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Design and Evaluation of a Novel Magnetoactive Biopsy Capsule Endoscope Robot

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***Abstract* –Due to the continuous improvement of people's living standard, the prevalence of gastrointestinal disease, surgery for patients will produce a large number of traditional stomach discomfort, therefore wireless capsule endoscopy as a kind of new visual diagnosis tool has been widely used in the diagnosis of gastrointestinal tract. In this paper, a novel biopsy capsule endoscope robot controlled by an external magnetic field is designed. According to the working principle of the CAM structure, the biopsy module is proposed and manufactured. At the same time, the control system of the robot is introduced, including the driving system of the capsule robot and the biopsy process of the biopsy module. The biopsy capsule robot is driven by a three-axis Helmholtz coil system, with the propeller as the driving device and the CAM structure as the biopsy device. A micro - barbed device with three micro barbs was designed as the head of the biopsy, which can reduce the damage to the patient's gastrointestinal tract. Furthermore this paper also conduct force analysis on the biopsy forceps and evaluate the cutting force of the biopsy. Finally, in order to verify the feasibility of the biopsy function, we carry out a series of biopsy experiments on the robot in a fluid-filled pipeline.**

Index Terms - Biopsy module, Active capsule robot, Helmholtz coil, CAM structure

I. Introduction

As a result of the fast pace of contemporary life, most people pay less attention to the health of diet, and digestive tract diseases have increasingly become a major factor that seriously threatens people's health[1]. At the same time, commercial capsule endoscope has become a more practical solution for endoscopy technology. The research on capsule endoscope is mainly divided into two aspects: one is the research on the active motion control of capsule robot, mainly from two aspects of energy supply and drive mode[2]. Another problem is the research on the function of capsule robot. The energy supply of capsule robot can be divided into electric energy drive and magnetic energy drive. The electric energy drive is mainly powered by the built-in power supply or the wireless power supply device of capsule robot[3]-[6]. Magnetic energy drive is mainly driven by the external magnetic field to control the magnet inside the capsule robot and produce coupling effect. Capsule endoscopy robot can through the micro motor or magnetic field through the human body, through the wireless signal transmission lesion area of relevant information to the doctor for a diagnosis, so the commercialization of capsule endoscopy for the diagnosis of gastrointestinal tract provides a comfortable and painless, safe and convenient solution, make the patients get rid of the rectum insert colonoscopy and retching, the feeling of discomfort and pain, and at the same time reduce the damage to mucous membranes[6]. However, the movement mode of commercial capsule endoscope has the problems of high missed detection rate and low success rate. It may miss some important lesion areas and forget to examine, nor can it take out tissue samples for more analysis[8]-[10]. Secondly, most of the capsule endoscopes only have the function of image or video acquisition, without the function of drug administration or biopsy, which is not conducive to doctors' in-depth study and has certain limitations[11].

In 2000, the M2A wireless capsule endoscope developed by Given Image opened a new window for medical practitioners in the treatment of digestive tract diseases [12]. The M2A capsule endoscope robot has a diameter of 12mm and a length of 25mm. Small in size and easy to swallow. Doctors based their diagnosis on the fact that the system has a sensor device worn around the waist to receive data. A built-in camera sends images to the device in real time. The maximum working time of the robot is 8 hours due to the limitation of internal power supply. The movement mode depends on the peristaltic passive movement of the digestive system. Because of the special physiological structure of the digestive tract. Doctors cannot adjust the position of the robot flexibly in real time according to the diagnostic needs. As a result, the missed detection rate is high. M2A is mainly suitable for the detection of the small intestine[13]. Subsequently, the company developed capsule endoscopes for the detection of other structures of the digestive tract, which are respectively PillCam SB, PillCam ESO, PillCam COLON and PillCam PATENCY[14]. In 2015, Chonnam National University of South Korea proposed a new type of robotic biopsy device based on morphology memory alloy active movement capsule endoscope[15], and conducted in vitro biopsy test to verify the feasibility of integrating the biopsy device into the capsule endoscope prototype using electromagnetic drive system. Shape memory alloy has many disadvantages such as high energy consumption and slow response[16]. The shape memory alloy leads can cause tissue damage, and the use of shape memory alloy limits the performance of capsule robot.

