# Electromagnetic actuation system using Helmholtz pairs for micro-robot locomotion

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***Abstract*— In this study, we propose the electromagnetic actuation (EMA) system using external Helmholtz coil pairs for micro-robot locomotion for the purpose of biological applications. The micro-robot is composed of permanent magnet (PM) and the newly proposed EMA system consists of only two coil pairs allowing different current intensity into each coil to derive torque and thrust on the horizontal plane. The generating magnetic field by the EMA system is analyzed through the finite element analysis and we verify the feasibility of the proposed system. The newly proposed EMA system has the benefit of reducing the power consumption as well as the total volume in comparison with the previous Helmholtz and Maxwell coil based system.**

***Index Terms* — Electromagnetic actuation, micro-robot, Helmholtz coils, finite element analysis.**

## I. Introduction

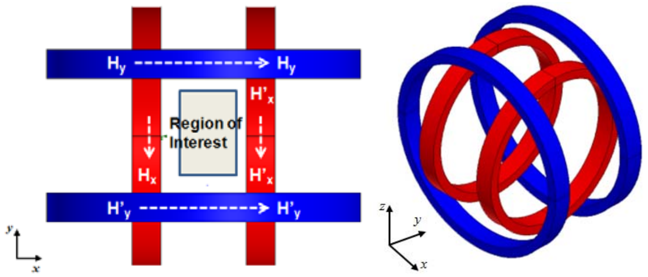
Due to the size limitation of the micro-robot for biological/medical applications, the micro-robot of self-propulsion type which has the actuation part including the power source and relevant mechanisms is not appropriate. To overcome such defects, several actuation mechanism types have been proposed to propel the microrobot by a remote site energy source [1]. Among several actuation mechanisms, an EMA system composed of pairs of Helmholtz and Maxwell coils has been suggested with its variations and it has a beneficial effect on theoretical analysis and system fabrication due to its simplicity [2-5]. The micro-robot is fabricated using permanent magnet and it is aligned and propelled due to the magnetic field generated by Helmholtz and Maxwell coil pairs. Other EMA system called OctoMag is suggested for five-degree-of-freedom control for a ferromagnetic material based micro-robot using external electromagnet rod combinations [1, 6-8].

In the EMA system using two coil pairs, a uniform magnetic field generated from a Helmholtz pair can produce torque to align the micro-robot to a desired direction while a uniform gradient magnetic flux by a Maxwell coil pair generates driving force. In this study, a novel EMA system for the locomotion of the PM type micro-robot is proposed and we focus on showing the feasibility of the system through numerical simulation. Differently from previous works, the proposed EMA system requires only one stationary Helmholtz pair for each *x*- and *y*-axis. It demonstrates that instead of two coil pairs per one direction as in the previous system, just a coil pair is enough to generate both of torque and thrust force by controlling the coil current. Because of the removal of another coil pair, the newly proposed system can have a smaller volume and lower power consumption than the previous EMA system [2]. To verify the feasibility of the proposed EMA system, numerical simulation and theoretical analysis are executed. Comparisons between simulation results and theoretical analyses show that numerical simulation reflects electromagnetic phenomena well and the newly proposed EMA system is available for the further process.

## II. Design of the EMA System

The proposed EMA system is composed of two Helmholtz coil pairs as shown in Fig. 1. Two pairs are perpendicularly arranged along the *x*- and *y*-axis to promote *x*-*y* plane maneuvering of the micro-robot. For generating a uniform magnetic field to align micro-robot to a desired direction, the radius ($r$) of the coils is set to be equal to the distance ($d$) between $H_x$ and $H_x$' or $H_y$ and $H_y$' which represent Helmholtz coil pairs to *x* and *y* axis, respectively [9]. If currents of a coil pair flow to the same direction with the same intensity, it can generate a uniform magnetic field along its axis. Therefore, two pairs of Helmholtz coils, which are arranged perpendicular to each other, can generate a uniform magnetic field along a desired direction in the *x*-*y* plane and can align the micro-robot in any desired direction.

In the previous EMA system, a pair of coils described by the relation of $d = \sqrt{3}r$ and the current input with same magnitude and opposite direction becomes a Maxwell coil pair. In the newly proposed system, a uniform magnetic flux gradient is generated by injecting specific current combination although the coil distance is set to $d=r$. To find the specific current value, theoretical and simulation analyses are required.




(a) (b)

Fig. 1. Schematic of the proposed EMA system: (a) 2-D view in x-y plane and (b) 3-D view.

