Enhanced locomotive and drilling microrobot using precessional and gradient magnetic field

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**Abstract**

We propose a new electromagnetic actuation (EMA) system for an intravascular microrobot with steering, locomotion and drilling functions. The EMA system consists of 3 pairs of Helmholtz coil and 1 pair of Maxwell coil. Generally, Helmholtz coils can align a microrobot in a desired direction by generating a uniform magnetic flux. If the uniform magnetic field generated by Helmholtz coils can be rotated, a microrobot with Helmholtz coils can also be rotated. On the other hand, a Maxwell coil, which generates a constant gradient magnetic flux, can supply the propulsion force for the microrobot. A microrobot actuated by the proposed EMA system has a spiral shaped body containing two magnets with different magnetization directions. With the proposed EMA system, the microrobot can move to the target region and perform drilling there by the precessional magnetic field of the Helmholtz coil pairs. The propulsion force for the microrobot is produced by the gradient magnetic field generated by the Maxwell coil pair. The moving velocity and the drilling performance of the microrobot can be increased by the propulsion force of the Maxwell coil pair. Through various tests, the feasibility and enhancement of the microrobot actuated by the proposed EMA system were verified.

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1. Introduction

Recently, vascular diseases in people have been on the rise owing to fatty food consumption and lack of exercise [1,2]. Especially, the mortality rate by coronary artery diseases has been increasing. Coronary arteries are important vessels that supply nutrients to the heart. Generally, the treatments for blood vessel related diseases are roughly divided into drug therapy, coronary artery bypass graft (CABG), and catheterization. Drug therapy is used for thrombolysis or blood clot restraint in the vessel. In CABG, an additional artery connection is made by graft, bypassing the blocked coronary arteries. However, because CABG operation is performed as laparotomy, the procedure of CABG is very difficult and requires a long patient recovery time. Finally, compared with CABG, catheterization is a relatively simple, minimally invasive operation and has a short patient recovery time. However, surgeons must exercise a skillful technique to penetrate the chronic total occlusion (CTO) in the blood vessels, and catheterization has some limitations in CTO treatments [3].

In this paper, a wirelessly driven intravascular microrobot was developed to overcome the weaknesses in the existing cardiovascular surgical methods [4]. Generally, an intravascular microrobot might consist of treatment tools, a sensing module and an actuation part. However, due to the size limitation of the microrobot, the actuation part with the power source is hard to integrate in the robot’s body [5,6]. Therefore, the actuation of the microrobot is performed by an external electromagnetic field.

Recently, several wireless microrobots actuated by an external electromagnetic field were proposed. B.J. Nelson suggested a ferromagnetic microrobot that could perform the locomotion function in a 2-dimensional plane, controlled by a pair of Helmholtz and Maxwell coils and a motorized rotating axis of the coil pair [7]. However, the rotation of the EMA coil system could be a serious limitation for medical application. We also proposed a 2-dimensional locomotive microrobot using an EMA system with two pairs of Helmholtz coils and two pairs of Maxwell coils [8]. In addition, for the reduction of system volume and power consumption, we suggested another modified EMA system consisting of two pairs of Helmholtz coils and only one pair of Maxwell coils [9]. The locomotion of these microrobots was made possible by using these EMA systems. However, the drilling motion of the microrobot was not mentioned. K.I. Arai developed a microrobot using an EMA system using 3 pairs of Helmholtz coils. The locomotion of the microrobot synchronizes with the drilling. The microrobot could rotate about its axis by the rotational magnetic field generated by the Helmholtz coil pairs. Because the microrobot has a spiral shape body, the rotation of the microrobot generates thrusting force and locomotion. When the microrobot reaches a blocked vessel, the microrobot can drill the blockage [10,11].
In this paper, we propose an enhanced EMA system for the improvement of the locomotion and drilling performances of a microrobot in 2-dimensional space. The proposed EMA system consists of 3 pairs of Helmholz coils and 1 pair of Maxwell coils. In addition, the microrobot in our study also has a different structure from the above-mentioned microrobots, having a spiral shape body and consisting of two magnets with different magnetization directions. For actuation, an actuation algorithm is formulated for fusion of the precessional magnetic field and the gradient magnetic field. Finally, through various experiments, we evaluate the enhancement of locomotive and drilling performances achieved by the proposed EMA system and show the feasibility of the microrobot using the proposed EMA system for medical application.