Magnetic drive method, meanwhile, has gradually become many researchers think that biopsy is the endoscopic robot driver module of the most effective method, compared with the traditional method of the built-in battery or micro motor, magnetic driven capsule robot show more safe, through the combination of uniform magnetic field and gradient magnetic field, can make the endoscopic robot to reach any part of the doctor wants to check. Therefore, it has been applied in many studies. For example, Xiao Simi et al. Magnetic torsion spring (MTS) was used to complete the small intestine sampling experiment. Long dragon son and so on. Control a small magnet in the WCE to drive a thin needle to achieve reciprocating motion. Then, the capillary effect of a fine needlecan be used to collect the deeper tissue of the tumor[17]. Mankunho et al. Multiple sampling is achieved by controlling the rotation of a single magnet to drive the four blades of the biopsy tool. It is easy to see that the endoscopic capsule robot with integrated functions such as drug delivery, biopsy and so on will inevitably be large in size, making it difficult for the patient to swallow again. And the response time of the biopsy module of some robots is slower. Therefore, it will lead to low utilization efficiency, relatively simple processing method and not flexible enough operation. To solve these problems, we designed a new biopsy endoscope robot[18]. Combined with the work of others in our team, we realized the specific positioning, active movement and precise biopsy functions.

In this paper, a new CAM - based biopsy module is proposed. Cam mechanism is a high pair mechanism composed of three basic components: CAM, follower and frame. Cam is a component with a curved profile or groove, generally as an active part, for constant rotary motion or reciprocating linear motion. By the rotary movement of the CAM or reciprocating movement to promote the follower for the provision of reciprocating movement or swing mechanism. In this design, the CAM is connected to the circular radial magnet, and a micro barb biopsy device is placed on the top of the follower, so as to achieve the accuracy of biopsy.

The specific structure of this paper is as follows: In the second part, we show the overall robot structure and the design of the biopsy module. In the third part, we introduce the control system of the robot. In the fourth part, we assembled the robot and experimented on its motion characteristics and the biopsy process to verify its possibility. In the last part, we conclude the conclusion and express the prospect for the future.

II. Design of Structure

Prior to our team's research, a capsule endoscopic robot has been developed to carry out image acquisition as well as diagnose and determine the location of lesions. Because they did not realize the function of biopsy, a biopsy module based on image diagnosis is proposed in this paper. We determine the specific location of the lesion through image diagnosis technology, and then biopsy the lesion area through the biopsy module. After the biopsy is completed, medical analysis of the biopsy tissue is performed. So as to complete the entire operation.

A. *Overall Structure Introduction*

The overall structure of the biopsy capsule endoscope robot is shown in Fig. 1. The shooting module is fixed on the front of the robot, and the module is used to shoot the situation in the intestinal tract for the doctor to observe. The robot is composed of two permanent magnets, a CAM, a spring, a micro barb, a baffle, a propeller and a thin shaft in the middle. The permanent magnet 1 is fixed with the CAM, and the permanent magnet 2 is fixed with the propeller through a thin rod. The biopsy endoscope capsule robot is driven by two radially magnetized permanent magnets that can rotate in a magnetic field generated by a triaxial Hertz coil. When the corresponding magnetic field is generated around, the propeller will generate forward thrust as the permanent magnet rotates, so as to push the robot to reach the corresponding lesion area. At the same time, the three-phase current needs to be changed, and the magnetic field can be changed to make the propeller rotate in reverse and generate reverse thrust, so as to achieve accurate reach.

