

Development of a Novel Wireless Spiral Capsule Robot with Modular Structure

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Abstract – Due to the limitations of the size of the wireless capsule robot using in diagnosis and treatment of gastrointestinal diseases, various functional modules cannot be integrated into a single capsule robot, which caused the practicality of the robot being reduced. This paper proposed the wireless spiral capsule robot with modular structure driven by the external magnetic field which have the mechanism that can combine and separate two robots have the Modular Structure. This robot system has two robots, namely the guide robot and auxiliary robot. The control system of the robot including the driven system, motion control and modular docking of the robots was presented. Both of the robots have two helical diversion grooves but the spiral directions are different between the two robots. In this way, they can move to each other under the same external magnetic field. This paper proposed a mechanism to make the auxiliary robot dock with the guide robot by the modular interface with the magnets and the modular structure is generic with multiple auxiliary robots. The 3D models of the robots were designed through the SolidWorks and fabricated by 3D printer. Then the active locomotive test for the two robots was taken using a three-axis Helmholtz coils system. Finally, the feasibility of the docking action with the modular structure was verified. The developed capsule robot can be used to improve the capsule robot system and help for future medical applications.

Index Terms - modular structure, wireless capsule robot, robots rendezvous and docking, Helmholtz coils

I. INTRODUCTION

Gastrointestinal (GI) diseases have become an important factor threatening our national health. The current method of treating gastrointestinal diseases is to deliver the endoscope attached to the medical hose into the patient's digestive tract. In the process, the friction between the medical hose and the digestive tract wall will give the patient a great deal of pain. Simultaneously, it is also possible to cause secondary damage to the digestive mucosa. Furthermore, the traditional endoscopy posture cannot be flexibly adjusted. Since its inception in 2000, Iddan proposed the wireless capsule robots [1], wireless capsule endoscopy (WCE) was particularly popular in the past decade. As a new digestive GI disease diagnosis technology, WCE Capsule endoscope has the advantages of noninvasive, painless and easy to check. In recent years, WCE has been used as a routine method to diagnose many GI diseases [2]. But the major problem of most

of current commercial capsules is the lack of control of movement. These capsules, however, can only achieve passive movement relying on the peristalsis of the digestive tract, and cannot be controlled to apply the acceleration, stop, reverse and other actions. This problem limits the WCE's observation and manipulation for the digestive tract.

Some researchers are looking for ways to implement the WCE's actuation method. A variety of motor-driven micro-robots have been developed so far. Gao et al have designed a capsule robot which based on motor and powered by wireless power transmission [3]. Quirini et al proposed a solution for the active locomotion of micro robot in GI tract. The microrobot designed by Quirini actuated by a brushless minimotor and has a legged locomotion system embedded in it [4]. As we all know, the size restrictions of the capsule robot limit the capability of its integrated components. The motor and the onboard chip will occupy a large part of the space within the capsule. On another side, it is kind of dangerous to swallow the circuit board, motor or battery into the body. So the capsule robots have relatively large limitations which are driven by a motor in themselves and controlled by the onboard chip to drive the robots.

It's increasingly popular to design capsule robots which are driven by external magnetic field for the researchers. Apart of them utilize the external permanent magnet. Kim proposed a capsule endoscope with active mobility in the human digestive system [5]. Its mechanism forms a right-handed or left-handed thread based on the rotating direction. It can perform either a spiral motion or translation motion by an internal permanent magnet and an external permanent magnet mounted on a rotational actuator Outside of the robot.

Zhang et al designed a three-axis orthogonal square Helmholtz coils to create a universal uniform magnetic spin vector which also called rotating magnetic field as an energy source by feeding with three phase sine currents [6-7] and presented a double compensation method to increase the magnitude and orientation accuracy of the rotating magnetic vector effectively[8]. They also proposed a variable-diameter capsule robot for active locomotion based on multiple wedge effects using an outer rotating magnetic field [9]. Fu et al from Guo lab proposed the magnetically actuated hybrid microrobot with hybrid motion driven by a rotational magnetic field which

is generated by 3 axes Helmholtz coils [10]. Its two motion mechanisms comprised the spiral jet motion moved by rotating its body and fin motion moved by vibrating its body. In the following study, they designed the shrouded propeller mechanism to achieve a high level of medical safety as well as effective propulsive performance [11]. Compared to the permanent magnet's external magnetic field, the external magnetic field uniformity and controllability generated by the Helmholtz coils are significantly improved.

