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Structural Design and Analysis of a New Four-blade Biopsy Capsule Endoscope

Xinyi Liu [1], Jian Guo [1,2*]

[1]Tianjin Key Laboratory for Control Theory & Application Complicated Systems and Intelligent Robot Laboratory

Tianjin University of Technology

Binshui Xidao Extension 391,
Tianjin,300384,China

fuqiang6369@hotmail.com;

1557355266@qq.com.

Shuxiang Guo[1,2,3*]

[2] Shenzhen Institute of Advanced Biomedical Robot Co., Ltd.

No.12, Ganli Sixth Road,
Jihua Street, Longgang District

Shenzhen,518100,China

**corresponding author:*
jianguo@tjut.edu.cn;

Qiang Fu[1] and Baotian Mo[1]

[3] Key Laboratory of Convergence Medical Engineering System and Healthcare Technology,The Ministry of Industry and Information Technology,School of Life Science

Beijing Institute of Technology

No.5, Zhongguancun South Street,
Beijing,100081, China

**corresponding author:*
guoshuxiang@hotmail.com

Abstract **–Due to the rapid spread of COVID-19 around the world, people's diet environment has also changed, and gastrointestinal diseases have become a common disease around us so far, and the prevalence is on the rise. But because traditional treatments for gastrointestinal diseases are unfriendly to patients, they often require the administration of anesthetics, which can cause side effects. Wireless capsule endoscope is a kind of medical robot that can alleviate the pain of patients, and the research on wireless capsule endoscope has been gradually mature at home and abroad, this paper designed a new four-page propeller-driven biopsy capsule robot. The optimal number of propeller pages is obtained by comparing the velocity of three different numbers of propeller blades in the pipeline. The three axis Helmholtz coil driving system and biopsy module based on CAM structure are also introduced. At the same time, the anchoring module used for precise biopsy of the robot is introduced, so as to ensure that the biopsy capsule robot can reach the specified position quickly and accurately and complete the biopsy task. Finally, we use simulation software to simulate the velocity and pressure of different propeller blades in the same liquid.**

Index Terms - Four propeller, Magnetically controlled capsule robot, Helmholtz coil, Anchor structure

I. INTRODUCTION

As the global cancer mortality rate is increasing year by year, the examination and treatment of various cancers have been widely concerned. Gastrointestinal cancer, in particular, has become a disease we cannot ignore due to its high mortality rate[1]. But in recent years, the mortality rate of gastrointestinal cancer has decreased, which is closely related to the timing of prevention, diagnosis and treatment of gastrointestinal cancer[2]. If cancer is found in the gastrointestinal tract early, the survival rate is more than 90 percent within five years after treatment. The traditional gastroenteroscopy equipment for human body examination is mainly the cable endoscope, which can enter the stomach through the mouth or other natural channels, or enter the body through a small incision made by surgery, for gastrointestinal examination, hemostasis, biopsy and polyp removal[3]. In addition, some patients with cardiopulmonary insufficiency, the probability of sudden death during the examination[4]. The power supply mode of the wireless capsule endoscope can be divided into electric energy drive and magnetic energy drive[5]. The electric energy drive is mainly powered by the internal power supply or wireless power supply device of the capsule robot[5]. The magnetic energy drive mainly controls the magnet inside the capsule robot through the external magnetic field. The capsule gastroscope can examine the stomach, along with the small and large intestine, in a much shorter process, especially for a capsule robot capable of active movement[7].

The ideal capsule robot should be multifunctional, not only with the function of shooting inspection, but also with the function of drug delivery, biopsy and so on[7]. The capsule robot swallowed into the stomach can rotate from multiple angles and move autonomously under the action of the external control device to ensure that the image robot does not leave a blind spot to the inspection area[14]. When the image robot takes the internal image of the intestine, it will be transmitted to the computer through the external video receiving module for medical staff to analyze and process[12]. Due to the small size of capsule robot, other functions such as drug application and biopsy can not be realized by a capsule robot, so there are multiple capsule robot to complete the design[11].

In 2015, a team at Chunnam National University in South Korea designed a capsule robot capable of delivering drugs[9]. The opening and closing of the storehouse uses the principle that the magnetic force of two soft magnets can be eliminated under the action of the external magnetic field[6]. Its disadvantage is that the medicine in the storehouse can only rely on gravity to fall.

