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Two-dimensional actuation of a microrobot with a stationary two-pair coil system

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Abstract
This paper proposes a new two-dimensional (2D) actuation method for a microrobot that uses a stationary two-pair coil system. The coil system actuates the microrobot by controlling the magnitude and direction of the external magnetic flux. The actuation of the microrobot consists of an alignment to the desired direction and a linear movement of the microrobot by non-contact electromagnetic actuation. Firstly, the actuation mechanism of the stationary coil system is theoretically derived and analyzed. Secondly, the tendency of the magnetic flux in the coil system are analyzed and compared by preliminary theoretical analysis. Through various locomotive experiments of the microrobot, the performance of the electromagnetic actuation by the proposed stationary two-pair coil system is evaluated. Using the proposed 2D actuation method, the microrobot is aligned to the desired direction by Helmholtz coils and is driven to the aligned direction by Maxwell coils. By the successive current control of the coil system, the microrobot can move along a desired path, such as a rectangular-shaped or a diamond-shaped path.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Lack of exercise and ageing have led to an increase of cardiovascular diseases in modern society. Foremost, coronary artery disorders around the heart are critically on the rise [1, 2]. For the treatment of coronary arterial diseases (CAD), drug therapy, coronary artery bypass graft (CABG) and catheterization are widely used. Drug therapy is in limited use for dissolution and inhibitory actions against the growth of thrombi in coronary arteries. CABG, which provides a detour vessel to the blocked artery, has drawbacks, such as a long recovery time, in addition to its difficulty and the high cost of the operation. Compared with CABG, the catheterization method is a simpler surgical operation, and thus widely used in hospitals. However, the catheterization method using a soft guide wire is limited as a medical treatment for chronic total occlusion (CTO). Especially, if CTOs were hardened by complex fibrocalcific atherosclerosis with chronic organized thrombus [3].

Hence, for the treatment of CAD, technologies that can allow microrobots to move in the blood vessel to heal diseases have been developed [4]. Generally, a microrobot consists of actuating parts, sensing parts, power sources and remedy tools. These parts are essential for medical application of microrobots. Due to the size limitation, however, these parts are difficult to integrate into a microrobot, especially the actuation part including the its power source. As a solution, several actuation mechanisms are used to propel the microrobot from a remote site [5].

One of the many studies on MEMS and robot technologies has been on the use of an electromagnetic field as a driving force for microrobots [5]. Martel proposed a magnetic resonance imaging (MRI) system based actuation method [6, 7], which generates the actuation force for the locomotion of a microrobot by using the uniform magnetic

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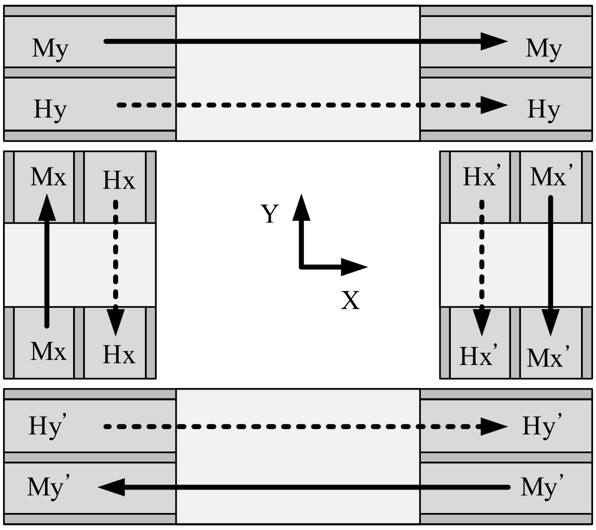


Figure 1. Schematic diagram and current direction of coil system. Hx–Hx': x axis Helmholtz coil pair, Mx–Mx': x axis Maxwell coil pair, Hy–Hy': y axis Helmholtz coil pair, My–My': y axis Maxwell coil pair.

flux and the uniform gradient flux of the MRI system. This method can perform the propulsion and the position tracking of the microrobot by the repetition of propulsion phases and tracking phases in an MRI system [7]. However, MRI only has a pair of Helmholtz coils and cannot rotate the microrobot to the desired direction. That is, it restricts the degree of freedom (DOF) of the microrobot because it works under the limitation of the MRI system. Therefore, it is impossible to control the posture of the microrobot.

Nelson moved a ferromagnetic microrobot in a 2D plane with Helmholtz and Maxwell coil pairs which can be rotated by motor [8]. The Helmholtz coil generated a uniform magnetic field and was rotated to produce a torque on the microrobot. Therefore, the rotating Helmholtz coil aligned the microrobot to the desired direction. Then the Maxwell coils were activated to generate a uniform gradient magnetic flux and to move the microrobot in a straight line. Overall, the microrobot was moved in a 2D plane by the rotating one-pair coil system.

Sitti conducted an experiment in which a permanent magnet micrometer size robot was moved by using five rectangle type coils [9]. The microrobot in this method repeats a stick-slip motion to move forward after sending a current to the fixed coils. A fixed structure is advantageous, but the repeated stick-slip motion is not appropriate for medical applications.

This paper proposes a new electromagnetic field generating system that consists of two pairs of stationary Helmholtz and Maxwell coils. By controlling the current in each coil, the magnetic flux in the region of interest (ROI) can be controlled. Therefore, the proposed electromagnetic system can manipulate the microrobot in the ROI. To verify the proposed system, theoretical analyses are compared with numerical simulation data. Finally, by testing the locomotion of a microrobot, the feasibility of the microrobot actuation system is evaluated.