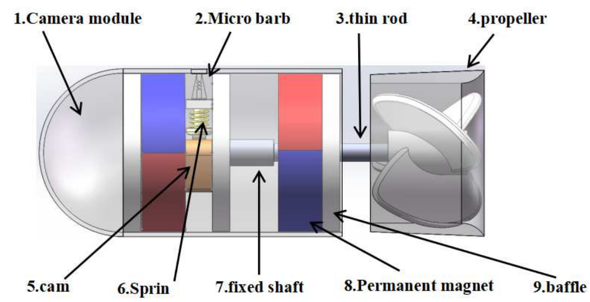


Fig. 1 Biopsy robot based on CAM structure

B. *Biopsy Module*

When they arrive in the lesion area, first of all, we let it stop moving, change the direction of current, so that the change of magnetic field, permanent magnet driven CAM rotate, from inside the robot micro barb, capture living tissue biopsy module, captive living tissue by micro barb stuck in biopsy in the module, will continue to rotate shrink its return to inside the capsule, so as to complete the whole process of biopsy. When the biopsy is complete, the strong external magnetic field is removed, and the robot returns to its original motion and then moves forward. This is a functional description of the entire biopsy.

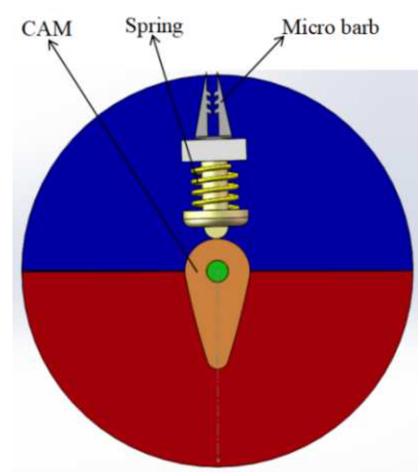


Fig. 2 Structure of biopsy module

As shown in Fig. 3, the head of the biopsy module is a biopsy forceps, which has six miniature barbs designed to be symmetrically distributed on the inner walls of both sides of the biopsy forceps, ensuring the tissue recovery rate of the biopsy. It can also reduce the pain of patients.Because the printing precision may have a little error.

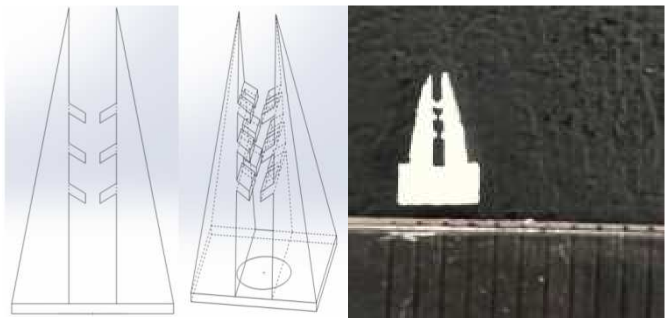


Fig. 3 The biopsy forceps

Fig. 4 shows the entire biopsy process. The biopsy forceps are gradually extended from the inside of the capsule robot through the rotation of the magnet. After successfully extracting the tissue, they are returned to the inside of the capsule robot to complete the biopsy.

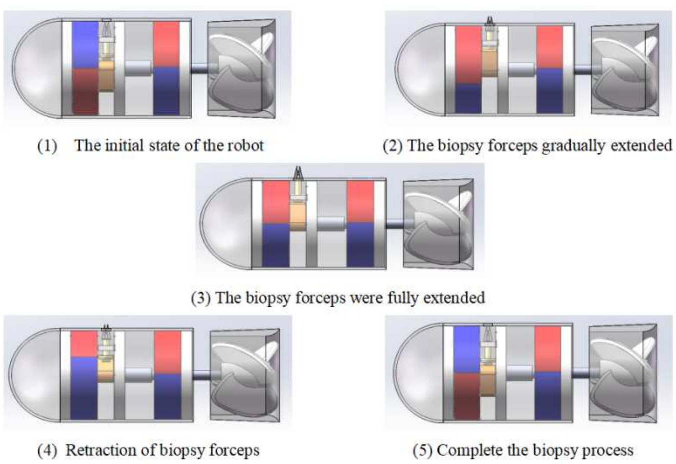


Fig.4 The capsule robot biopsy process

III. PERFORMANCE ANALYSIS OF BIOPSY ROBOT

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. The design of the robot because of the small size, and the need for built-in magnets, so can not use the traditional processing methods. Therefore, the whole robot is divided into several small parts, and each part is 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. Fig. 5 shows the printed robot part structure.