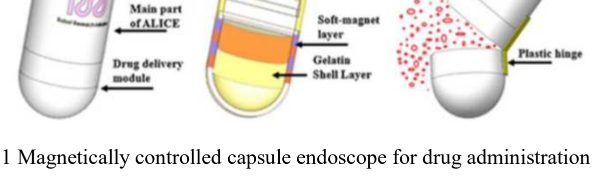

Fig. 1 Magnetically controlled capsule endoscope for drug administration

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Leung of the Chinese University of Hong Kong has proposed a new inflatable wireless capsule robot[18]. The robot is 14 mm in diameter and 60 mm in length and consists of an inflatable silicone balloon and a treatment module containing a gas generation chamber, an acid syringe and a circuit box, which are connected together by flexible joints into a silicone balloon6[15]. When the robot reaches the affected area, it can stop at the bleeding site in the intestine.

Fig. 2 Hemostatic capsule robot

In order to solve the problem of capsule robot active movement in human body, Valdastri et al from University of Pisa in Italy proposed a 12-legged capsule robot[17]. The structure of the robot is shown in Fig. 3, with a diameter of 11 mm and a length of 25 mm, which can overcome gravity climbing in a smooth tubular environment[16].Experiments proved that the performance of the capsule robot is equivalent to the friction of the colonoscopy on the human intestine during a standard colonoscopy.

Fig. 3 Twelve robot leg capsule robot models and objects

Although the function of various medical capsule robot has been developed and the experiment for the feasibility, but in order to perform a complete medical mission, internal capsule robot usually integrate multiple modules, makes the robot is too complex and at the same time, due to its special application scenario, the function of a single capsule robot load capacity will be severely limited[11].

In this paper, a new four - page propeller blade - driven biopsy capsule endoscope is designed. Propeller is a device that converts the driving force of magnetic field into propulsion force by rotating blades in water. This allows the capsule robot to move forward and backward faster in the liquid. In this design, the propeller is connected to the circular radial magnet, and the internal radial magnet rotates through the external magnetic field to drive the rotation of the propeller, so as to achieve rapid biopsy.Different from the traditional propeller drive method, the innovation of this study lies in the use of four-page propeller blades to drive the biopsy capsule endoscope, which can accelerate the treatment process and improve the efficiency of surgery while ensuring the safety of patients.

The specific structure of this paper is as follows: In the second section, we introduce the overall structure of the robot and the design of various internal modules, focusing on the propeller drive module and anchor module. In the third section, we introduce the control system based on the principle of three axis Helmholtz coil. In the fourth section, we simulated propellers with different blades in the same liquid environment, and conducted experiments on their motion characteristics and biopsy process to verify its possibility. The last part is our conclusion and future work to be improved.

II. DESIGN OF STRUCTURE

The drug delivery capsule endoscopy robot and biopsy capsule endoscopy robot studied by our team before were based on the experiments of three-page propellers, and found the most appropriate pipe lengths for different pipe lengths of the three-page propellers. That is, the velocity of propeller in pipe is the fastest at 13mm. This paper puts forward a new kind of four pages of propeller as a driver, and two propellers and three pages of propeller under the environment of the same experiment, after good lesion area determined by image diagnosis technology, using four pages of propeller will be transported to the lesion area of biopsy robot rapid biopsy, finally out of the body, to complete the biopsies of patients with gastrointestinal surgery.

A. The proposed structure

The overall structure of the biopsy capsule robot with a four-page propeller is shown in Fig 4. The whole robot is roughly divided into three parts: the drive module for driving the propeller; An anchoring module for fixing the robot; Biopsy module for performing biopsy. The whole robot consists of three permanent magnets, a CAM, a spring, a miniature barb, a baffle, an anchoring mechanism, a propeller and a thin shaft connecting rod in the middle. Permanent magnet 1 is fixed with the CAM, permanent magnet 2 is fixed with the anchoring module through a thin rod, and permanent magnet 3 is connected with the propeller inside the propeller. The biopsy endoscope capsule robot is driven by three permanent magnets magnetized radially that rotate in a magnetic field generated by a three-axis Hertz coil. When the corresponding magnetic field is generated around, the propeller will generate forward forward thrust along with the rotation of the permanent magnet, thus driving the robot to the corresponding lesion area. At the same time, the three-phase current needs to be changed, and the magnetic field can be changed to reverse the rotation of the propeller to produce reverse thrust, so as to achieve accurate arrival.

