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Performance Evaluation of the Assembly Mechanism for Multimodule Capsule Robots Docking

Lingling Zheng[1] and Shuxiang Guo[2,3]

[1]*Graduate School of Engineering,*
[2]*Department of Intelligent Mechanical Systems Engineering,*

Kagawa University,
Takamatsu, Kagawa 761-0396, Japan

s19d504@stu.kagawa-u.ac.jp

[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,
Haidian District, Beijing 100081, China

guo.shuxiang@kagawa-u.ac.jp

***Abstract* – Even though swallowable capsule endoscopy has many obvious advantages, it has been restricted from further application due to the low diagnostic efficiency. One explanation for this is that the capsule endoscopy is just equipped with image acquisition and transmission functions, which is far from enough to diagnose Gastrointestinal (GI) diseases. To improve the detection efficiency of the capsule endoscope, we proposed a concept of multiply module capsule robots and a novel assembly method in the previous research. A further simulation analysis of the assembly mechanism was presented in this paper. By applying a force on the claws, the deformation of the claws under this force is calculated. In the simulation, the claw mechanism with six claws was analyzed, and according to the simulation results, the maximum displacement of the claw tip was 1 mm under the load with a force of 39.42 mN. The results prove the feasibility of the assembly mechanism for docking the robot modules.**

***Index Terms* – Multimodule capsule robot, assembly mechanism, simulation analysis, deformation.**

I. INTRODUCTION

With the improvement of endoscopic technology, more and more gastrointestinal diseases can be treated and prevented. Some gastrointestinal diseases like gastritis and ulcers can be observed by the image information collected by the endoscopes [1]. The use of endoscopes to confirm or treat some diseases requires the assistance of special functions or structures. Traditional gastrointestinal endoscopes even perform minor surgery during the detection procedure [2]. However, the capsule endoscope as the most potential alternative to the traditional endoscope is limited by the internal space [3]. Some capsule endoscopies have been applied in clinical practice. Nonetheless, the commercial products in the market, including the PillCam™ capsule endoscopy system, and Olympus endocapsule system, are performed passive movement in the gastrointestinal tract. The passive movement relying on the peristalsis of the organ reduces the accuracy of diagnosis and the efficiency of the testing procedures [4]. Therefore, many capsule microrobots with active locomotion were developed by the research teams. In the past few years, we also presented many kinds of microrobots with active locomotion or other function [5]-[17].

The volume of the common commercial capsule endoscopy is 26mm x 13mm in size approximately. Since the internal images of the gastrointestinal tract are needed for medical diagnosis, the camera and the image transmission mechanism must be equipped inside of the capsule endoscopy [18]. It`s hard to add the special structure for other functions of the capsule endoscopy by using the remaining space. However, simplify medical procedures is a trend of technology development. So, many research groups are focus on the development of modular capsule robots. Nagy *et al*. designed swallowable modular robots, and they can self-assembly in the gastrointestinal (GI) tract [19]. They use the magnets placed on the mating faces of the modular robots as the driving mechanism to complete self-assembly. The proposed snake-type robots are able to successfully achieve assmble with the magnetic joints in the irregular paths. S -S Yoo *et al*. proposed a modular robot system, and the locomotive elements are capable of assembling into a larger and more complex robot [20]. The elements can achieve docking orientation by permanent magnets attached in the capsule robot. They can fully assembled in a four-capsule unit and move follow the user-directed. A prototype modular capsule robot system was introduced by L. Kim *et al*., which contains the functional multiple robotic capsule modules [21]. The assembled robot modules can achieved the active locomotion via the collaborative actuation mechanism equipped the permanent magnets attached at each end of the connectors. K. Harada *et al*. [22] developed a reconfigurable modular robotic system, which can assembled in the stomach cavity. The permanent magnets attached at each end of the module can help the robot modulars to self-alignment and docking. S. Guo *et al*. [23]-[27] presented multiple capsule robots with the joint permanent magnets which can form a new constructions via mutual docking and release. All these developed modular robots can assemble by using the permanent magnet. However, the assembly mechanisms via the permanent magnet have many limitations, like the contradiction of the docking force and separation force.

A novel assembly mechanism for docking and separation of the robot modules was developed in our previous research [28]. The developed microrobot modules equipped the thread mechanism and the claw mechanism, respectively. Using the novel mechanism, the robot modules can realize docking stably and separate easily in the intestine. Only the preliminary design and analysis of the assembly mechanism were discussed and verified in [28]. So, this research will further explore the interaction force and the deformation of the assembly mechanism during the docking and separation process.