In addition to the study of active locomotion, many researchers have also studied the additional functions of WCE such as biopsy, drug delivery, anchoring and so on. Beccani et al design a drug delivery capsule (DDC) based on a coil-magnet-piston mechanism [12]. Choi et al proposed a capsule-type magnetic microrobot that can navigate along a tubular environment and selectively release drugs in different target points actuated by a magnetic navigation system [13]. The capsule robot has two cylindrical drug chambers and can be driven by a magnetic gradient and release drugs at different positions by using uniform rotating magnetic fields. Le et al presented a drug delivery module for active locomotive capsule endoscopy using electromagnetic actuation [14]. Kim proposed a mechanism for targeted drug release based on active locomotion which method is a magnetic torque control based on a rotating magnetic field using a three-axis Helmholtz coils system [15]. Yim et al also design a capsule endoscope which can carries and releases thermo-sensitive, untethered microgrippers inside the stomach and retrieves them after they self-fold and grab tissue samples to offer the function of biopsy [16]. Zhou et al proposed a magnetically actuated anchoring system for WCE by employing the principle of a switchable magnetic spring [17].

It is easy to find that the size of most of the commercial or other experimental capsule endoscopies which integrated medical functions robot are unavoidably big. This factor leads to their low utility. Another existing problem is that the amount and types of drug carried by many DDC are limited, which makes them can only withdraw before the next procedure after the drug has been used. The treatment is relatively simple and operation is not flexible enough. The last problem is that these WCE's part of diagnosis and treatment components are not separated. Therefore, after a procedure of diagnosis and treatment, the WCE will withdraw as a whole. And in the next procedure, the doctors must reposition the disease site which has been located before.

In order to solve these problems, this paper proposes an innovative method which employs modular structure to realize the separation of various functions to the module. In detail, the whole robot can be divided into several modules which conclude the guide module robot and the auxiliary module robot. The robots' interface is modular and the same auxiliary module robot with the same interface can dock with the guide module robot in the same way. In order to effectively reduce the volume of a single robot into the digestive tract, each module robot can be controlled separately as needed. After the inspection of the guide module robot, the treatment module

robot can be swallowed and then dock with the guide module robot and save the long time to reposition the target location.

This paper is structured as the following. In section II, we showed the model of proposed wireless spiral capsule robot with modular structure and the procedure of its work. In section III, we presented the control system of the robot including driven system of the magnetic field, motion control and modular docking of the robots. In section IV, we assemble the robot and experiment with its movement and docking in order to verify our model. The last is our conclusions and the future work.

II. THE PROPOSED WIRELESS SPIRAL CAPSULE ROBOT WITH MODULAR STRUCTURE

A. The Model of Wireless Spiral Capsule Robot with Modular Structure

The wireless spiral capsule robot with modular structure concludes two main units: the guide and the auxiliary robot, as shown in Fig. 1. Both of the spiral capsule robots have a built-in permanent magnet which magnetized in the radial direction and can perform a spiral motion driven by an external rotating magnetic field. And two magnets which are magnetized in the axial direction are placed in the rear of the guide robot and in the front of the auxiliary robot, respectively. These two magnets can be utilized to combine two parts of the robot through the force of different poles of magnets.

B. Fabrication of Robots

In the case of limiting the size of the robot and placing two magnets inside a microrobot is not easy to manufacture by using the traditional processing methods.

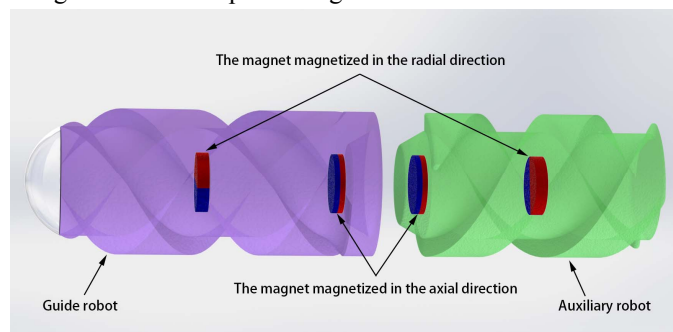
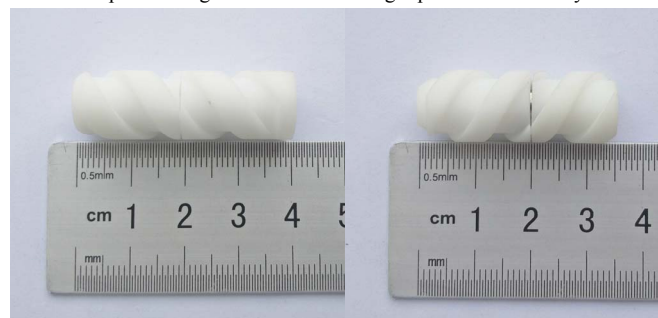