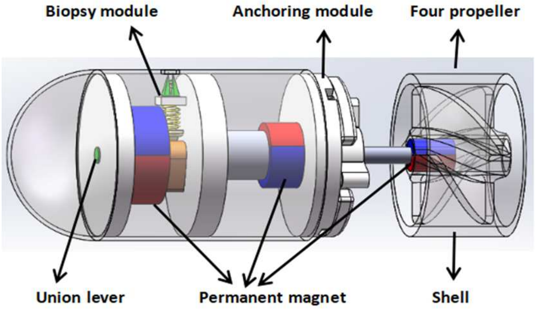

Fig. 4 The four-page propeller biopsy capsule robot

B. *Robot manufacturing*

Because the robot is small in size and requires built-in magnets, traditional processing methods cannot be used. So the whole robot was divided into several different parts, and each part was printed using a 3D printer. Because the resin material has strong plasticity, corrosion resistance and water resistance, the material used for printing is white Future R4600 resin. The machining accuracy of the robot is 0.1mm, which is suitable for the robot in this study.

C. *Propeller drive module*

The propeller drive module is designed in the tail of the robot, and the propeller is connected to a small radial magnet in the heart. The magnet can rotate through the change of the external magnetic field, thus driving the propeller rotation. Thus pushing the whole biopsy robot forward. When it reaches the lesion area, we first make it stop moving and change the direction of current, so as to change the magnetic field. Permanent magnet 2 drives the anchoring module to rotate, so that the robot is fixed in the lesion area.Finally, the permanent magnet 1 drives the CAM to rotate by changing the direction of current again, and the biopsy forceps extend out from the inside of the robot to complete the biopsy sampling task of the lesion area through the expansion of the CAM. Fig. 5 shows propeller modeling with different numbers of blades.Their outer protective shells are the same size and thickness all 1mm and all 10mm in length.So the only difference is the number of internal blades.

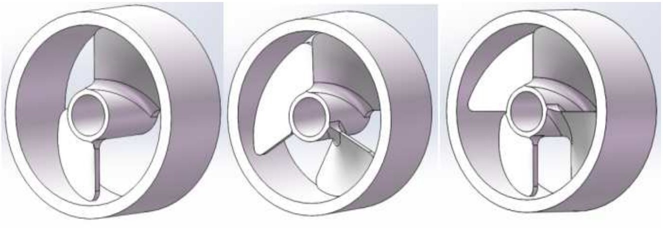

Fig. 5 Mechanical structure drawing of propeller

Fig. 6 shows the entire biopsy process. The biopsy forceps gradually extend from the inside of the capsule robot through the rotation of the magnet. After successfully extracting the tissue, they return to the inside of the capsule robot to complete the biopsy.

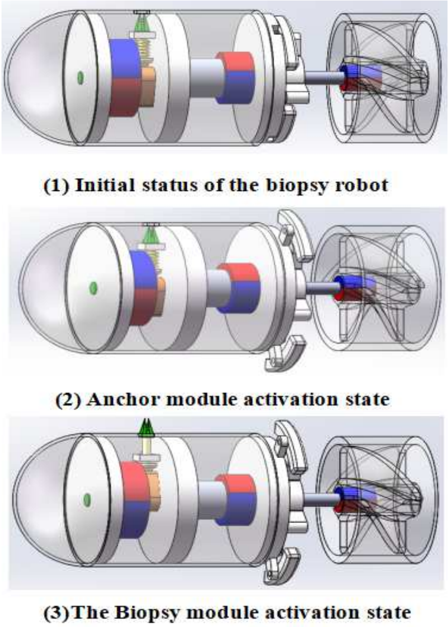

Fig.6 The capsule robot biopsy process

III. ROBOT PERFORMANCE ANALYSIS OF PROPELLER IN PIPELINE

The mechanism of the robot movement used in this research is to generate thrust by the propeller rotating in the liquid to promote the movement of the robot. Therefore, the design of the propeller structure greatly affects the movement characteristics of the entire robot.

A. *Propeller thrust and torque*

The propeller blades are powered by radial magnets inside the capsule robot. The magnets cause the blades to rotate at high speed in the pipe, and the propeller converts the spinning power of the magnets into forward thrust. The robot's movement in the liquid creates resistance in the opposite direction of its movement. So, in order for the robot to perform an inspection, it has to be a force acting on the robot and equal to the resistance, and the direction is forward. This force is called thrust.