The current paper is organized as follows. Section II describes the structure and principle of the assembly mechanism. Simulation analysis of the deformation of the claw mechanism was proposed in Section III IV. Finally, the conclusion and future work are summarised in Section IV.

II. STRUCTURE AND PRINCIPLE OF THE MECHANISM

A. Surgical procedures description

The clinical target for the capsule endoscope is the detection and diagnose of the entire digestive tract. The doctor preliminary judges the condition of the digestive tract diseases through the captured image information of the capsule endoscopy. In the medical process, the only image function is not enough, and many diseases require further examination or treatment. Surgical process simplification is an important symbol and development direction of medical progress. That means more medical functions are added to the fewer medical procedures. For example, some small bowel polyps can be directly removed, and the biopsy from suspicious lesions can be performed in traditional endoscopic surgery. Therefore, the modular microrobot system has been developed to extend capsule endoscope function.

Recently in [28], we proposed a novel concept of a multi-module capsule robot system with one main module and functional modules. Utilizing the main module to check the intestinal conditions is the first step of the endoscopy procedure. When the module finds out some suspicious lesion needing further treatment, the functional module will be selected and swallowed. The functional modules move to the target position with the main module and perform the corresponding treatment procedure. Finally, they will be discharged during a bowel movement. Besides, the main module can provide guidance and support to the functional modules and cooperative actions with the functional modules during the surgical procedures.

B. Design features

The modular microrobot system consists of one main functional module and several additional functional modules. The assemble action is the basic collaboration of the multiple modules. The assemble action can be divided into two processes: docking and separation. The requirements of the docking and separation process include the easy method and the stable state. Therefore, we developed an assembly mechanism with a rod mechanism and a claw mechanism, as shown in Fig. 1. It is mainly composed of a threaded rod and circularly arranged claws. The motion states of the mechanism during docking and separation have been introduced in [28]. In the docking process, the robots move toward each other, and the rod gets into the hole with the assistance of guidance of the sunken base. The rod enters the hole entirely, and the docking task is completed. During separation, the docked robots rotate in opposite directions. The rod will screw out of the hole following threads on the rod mechanism. Fig. 2 shows the two statuses of the assembly mechanism, where (a) is for docking and (b) is after separation.

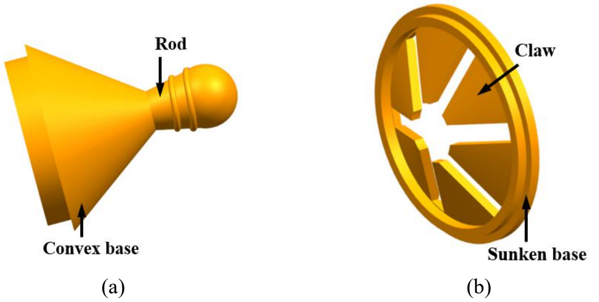


Fig. 1. Assembly mechanism [28]. (a) Rod mechanism. (b) Claw mechanism.

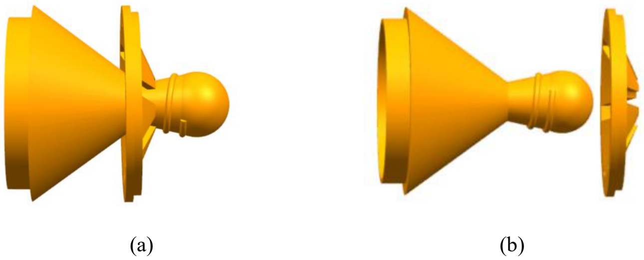

(a) (b)

Fig. 2. Two statuses of the assembly mechanism. (a) Docking. (b) Separation.