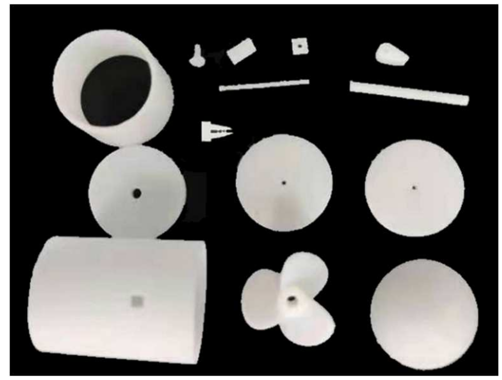


Fig. 5 The parts drawing of the biopsy robot

A. Stress Analysis of CAM Structure

The Cartesian coordinate system from x,y,0 points of the contact point of the CAM surface contour curve and the follower at the convex bottom to the contact point is represented by a vector $R(r,\theta)$. R represents the module of the vector R and θ represents the included Angle between the vector R and the X axis. According to its geometric relationship, it can be concluded that:

$$R=\begin{bmatrix} x \\ y \end{bmatrix}=\begin{bmatrix} r\cos\theta \\ r\sin\theta \end{bmatrix} \tag{1}$$

$$\dot{R}=\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}=\begin{bmatrix} \dot{r}\cos\theta-r\dot{\theta}\sin\theta \\ \dot{r}\cos\theta+r\dot{\theta}\sin\theta \end{bmatrix}=\begin{bmatrix} \cos\theta-r\sin\theta \\ \sin\theta+r\cos\theta \end{bmatrix}\begin{bmatrix} \dot{r} \\ \dot{\theta} \end{bmatrix} \tag{2}$$

$$\ddot{R}=\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix}=\begin{bmatrix} \ddot{r}\cos\theta-2\dot{r}\dot{\theta}\sin\theta-\dot{r}\ddot{\theta}\sin\theta-r\dot{\theta}^2\cos\theta \\ \ddot{r}\sin\theta+2\dot{r}\dot{\theta}\cos\theta+\dot{r}\ddot{\theta}\cos\theta-r\dot{\theta}^2\sin\theta \end{bmatrix} \tag{3}$$

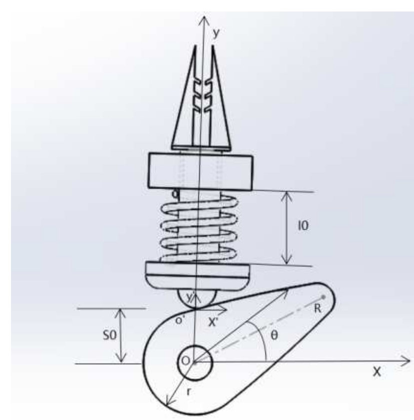


Fig. 6 Stress analysis of CAM structure and biopsy forceps in horizontal and vertical directions

In the above formula, $\ddot{y}$ is the acceleration of the contact point between the CAM curve surface and the convex bottom follower in the Y direction, that is, the acceleration of the vertical up and down movement of the convex bottom follower. Therefore, the acceleration of the biopsy device is equivalent by the transfer effect. The speed and acceleration of the vertical up and down motion of the follower will have a great influence on the movement. Therefore, the CAM follower is taken as the research object, as follows:

$$F - F_h - F_f - F_g = ma \quad (4)$$

$$F = ma + F_h + F_f + F_g \quad (5)$$

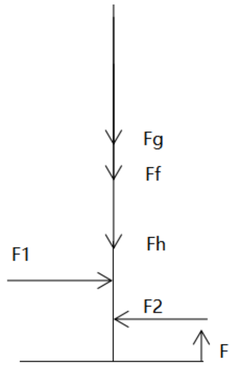


Fig. 7 Schematic diagram of the force on cam structure

$$F_x r\cos\theta = M_T \quad (6)$$

$$F_h = K[I_0 - (S_0 - r\sin\theta)] \quad (7)$$

I_0 is the original length of the spring, S_0 the distance from point O to the bottom edge of the moving pair,and K is the spring stiffness coefficient.