2. Design and fabrication of a stationary two-pair coil system

Our new electromagnetic system consists of two pairs of Helmholtz and Maxwell coils, which are fixed perpendicularly. Generally, Helmholtz coils create a uniform magnetic flux. Therefore, when a permanent magnet is used as a microrobot, Helmholtz coils can align the microrobot in the direction of the Helmholtz coils. Maxwell coils generate a uniform

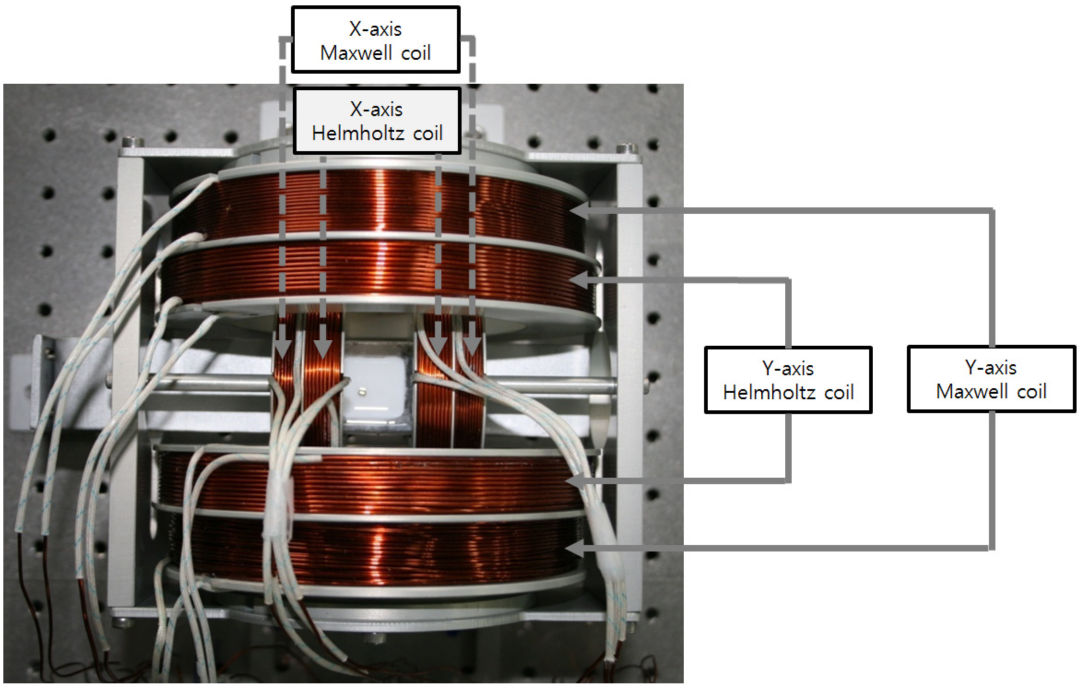


Figure 2. Fabrication of proposed electromagnetic actuation system.

Table 1. Specification of stationary coil system.

Coils	Radius (mm)	Diameter of copper wire (mm)	Coil turns
X axis Helmholtz coil	32	1.0	105
X axis Maxwell coil	30	0.8	197
Y axis Helmholtz coil	60	1.2	110
Y axis Maxwell coil	56.5	0.9	390

gradient of magnetic flux. The uniform gradient of magnetic flux can produce the propulsion force for the microrobot [8]. Figure 1 shows a schematic diagram of the proposed two pairs of coils for the electromagnetic actuation (EMA) system. In figure 1, Hx–Hx' and Hy–Hy' mean the Helmholtz coil pairs of $x(-)$ and $y(-)$ axis, respectively. In addition, Mx–Mx' and My–My' are the Maxwell coil pairs of the x and y axes, respectively.

The current of each coil can be controlled. Figure 1 shows the current directions of the two-pair EMA system in the directions of the x and y axes. Generally, the Helmholtz coil consists of two pairs of solenoid coils. For the generation of a uniform magnetic flux, the radius r of the Helmholtz coil solenoid equals the distance d between Hx and Hx' (or Hy and Hy'); that is, the Helmholtz coil has the relation of $d = r$. The current of the Helmholtz coil flows in the same direction and has the same intensity. One pair of Helmholtz coils can generate a uniform magnetic flux along the axis. If two pairs of Helmholtz coils are arranged perpendicularly, the magnetic flux generated by each pair of Helmholtz coils can be defined as a magnetic flux vector. The vector sum of the magnetic fluxes is considered to be the final magnetic flux generated by the two pairs of Helmholtz coils. Therefore, two pairs of Helmholtz coils can generate a uniform magnetic flux along a desired direction in a 2D plane and can align the microrobot in that direction [8].

Similarly, the Maxwell coil consists of a pair of solenoid coils. Ideally, a Maxwell coil has the relation of $d = \sqrt{3}r$, where d denotes the distance between the two solenoid coils and r means the radius of the solenoid. The current intensities of a Maxwell coil are the same, but the current flow directions are opposite. The magnetic flux density of Maxwell coils is also defined as a vector. The gradient of the magnetic flux density is generated along the axis.

In the design of the overall system, the sizes and the arrangement of the coil systems were considered for the positioning of the ROI inside the Helmholtz and Maxwell coils. In addition, we designed the diameter of the Helmholtz coil to be different from that of the Maxwell coil for the minimization of space restriction. Therefore, every coil pair has a different diameter from each other, but satisfies the ideal definition of a coil pair. Finally, in order that each Helmholtz coil pair (Hx–Hx' and Hy–Hy') has the same magnetic flux with the same current and each Maxwell coil pair (Mx–Mx' and My–My') has also the same gradient of magnetic flux with the same current, the numbers of coil turns and the positions of the coils are decided. The specification of the coil system is summarized in table 1.

