechatronics and Automation,* pp. 2000-2004, August 6-9, Takamatsu, Japan, 2017.
2. Lingling Zheng, Shuxiang Guo, **Zixu Wang**, "Performance Evaluation of an Outer Spiral Microrobot in Pipes in Different Environments", *Proceedings of 2020 IEEE International Conference on Mechatronics and Automation*, pp.643-647, Beijing, China, 2020

Biographic Sketch

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