2. Basic electromagnetic theory

A pair of Helmholz coils generates a uniform magnetic field, generally consisting of two identical circular magnetic coils, where the radius \( r \) of the coil is equal to the distance \( d \) between the coils [12]. In addition, the currents in these coil flows in the same direction and have the same intensity. However, in this paper, we introduce Helmholz coils of a square shape, where the width \( w \) and the distance \( d \) of the square Helmholz coils are related by \( w = 1.089 d \) [13]. Similar to circular Helmholz coils, the currents of the square Helmholz coils flow in the same direction and have the same intensity. Compared with circular Helmholz coils, square Helmholz coils have a large region of interest (ROI) and a large working space. Pairs of Helmholz coils can generate a uniform magnetic field in a desired direction to align the microrobot in that desired direction. That is, when a microrobot is not aligned in a desired direction, a torque \( \tau \) is generated by Helmholz coil pairs to align the microrobot, as follows:

\[
\tau = VM \times B
\]  

(1)

where \( V \) and \( M \) denote the volume and magnetization of the microrobot and \( B \) means the magnetic flux.

A pair of Maxwell coils generates a constant gradient magnetic field, generally consisting of two identical circular magnetic coils related by \( d = \sqrt{3} r \), where \( r \) and \( d \) denote the radius of the coil and the distance between the coils, respectively [14]. Unlike the currents of Helmholz coils, the currents of Maxwell coils have the same intensity, but they flow in opposite directions. Generally, the constant gradient magnetic field generated by Maxwell coils supplies propulsion force to a microrobot in the axial direction and the perpendicular direction. The propulsion force \( F \) can be described as:

\[
F = V(M \cdot \nabla)B
\]  

(2)

where \( \nabla \) is a gradient operator.

A microrobot can be aligned in a desired direction and its locomotion is governed by Eq. (2). Therefore, when a pair of Maxwell coils is placed in the \( z \)-axis, the propulsion forces \( F_x \), \( F_y \), and \( F_z \) [9,15] of the microrobot exerted by the Maxwell coil can be described as:

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix}
= \begin{bmatrix}
0.5M_{gx} \\
0.5M_{gy} \\
M_{gz}
\end{bmatrix}
\]  

(3)

where \( M_{gx}, M_{gy}, \) and \( M_{gz} \) denote the directional magnetizations of the microrobot and \( g_x \) is the gradient of the magnetic field generated by the \( z \)-axis Maxwell coils. From Eq. (3), in \( x-y \) plane, the propulsion force of a microrobot can be generated by using the \( z \)-axis Maxwell coils.

3. Combination of precessional magnetic field and gradient magnetic field

3.1. Configuration of EMA system and microrobot

The configuration of the proposed EMA system is shown Fig. 1. Fig. 1(a) means the schematic diagram of the proposed EMA coil system with the current direction and the magnetic field map generated by the Maxwell coil pair. The three pairs of square shaped Helmholz coils are placed in the \( x \)- \( (H_x) \), \( y \)- \( (H_y) \), and \( z \)-axis \( (H_z) \). In addition, one pair of circular shaped Maxwell coil pair is placed in the \( z \)-axis \( (M_z) \). When the proposed EMA system is applied as medical equipment, it has a cylindrical working space in Fig. 1(b). In addition, for clinical application, an enlarged model of the EMA system should be developed.

The Helmholz coil pairs generate the rotational magnetic field using sine wave currents. For rotational motion in the axial direction of the microrobot, the generated rotating magnetic field should coincide with the magnetization direction of the microrobot. The direction of the generated propulsion is also determined by the magnetization direction of the microrobot. As shown in Eq. (3), the Maxwell coil pair in the \( z \)-axis generates the propulsion force of the microrobot in the \( x \)-, \( y \)-, and \( z \)-axis directions. However, because the microrobot is rotated at a high velocity and moved inside a vessel in the \( x-y \) plane, we neglect the \( z \)-axis force and only consider the generated force in the \( x-y \) plane for the actuation of the microrobot.