In the process of propeller rotating forward, thrust is generally generated by water diversion, and the water flow is affected by the action of the propeller to obtain additional speed contrary to the thrust direction, which is usually called the induced speed. In the actual operation of the propeller, the induced velocity is mainly axial induced velocity V. And circumferential induced velocity V. In the propeller theory, the free vortex line of the propeller is approximately considered as the spiral line. According to the lift line theory, the free vortex is distributed in two regions: the blade area and the wake along the edge. In absolute cylindrical coordinates, the coordinates of the field points are set to $P(x,r,\theta)$. The line element of vortex linere dl is (x_0,r_0,θ_0) .The loop quantity around the vortex line is Γ.As shown in fig 7. According to the Biotte-Swart theorem, the induced velocity at P point:

$$v = \frac{\Gamma}{4\pi}\int_L \frac{R \times dl}{R^3} \tag{1}$$

Where R is the radius vector diameter from point (x_0, r_0, θ_0) to point P , R is the radius of propeller.

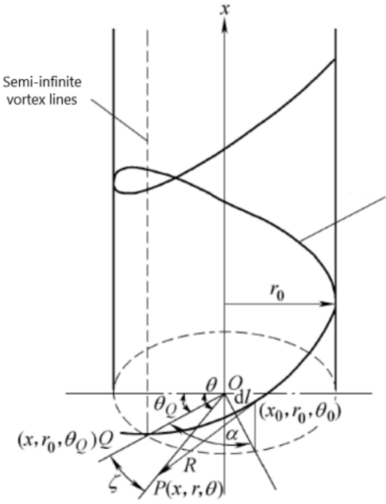

Fig. 7 Spiral vortex system, field point and coordinate system

According to the theory of propeller lift line, the blade element is treated as a two-dimensional wing when calculating the force of propeller.Suppose that the advance speed (incoming flow velocity) of the self-reconstructed propellers is V_A The rotational angular velocity is $\omega = 2\pi n$. If micro-segment dr is intercepted at radius r , the axial velocity of this micro-segment dr is $\omega_1 r_1 \sin\theta$,the circumferential speed is $V_A + \omega r$ .According to Rukowski's theorem, the lift of the leaf body acting at the dr micro segment on the leaf is

$$dL = \rho v_R \Gamma(r) dr \tag{2}$$

In the formula, P is the density of water, and v_R is the amplitude of the incoming velocity, rotation velocity, axial and circumferential induced velocity and velocity of the propeller. $\Gamma(r)$ is the loop of A blade at radius r.

The momentum theorem can be used to find the thrust of the propeller. The mass of fluid flowing through the propeller disk surface (area A_0) per unit time is $m = \rho A_0 (V_A + u_{a1})$,The momentum flowing in from the section AA_1 in the far front of the flow tube is $\rho A_0 (V_A + u_{a1}) V_A$, and the momentum flowing out of the section CC_1 in the far rear is $\rho A_0 (V_A + u_{a1})(V_A + u_a)$. Therefore, the value of the momentum gained by the water flow in a unit time is:

$$\rho A_0 (V_A + u_{a1})(V_A + u_a) - \rho A_0 (V_A + u_{a1}) V_A = \rho A_0 (V_A + u_{a1}) u_a \tag{3}$$

According to the momentum theorem, The reaction force of the fluid is the thrust, so the thrust *Ti* generated by the propeller is:

$$T_i = m \quad u_a = \rho A_0 (V_A + u_{a1}) u_a \tag{4}$$

In the above formulas, ρ is the density of the fluid.

In order to find the relationship between the speed increase u_{a1} at the disk surface and the speed increase u_a at infinity rear. There are the following relations in front of and close to the disk surface:

$$p_0 + \frac{1}{2}\rho V_A^2 = p_1 + \frac{1}{2}\rho (V_A + u_{a1})^2$$

$$p_1 = p_0 + \frac{1}{2}\rho V_A^2 - \frac{1}{2}\rho (V_A + u_{a1})^2 \tag{5}$$

And far behind and close to the disk:

$$p_0 + \frac{1}{2}\rho (V_A + u_a)^2 = p_1' + \frac{1}{2}\rho (V_A + u_{a1})^2$$

$$p_1' = p_0 + \frac{1}{2}\rho (V_A + u_a)^2 - \frac{1}{2}\rho (V_A + u_{a1})^2 \tag{6}$$

The pressure can be obtained from the formulas (2) and (3):

$$p_1' - p_1 = \rho \left(V_A + \frac{1}{2} u_a \right) u_a \tag{7}$$

The disk area is A_0 , another expression T_i produced by the propeller is:

$$T_i = (p_1' - p_1) A_0 = \rho A_0 \left(V_A + \frac{1}{2} u_a \right) u_a \tag{8}$$

By comparing (4) with (8), what will be concluded is:

$$u_{a1} = \frac{1}{2} u_a \tag{9}$$

It can be seen from the formula that the greater the axial induced velocity, the greater the thrust generated by the propeller.

