Novel electromagnetic actuation system for three-dimensional locomotion and drilling of intravascular microrobot

Chungseon Yu, Juhyun Kim, Hyunchul Choi, Jongho Choi, Semi Jeong, Kyoungrae Cha, Jong-oh Park*, Sukho Park*

Dept. of Mechanical Engineering, Chonnam National University, 300, Yongbong-dong, Buk-gu, Gwangju 500-757, Republic of Korea

ARTICLE INFO

Article history:
Received 29 January 2010
Received in revised form 4 April 2010
Accepted 20 April 2010
Available online 7 May 2010

Keywords:
Microrobot
Electromagnetic
Helmholtz coil
Maxwell coil
Drilling
3D locomotion
Coronary artery occlusion

ABSTRACT

Various types of actuation methods for microrobots have been proposed. Among the actuation methods, electromagnetic based actuation (EMA) has been considered a promising actuation mechanism. In this paper, a new EMA system for three-dimensional (3D) locomotion and drilling of the microrobot is proposed. The proposed system consists of four fixed coil pairs and one rotating coil pair. In detail, the coil system has three pairs of stationary Helmholtz coil, a pair of stationary Maxwell coil and a pair of rotating Maxwell coil. The Helmholtz coil pairs can magnetize and align the microrobot to the desired direction and the two pairs of Maxwell coil can generate the propulsion force of the microrobot. In addition, the Helmholtz coil pairs can rotate the microrobot about a desired axis. The rotation of the microrobot is a drilling action through an occlusion in a vessel. Through various experiments, the 3D locomotion and drilling of the microrobot by using the proposed EMA system are demonstrated. Compared with other EMA systems, the proposed system can provide the advantages of consecutive locomotion and drilling of the microrobot.

1. Introduction

Modern people suffer from cardiovascular diseases due to lack of exercise and aging. The coronary arteries, which supply the heart with nutrients, are especially important vessels. Abnormal coronary arteries surround the heart causes cardioplegia and increase of death rate [1,2]. For treatment of coronary arterial diseases (CAD), drug therapy, coronary artery bypass graft (CABG) and catheterization are used.

Generally, drug therapy is restrictively used for dissolution and inhibition of thrombus growth in the coronary artery. And CABG, which makes a detour artificial vessel around the blocked vessel in the coronary artery, is a serious surgical operation and requires a long recovery time for the patient. Finally, catheterization, which is a comparatively simpler surgical operation than the CABG procedure, is widely performed. However, the catheter-based treatment of chronic total occlusion (CTO) in the coronary artery is limited by the delicate nature of the operation [3].

Meanwhile, to treat injuries like a thrombus and an occlusion in coronary arteries, the use of an intravascular microrobot in the blood vessel is planned. The intravascular microrobot consists of three parts: an actuation part, sensing part and treatment tool part. However, it is very difficult to integrate the actuator into the microrobot because of the small size and volume of the microrobot [4]. To solve this problem, an electromagnetic based actuation (EMA) system that can manipulate the position of the microrobot using an electromagnetic field is investigated.

Recently, there has been extensive research on MEMS and robot technologies. On research investigated the use of an electromagnetic field to provide the locomotive force for the microrobot [5]. Nelson reported the planar movement of a ferromagnetic microrobot using Helmholtz and Maxwell coil pairs, which can be rotated by a motor [6]. The rotation of the Helmholtz coil pairs can generate a torque to rotate the ferromagnetic microrobot, and the Maxwell coil pairs can generate the propulsion force for the microrobot in an axial direction; consequently, the microrobot can move in the 2D plane. He also proposed a microrobot that mimicked the locomotion of bacteria flagella [7]. The spiral type microrobot is rotated by an external rotational magnetic flux, and the rotation generates the propulsion force. However, the propulsion force produced by rotation is very small and cannot overcome the force of blood flow. Arai proposed an EMA system consisting of three Helmholtz coil pairs and showed the actuation of a spiral type microrobot [8]. Similarly, the propulsion force produced the rotational electromagnetic field was very weak against the force of blood flow.