Fig. 1 The 3D Model of wireless spiral capsule robot with modular structure. The left part is the guide robot and the right part is the auxiliary robot.



(a) Guide robot (b) Auxiliary robot

Fig. 2 The prototypes of two capsule robots.

TABLE I
PARAMETERS OF ROBOTS

	Length (mm)	Diameter (mm)	Grooves Depth (mm)	Grooves Width (mm)	Grooves Number (mm)
Guide robot	39.4	12.5	1.5	4.5	2
Auxiliary robot	33.8	12.5	1.5	4.5	2

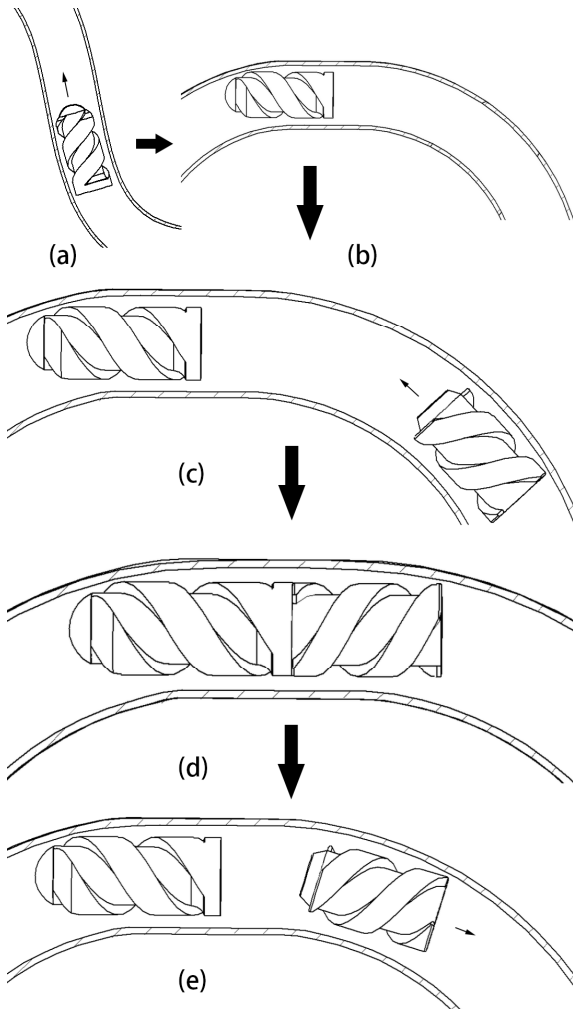


Fig. 3 The schematic diagram of diagnosis and treatment diagnosis and treatment for the guide robot and the auxiliary robot.

So we divided the single robot model into several parts and then printed the each individual part using the 3D printer from ABS plastic.

The fabricated capsule robots are shown in Fig. 2. The machining accuracy of the robot is 0.1 mm, which is sufficient for the robots of this paper. Table I lists the parameters of both of the proposed guide robot and auxiliary robot.

C. The Procedure of Diagnosis and Treatment

Fig. 3 describe the whole procedure of inspection and treatment of the wireless spiral capsule robot with modular structure.

The following is the specific steps of its work:

- The guide modular robot enters the digestive tract and rotates forward under the action of the external rotating magnetic field;
- After reaching the destination, the guide modular robot remains in place by stopping the external magnetic field.
- Subsequently, the auxiliary modular robot with treatment function enters the digestive tract followed the forward robot.
- When two robots meet each other and the distance between them is short enough, the auxiliary modular robot will dock with the guide modular robot by the force of the two magnets which are magnetized in the axial direction.
- When the auxiliary modular robot completes its mission, it can undock by changing the direction of the rotating magnetic field.