B. Control System

Since the robot in this design is composed of three internal radial magnets, it needs to be driven by the external rotating magnetic field and directional magnetic field generated by the external three-axis Helmholtz coil. Therefore, the system consists of a four-blade biopsy capsule endoscope and an electromagnetic drive system. The four-blade biopsy capsule endoscope is composed of three radial magnets. The three-axis Helmholtz coil in the electromagnetic drive system is used to generate a universal space rotating magnetic field to realize the wireless control, active motion and biopsy experiment of the four-blade biopsy capsule endoscope. The positioning system previously proposed by our team is used to detect the position and attitude of the capsule robot in real time, providing real-time feedback to the operator. The electromagnetic drive system consists of a master control system and a slave operating system. According to the real-time examination results, the control instructions are transmitted to the slave end through the master controller. After receiving control instructions from the end system, the external magnetic field controls the four-blade biopsy capsule endoscope to perform detection and treatment tasks in the unknown and dynamic gastrointestinal environment of the human body.

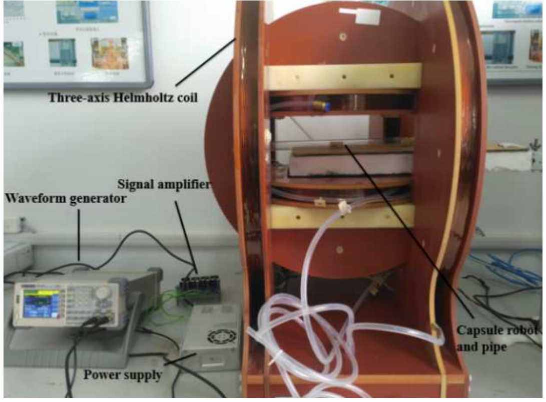

Fig. 8 Experimental platform

IV. INFLUENCE OF BLADE NUMBER ON HYDRODYNAMICS OF PROPELLER

A. Simulation of Robot Motion

The performance of the pipe propeller depends not only on the pipe parameters, but also on the number of propeller blades.Therefore, this paper mainly carries out fluid simulation on the number of blades of different propellers under the same pipe parameters and compares their simulation data to get the most suitable number of blades. It is analyzed from the perspective of hydrodynamic performance and fluid simulation.

As shown in Fig 5, the diameters and lengths of all three conduits are the same. The outer part of the catheter is made up of a smooth surface. The number of propeller blades inside the three tubes is two, three and four, respectively. The speed of the propeller is 400r/min, the density of the fluid is 800kg/m3, and the viscosity of the liquid is 1.2Pas. Fig. 9-11 shows the flow diagrams of two-blade propeller, three-blade propeller and four-page propeller in the same external liquid environment.Because of the small size of the robot designed in this paper, it would be challenging for the manufacturing process to choose a propeller with five blades or more blades.And if you have an infinite number of blades at the same size then the direction of the flow will always deviate vertically upwards.Compared with the two-bladed propeller, the forward and backward motion efficiency improved by 64.6%. Compared with the three-page propeller, the efficiency is increased by 50.5%.