Previous studies proposed an EMA system using two stationary coil pairs to produce the locomotion of a cylinder shape ferromag-
microrobot in 2D plane [9]. This EMA system consisted of two pairs of stationary Helmholtz coils and Maxwell coils in the x and y directions. In addition, another EMA system consisting of a pair of stationary Helmholtz and Maxwell coils about the central x-axis was proposed and the 3D locomotion of the microrobot using this EMA system was demonstrated [10]. The above EMA systems are limited to the locomotion of an intravascular microrobot.

This paper proposes a new EMA system for the 3D locomotion and drilling of a microrobot. The coil system consists of three pairs of stationary Helmholtz coils, a pair of stationary Maxwell coils and a pair of rotating Maxwell coils. In addition, the spherical microrobot including a cylinder magnet with rough bumps on the surface is designed and fabricated. The proposed EMA system propels and rotates the microrobot, and the rotation of the microrobot results in the drilling through the occlusion part. Through various experiments, the 3D locomotion and drilling of the microrobot using the proposed EMA system are demonstrated.

### 2. Actuation mechanism of EMA system

#### 2.1. Coil configuration

For the 3D locomotion and drilling of a microrobot, an EMA system was designed. Fig. 1 shows a schematic diagram of the proposed EMA system. In the region of interest (ROI), three pairs of Helmholtz coils magnetize and align the microrobot in the desired direction and the two pairs of Maxwell coils propel the microrobot to the aligned direction. In addition, the three pairs of Helmholtz coils generate a rotational magnetic field and rotate the microrobot. Generally, the radius of the Helmholtz coils is equal to the distance between the coils. Similarly, the radius of the Maxwell coils (r) is related to the distance (d) between the coils as \( d = \sqrt{3}r \).

For the fabrication of the EMA system, the sizes and the arrangement of the Helmholtz and Maxwell coils are considered. Firstly, the range of ROI is decided, where ROI can be defined as the workspace of the microrobot. Based on the specific range of ROI, the Helmholtz and Maxwell coils are set to different diameters to minimize the space restriction. Therefore, all coil pairs (\( H_x, H_y, H_z, M_z \) and \( M_{xy} \)) have different diameters, where \( H_x, H_y, \) and \( H_z \) mean the Helmholtz coil pairs on the x-axis, y-axis, and z-axis, respectively. In addition, \( M_z \) denotes the Maxwell coil pair on the z-axis and \( M_r \) denotes the rotating Maxwell coil pair, which can generate the propulsion force in the R–Z plane. In general, for the generation of the same uniform magnetic fields by all Helmholtz coil pairs and the same gradient magnetic fields by all Maxwell coil pairs, the number of turns of the winding wire in the above coil pairs is considered and designed. Then, the magnetic field generated by the coil current can be easily controlled to actuate the microrobot. Table 1 shows the detailed specification of the proposed EMA coil system. Based on the specification of the coil system, when the same current is applied to the Helmholtz coil pairs (\( H_x, H_y, \) and \( H_z \)) the generated uniform magnetic fields (\( B_x, B_y, \) and \( B_z \)) have the relation of (\( B_x : B_y : B_z = 0.76 : 0.81 : 1 \)). In addition, if the same current is applied to the rotating and stationary Maxwell coil pairs, the generated gradients of the magnetic fields (\( \partial B_r / \partial r \) and \( \partial B_z / \partial z \)) have the relation of \((\partial B_r / \partial r) : (\partial B_z / \partial z) = 1.67 : 1 \).

#### 2.2. Alignment and propulsion mechanism

Generally, the Helmholtz coil pair generates a uniform magnetic field, and when a permanent magnetic microrobot is located in the ROI, the microrobot is aligned to the direction of the uniform magnetic field. The torque \( \tau \) for the alignment is generated as

\[
\tau = VM \times B
\]

