Utilization of Magnetic Gradients in a Magnetic Navigation System for the Translational Motion of a Micro-Robot in Human Blood Vessels

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This paper proposes a method to generate the translational motions of a micro-robot in human blood vessels by utilizing the magnetic gradients of a magnetic navigation system (MNS). The proposed method was applied to the MNS composed of a Maxwell coil, Helmholtz coil, and uniform and gradient saddle coils, and it was verified through the experiment demonstrating the rectilinear and translational motions of a micro-robot in a plane. This paper also discusses the effective aligning angle for the translational motion of a micro-robot to reduce the required magnetic gradients of the MNS. This research contributes to the effective and therapeutic manipulation of a micro-robot in human blood vessels.

Index Terms—Magnetic gradient, magnetic navigation system, micro-robot, translational motion.

I. INTRODUCTION

CORONARY artery diseases such as angina pectoris and myocardial infarction have become prevalent in modern society due to obesity and insufficient exercise [1]. As a surgical treatment, percutaneous coronary intervention (which unclogs the clogged blood vessels with a guided catheter) has been employed widely [2]. Since the catheter is manually operated by a medical doctor, it has limitations in applications to twisted, narrow blood vessels, or to deliver drugs to various target points precisely. Several researchers have investigated the use of micro-robots manipulated by a magnetic navigation system (MNS) as a possible surgical alternative to percutaneous coronary intervention [3]–[7]. Since the manipulating power of a micro-robot is provided by the MNS located outside of the human body, the size of the micro-robot can be effectively reduced so that it can navigate through twisted, narrow blood vessels and deliver drugs to cure the diseased area.

Several researchers have shown that an MNS can generate the rectilinear motions of a micro-robot along its aligned direction [5]–[7]. Ishiyama et al. showed that an MNS can generate the drilling motions of a spiral-type micro-machine in silicone oil by using rotating magnetic fields [5]. Jeon et al. showed that one pair of Maxwell and gradient saddle coils can generate the propelling magnetic force for a micro-robot along its aligned direction [6]. Choi et al. showed that the magnetic gradient from one vertically placed Maxwell coil can propel a micro-robot in any aligned direction in a plane [7]. However, prior researchers did not succeed in generating the translational motion of a micro-robot that enables it to move parallel to the rectilinear motion along the propelling direction. Fig. 1 shows the rectilinear motion and translational motion of a micro-robot in a human blood vessel. The translational motion of the micro-robot in addition to its rectilinear motion enables it to move effectively along the rugged and twisted human blood vessels. The translational motion is especially required to move the micro-robot precisely to the target point in order to effectively drill the clogged vessels or inject the drugs to the diseased area of the human blood vessels.

This paper proposes a method to generate both rectilinear and translational magnetic force for a micro-robot by utilizing the magnetic gradients in an MNS so that the micro-robot can move in any direction with respect to its aligned direction in a plane. We derive the relationship of the magnetic gradients between two gradient coils by using the equation of magnetic force and Maxwell’s equations, and apply the proposed method to an MNS composed of Maxwell, Helmholtz, and saddle coils. We then verify the proposed method by carrying out an experiment demonstrating the rectilinear and translational motions of a micro-robot along various moving paths in a plane. We also examine the effective aligning angle for the translational motion of the micro-robot to reduce the required magnetic gradients in the MNS.

II. DEVELOPMENT OF TRANSLATIONAL MOTIONS OF A MICRO-ROBOT IN AN MNS

A. Magnetic Force and Torque of a Micro-Robot

For a micro-robot composed of a permanent magnet in an external magnetic field, the propelling and aligning principles are
based on the following equations of magnetic force and torque [8]:

\[
\begin{align*}
\vec{F} &= \mu_0 V \begin{bmatrix} M_x \frac{\partial H_x}{\partial x} + M_y \frac{\partial H_y}{\partial y} + M_z \frac{\partial H_z}{\partial z} \\
M_x \frac{\partial H_y}{\partial x} + M_y \frac{\partial H_x}{\partial y} + M_z \frac{\partial H_z}{\partial z} \\
M_x \frac{\partial H_z}{\partial x} + M_y \frac{\partial H_x}{\partial y} + M_z \frac{\partial H_y}{\partial z} 
\end{bmatrix} \\
\vec{T} &= \mu_0 V \begin{bmatrix} M_y H_z - M_z H_y \\
M_z H_x - M_x H_z \\
M_x H_y - M_y H_x 
\end{bmatrix}
\end{align*}
\]

where \( \mu_0, V, M_x, M_y, M_z, H_x, H_y, \) and \( H_z \) are the magnetic permeability of free space, the volume, and the magnetizations of the micro-robot and magnetic field intensities along the \( x, y, \) and \( z \)-directions, respectively. Since the magnetic force is proportional to the magnetic gradients and the magnetic torque is proportional to the magnetic field intensities, the magnetic force and the magnetic torque of a micro-robot can be independently controlled.

An MNS is generally composed of two kinds of magnetic coils, referred to as the uniform coil and the gradient coil. The uniform coil generates a uniform magnetic field near the center of the coil so that it can generate the aligning magnetic torque for a micro-robot. The gradient coil generates a linear magnetic gradient near the center of the coil so that it can generate the propelling magnetic force for the micro-robot along its aligned direction. Thus, an MNS composed of a uniform coil and gradient coil can manipulate a micro-robot in human blood vessels.

**B. Magnetic Fields in the MNS**

Generally, the distribution of a static magnetic field in space can be characterized by the following Maxwell’s equations:

\[
\nabla \cdot \vec{B} = 0 \\
\nabla \times \vec{B} = \mu_0 \vec{J}
\]

where \( \vec{J} \) is the total current density. Assuming that the shape of a gradient coil is geometrically symmetric as shown in Fig. 2, the general expression of the magnetic field near the center of an arbitrary gradient coil can be expressed as follows:

\[
\vec{H} = \begin{bmatrix} a & b & -a \end{bmatrix}^T
\]

where \( a \) and \( b \) are constant values depending on the geometries of the coil, and \( g \) is the magnetic gradient depending on the magnitude of the current flowing in the coil. Considering that the coefficients \( a \) and \( b \) are constant values, the ratio of the magnetic field along the \( x, y, \) and \( z \)-directions always remains constant.

The translational motions of a micro-robot in a plane can be represented by the aligning angle \( \theta \) and the translating angle \( \phi \), as shown in Fig. 2. Since this research intends to determine the magnetic gradients required to generate the translational magnetic force of a micro-robot along any desired direction \( \theta + \phi \) in a plane with respect to its aligned direction \( \theta \), the MNS requires at least two gradient coils. This research proposes two gradient coils so that the MNS can conveniently generate various magnetic gradients to generate the translational magnetic force of a micro-robot by controlling only two input currents in the MNS. The proposed method is applied to the MNS shown in Fig. 2, which is geometrically and magnetically efficient for application to the human body [6]. The MNS has one pair of uniform coils composed of a Helmholtz coil and uniform saddle coil, and another pair of gradient coils composed of a Maxwell coil and gradient saddle coil, as shown in Fig. 2. The magnetic field near the center of the MNS can be expressed as follows [6]:

\[
\vec{H}_{MNS} = \begin{bmatrix} d_h + (g_y + g_m)x \\
d_u + (-2.4398g_y - 0.5g_m)y \\
(1.4398g_y - 0.5g_m)z
\end{bmatrix}
\]

where \( d_h, d_u, g_m, \) and \( g_y \) are the magnetic field intensities and magnetic gradients, respectively, and the subscripts \( h, u, m, \) and \( y \) correspond to the Helmholtz coil, uniform saddle coil, Maxwell coil, and gradient saddle coil, respectively.