$$\sum M_{F2} = 0, F_1 H = Fr\cos\theta \quad (8)$$

$$H = \frac{Fr\cos\theta}{F_1}, F_2 = F_1 \quad (9)$$

$$F_f = (F_1 + F_2)f = \frac{2fFr\cos\theta}{H} = \frac{2fM_T}{H}, H = \frac{2fM_T}{F_f} \quad (10)$$

Where F is the contact pressure between the follower of the CAM, F_h is the spring resistance, F_f is the friction force between the follower and the CAM, F_g is the working pressure, m is the mass of the follower, and a is the acceleration of the follower, the stress diagram of CAM structure is shown in Fig. 7,so

Where H is the displacement of the moving pair, i.e. the extension length of the biopsy forceps. It can be seen from the formula that the displacement length of biopsy forceps is related to the size of F and f. The larger the F value is, the smaller the f value is, and the larger the displacement is. The smaller the F value is, the larger the f value is, and the smaller the displacement is.

We also performed mechanical simulation of the biopsy forceps. When a sufficient force is applied, a corresponding deformation occurs. It also ensures that the tissue taken in the internal biopsy can smoothly enter the inside of the robot, improving the accuracy of the biopsy. Fig. 8 shows the static stress analysis simulation and static displacement simulation of the biopsy forceps.

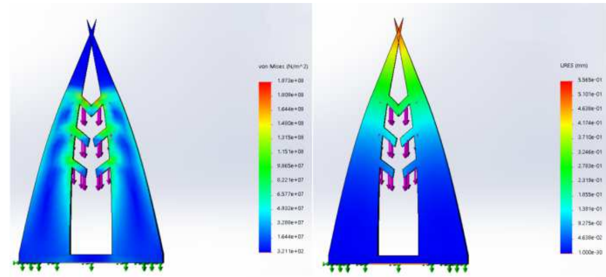


Fig. 8 Simulation diagram of static stress and displacement of biopsy forceps

B. *Control System*

As described in Part I, the experimental platform can be driven by an external rotating magnetic field generated by a three-axis Helmholtz coil on two permanent magnets in the center of a radially magnetized robot. Each axis of a triaxial orthogonal Helmholtz coil is formed by a pair of parallel coils. The coil is tightly wound around a certain number of turns of wire. Because of its simple structure and good magnetic field uniformity, rotating magnetic field can be generated. The three-phase AC power supply PCR3000LE2 that drives the coil. Main end PC and operating handle for wireless control. Peristaltic pump that simulates human digestive tract environment.When an alternating current is applied, the rotating magnetic field generated by the three-axis Helmholtz coil rotates the radially magnetized magnet. According to the theory of electromagnetism and the knowledge of space geometry, if two groups of Helmholtz coils are orthogonal to each other, a uniform magnetic field plane will be generated at the center of the coil; if two pairs of orthogonal combinations in the space of three groups of Helmholtz coils, a rotating magnetic field space of eight directions in a space will be generated. Therefore, it is used in the magnetic field generating device of the magnetic capsule robot. After starting the device, the capsule robot performs a rotating motion, whose axis of rotation is the central axis under the action of magnet rotation. At this time, the propeller drive device generates forward driving force. Fig. 9 shows the overall control system of the robot.