III. THE CONTROL SYSTEM OF MODULAR CAPSULE ROBOT

A. The Driven System of Magnetic Field

The single axis Helmholtz coils system consists of two identically wound layered coils with the same number of turns and enwinding mode, and with a specific geometry wherein the mean radius is equal to the distance between the two coils. When either AC or DC power is fed to a pair of Helmholtz coils, a uniform magnetic field is generated within a certain volume of the Helmholtz coils. Based on this principle, a uniform-magnetic spin vector in a plane which can be also called rotating magnetic field can be created inside two-axis orthogonal Helmholtz coils fed with two phase sine currents with ninety degree phase difference. And in order to produce a stable universal rotating magnetic field, we can use the three-axis Helmholtz coils fed with three phase sine currents. Fig. 4 shows the model of three-axis Helmholtz coils, a rotating uniform magnetic field around normal vector \mathbf{n} is generated by feeding three phase sine currents define by (1) to the three-axis Helmholtz coils separately [7]. Table II shows the specification of three-axis Helmholtz coils used in this paper.

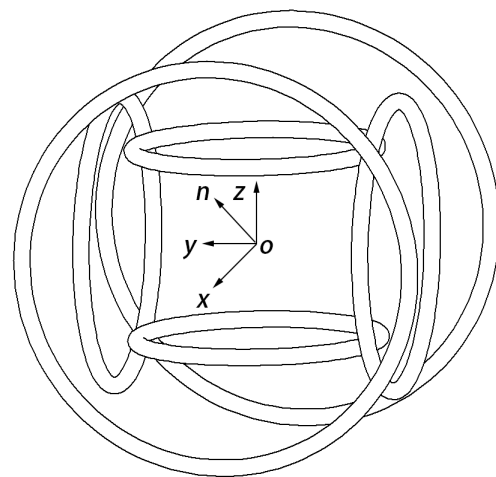


Fig. 4 The model of three-axis Helmholtz coils.

TABLE II
SPECIFICATION OF THREE-AXIS HELMHOLTZ COILS

	Wire Diameter (mm)	Turns Per Coil (times)	Physical Radius(mm)	Resistance(Ω)
X axis	1.8	216	294.3	5.52
Y axis	1.8	174	211.4	3.29
Z axis	1.8	126	157.4	1.86

$$\begin{cases} I_x = -I_0 \sin(\alpha) \sin(\omega t - \phi_x) \\ I_x = -I_0 \sin(\alpha) \sin(\omega t + \phi_y) \\ I_x = -I_0 \sin(\alpha) \sin(\omega t) \end{cases} \quad (1)$$

where $\tan \phi_x = \frac{\cos \beta}{\cos \gamma \cdot \cos \alpha}$; $\tan \phi_y = \frac{\cos \alpha}{\cos \gamma \cdot \cos \beta}$; α, β, γ

are the coordinate angles between the spin vector \mathbf{n} and x -axis, y -axis and z -axis respectively in the orthogonal coordinate system; I_0 is the amplitude of the applied electrical current; ω is the angular speed of the applied electrical current.

B. The Motion Control of Robots

As described in the second part, the permanent magnets in the center of the two robots which magnetized in the radial direction can be driven by the external rotating magnetic field generated by the three-axis Helmholtz coils. And meanwhile, the robots perform a spiral motion which rotation axis was the center axis under the rotation of the magnet. As shown in Fig. 1, the guide modular robot has two helical diversion grooves that the spiral direction is clockwise when the sight is from its head to tail. When it rotates in the liquid and its direction of rotation is counterclockwise, as a result of the reaction force exerted by the liquid flow on its helical guide groove, the guide robot will move forward simultaneously, as shown in Fig. 5.

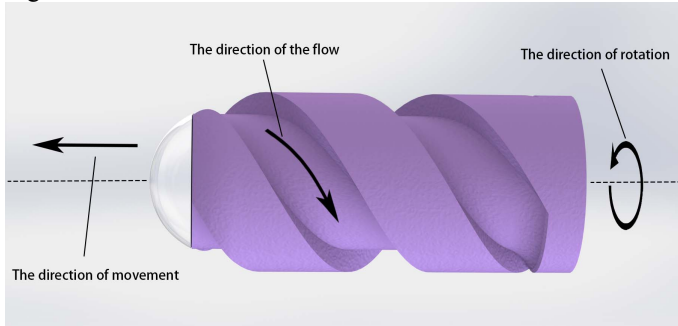


Fig. 5 The rotational motion and axial motion of the guide robot.