**C. Translational Motions of a Micro-Robot**

For the MNS in Fig. 2, the aligning motion of a micro-robot along the angle \( \theta \) in the horizontal \( xy \)-plane can be generated by satisfying the following current relationship between the Helmholtz coil and the uniform saddle coil [6]:

\[
i_u = 1.1917 \tan \frac{r_u}{r_h}
\]

where \( i_h, i_u, r_h, \) and \( r_u \) are the currents and radii of the Helmholtz coil and uniform saddle coil, respectively.

We utilize (1) and (6) to derive the condition to generate the translational magnetic force of a micro-robot along the angle \( \theta + \phi \) while the micro-robot is aligned along the angle \( \theta \) in the \( xy \)-plane:

\[
\frac{F_y}{F_x} = \frac{\mu_0 MV \sin(\theta + \phi)}{\mu_0 MV \cos(\theta + \phi)} = \frac{\sin(\theta + \phi)}{\cos(\theta + \phi)}.
\]

From (8), the required relationship of the magnetic gradients between the Maxwell coil and the gradient saddle coil can be derived as follows:

\[
g_m = \frac{4.8796 \tan \theta + 2 \tan(\theta + \phi)}{\tan \theta + 2 \tan(\theta + \phi)} g_y.
\]

Considering that the magnetic gradients \( g_m \) and \( g_y \) can be expressed in terms of their currents and radii as shown in (10) and (11) [6], the translational magnetic force of a micro-robot can be expressed as (12) in terms of the current in the gradient saddle coil:

\[
g_m = \frac{16}{3} \left( \frac{3}{7} \right)^{\frac{2}{3}} \frac{i_m}{r_m^2}
\]

Fig. 2. MNS composed of Maxwell coil, Helmholtz coil, and uniform and gradient saddle coils.
TABLE I
MAJOR SPECIFICATIONS OF THE MNS

<table>
<thead>
<tr>
<th>Coil</th>
<th>Radius (mm)</th>
<th>Diameter of copper wire (mm)</th>
<th>Coil turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxwell coil (MC)</td>
<td>78.0</td>
<td>1.1</td>
<td>197</td>
</tr>
<tr>
<td>Gradient saddle coil (GSC)</td>
<td>59.0</td>
<td>0.8</td>
<td>135</td>
</tr>
<tr>
<td>Helmholtz coil (HC)</td>
<td>80.0</td>
<td>1.0</td>
<td>144</td>
</tr>
<tr>
<td>Uniform saddle coil (USC)</td>
<td>44.0</td>
<td>0.8</td>
<td>135</td>
</tr>
</tbody>
</table>

\[
\theta_g = 0.3286 \frac{r_g}{r_g} \\
\vec{P} = \frac{1.3077 \mu_0 MV \vec{i}_g \sec(\theta + \phi) \sin \theta}{(\tan \theta + 2 \tan(\theta + \phi))r_g^2}
\times \left( \cos(\theta + \phi) \hat{i} + \sin(\theta + \phi) \hat{j} \right)
\]

where \( i_m, i_g, r_m, \) and \( r_g \) are the currents and radii of the Maxwell coil and gradient saddle coil, respectively. Therefore, the MNS can generate the rectilinear and translational motions (\( \phi = 0^\circ \)) and translational motions (\( \phi \neq 0^\circ \)) of a micro-robot.

III. RESULTS AND DISCUSSION

Fig. 3 shows an experimental setup to verify the proposed method. Table I shows the major specifications of the MNS. A half cylindrical micro-robot with a diameter of 2 mm, length of 5 mm, and axial magnetization of 955 000 A/m is placed in a dish in the center of the \( xyz \)-plane as shown in Fig. 3. The dish is filled with highly viscous transparent silicone oil with viscosity of 350 cP so that the movement of the micro-robot can be clearly observed. This research generates the rectilinear and translational motions of the micro-robot along the predetermined paths while the micro-robot is aligned along one direction. Fig. 4 shows the translational motions of the micro-robot along the rectangular moving path while the micro-robot is aligned along the angle \( \theta = 45^\circ \). Fig. 5 shows the rectangular and translational motions of the micro-robot along the diamond-shaped moving path while the micro-robot is aligned along the angle \( \theta = 15^\circ \). The input currents in the MNS for each moving path were calculated by using (7), (9), (10), and (11), as shown in Tables II and III. Figs. 4 and 5 show that the calculated currents generate the rectilinear and the translational motions of the micro-robot in a plane.