The proposed two-pair EMA system was fabricated, as shown in figure 2, to satisfy the above mentioned design

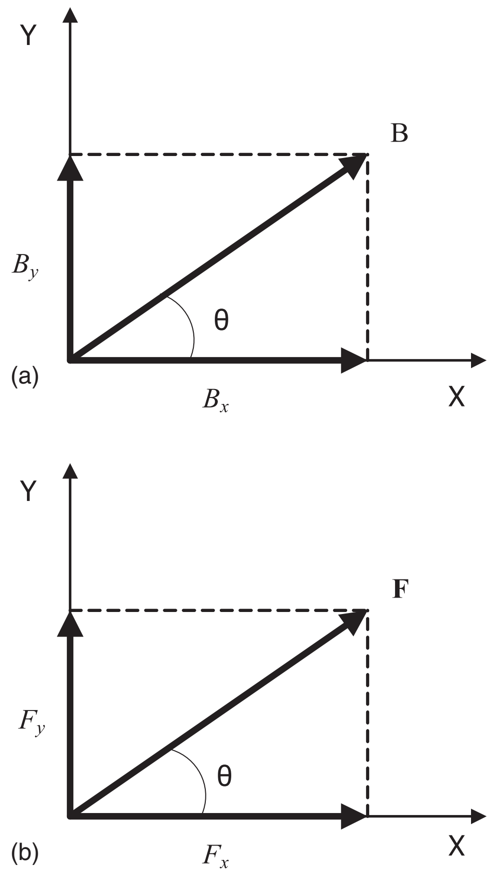


Figure 3. Analysis of electromagnetic actuation mechanism. (a) Magnetic flux intensity generated by Helmholtz coils. (b) Force generated by Maxwell coils.

conditions. The cores of the coil system and the frame of the EMA system were manufactured using aluminum. Aluminum has good thermal conductivity and the same permeability as air. In addition, the frame was designed to have sufficient ROI space for the sample location and the observation of the microrobot.

3. Theoretical analysis of stationary two-pair coil system

3.1. Basic theory

Generally, when an electrical current flows in a wire, a magnetic field is generated according to Biot–Savart theory [10]. If a current flows in a solenoid coil, the magnetic flux intensity is defined at a point which is distant from a center. The magnitude of the magnetic field is decided by the current intensity. If the coil has a circular shape and the current has a magnitude of i, the magnetic field along the center of the coil is calculated by the following equation:

$$H = \oint \mathrm{d}H = \frac{ir^2}{2(r^2+z^2)^{\frac{3}{2}}}, \quad (1)$$

where i is the current intensity and r is the radius of the solenoid. z is the axial coordinate when the center is zero. In

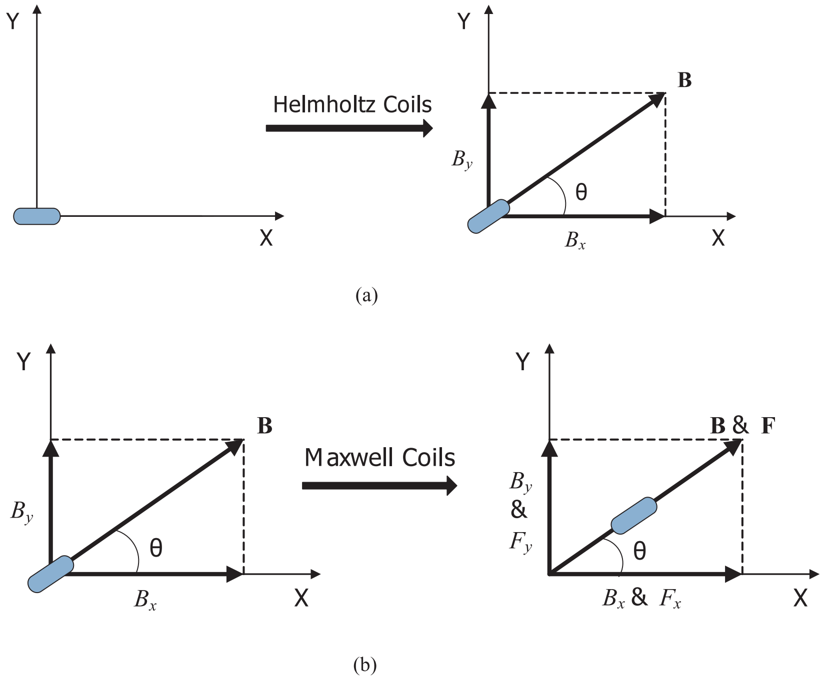


Figure 4. Electromagnet actuation mechanism of the microrobot. (a) Rotation of the microrobot by Helmholtz coils. (b) Propulsion of the microrobot by Maxwell coil.

equation (1), the magnitude of the magnetic field generated by the coil is directly proportional to the current intensity and is in inverse proportion to z^3. From equation (1), the magnetic flux intensity of Helmholtz and Maxwell coils can be calculated [8].