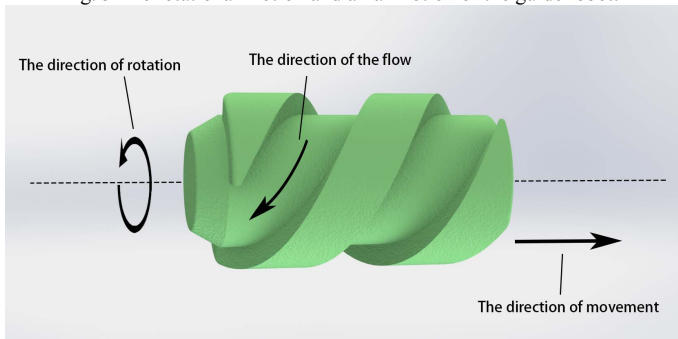


Fig. 6 The rotational motion and axial motion of the auxiliary robot.

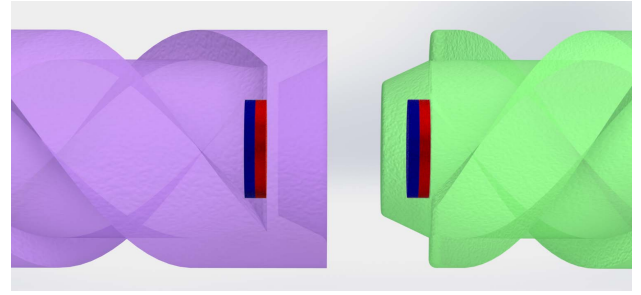


Fig. 7 The docking part of two robots.

Similarly, the performance of the permanent magnet which magnetized in the radial direction of the auxiliary modular robot in the rotating magnetic field is consistent with that of the forward robot. But the spiral direction of helical diversion grooves on it is opposite to the guide robot. It's counterclockwise when the sight is from the robot's head to tail. This leads to the fact that its axial direction is opposite to that of the guide modular robot when they are under the same rotating magnetic field, as shown in Fig. 6.

Based on this principle, the auxiliary robot can follow and meet the guide robot in the same magnetic field. And it can also be separated after the two robots have docked because of the opposite movement of them.

C. Modular Docking Control of Guide and Auxiliary Robot

A tapered groove which tilt angle is 30° is designed in the rear of the guide robot. And with it is the conical bulge which in the front of the auxiliary robot and its tilt angle is also 30° . So these two structures can be fitted with each other. The docking interface can be modularized, and in this case, all of the auxiliary robots can dock with the robots which have the guide robot's docking interface.

In order to make two robots docking and keeping the state, there should be a mechanism to attract two robots together. Fig. 7 describes the mechanism to achieve this purpose. As is shown in this figure, two permanent magnets which are magnetized in the axial direction are placed in the rear of the guide robot and in the front of the auxiliary robot. Therefore, when the distance between them is close enough, the magnetic force generated between the two magnets will attract the two robots together. The size of the magnetic force between the two magnets when they are docked can be altered as long as adjusting the position of the magnets in the robots.

IV. EXPERIMENTS AND RESULTS

A. Movement Experiments

We conducted *in vitro* movement experiments of both guide and auxiliary robot in the transparent straight acrylic pipe which length is 30cm filled with water. The experimental platform is shown in Fig. 8. In this paper, the motion characteristics of the robots were studied on a single axis. Therefore, we only need a rotating magnetic field in a plane which can be generated by the y -axis and z -axis fed with two-phase sine currents with ninety-degree phase difference output by a waveform generator.