### Table 1

<table>
<thead>
<tr>
<th>Coils</th>
<th>Radius (mm)</th>
<th>Diameter of copper wire (mm)</th>
<th>Coil turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxwell coil XY</td>
<td>43.0</td>
<td>1.0</td>
<td>91</td>
</tr>
<tr>
<td>Maxwell coil Z</td>
<td>78.0</td>
<td>1.1</td>
<td>180</td>
</tr>
<tr>
<td>Helmholtz coil X</td>
<td>163.0</td>
<td>1.8</td>
<td>224</td>
</tr>
<tr>
<td>Helmholtz coil Y</td>
<td>124.0</td>
<td>1.5</td>
<td>180</td>
</tr>
<tr>
<td>Helmholtz coil Z</td>
<td>80.0</td>
<td>1.0</td>
<td>144</td>
</tr>
</tbody>
</table>
where $V$ and $M$ denote the volume and the magnetization of the microrobot. $B$ means the magnetic flux, defined as $B = \mu_0 H$, where $\mu$ is the permeability of the material, $\mu_0$ is the permeability in vacuum, and $H$ is the magnetic field strength. Because the Helmholtz coil pair generates a uniform magnetic flux along an axis, the magnetic flux of the three pairs of Helmholtz coils can be defined as the vector sum of the magnetic fluxes in the desired direction. Therefore, the three pairs of Helmholtz coil can generate a uniform magnetic flux in the desired direction in 3D space, and the permanent magnet can be aligned in this desired direction.

Fig. 2 shows the alignment direction ($\alpha$, $\theta$) of the microrobot. For the alignment of the microrobot, three Helmholtz coil pairs ($H_x$, $H_y$, and $H_z$) are used and the coil currents are adjusted such that the following relations are satisfied:

\[
\left\{ \tan^{-1}\left(\frac{B_y}{B_z}\right), \tan^{-1}\left(\frac{B_z}{\sqrt{B_x^2 + B_y^2}}\right) \right\}
\]

where $B_x$, $B_y$, and $B_z$ are the magnetic fluxes by $H_x$, $H_y$, and $H_z$, respectively.

The Maxwell coil pairs generate a uniform gradient magnetic flux along an axis. The uniform gradient magnetic flux produces the propulsion force at the permanent magnet as follows:

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

where $F$ is a propulsion force of the microrobot by the magnetic field and $\nabla$ means a gradient operator. The uniform gradient magnetic field of the Maxwell coil pairs generates the propulsive force of the microrobot. Fig. 3(a) shows the arrangement of the two Maxwell coil pairs. One stationary Maxwell coil pair is positioned in the $Z$-axis and generates the propulsive force to the $Z$-axis direction. The other rotational Maxwell coil pair is aligned to the desired direction, $\alpha$, where the rotational axis is named as the $R$-axis. Thus, the rotational Maxwell coil pair generates the propulsive force to the $R$-axis direction. Consequently, the two Maxwell coil pairs are perpendicularly positioned in the $R$-axis and $Z$-axis to generate a uniform gradient magnetic field along these directions. Therefore, the magnetic field on the $R-Z$ plane using the two pairs of Maxwell coils is described as

\[
\begin{bmatrix}
B_r \\
B_z
\end{bmatrix} = \begin{bmatrix}
gr_r - 0.5 g_z r \\
g_z z - 0.5 g_r z
\end{bmatrix}
\]
as

\[
\begin{bmatrix}
F_x \\
F_z
\end{bmatrix} = \begin{bmatrix}
MV \cos \theta (g_r - 0.5g_z) \\
MV \sin \theta (g_z - 0.5g_r)
\end{bmatrix}
\] (5)

For the propulsion of the microrobot in the aligned direction (\(\theta\)), the ratio of the \(r\) and \(z\) directional components of the force should be equal to \(\tan \theta\), as shown in Fig. 3(b). Therefore, the following equation can be derived as

\[
\frac{F_z}{F_r} = \tan \theta = \frac{MV \sin \theta (g_z - 0.5g_r)}{MV \cos \theta (g_r - 0.5g_z)}
\] (6)

and thus the result of \(g_r = g_z\) can be derived. This means that the \(R\)- and \(Z\)-axis Maxwell coil pairs generate the same gradient magnetic field, and the resulting propulsion force vector is aligned along the direction \((\alpha, \theta)\). Therefore, the microrobot is aligned to the desired direction \((\alpha, \theta)\) and is driven forward in the aligned direction.

For the propulsion of the microrobot in the desired direction \((\theta)\), the gravitational force on the microrobot should be compensated. For the compensation of the gravitational force, Eq. (6) is modified as

\[
\frac{F_z - mg}{F_r} = \tan \theta = \frac{MV \sin \theta (-0.5g_r + g_z) - mg}{MV \cos \theta (g_r - 0.5g_z)}
\] (7)

where \(m\) denotes the mass of the microrobot. When the coil currents in the two Maxwell coil pairs are derived using Eq. (7) and supplied, the microrobot can be propelled in the aligned direction \((\alpha, \theta)\).