Firstly, the magnetic intensity, H_{h}, generated by the Helmholtz coil is derived as

$$H_{\mathrm{h}} = \frac{inr^2}{2}\left(\frac{1}{\left[r^2+\left(\frac{d}{2}-z\right)^2\right]^{\frac{3}{2}}}+\frac{1}{\left[r^2+\left(\frac{d}{2}+z\right)^2\right]^{\frac{3}{2}}}\right), \tag{2}$$

where i is the current intensity at the coil and r, n, and d denote the radius of the solenoid, the number of coil turns, and the distance between a pair of solenoids, respectively. Similarly, the magnetic intensity, H_{m}, generated by the Maxwell coil is calculated as

$$H_{\mathrm{m}} = \frac{inr^2}{2}\left(\frac{1}{\left[r^2+\left(\frac{d}{2}-z\right)^2\right]^{\frac{3}{2}}}-\frac{1}{\left[r^2+\left(\frac{d}{2}+z\right)^2\right]^{\frac{3}{2}}}\right). \tag{3}$$

In general, the Helmholtz coils generate a uniform magnetic field, and when the permanent magnetic microrobot is located in the ROI and the microrobot is not aligned with the direction of the uniform magnetic field, the following torque, $\boldsymbol{\tau}$, is generated as

$$\boldsymbol{\tau} = V\mathbf{M}\times\mathbf{B}, \tag{4}$$

where V and $\mathbf{M}$ are the volume and magnetization of the microrobot, respectively. $\mathbf{B}$ denotes the magnetic flux and is defined as $\mathbf{B} = \mu_0\mu_r\mathbf{H}$, where μ_r is the permeability of the environment of the microrobot and μ_0 is the permeability of a vacuum. Because the Helmholtz coils generate a uniform

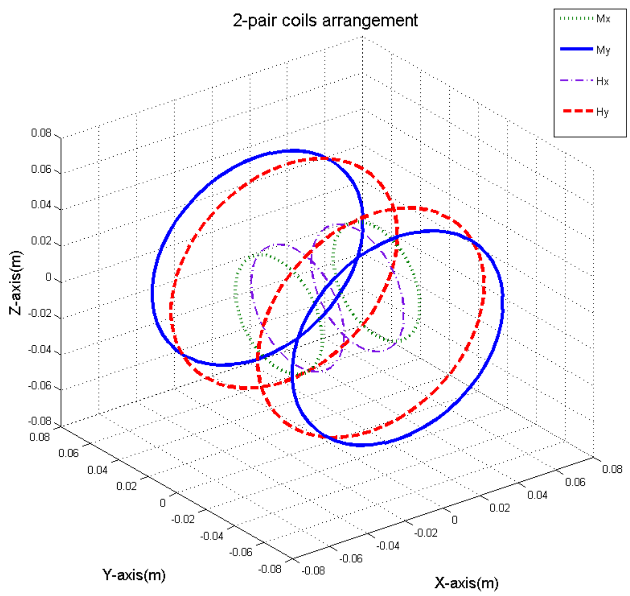


Figure 5. Coil arrangement of the electromagnetic actuation system for numerical analysis.

magnetic flux intensity along the axis, the magnetic flux using two pairs of Helmholtz coils can be defined as the vector sum of the magnetic fluxes, generated by each of the Helmholtz coils. Therefore, by using two pairs of Helmholtz coils, a uniform magnetic flux in the desired direction can be generated, and the permanent magnet can be aligned in that direction.

A Maxwell coil generates a uniform gradient magnetic flux intensity along its axis. The uniform gradient magnetic flux produces a propulsion force at the permanent magnet as

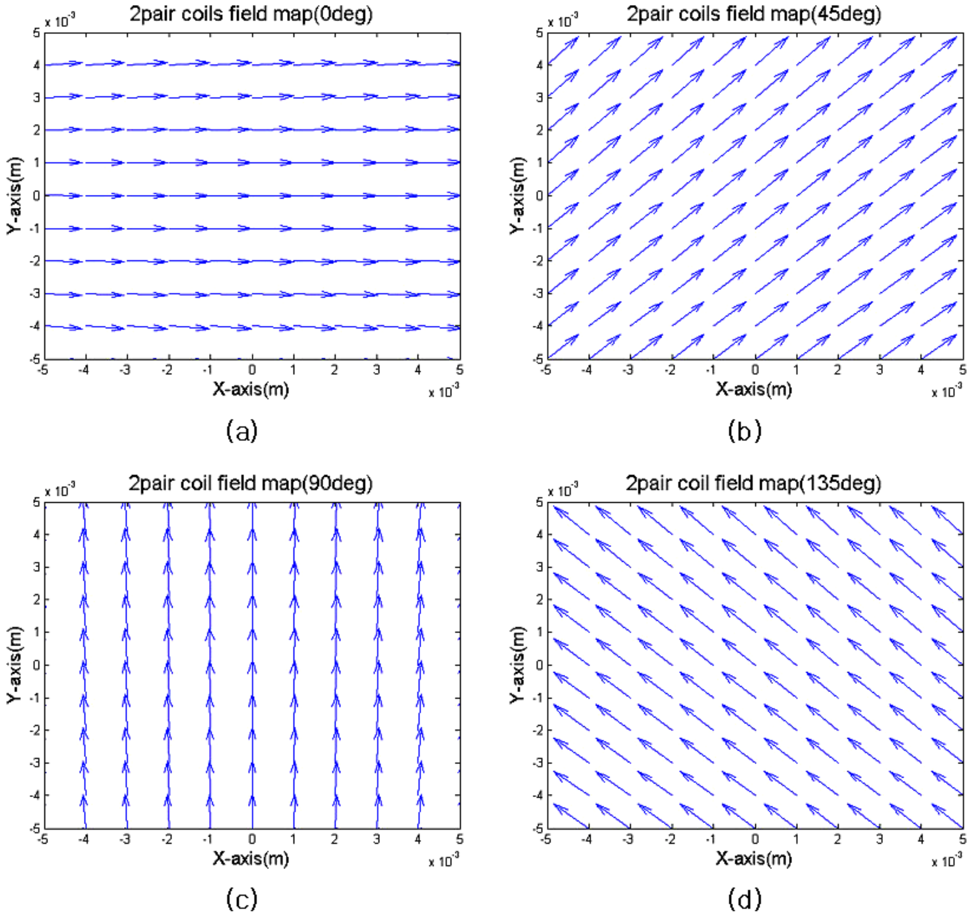


Figure 6. Magnetic field map by numerical analysis. (a) Desired direction: 0°, (b) desired direction: 45°, (c) desired direction: 90° and (d) desired direction: 135°.