As shown in Fig. 2, the magnetization direction \( (\theta) \) of the microrobot is determined by the arrangement of the permanent magnets inside the microrobot. Fig. 2(a) shows the magnetization direction of \( \theta = 90 \). When the rotating magnetic field about the \( x \)-axis is generated by the three pairs of Helmholz coils, the spiral shaped microrobot moves along the \( x \)-axis. Fig. 2(b) shows the magnetization direction \( \theta = 0 \). The microrobot was driven by the propulsion force from the pair of Maxwell coils. In Fig. 2(c), the magnetization of the microrobot could be the combined structures of Fig. 2(a) and (b). Consequently, based on the vector sum of the magnetization directions of the different magnets (Fig. 2(a) and (b)), the magnetization direction of the microrobot was approximately regarded as about \( \theta = 45 \). For the verification of the magnetization direction of the microrobot, the two pairs of Helmholz coils in \( x \)- and \( y \)-axis were used. Firstly, when the two pairs of Helmholz coils generate the same uniform magnetic fields, the microrobot was aligned with the \( x \)-axis direction. Secondly, when the \( x \)-axis Helmholz coils generates the uniform magnetic field, the aligned direction of the microrobot is about \( 45 \). Therefore, we confirmed that the magnetization direction of the microrobot could be regarded as about \( \theta = 43-47 \).

3.2. Rotational precessional magnetic field

As shown in Fig. 2(c), the magnetization direction of the microrobot was about \( \theta = 45 \). To move the microrobot with a spiral shape in the desired locomotion direction \( (\alpha) \) in the magnetization direction \( (\theta) \), a rotational precessional magnetic field is necessary. Fig. 3 shows the precessional magnetic field and the locomotion of the microrobot with spiral shape. Fig. 3(a) shows the case of \( \theta = 45 \), \( \alpha = 0 \) and Fig. 3(b) the case of \( \theta = 45 \), \( \alpha = 30 \).

For the locomotion of the microrobot in two-dimensional space, a rotational precessional magnetic field should be generated. That is, the currents of the Helmholz coil pairs should be determined as:

\[
l_x = \frac{[m \cos(\theta + \alpha) + m \cos(\theta - \alpha)]}{2} - \frac{[m \cos(\theta + \alpha) - m \cos(\theta - \alpha)] \cos \omega t}{2}
\]  

(4)
\( I_y = \frac{m \sin(\theta + \alpha) - m \sin(\theta - \alpha)}{2} \)
\( + \frac{m \sin(\theta + \alpha) + m \sin(\theta - \alpha) \cos \omega t}{2} \)
\( I_z = m \sin \theta \sin \omega t \)

where \( I_x, I_y, \) and \( I_z \) denote the current values of \( x-, y-, \) and \( z- \) axis Helmholtz coil pairs, respectively. In addition, \( m \) and \( \omega \) denote the magnitude of the Helmholtz coils current and the angular velocity, respectively.

3.3. Constant gradient magnetic field

With the proposed EMA system, the microrobot can be supplied additionally with propulsion force by the \( z- \) axis Maxwell coils.
pair. Based on Eqs. (4)-(6), the rotating precessional magnetic field rotates the microrobot about the axial direction. Because the microrobot rotates about the axial direction, the magnetization direction of the microrobot could change with the rotating precessional form in Fig. 3. If the rotational speed of the microrobot was fast, it is regarded that the magnetization direction of the microrobot is same as the axial direction. Therefore, when the constant gradient magnetic field was generated by the z-axis Maxwell coils pair, the propulsion force of the microrobot can be generated along the axial direction. In addition, when the microrobot is aligned in a desired direction and rotated about a desired axis in the x-y plane, the propulsion force of the microrobot is given by Eq. (3). Therefore, it is expected that this additional propulsion force can enhance the moving velocity and the drilling performance of the microrobot.

4. Fabrications of EMA coil system and microrobot

4.1. Design and fabrication of EMA coil system

The specification of our fabricated EMA system is described in Table 1. In this table, $H_x, H_y$, and $H_z$ denote the x-, y-, and z-axis Helmholtz coils, respectively. And $M_z$ denotes the z-axis Maxwell coils. Fig. 4 shows the 3D modeling of the proposed EMA coil system. Based on the specification of Table 1 and the system configuration of Fig. 4, the proposed EMA system was designed and fabricated, as shown in Fig. 5. The square shaped Helmholtz coil pairs were positioned in the x-, y-, and z-axis and the circular shaped Maxwell coil pairs were positioned in the z-axis. Compared with circular shaped Helmholtz coil pairs, square shaped Helmholtz coil pairs realized a larger inner space. Therefore, for medical applications, square shaped Helmholtz coil pairs can offer a valuable advantage since the EMA system needs to have sufficiently large inner space to accommodate the patient body [12]. In addition, considering the non-magnetization and heat emission from the ohmic resistance of the coils, the structure of the EMA system was made of aluminum.