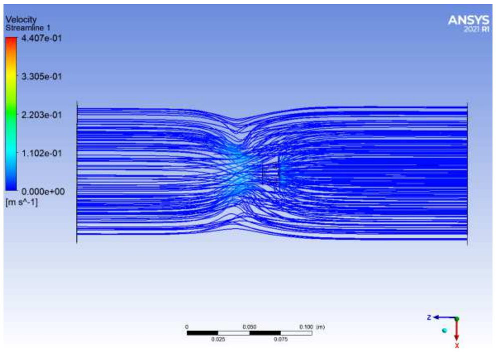

Fig. 9 Flow diagram of two blade propeller

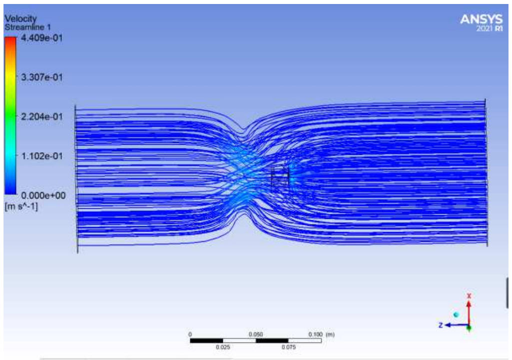

Fig.10 Flow diagram of three blade propeller

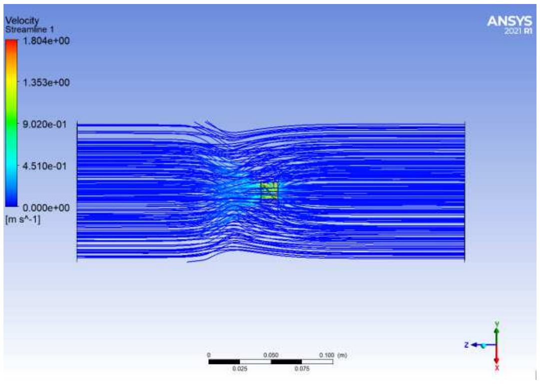

Fig.11 Flow diagram of four blade propeller

Finally, we simulate the speed and pressure of two-bladed propeller, three-bladed propeller and four-page propeller in the same external liquid environment, and get the corresponding simulation diagram. These simulation diagrams are obtained through the fluid simulation function of Ansys software.

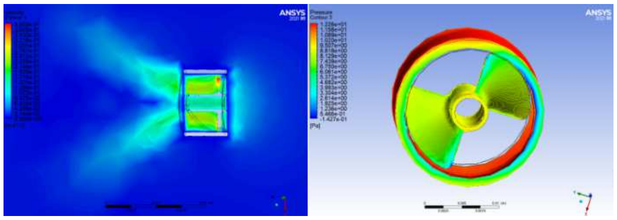

Fig. 12 Simulation of speed and pressure of a two-bladed propeller

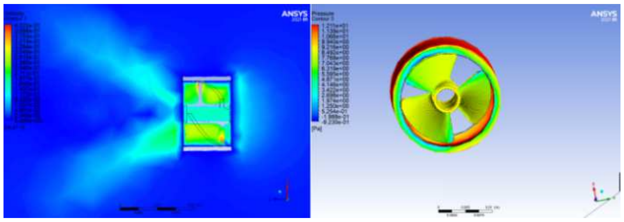

Fig. 13 Simulation of speed and pressure of a three-bladed propeller

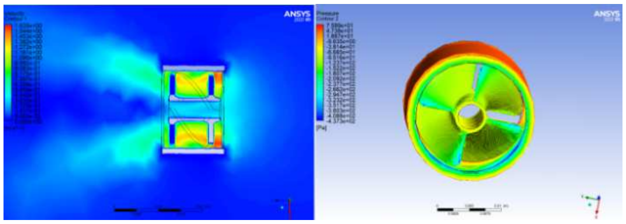

Fig. 14 Simulation of speed and pressure of a four-bladed propeller

Through comparison of simulation data, we can clearly analyze that the four-bladed propeller has a faster flow rate than the other two objects in the same liquid environment. Although the pressure will increase, the overall flow rate is still faster. The speed of the tiny propeller can also ensure the patient's health.Therefore, we choose the four-bladed propeller as the propulsion device of biopsy capsule endoscope.

V. CONCLUSIONS

The structure design of a new four-blade biopsy capsule endoscope is proposed, which includes biopsy module, anchor module and propeller drive module. The biopsy capsule robot uses SolidWorks software for 3D model design, and uses 3D printing technology to successfully print the robot. Then we introduced the control system of the robot, including the robot drive system, force analysis, motion control and biopsy process. This design focuses on the simulation analysis of different propeller blades in the same liquid environment. The simulation software is ANSYS. By comparing the results, we can find that the four-propeller propeller has the maximum thrust for the capsule endoscope in the same liquid environment.

In the future work, we should focus on improving and exploring how to achieve accurate biopsy of the targeted lesion area. This is the most important part of the test of the robot biopsy function, but also a key step to enable the robot to continuously push forward to the product.

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