C. Docking principle

Fig. 3 shows the deformation of the claw mechanism during the docking process. The claw mechanism in the schematic has 6 claws arranged in a circular, and the tilt angle is about 33.7°. Fig. 3 (a) shows the section view of the claw mechanism in separation status. When the capsule modules were in separation status, a hole with the diameter of d is formed in the center of the circularly arranged claws. At the beginning of the docking process, the two modules approach each other and bring the rod mechanism and the claw mechanism into contact. Fig. 3 (b) shows the section view of the claw mechanism in the docking process. As the distance between the two modules gets closer, the rod mechanism causes pressure named F, and the F is normal to the surface of claws. When the pressure increases, the claw mechanism will increase the elastic deformation in response. The diameter of the middle hole after elastic deformation is D. When the diameter D is as large as the top of the rod mechanism, the rod mechanism is inserted into the hole in the center of the claw mechanism. Due to the diameter of the middle part of the rod mechanism is smaller than diameter d, the claw mechanism returns to its original shape, with the diameter of the hole in the center is d. Since the claws of the claw mechanism are inclined inward, the connection state of the two modules can be ensured after the docking.

D. System overview

We constructed a magnetic control system composed of a three-axis Helmholtz coil to manipulate the multiple robots, as shown in Fig. 4. During the surgical process, the patient lies inside the magnetic control system after swallowing the capsule robots. The capsule robots contenting the main module and functional module are swallowed after the doctor`s recommendation. Using the 3-axis Helmholtz coil can generate a rotating magnetic field to drive multiple capsule robots to rotate. The rotational motion of the robot not only can make the robots propel in a tubular environment but also can realize docking and separation movement. Two pairs of orthogonal Helmholtz coils inject sinusoidal current with π/2 phase difference, and the same frequency can produce two sets of orthogonal sinusoidal harmonic magnetic fields. Following the principle of superposition, the resultant magnetic field is identified as follows:

$$\boldsymbol{B_0}(\boldsymbol{wt}) = \boldsymbol{B_0}\cos \boldsymbol{wt} + \boldsymbol{i}\cdot \boldsymbol{B_0}\sin \boldsymbol{wt} \qquad (1)$$

where, $\mathbf{B_0}$ is the amplitude of the rotating magnetic field, w is the angular velocity of the rotating magnetic field, $\mathbf{B_0}\cos wt$ represents magnetic induction intensity of the x-axis coil at time t, $\mathbf{B_0}\sin wt$ represents magnetic induction intensity of the y-axis coil at time t, and $\boldsymbol{B_0}(wt)$ represents the magnetic vector sum of the two-axis coils at time t.

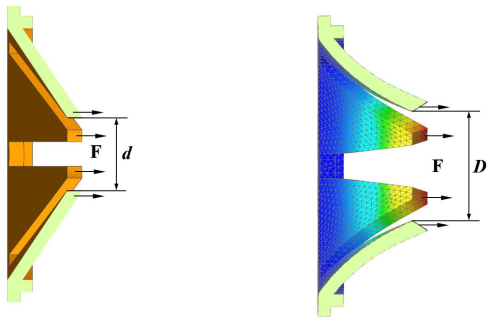
A magnet installed inside the robot under an external magnetic field of the 3-axes Helmholtz coil experiences magnetic torque as follows:

$$\boldsymbol{T} = \boldsymbol{M} \times \boldsymbol{B} \qquad (2)$$

where, $\boldsymbol{M}$ is the magnetic moment of a magnet and $\boldsymbol{B}$ is the magnetic flux density at any position on the axis of the Helmholtz coils.

III. SIMULATION ANALYSIS

A. Simulation Settings



(a) (b)

Fig. 3. Deformation of the claw mechanism. (a) Section view of the claw mechanism in separation status. (b) Section view of the claw mechanism in the docking process.

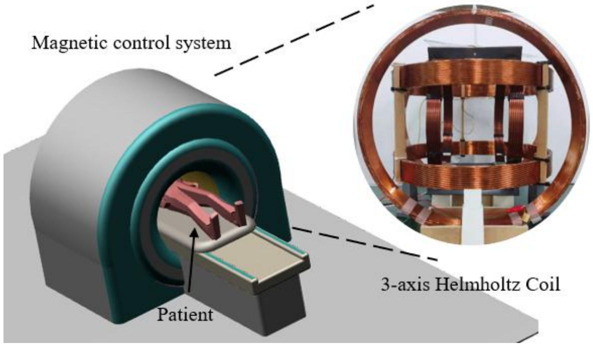


Fig. 4. Schematic diagram of the magnetic control system.

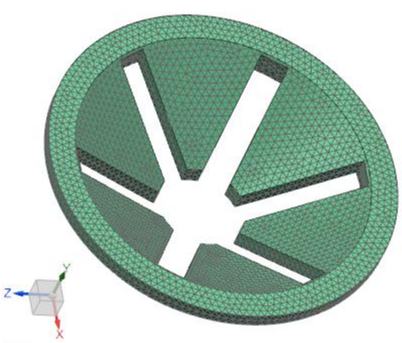


Fig. 5. Grid partition of the claw mechanism.