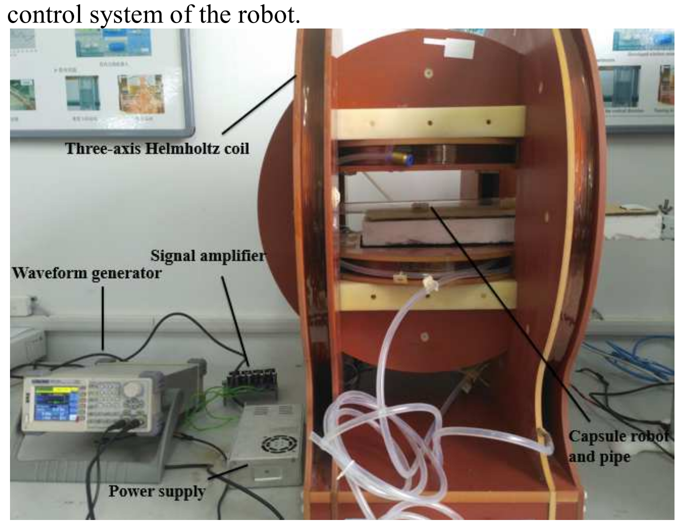


Fig. 9 Experimental platform

IV. Experimental Results

A. Experiments of Robot Motion

After the robot was printed and assembled, we evaluated and analyzed the forward and backward motion characteristics of the robot shaft. We used an acrylic tube with a length of 30cm, and cut 15cm in the middle part as the displacement length of the robot. We recorded the movement time every 1Hz, and after analyzing the experimental data, we obtained the curve graph of the relationship between the current frequency and the moving speed of the robot moving forward and backward. We found that the initial frequency was 3Hz for both forward and backward motion. At this time, the propeller rotates to make the robot move in an axial direction, and this frequency is the current frequency. When the current frequency is 11Hz, the forward and backward axial velocity of the robot almost drops to 0, so the forward and backward cutoff frequencies of the robot are both 11Hz. We can see from the graph of the experimental data that the robot has the fastest axial motion speed around 9Hz, so in the following biopsy experiment, we set the robot's frequency as 9Hz to ensure the robot's motion speed.

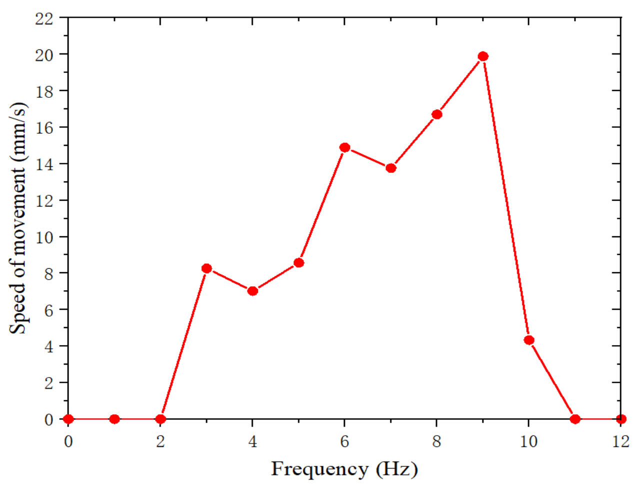


Fig. 10 The relationship between the current frequency and the average speed of the robot's moving forward

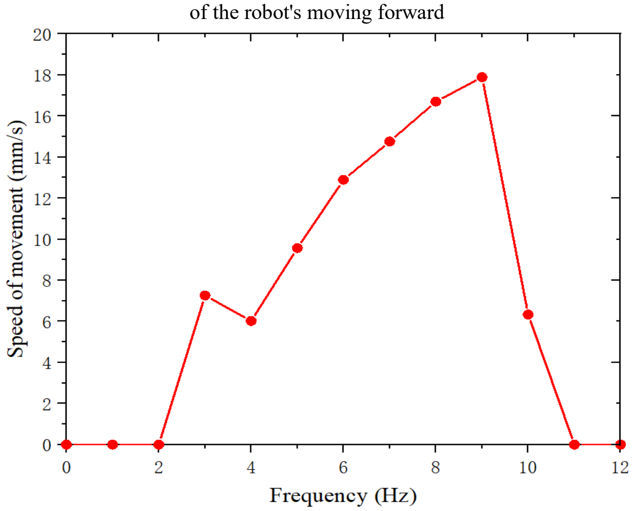
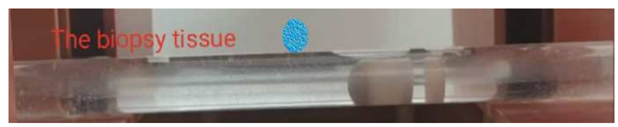