follows,

$$F = V(\mathbf{M}\cdot\nabla)\mathbf{B}. \tag{5}$$

Therefore, a change of the gradient magnetic intensity produces a propulsion force. The detailed analysis of the electromagnetic actuation of the microrobot is derived in section 3.2.

3.2. Analysis of electromagnetic actuation mechanism

Firstly, for the alignment of the microrobot to a desired direction, the Helmholtz coils in the proposed coil system are used. From equation (4), the torque generated by the two pairs of the Helmholtz coils is derived as

$$\boldsymbol{\tau} = V[M_x\mathbf{i}+M_y\mathbf{j}]\times[B_x\mathbf{i}+B_y\mathbf{j}] = V(M_xB_y-M_yB_x)\mathbf{k} \tag{6}$$

where M_x and M_y denote the magnetization value of each axis, B_x and B_y the magnetic fluxes, and $\mathbf{i}$, $\mathbf{j}$ and $\mathbf{k}$ are the unit vectors of each axis, respectively. Therefore, if the permanent magnetic microrobot is misaligned with the desired direction, θ, a torque in the microrobot is generated and can rotate the microrobot to the desired direction. When the microrobot is aligned to the desired direction, the torque becomes zero and the magnetization value of each axis is expressed as $M_x = M\cos\theta$ and $M_y = M\sin\theta$. From equation (6), the following condition is derived as

$$M\cos\theta B_y - M\sin\theta B_x = 0, \tag{7}$$

and the condition can be rewritten as $\frac{B_x}{B_y} = \tan\theta$. Therefore, to align the permanent magnetic microrobot to a desired direction, two pairs of Helmholtz coil (H_x, H_y) are used and the coil currents are adjusted until the ratio $\frac{B_x}{B_y}$ becomes $\tan\theta$. Figure 3(a) described the magnetic flux intensity generated by the pairs of Helmholtz coils.

Secondly, to move the microrobot in the desired direction, two pairs of Maxwell coils are used. Generally, a Maxwell coil pair generates a uniform gradient magnetic flux in the axial direction. In addition, a Maxwell coil also generates a uniform gradient magnetic flux in the perpendicular direction. Therefore, the magnetic field on the x–y plane from the two pairs of Maxwell coils is described as

$$\begin{bmatrix} B_x \\ B_y \end{bmatrix} = \begin{bmatrix} g_x x - 0.5 g_y x \\ g_y y - 0.5 g_x y \end{bmatrix}, \tag{8}$$

where B_x and B_y denote the magnetic field in each direction and g_x and g_y denote the magnetic flux gradients generated by each coil [11]. If the volume, V, and the magnetization values,