4.2. Design and fabrication of microrobot

In order for the microrobot to effectively perform its locomotion and drilling with the proposed EMA system, the microrobot should be spiral shaped and have two magnets with different magnetization directions. Fig. 6 shows the modeling and fabrication of the microrobot. Fig. 6(a) shows the body design of the microrobot and Fig. 6(b) shows the structural design of the microrobot. The microrobot’s body, fabricated by rapid prototype (RP) machining, had empty inner space for the insertion of the two permanent magnets with 5 mm of length and 1 mm of diameter. Fig. 6(c) shows the fabricated microrobot with a diameter of 2.7 mm, spiral height of 0.7 mm, and total length of 20 mm. The purpose of this study is to verify the feasibility of the proposed microrobot using precessional and gradient magnetic fields. Therefore, the optimization of the shape of the microrobot was not considered. As the permanent magnets, two cylindrical neodymium magnets were used, where one magnet had an axial magnetization direction and the other magnet had a diagonal magnetization direction.

5. Experiments

5.1. Experimental setup

Fig. 7 shows the overall experimental setup of the EMA control system. The overall EMA system consists of (a) a joystick (Saitek

| Table 1 | Specification of EMA system. |
|---|---|---|---|---|
| Coils | $H_x$ | $H_y$ | $H_z$ | $M_z$ |
| Width (mm) | 250 | 180 | 130 | N/A |
| Distance (mm) | 272.25 | 196.02 | 141.57 | 147 |
| Radius (mm) | N/A | N/A | N/A | 85 |
| Diameter of copper wire (mm) | 2.0 | 1.8 | 1.5 | 1.5 |
| Coil turns | 577 | 415 | 300 | 290 |
Flight Throttle Quadrant, Logitech Extreme 3D pro) for control of current, frequency, steering and locomotion of the microrobot, (b) a PXI controller (National Instruments), (c) an EMA coil system and (d) power suppliers (Agilent 6675A, California Instruments MX15 & 3001iX).

In Section 3.1, we mentioned that the magnetization direction of the microrobot is approximately \( \theta = 45^\circ \). Because of the arrangement of the magnets and the fabrication error of the microrobot, the magnetization direction is not exactly \( \theta = 45^\circ \) and an undesirable oscillation motion of the microrobot can be observed. Therefore, for the precise experiment, the oscillation motion of the microrobot by the magnetization direction error can be compensated by the current tuning of EMA coil system.

5.2. 1-Dimensional locomotion test

First, we tried to verify the relation between the locomotive performance and the propulsion force generated by the Maxwell coil pair. For the verification test, the microrobot was inserted into a straight acrylic pipe which was filled with water. In the acrylic pipe, we measured the moving velocity of the microrobot as the current of the Maxwell coil pair was changed. In detail, to generate the rotational, precessional magnetic field, the current of the Helmholtz coil pairs was set to 10 A and the frequency was maintained constant at 20 Hz. To generate the propulsion force, the current of the Maxwell coil pair was increased from 0 A to 8 A. When the current of the Maxwell coil pair was 0 A, there was no gradient magnetic field by the Maxwell coil pair, and only the precessional magnetic field generated by the Helmholtz coil pairs made the microrobot rotate. The gradient of the magnetic field generated by the Maxwell coil pair increased in proportion to the applied current of the Maxwell coil pair. When the Maxwell coil pair was supplied with current of 1 A, a gradient magnetic field of 0.05 T/m was generated, which enhanced the locomotive and drilling performance of the microrobot [16]. In addition, when the microrobot is aligned with x-axis direction, the propulsion force of the microrobot by the x-axis gradient magnetic field by z-axis Maxwell coil pair could be calculated by Eq. (2) and summarized as Table 2.