Fig. 11 The relationship between the current frequency and the average speed of the robot backward motion

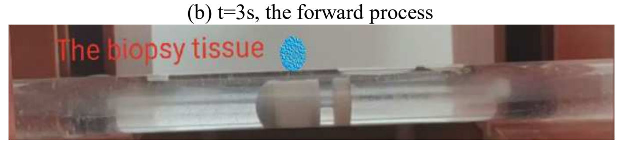
B. Experiments of Robot Biopsy

After the movement performance of the robot is verified and the experiment is successful, the biopsy process of the biopsy robot is experimented to verify the feasibility of the biopsy module. First, we marked a blue dot as our biopsy target tissue, and placed the biopsy endoscope robot on the right side of the tube, as shown in Fig. 12(a). The tube was used to simulate the intestinal environment of the human body. A current is then fed into the three-axis Helmholtz coil to generate a magnetic field that controls the robot's movement from right to left. And when we get to the biopsy target, we stop it. By changing the directional magnetic field, the two magnets inside the robot are rotated in a radial way, so that the CAM module rotates and the biopsy forceps are extended. As shown in Fig. 12(d), the biopsy forceps are successfully extended at the biopsy target tissue. After the completion of the biopsy process, the magnetic field is changed back to the original direction of the magnetic field, so that the biopsy robot continues to move forward, so as to complete the entire biopsy process.

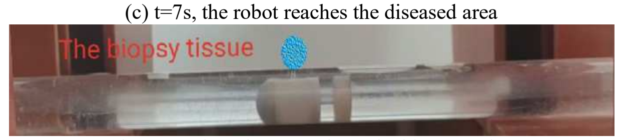
(a) t=0s , the motion state



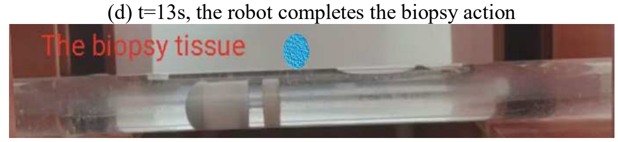
(b) t=3s, the forward process



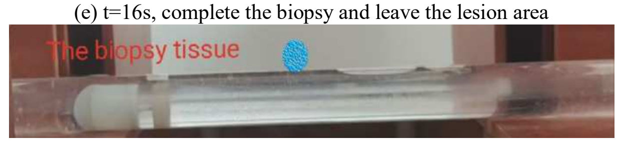
(c) t=7s, the robot reaches the diseased area



(d) t=13s, the robot completes the biopsy action



(e) t=16s, complete the biopsy and leave the lesion area



(f) t=20s, the robot completes the biopsy proces

Fig. 12 A snapshot of the implementation of the biopsy function

V. Conclusions

In this paper, a biopsy capsule robot with autonomous movement ability was proposed, the robot consists of a biopsy module and a driver module. We used SolidWorks software to draw the overall structure of the robot and used 3D printing technology to print the robot. Then, the robot control system was recommend, including the robot drive system, force analysis, motion control and biopsy process. The driving system used a three-axis Helmholtz coil to generate a rotating magnetic field to drive the robot to carry out a locomotive test evaluation. The feasibility of the biopsy function was proved by the successful biopsy experiments. The experimental results showed that the motion speed of the biopsy capsule robot increases with the change of driving frequency. As two radially magnetized permanent magnets were used in biopsy robot, the frequency range of the magnetic field driven by the robot was reduced by half. Due to the lack of the water impact force caused by the modular interface blocking, the movement speed of the robot after 11Hz was guided to suddenly decrease. In the experiment we designed, the capsule robot can be controlled to stop at a specific position. After the robot stops, it can smoothly run the CAM module so that the biopsy forceps can be extended. The maximum biopsy extension length was 3 mm and the opening direction was arbitrary. Once the biopsy is complete, the capsule robot can be controlled to move forward.

In future, the accuracy of biopsy function should be continuously improved, which is the responsibility for patient's health.

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