This research examines the variation of the required magnetic gradients in the MNS due to the change of the aligned angle of the micro-robot. Fig. 6 shows the magnetic gradients in the Maxwell and gradient saddle coils required to generate a unit translational magnetic force ([\( F/\mu_0 MV \]) = 1) due to the change of the aligning angle \( \theta \). It is assumed that the translating angles of the micro-robot \( \theta + \phi \) are \( 0^\circ \), \( 30^\circ \), \( 45^\circ \), and \( 60^\circ \) in the

TABLE II
INPUT CURRENTS IN THE MNS FOR THE RECTANGULAR MOVING PATH OF A MICRO-ROBOT ALIGNED ALONG THE ANGLE OF \( \theta = 45^\circ \) (A)

<table>
<thead>
<tr>
<th>Coil</th>
<th>Path 1</th>
<th>Path 2</th>
<th>Path 3</th>
<th>Path 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>8.00</td>
<td>8.00</td>
<td>-8.00</td>
<td>-8.00</td>
</tr>
<tr>
<td>GSC</td>
<td>-2.67</td>
<td>-13.03</td>
<td>2.67</td>
<td>13.03</td>
</tr>
<tr>
<td>HC</td>
<td>13.00</td>
<td>13.00</td>
<td>13.00</td>
<td>13.00</td>
</tr>
<tr>
<td>USC</td>
<td>9.09</td>
<td>9.09</td>
<td>9.09</td>
<td>9.09</td>
</tr>
</tbody>
</table>
TABLE III

INPUT CURRENTS IN THE MNS FOR THE DIAMOND-SHAPED MOVING PATH OF A MICRO-ROBOT ALIGNED ALONG THE ANGLE OF $\theta = 15^\circ$ (A)

<table>
<thead>
<tr>
<th>Coil</th>
<th>Path 1</th>
<th>Path 2</th>
<th>Path 3</th>
<th>Path 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>8.00</td>
<td>8.00</td>
<td>-8.00</td>
<td>-8.00</td>
</tr>
<tr>
<td>GSC</td>
<td>-5.68</td>
<td>-10.20</td>
<td>5.68</td>
<td>10.20</td>
</tr>
<tr>
<td>HC</td>
<td>13.00</td>
<td>13.00</td>
<td>13.00</td>
<td>13.00</td>
</tr>
<tr>
<td>USC</td>
<td>2.44</td>
<td>2.44</td>
<td>2.44</td>
<td>2.44</td>
</tr>
</tbody>
</table>

first quadrant of the $xy$-plane. This shows that there is an effective range of the aligning angle near $45^\circ$ at which the required magnetic gradients are relatively small regardless of the translating angles, so the translational magnetic force can be effectively generated in the translating direction. Ineffective aligning angles also exist near $\theta = 0^\circ$ and $\theta = 90^\circ$, at which the required magnetic gradients in the MNS become infinitely large regardless of the translating angles. Considering the geometric symmetry of the MNS, this result can be similarly applied to the case in which the translating angle of the micro-robot is above the range $\theta + \phi = 0^\circ \sim 90^\circ$. Thus, the micro-robot can be effectively translated by first aligning it along the diagonal directions in the $xy$-plane regardless of its translating angle.

IV. CONCLUSION

This research developed a method utilizing the magnetic gradients of an MNS to generate the rectilinear and translational motions of micro-robots in human blood vessels. Our results contribute to the effective and therapeutic manipulation of micro-robots in human blood vessels.

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