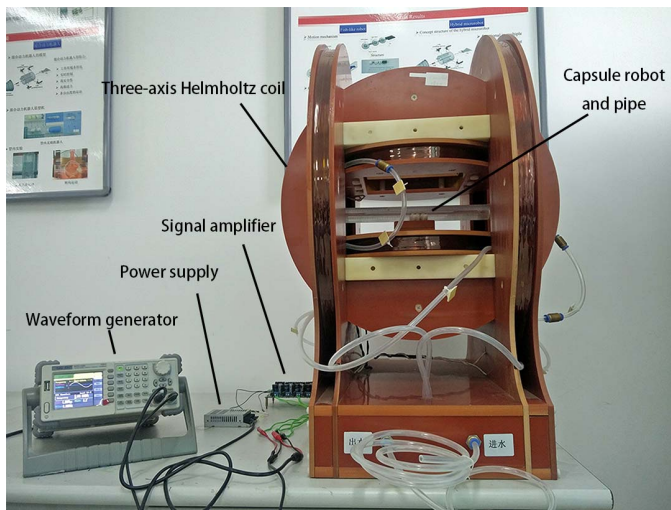
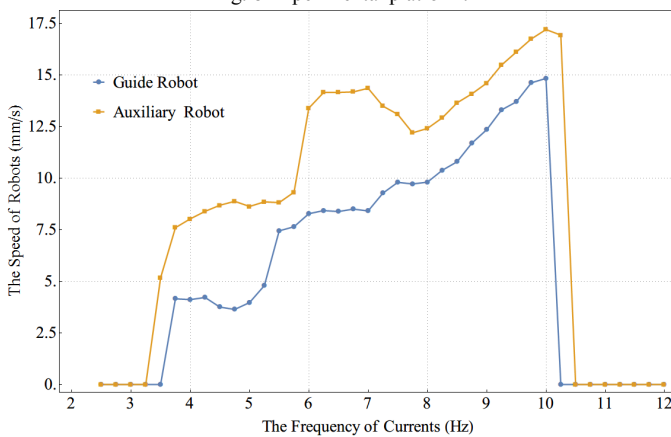
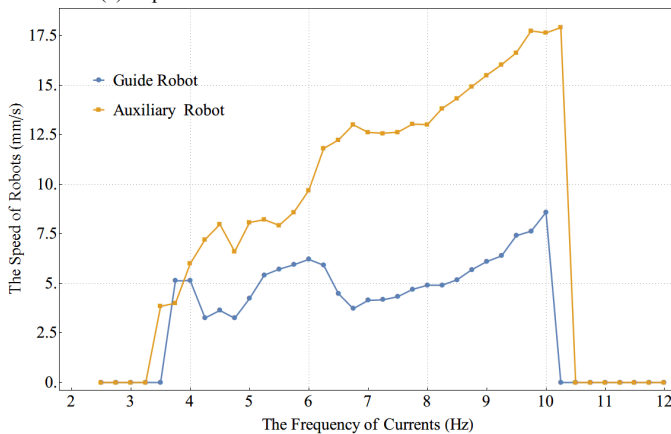


Fig. 8 Experimental platform.



(a) Experimental results when the robots moved forward



(b) Experimental results when the robots moved backward

Fig. 9 The speed of robots as a function of the frequency of currents fed to the coils

The waveform signals also need to be amplified before accessing the coils by the signal amplifier.

The experiments we carried out in this section include two parts which are the forward and backward movement of the guide robot and auxiliary robot, respectively. The movement speeds of the robots was measured every 0.25 Hz from 2.5 Hz to 12 Hz of the frequency of currents. Fig. 9 compares the experimental data of two robots moved forward and backward.

The velocity was increased according to changes in the driving frequency overall. It is obvious that the frequency range at which the guide robot starts moving is smaller than the auxiliary robot. The reason is that the area of the guide robot in contact with the pipe wall is larger than that of the auxiliary robot, which causes the static friction of the guide robot to be greater than that of the auxiliary robot. So the guide robot will be a little harder to start moving than the auxiliary robot. Another point which made us focus on is that the sudden drop of the guide robot's velocity when it was moving backward in 6.5 Hz in Fig. 9 (b). The reason for this fact is that a gap behind the helical diversion grooves on the guide robot shown in Fig. 5, which was actually the modular interface. When the robot was rotating and moving backward, the high-speed rotating gap would block the flow into the grooves and cause insufficient impulse force in high frequency. Therefore, the lack of performance of the guide robot when it moved backward happened.

The driving frequency of 10 and 10.25 Hz produced the maximum velocity of 8.6 mm/s of the guide robot and 17.9 mm/s of the auxiliary robot when they were moving backward, respectively. And the minimum velocity of the guide robot and the auxiliary robot was 4.2 mm/s and 5.7 mm/s in 3.75 Hz and 3.5 Hz. When they moved forward, the maximum velocity is 14.8 mm/s for the guide robot and 17.2 mm/s for the auxiliary robot in the same frequency of 10 Hz. The minimum velocity of the guide robot and the auxiliary robot was 5.1 mm/s and 3.8 mm/s in 3.75 Hz and 3.5 Hz.