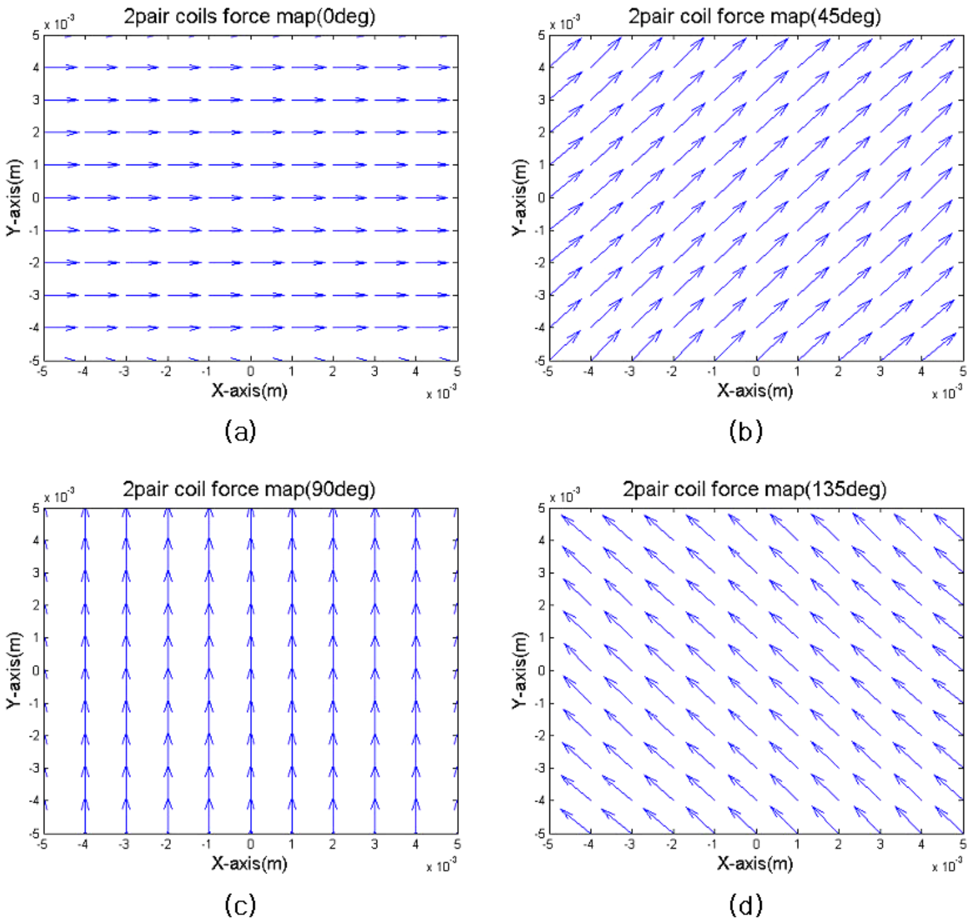


Figure 7. Force map by numerical analysis. (a) Desired direction: 0°, (b) desired direction: 45°, (c) desired direction: 90° and (d) desired direction: 135°.

M_x and M_y, of the microrobot are given, the propulsion force equation can be derived as

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = V \begin{bmatrix} M_x \frac{\partial B_x}{\partial x} + M_y \frac{\partial B_y}{\partial x} \\ M_x \frac{\partial B_x}{\partial y} + M_y \frac{\partial B_y}{\partial y} \end{bmatrix}, \tag{9}$$

where F_x and F_y denote the propulsion force in each direction. From equations (8) and (9), the force equation can be rewritten as

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = V \begin{bmatrix} M \cos\theta (g_x - 0.5 g_y) \\ M \sin\theta (g_y - 0.5 g_x) \end{bmatrix}. \tag{10}$$

The microrobot is aligned in the desired direction and is driven forward in that direction. That is, the direction of the magnetic flux intensity by the Helmholtz coils and the direction of the force by the Maxwell coils should coincide, as shown in figure 3(b). In order to propel the microrobot in a direction, θ, the ratio of the force components has to equal $\tan\theta$. Therefore, the following equation can be derived.

$$\frac{F_y}{F_x} = \tan\theta = \tan\theta \frac{g_y - 0.5 g_x}{g_x - 0.5 g_y}. \tag{11}$$

When equation (11) is satisfied, the propulsion force of the permanent magnet microrobot in the aligned direction is generated and the microrobot can move in that direction. From equation (11), the result of $g_x = g_y$ can be derived. This result means that the gradient of each Maxwell coil pair should generate the same gradient magnetic flux.

The above analysis explains the electromagnetic actuation of the microrobot, as shown in figure 4. As shown in figure 4(a), the microrobot is aligned in the desired direction by the Helmholtz coils. The coil currents of the Helmholtz coils are adjusted until the ratio of the magnetic fluxes of the axes $(\frac{B_x}{B_y})$ becomes $\tan\theta$. After the alignment of the microrobot, the two Maxwell coils induce the same gradient magnetic flux and generate a propulsion force in the desired direction, as shown in figure 4(b). When the Maxwell coils generate the same gradient magnetic flux, the direction of the propulsion force is decided by the pair of Helmholtz coils. The magnitude of the propulsion force is controlled by the magnitude of the gradient magnetic flux of the pair of Maxwell coils.

4. Numerical analysis of electromagnetic actuation system

The magnitude and direction of the magnetic fluxes that are generated by Helmholtz coils and Maxwell coils are governed by the Biot–Savart law. In this paper, the magnetic fluxes and the gradient of the magnetic fluxes generated by Helmholtz and Maxwell coils are calculated. The ROI is selected as the square region of 10 mm width and 10 mm length in the center

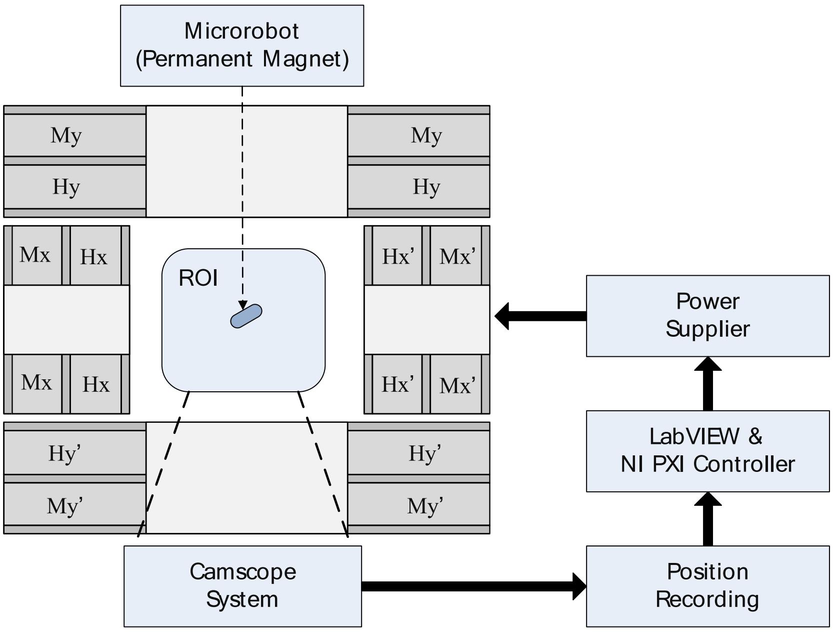


Figure 8. Overall experimental setup.