2.3. Drilling mechanism

When the microrobot is located at the target occlusion point, the drilling procedure of the microrobot is started. The drilling is
achieved by the rotation of the microrobot on the desired axis. Fig. 4 shows the schematic diagram of the rotational motion of the microrobot. As shown in Fig. 4, the three stationary Helmholtz coil pairs generate the rotational magnetic field and the microrobot with a permanent magnet is synchronized to the rotational magnetic field and rotated. If the microrobot has many rough bumps on its surface, the rotating microrobot might drill through an occlusion part.

For the rotational motion of the microrobot, the coil currents of the three Helmholtz coil pairs are derived by Eqs. (8)–(10):

\[ B_x(t) = B_0 \left\{ \cos \left( \alpha + \frac{\pi}{2} \right) \sin(\omega t) + \cos(\alpha + \frac{\pi}{2}) \cos(\theta) \cos(\omega t) \right\} \] (8)

\[ B_y(t) = B_0 \left\{ \sin \left( \alpha + \frac{\pi}{2} \right) \sin(\omega t) \right\} \] (9)

\[ B_z(t) = B_0 \left\{ \sin(\theta) \sin(\omega t) \right\} \] (10)

where \( \omega \) is the rotational frequency of the microrobot and \( B_0 \) is the initial magnetic flux.

3. Fabrication of EMA system

3.1. EMA coil system

Based on the actuation mechanism in the previous section, the EMA system was designed and fabricated as shown in Fig. 5(a) and (b). The rotational Maxwell coil pairs were positioned inside the EMA system and were driven by a stepping motor (pk264a1-SG36,
oriental motor company). To dissipate the heat generated by the ohmic resistance of coils, the structure of the EMA system was made of aluminum. To investigate the motions of the microrobot in ROI, unnecessary parts in the outer frame blocks of the EMA system were removed. In addition, the wound coil wires were insulated with insulating tape. The size of the fabricated EMA system was 50 cm in width, 43 cm in height, and 35 cm in depth and it weighed about 50 kg.

3.2. Sphere shape microrobot

The locomotive and drilling microrobot was designed and fabricated, as shown in Fig. 6(a) and (b). The microrobot is spherical, and has a cylinder type neodymium magnet of 1 mm diameter and 1 mm length. For the drilling, rough bumps were made on the surface of the microrobot using aluminum oxide. The fabricated microrobot with the bumpy surface had a 3 mm diameter, as shown in Fig. 6(b).

4. Experiments

4.1. Experimental setup

Fig. 7 shows the overall schematics of the experimental setup. The microrobot was positioned in ROI on the test bed of the EMA system. To observe the microrobot and record the still images of the experimental results, a camscope (Sometech Vision) was used. To control the direction of the currents, a relay circuit was fabricated. The coil currents were supplied by programmable power suppliers (Agilent 6675A), which were controlled by the NI-PXI 1042Q controller with LabVIEW software. PXI and Motion controller (National Instruments) were used to control of the coil current and the rotational motor, and the graphical user interface (GUI) with a control algorithm for the EMA system was developed using LabVIEW software. By using the control panels in the GUI, the magnitude and the direction of the coil current, the propulsion direction of the microrobot, and the rotation of the motor could be controlled.

4.2. Experimental results: 3D locomotion of microrobot

The actuation performances of the microrobot using the proposed EMA system were validated by experiments. Firstly, locomotion tests of the microrobot were performed on a horizontal plane. As mentioned in Section 3, the magnitude and direction of the magnetic field were arbitrary regulated by controlling the currents of the Helmholtz coil pairs. Therefore, the direction of the magnetic field was changed by modulating the ratio of the current flows of the Helmholtz coil pairs, and the microrobot was aligned to the desired direction. In addition, the rotating Maxwell coil pair provided a uniform gradient magnetic field and generated the propulsion force of the microrobot in the aligned direction. Fig. 8 shows that the microrobot can move in various desired directions on the 2D horizontal plane. For these locomotion tests on a horizontal plane, a planar test bed with a 2 cm × 2 cm inner space was used. The proposed microrobot with a bumpy surface including a cylinder type neodymium magnet was also used as the test microrobot.

