Performance Evaluation of a Magnetic Microrobot Driven by Rotational Magnetic Field

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Abstract – Wireless capsule microrobots have potential to radically accomplish many medical procedures. Various electromagnetic actuation control systems are utilized to realize the motion control of the wireless capsule microrobot. In this paper, a tele-operation system provides telepresence by allowing a doctor to remotely control a wireless capsule microrobot through a master device. Based on a simplified mechanical model, we also analyzed and developed a wireless microrobot. And then we obtained the relationship between the magnetic flux density changing frequency and the moving speed to realize the real time control and flexible motion by experiments. The experimental results appear in a good performance on flexibility.

Index Terms –Wireless microrobot; Rotational magnetic field; 3-axis Helmholtz coils; Tele control system

I. INTRODUCTION

Wireless capsule microrobot is employed in a wide range of biomedical application with MEMS technology. They are both safe reliable and can be carried deeply within the tissue of living organisms to perform tasks [1]-[5]. Many capsule endoscope microrobots have been developed for examining a tubular digestive system. They are used in hard to reach locations of the body and can obviate the need to open and close a surgical field [6]-[8]. A wireless capsule microrobot (M2A) has been developed [9]. The microrobot with a camera inside is swallowed and transmits its images to the external monitor. The doctor can treat the disease in small intestine. Meanwhile, kinds of capsule microrobot which are used in tissues and organs of human body are developed [10]-[14]. But these capsule microrobots are the passive motion by peristalsis and gravity without controlling its position or orientation. To overcome these disadvantages, kinds of researches have been developed to realize flexible control for the microrobot [15]-[20]. Currently, various EMA (electromagnetic actuation) systems are used to drive the microrobot due to its simplicity. For example, Honda developed a wireless microrobot with a tail fin which can only move in one direction [21]. Thomas W. R. proposed magnetic helical microrobot which is driven by a non-uniform magnetic fields emanating from a single rotating-permanent-magnet (RPM) manipulator [22]. Sehyuk Yim also proposed a magnetically actuated soft capsule endoscope (MASCE) as a miniature mobile robot platform for diagnostics in medical application [23]. Khamese designed a microrobotic system [24].

In our research, different kinds of wireless microrobot have been developed by driven EMA system. For example, a fish-like microrobot with a tail is driven by a uniform oscillating magnetic field which is proved the energy of the forward motion and backward motion [25]-[27]. In this paper, a tele-operation EMA control system has been proposed to realize the energy supply by wireless and flexibility movement. To realize the position and posture control, we build a simplified mechanical model for our proposed wireless microrobot and analyzed. We obtained the relationship between the magnetic flux density changing frequency and the moving speed by experiments. Finally, using the relationships, the operator can view a monitor and control the wireless microrobot to realize flexible motion in the pipe.

This paper is organized as follows. Firstly, we introduce the tele-operation EMA control system. Secondly, we build a simplified mechanical model for the wireless microrobot and explain its movement mechanism. Thirdly, we introduce the rotational magnetic fields for driving the wireless microrobot and evaluate the performance. Fourth, the experiments and results are discussed. The final part of the paper presents our conclusions.

II. WHOLE CONTROL SYSTEM

A. Whole control system

In previous research, we have been developed several control system for controlling the microrobot to achieve the flexible motion in the pipe, as shown in Fig.1. Fig. 1 (a) shows electromagnetic actuation system composed of solenoid coil, which is used to control the fish-like type magnetic actuated microrobot by a MTX sensor. This type of microrobot realized the forward motion with the shape of the solenoid coil. But it has a problem that the path of the movement is limited due to the shape of the solenoid coils. Fig. 1 (b) shows electromagnetic actuation system composed of electromagnet. The movement path of microrobot is not limited, but the movement of the microrobot is unstable due to the electromagnet is asymmetric. Therefore, we proposed a novel electromagnetic actuation system composed of a
A. Console for manipulating the microrobot in the pipe, a controller for generating the signals to realize the speed control and direction control, and 3-axis Helmholtz coil which is generated the external magnetic field for stable movement, as shown in Fig. 2.

B. 3-axis Helmholtz coil

Generally, the wireless microrobot is driven by the external magnetic fields, which is generated by Maxwell coils or Helmholtz coils. In our research, the 3-axis Helmholtz coils are used to generate a rotational magnetic field to control the wireless spiral microrobot. 3-axis Helmholtz coils can make the robot move in the three dimensional space.

C. Rotational Magnetic Fields

The propulsive force and torque are supplied by rotating the wireless microrobot. When either an alternating magnetic field or a rotational magnetic field is applied in the plane normal to the axis of the spiral, the magnet rotates due to magnetic torque \( T \). The magnetic torque acting on the o-ring magnet in the external magnetic field of the 3-axis Helmholtz coils is given by the equation (1):

\[
T = VM \times B
\]  

Where, \( M \) is the average magnetization of the internal magnet and \( V \) is the volume of the internal magnet. \( B \) is magnetic flux density.