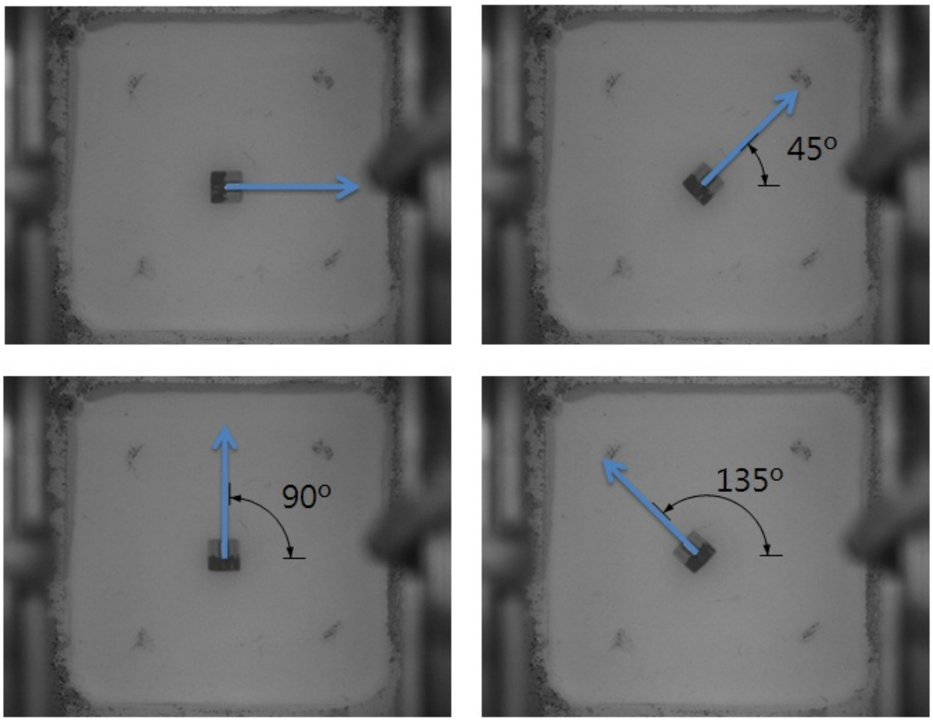


Figure 9. Rotation of microrobot by Helmholtz coils.

of the coil system. The thickness of the winding coils can be neglected. The winding coils are modeled as a single coil. However, the number of winding coils is considered. Figure 5 shows the arrangement of the coil system for the numerical analysis.

The currents applied to the Helmholtz coils (H_x, H_y) are adjusted to align the microrobot in the desired direction. The two Maxwell coils have the same current of 2 A. The numerical analysis was executed by MATLAB, and the magnetic field map and the propulsion force map were simulated for the desired directions (0°, 45°, 90°, 135°) of the microrobot.

The two proposed Helmholtz coils can generate a uniform magnetic flux in the desired direction. The ratio of the coil currents of the two perpendicular Helmholtz coil pairs determines the desired direction of the microrobot, according to $\frac{B_x}{B_y} = \tan\theta$. In addition, in order that the resultant magnetic flux from the two Helmholtz coil pairs has the same magnitude, the currents in these coils are adjusted from −2.8 to 2.8 A.

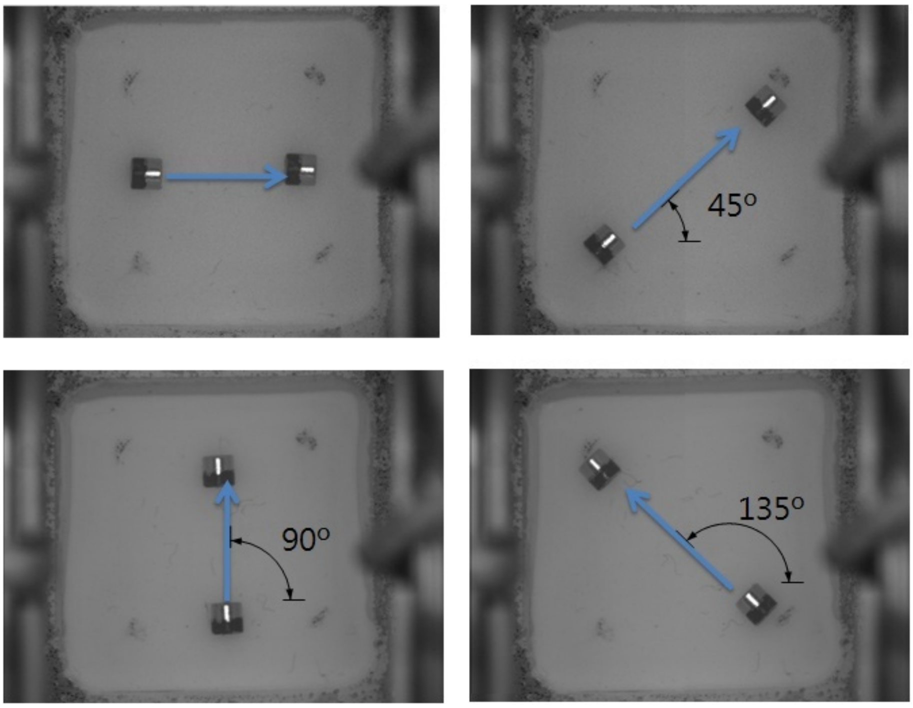


Figure 10. Propulsion of microrobot in the desired direction using Helmholtz coils and Maxwell coils.

As shown in figure 6, the numerical simulations confirmed that the proposed electromagnetic actuation system can generate uniform magnetic fluxes in the desired directions (0°, 45°, 90°, 135°). From the numerical analysis results, the variations of the magnetic flux in the ROI by x- and y-axis Helmholtz coils are less than 0.21% and 0.12%, respectively. Therefore, the magnetic flux can be regarded as nearly uniform.