The test was repeated ten times for all cases, and the experimental results were analyzed. Especially, the velocity and the drill duration of the microrobot could be calculated by the frame counting of the experimental movie file. Fig. 8 shows the summary of the experimental results, such as the mean value and the standard deviation of the locomotion velocity of the microrobot. As the current of the Maxwell coil pair increases, the moving velocity of the microrobot also increases. Therefore, the propulsion force generated by the Maxwell coil pair increased the moving velocity of the microrobot.

5.3. Drilling test

To evaluate the efficiency of the propulsion force by the Maxwell coil pair, drilling tests using the microrobot were executed. An acrylic pipe with a 0.2% agar blocked region was used for the drilling test, and the drilling durations were measured to evaluate the propulsion efficiency of the microrobot. At the end part
of the acrylic pipe (a model of blood vessel), a blockage was constructed with 0.2% agar of 1.35 kPa in hardness [17]. In addition, for the Helmholtz coil pairs, we used the same current (10 A) and the same frequency (20 Hz) as before, but changed the current of the Maxwell coil pair from 0 A to 8 A.

Fig. 9 shows the drilling experimental results of the microrobot. Fig. 9(a) and (b) shows the drilling performances of the microrobot during the time with and without the propulsion force by the Maxwell coil pair, respectively. The drilling performance of the microrobot was expected to be enhanced by the propulsion force of the Maxwell coil pair. As shown in the experimental results, the propulsion force enhanced the initial breakage of the agar surface for the insertion of the microrobot. However, after the initial insertion of the microrobot through the agar region, the drilling performance deteriorated seriously. In this case, the propulsion force of Maxwell coil pair might have enhanced the initial penetration of the microrobot into the agar surface. However, when the microrobot goes through into the agar blocked region, the contact surface between the microrobot and the agar could increase. In addition, the propulsion force by Maxwell coil pair induces the pushing force of the microrobot and the friction force between the microrobot and the agar block could increase and decrease the drilling performance, as shown in Fig. 9(b).

Therefore, we modified the drilling experiment such that the propulsion force by the Maxwell coil pair is applied only at the start of drilling. Fig. 9(c) shows the experimental results of the modified method. Initially, the microrobot quickly broke into the agar surface and inserted itself in the agar region by the propulsion force. After the microrobot inserted into the agar surface, it easily penetrated the agar blocked region without the propulsion force. In summary, the microrobot totally without the propulsion force by the Maxwell coil pair took about 60 s to drill into the agar block. However, the microrobot with the propulsion force was not able to drill into the agar block up to 100 s. However, the microrobot with the modified method took about 35 s to drill into the agar block.

Fig. 9. Drilling performance of microrobot.
Consequently, the modified method was verified to give the best drilling performance.

5.4. 2-Dimensional locomotion and drilling test

For the 2-dimensional locomotion and drilling test of the microrobot, a blood vessel phantom, which was fabricated by using RP machining, was introduced. The phantom is miniaturized model from the aorta to the femoral artery and the internal diameters of the vascular model are about 5–8 mm. In addition, the blood vessel of the phantom was filled with a mixture of water and glycerin at a ratio of 6–4 to simulate human blood and its viscosity.

Fig. 10 shows the path of the microrobot in the phantom and the experimental results of locomotion and drilling. Through the 2-dimensional locomotion and drilling test, the performance and the feasibility of the microrobot using the proposed EMA system were verified.

6. Conclusion

For the 2-dimensional actuation of a microrobot, an EMA system consisting of three square shaped Helmholtz coil pairs and one circular shaped Maxwell coil pair was proposed. The microrobot had a spiral shaped body and included two magnets with different magnetization directions. The Helmholtz coil pairs generated the rotating precessional magnetic fields, which yielded the locomotion and the drilling motion of the microrobot. The Maxwell coil pair generated the propulsion force of the microrobot, which enhanced the locomotive velocity and the drilling performance. Through the locomotion test and the drilling test of the microrobot in a 1-dimensional acrylic pipe, the performances of the microrobot using the proposed EMA system were evaluated. Finally, from the test in a blood vessel phantom, the medical feasibility of the microrobot using proposed EMA system was validated. Consequently, the results from this study will be used in the development of the fundamental technology of an intravascular therapeutic microrobot for removal of CTO and thrombus.

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Appendix A. Supplementary data

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