Secondly, locomotion tests of the microrobot on the vertical plane were executed and the experimental results are shown in Fig. 9. In this case, the rotating Maxwell coil pair and the stationary Maxwell coil pair were used to generate the propulsion force of the microrobot. In addition, the gravitational force of the microrobot was compensated. For these locomotion tests on the vertical plane, a cube type test bed was used and it was made of a transparent acrylic plate and filled with high viscosity silicone oil (350 cp). The silicone oil acts to reduce the abrupt motion of the microrobot. As shown in Fig. 9, the microrobot can move at 30°, 45°, 60°, and 90° on the vertical plane. Through the above locomotion tests, the fundamental 3D locomotion of the microrobot was demonstrated.

4.3. Experimental results: drilling of microrobot

The drilling tests of the microrobot were performed for two cases according to the occlusion material. First, 0.3% agar of jelly
type with soft characteristics was adopted. Second, a typical chalk with hard characteristics was tested. For the drilling tests, transparent PVC tubes of 8 mm diameter were prepared and the tubes were filled with the occlusion materials, respectively.

![Fig. 10. Clogging material: (a) drilling experiment of soft material (agar) and (b) drilling experiment of hard material (chalk).](image1)

![Fig. 11. Phantom of blood vessel: (a) 3D rendering of blood vessel and (b) fabrication result of phantom.](image2)

![Fig. 12. 3D locomotion and drilling of microrobot in blood vessel phantom.](image3)
Fig. 10(a) demonstrates the drilling results of the microrobot for the agar occlusion. In this test, when the microrobot arrived at the boundary of the agar, the microrobot started its rotational motion and drilled the agar using its bumpy surface. The microrobot went through the agar occlusion at the rotational frequency of 17–18 Hz. In the second drilling test, a typical chalk as a hard type material with about 3.0–3.2 of specific gravity and 2–3 of Mohs hardness was introduced. The drilling test of the hard occlusion material was executed at the rotational frequency of 4–5 Hz. The drilling results obtained after 10 min are shown in Fig. 10(b). Small particles from the chalk and the curved form of the chalk occlusion surface were observed. However, compared with the drilling performance of the soft agar occlusion material, the drilling performance of the chalk material was considerably lower. However, through the above drilling tests, the feasibility of drilling using the proposed EMA system was demonstrated.

4.4. Experimental results: 3D locomotion and drilling of microrobot in phantom of blood vessel

Finally, 3D locomotion and drilling experiments of the microrobot using a phantom of blood vessel were carried out. Fig. 11(a) shows a 3D rendering of the blood vessel, whose data were extracted from computed tomography (CT) images. From the rendering of the blood vessel, a phantom of the blood vessel in Fig. 11(b) could be fabricated by the rapid prototype (RP) process. The fabricated phantom is of a cube type with edge length of 3.7 mm, and the vessel is filled with high viscosity silicone oil (350 cp). As shown in Fig. 12, the microrobot starts to move from the front of the blood vessel to the top position. And the microrobot moves from the top position to the backside of the blood vessel. Finally, the microrobot showed its rotational motion to drill the occlusion part. Through these experiments, the 3D locomotion and drilling of the microrobot using the proposed EMA system were demonstrated.

5. Conclusions

We proposed an EMA system that would facilitate the locomotion and drilling of a microrobot. This EMA system was developed, tested in various experiments, and evaluated. The proposed EMA system consisted of three stationary pairs of Helmholtz coils, one stationary pair of Maxwell coils and one rotating pair of Maxwell coils. The microrobot with the proposed EMA system is spherical with rough bumps on its surface. The spherical microrobot including a cylinder neodymium magnet with rough bumps on the surface was designed and fabricated. The 3D locomotion and drilling of the microrobot using the proposed EMA system were demonstrated by various experiments. Compared with other EMA systems, the proposed system has an advantage of consecutive locomotion and drilling. Consequently, it is expected that the proposed EMA system can be used in important medical applications for intravascular therapy.

Acknowledgment

This work was supported by a Grant-in-Aid for Strategy Technology Development Programs (No. 10030037) from the Korea Ministry of Knowledge Economy.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.sna.2010.04.037.

References