In addition, the propulsion force maps are also calculated with the magnetization value and the gradient of the magnetic flux. The currents of the Maxwell coils have the same values, 2 A, and generate a propulsion force in the desired direction, aligned by the Helmholtz coils. The numerical analysis results are shown in figure 7. The simulation results show that uniform propulsion forces are generated and the force maps are very similar to the patterns of the uniform magnetic fluxes in figure 7. Thus, it was confirmed that the permanent magnetic microrobot can be aligned and moved by the proposed electromagnetic actuation system.

5. Experiments

5.1. Experimental setup

For the evaluation of our EMA system, preliminary tests were carried out. Figure 8 shows the overall experimental setup for the locomotion tests. For the actuation of the microrobot, the fabricated EMA coil system was used. As the microrobot, a cylindrical (diameter 2 mm, height 2 mm) neodymium magnet was introduced in these experiments.

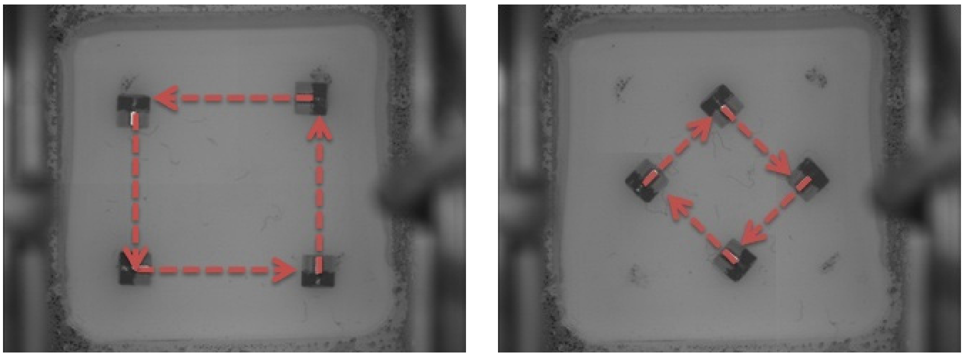
The microrobot was positioned in the center of the dish, which was filled with silicone oil of high viscosity (350 cp). Silicone oil generates a drag force as the velocity of the microrobot increases and reduces any abrupt motion of the microrobot. Therefore, the microrobot can reach a uniform velocity and can be easily controlled. To observe the movement of the microrobot, a camscope (Sometech Vision) was used. Still images and movies of the locomotion of the microrobot were recorded. The coil currents were supplied from power supplies (Agilent 6652A), which were controlled by a PXI controller with LabVIEW software (National Instruments). In addition, to change the direction of the coil current, an extra circuit based on relay components was fabricated and applied.

5.2. Experimental results

From theory and numerical simulation, it was confirmed that the direction of the microrobot is regulated by the two Helmholtz coil pairs and the movement of the microrobot in that direction by the two Maxwell coil pairs. In this section, through experiments, the motions of the microrobot actuated by the proposed EMA coil system were validated. For these experiments, the same currents values of Helmholtz coil pairs and Maxwell coil pairs as in the previous numerical analysis were applied.

Firstly, by controlling the currents of the Helmholtz coils, the magnitude and direction of the magnetic field were arbitrary regulated. Therefore, the direction of the magnetic field was changed by modulating the ratio of the current flows, and torque was generated to rotate the microrobot to the desired direction. Figure 9 shows the experimental results of the rotation of the microrobot. Through these experiments, it was validated that the microrobot could be aligned in the desired directions (0°, 45°, 90°, and 135°) by the two pairs of Helmholtz coils.

Secondly, the Maxwell coil pair provided a uniform gradient magnetic flux, and the two Maxwell coil pairs



(a) (b)

Figure 11. Locomotion of microrobot along a desired path. (a) Locomotion along a rectangular path. (b) Locomotion along diamond path.

combined with the Helmholtz coil pairs were used to generate the propulsion force in the aligned direction of the microrobot. Figure 10 shows that the microrobot can move in various desired directions. As in the previous experiments, the microrobot was first aligned in the desired direction (0°, 45°, 90°, and 135°) by the two Helmholtz coil pairs. For the locomotion of the microrobot, the two Maxwell coil pairs were used, and the microrobot moved along a linear path in the desired direction.

Finally, based on the above experimental results, the movements of the microrobot along a predefined path were tested. As the predefined paths, a rectangular-shape and a diamond-shape were selected and tested. The experimental results are demonstrated in figure 11, and it was validated that the microrobot could move along the predefined paths.

6. Conclusions

This paper proposed the use of a locomotive microrobot based on an electromagnetic field for the treatment of CAD. To solve the problem of the previous EMA system [6–9], which consists of one pair of Helmholtz and Maxwell coils and a rotating axis, the new stationary two-pair coil system was proposed. Firstly, theoretical analysis was carried out to confirm the actuation mechanism of the proposed EMA system. Secondly, through a numerical analysis of the EMA coil system, a magnetic field map and a force map were simulated. The results confirmed the agreement between the actuation theory of the EMA system and the numerical analysis. Finally, through various experiments, it was verified that the microrobot actuated by our EMA system could move along a desired direction and path. Consequently, the feasibility of the proposed microrobot actuated by the proposed EMA system was validated. In the future, for medical applications, the drag force of the microrobot in the blood vessel will be analyzed and the propulsion force of the microrobot measured. Through analysis and various experiments, we will estimate the feasibility of the microrobot in clinical applications.

Acknowledgments

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