## III. Define the Model and Simulation

The schematic models of the EMA system are displayed in Fig. 1(a) and (b) for 2-D and 3-D view, respectively. The material of the coil is copper and the boundary region is assigned as vacuum. $r_x$ , the radius of the $H_x$ and $H_x$' coil pair on $x$-axis is 8cm and the radius of $H_y$ and $H_y$' pair $r_y$ is set to 10cm. Distances of $d_x$ and $d_y$ are 8cm and 10cm, respectively and the width of coil $w$ is 1cm. The injected current at one coil is fixed to 20A while the other coil has different value in a wide current range of -100 ~ 100A. The numerical simulation is performed using the commercial finite element analysis (FEA) package, MAXWELL ver.13.

To verify the design concept, one pair of coils is modeled and simulated. Figure 2 shows the simulation result in which a coil current is fixed to 20A while the other coil current is set to 20A and 50A. The graph shows that one Helmholtz coil pair generates a uniform magnetic field for 20A and 20A case and a uniform magnetic field gradient for 20A and 50A case. Therefore, it is verified that a pair of coils may work both for Helmholtz and Maxwell coil by appropriate setting of the input current.

To theoretically analyze the proposed EMA system, the Biot-Savart's law that describes the magnetic field generated by an electric current is applied. The law is used to compute the resultant magnetic flux $B$ at position $r$ generated by a steady current $I$. The proposed EMA system consists of a pair of coils in each axis. Therefore, the magnetic flux at distance $x$ with input current $i_1$ and $i_2$ is defined as follows:

$$\mathbf{B} = \frac{\mu_0 n R^2 i_1}{2\left(R^2 + \left(\frac{h}{2} - x\right)^2\right)}\hat{i} + \frac{\mu_0 n R^2 i_2}{2\left(R^2 + \left(\frac{h}{2} + x\right)^2\right)}\hat{i} \qquad (1)$$

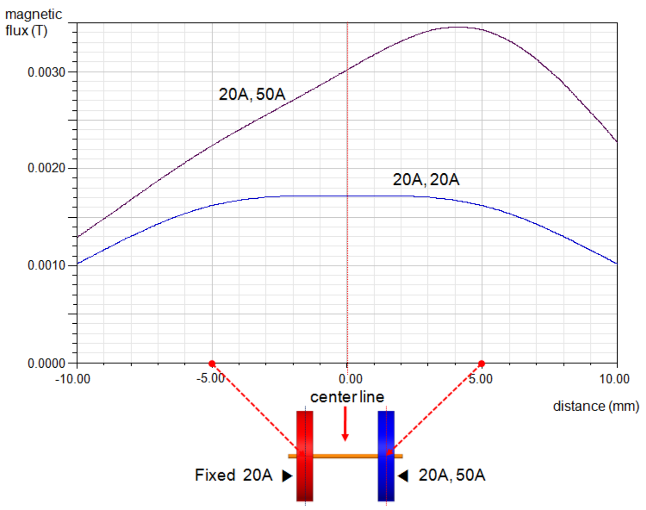



Fig. 2. Magnetic flux plot of the Helmholtz coil pair for various current combinations.

TABLE I

Comparison of the gradient magnetic flux at the center of coils.

| | Simulation result | Theoretical result | Error |
|---|---|---|---|
| *@ x=0* | *0.151 (T/m)* | *0.162 (T/m)* | 6.73 (%) |

where $R$ is the coil radius and $h$ is the distance between two coils. $n$ represents the number of coil turns. The first order derivative of (2) represents the gradient magnetic flux.

$$\frac{\partial \mathbf{B}}{\partial x} = \frac{\mu_0 n R^2}{2}\left[\frac{3\left(\frac{h}{2} - x\right)i_1}{\left(R^2 + \left(\frac{h}{2} - x\right)^2\right)^{\frac{5}{2}}} - \frac{3\left(\frac{h}{2} + x\right)i_2}{\left(R^2 + \left(\frac{h}{2} + x\right)^2\right)^{\frac{5}{2}}}\right]\hat{i} \qquad (2)$$

In the proposed system $R=h$ because it is based on a Helmholtz coils geometry and $x=0$ at the center of the coil designated in Fig. 2. Table I shows the result comparison between the theoretical and the numerical values and it is confirmed that the FEA based simulation is acceptable reflecting the small error value.

The modeling and verification process will be expanded to two Helmholtz pair system as in Fig. 1. Also, we are planning to analyze the modeling including the micro-robot before making and testing of a real system.

## IV. Acknowledgements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