B. Rendezvous and Docking Experiments of Robots

Finally, the docking action of the modular structure was verified. At the beginning of the experiment, the two robots were placed on both ends of the pipe, as shown in Fig. 10 (a).

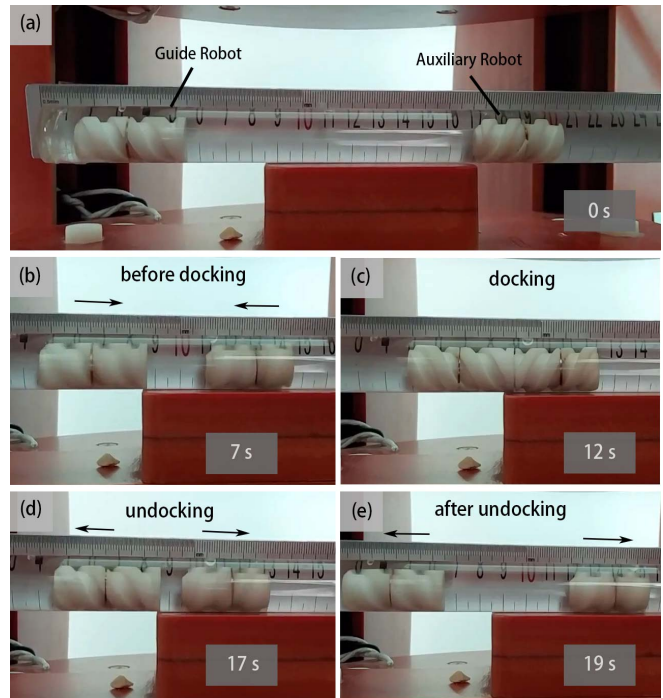


Fig. 10 The snapshots of the rendezvous and docking procedure.

Then two robots moved closer to each other driven by the rotating magnetic field. When they were close enough, the rotating water flow would prevent them from approaching, as shown in Fig. 10 (b). The impulsive force and the magnetic force between themselves describe in section III could overcome the resistance and then successfully dock in Fig. 10 (c). By reversing the direction of the rotating magnetic field, they were able to undock and separated in Fig. 10 (d) and (e). This experiment demonstrated the feasibility that the proposed wireless spiral capsule robot with modular structure could dock and undock in the pipe.

V. CONCLUSIONS

This paper proposed the wireless spiral capsule robot with active locomotion and a new mechanism for docking two robots by the modular docking interface. The 3D Models were designed through the SolidWorks and fabricated by 3D printer. Then the control system of the robot including the driven system, motion control and modular docking of the robots was presented. And the locomotive test for the evaluation of two robots driven by the rotating magnetic field using a three-axis Helmholtz coils system was taken. Finally, the feasibility of the docking action with the modular structure was verified. The experimental results reveal that the velocity of two robots was increased according to changes in the driving frequency. The velocity of the guide robot is lower than that of the auxiliary robot overall because of the bigger static friction caused by the bigger area in contact with the pipe wall. Due to the lack of the impulse force generated by the flow caused by the block of the modular interface, the guide robot's velocity had a sudden drop when it was moving backward in 6.5 Hz. The maximum velocity of the guide robot was about 14.8 mm/s in 10 Hz and minimum velocity was about 5.1 mm/s in 3.75 Hz when it moved forward. In the same forward movement, the maximum and minimum velocity of the auxiliary robot was 17.2 mm/s and 3.8 mm/s in 10 Hz and 3.5 Hz. When they moved backward, the maximum and minimum velocity of the guide robot is 8.6 mm/s and 4.2 mm/s in 10 Hz and 3.75 Hz, and to the auxiliary, it was 17.9 mm/s and 5.7 mm/s in 10.25 Hz and 3.5 Hz. The proposed spiral capsule robot realized the mobility include rotate forward and backward and ability for the docking and undocking action. Consequently, this study can help for future medical applications.

In the future, we will consider enhancing the movement of the robots and adding more additional function for the auxiliary robot.

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