In order to verify the feasibility of the assembly mechanism to realize the docking process, we simulated the claw mechanism with UG NX software. The 3D model of the claw component and the sunken base components were established by the CAD module of the UG NX software. Then add these components to assembly following the defined assembly constraints. One example of the claw mechanism model was given in Fig. 1 (b). The designed claw mechanism model has 6 claws with 0.5 mm thickness, and they are circularly distributed on the edge of the sunken base. A circular hole with a diameter of 3 mm is formed in the middle of the claws. The angle of inclination of the claw is 33.7°. The finite element mesh of the claw mechanism model was divided by used the CAE module. Fig. 5 shows the grid partition result with the mesh size of 0.25 mm. After dividing the geometry, we defined the material properties with Young`s modulus of 5 MPa and 0.48 Poisson ratio to approximate soft solid rubber.

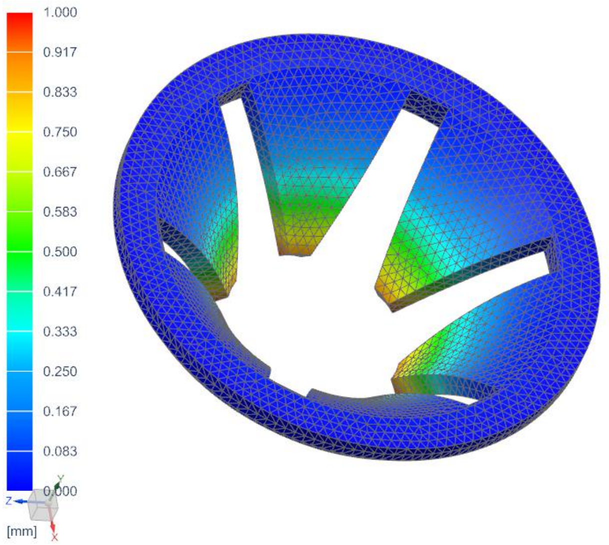


Fig. 6. Deformation result of the claw mechanism with force applied.

Owing to the sunken base connected to the main part of the microrobot, the cylinder constraint was set to fix the sunken base. Finally, we defined the load type and chose the center edge of the claws to input predefined force.

B. *Results and discussion*

A typical force-induced deformation of the claw mechanism is presented in Fig. 6. The color on the model represents the magnitude of the displacement of every unit in the 3-dimensional space. When various forces were applied to the claw mechanism, six claws deformed with different displacements. Great forces result in large deformation and materials with lower stiffness will have large deformations under the same applied forces. During the docking process, the rod mechanism needs to dock with the claw mechanism with the propulsive force produced by the interaction between the magnetic field outside and the magnet set in the capsule robot. The great propulsive force will be conducive to the smooth completion of the robot docking. The magnetic field and the magnet with great magnetic flux can generate larger propulsive force but result in large peripheral equipment with the high cost and large-volume capsule robots. High-cost equipment will not be conducive to promotion and use. Also, the volumes of capsule robots are limited by the size of the intestines. Therefore, the feasible method is to change the structural design and materials. In this research, we tried to optimize the structural design and material selection. We designed claw mechanisms with different numbers and structures of claws. In this simulation, the claw mechanism with six claws was analyzed, and according to the simulation results, the maximum displacement of the claw tip was 1 mm under the load with a force of 39.42 mN. The hole diameter of the claw mechanism was 4 mm when the maximum displacement of the claw tip was 1mm. The hole with 4 mm diameter will allow the rod mechanism to dock with the claw mechanism since the maximum diameter of the rod is less than 4 mm. Therefore, this design enables the capsule modules to complete the docking with the propulsive force.

IV. CONCLUSION

We developed an assembly mechanism that can perform multiply module capsule robots docking and separation. The mechanism was proposed in previous research [28]. We introduced the state of the assembly mechanism during the docking process. In this paper, we utilized the UG NX software to simulated the force applied to the claw mechanism to verify the feasibility of the structure. The simulation result proved that the feasibility of the proposed mechanism. In the future, we will focus on developing a novel mechanism to reduce the size of the assembly mechanism and improve assembly efficiency.

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