The 3-axis Helmholtz coil generates uniformed rotational magnetic field in any direction. The magnetic direction and magnetic flux density can be assigned as equations (2) (3) (4):

\[
B_x(t) = a_x \frac{r_x}{n_x} I_x \cos(\alpha \alpha) \cos \alpha
\]

\[
B_y(t) = a_y \frac{r_y}{n_y} I_y \cos(\alpha \beta) \cos \beta
\]

\[
B_z(t) = a_z \frac{r_z}{n_z} I_z \cos(\alpha \gamma) \cos \gamma
\]

Where, \( B_x(t) \), \( B_y(t) \) and \( B_z(t) \) denote the magnetic flux density of x-axis, y-axis and z-axis. \( \alpha \), \( \beta \) and \( \gamma \) denote an angle between the magnetic flux density and x-axis, y-axis, z-axis. \( a_x \), \( a_y \), and \( a_z \) is a constant.

Based on the theory above, the magnetic flux density of the 3-axis Helmholtz coils is analysed to realize control stable locomotion of the wireless microrobot. The results as shown in Fig. 3 proved that our designed 3-axis Helmholtz coils is effective and can obtain stable motion by generating the uniformed magnetic field.

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**Fig. 1** Whole control system (a) fish-like type magnetic microrobot driven by solenoid coil (b) Spiral type magnetic microrobot driven by electromagnet

**Fig. 2** Whole control system composed of a 3-axis Helmholtz coil
Several magnetic actuated microrobots have been developed [4] [27]. In this paper we used the spiral microrobot to evaluate the performance of the electromagnetic actuation system. The spiral microrobot is shown in Fig. 4. The wireless microrobot comprises two main parts, a spiral outer shell and an o-ring type magnet as an actuator. The spiral outer shell is made of polythene plastic. The spiral outer shell and the o-ring type magnet are connected by a strong adhesive. The o-ring type magnet is fitted inside the wireless microrobot. Specifications of the o-ring magnet and wireless microrobot are shown in Table I and Table II.

### III. WIRELESS SPIRAL MICROROBOT

![Fig. 3 Simulation results of the magnetic flux density and direction](image)

Fig. 3 Simulation results of the magnetic flux density and direction

### IV. EXPERIMENTS AND RESULTS

#### A. Experimental setup

![Fig. 4 Prototype of the wireless spiral microrobot](image)

![Fig. 4 Prototype of the wireless spiral microrobot](image)

**Table I**

<table>
<thead>
<tr>
<th>Specifications of the o-ring type magnet</th>
</tr>
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<tbody>
<tr>
<td>Outer diameter</td>
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<tr>
<td>Internal diameter</td>
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<tr>
<td>Height</td>
</tr>
<tr>
<td>Magnetic field</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Magnetization direction</td>
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**Table II**

<table>
<thead>
<tr>
<th>Specifications of wireless microrobot</th>
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<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Radial</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Material of the body</td>
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</tbody>
</table>

![Fig. 5 Experimental setup using the Phantom Omni](image)

![Fig. 6 Flow chart of the control instructions](image)

**Fig. 5 Experimental setup using the Phantom Omni**

**Fig. 6 Flow chart of the control instructions**

![Fig. 7 Experimental setup](image)

**Fig. 7 Experimental setup**

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878
A tele-operation control system has been developed to realize real time control for our wireless microrobot, as shown in Fig. 5. The flow chart of the control instructions for tele-operation control system is shown in Fig. 6.

B. Experiments and results

In this experiment, the Phantom Omni device is used to generate control instructions which are transmitted to 3-axis Helmholtz coil, which produces a frequency of the magnetic flux density to control movement of the wireless microrobot in the pipe. By adjusting the rotational angle of the handle from 0 degree to 90 degree, wireless microrobot achieves accelerated motion. By adjusting the rotational angle of the handle from 90 degree to 0 degree, wireless microrobot can achieve speed reduction motion. When the rotational angle of the handle is 0 degree, wireless microrobot achieves stop motion in the pipe. The Fig.7 shows the experimental results with Phantom Omni device.

![Fig. 7 Forward motion](image)

(a) $t=1s$, (b) $t=3s$, (c) $t=7s$, (d) $t=10s$

Fig. 7 Forward motion

![Fig. 8 Rotational motion](image)

(a) $\alpha=0^\circ, \beta=90^\circ, \gamma=0^\circ$, (b) $\alpha=45^\circ, \beta=45^\circ, \gamma=0^\circ$, (c) $\alpha=90^\circ, \beta=0^\circ, \gamma=0^\circ$, (d) $\alpha=180^\circ, \beta=90^\circ, \gamma=0^\circ$

Fig. 8 Rotational motion. The red line means the rotational direction of the microrobot

Experiments of rotational motion are shown in Fig. 8. The results indicated the wireless microrobot can realize flexible motion by controlling the external rotational magnetic fields using our proposed tele-operation control EMA system. We also realized the combinatorial motion, forward motion-turning motion-forward motion. Experiments results are shown in Fig. 9 and Fig. 10.

![Fig. 9 Measurement results with different rotational angle](image)

![Fig. 10 Relationship between the rotational angle and the time](image)

V. CONCLUSIONS

In this paper, a tele-operation EMA control system for our proposed wireless spiral microrobot has been developed to realize telepresence by allowing a doctor to remotely control through a Phantom Omni device. This causes less pain to the patients and there will be less tissue trauma. Thus reducing hospitalization time and enhancing recovery. Based on the previous study, especially we learned from the features of the magnetic flux density in Helmholtz coil. Then, we designed EMA system and analyzed the mechanism of the wireless microrobot. Secondly, we evaluated the characteristics of the tele-operation control system. At last, we realized the tele-operation control for our proposed wireless microrobot. By adjusting the angle of the handle, the wireless microrobot achieves flexible motion. The experimental results showed a good performance on flexibility.

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