Motion Control of Magnetic Microrobot Using Uniform Magnetic Field

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ABSTRACT A microrobot with untethered control in 3D space is a good choice to be applied in the fields of biomedicine with in small and confined workspace. In this paper, an electromagnetic actuation system (EMA) which combined with Helmholtz coil and Maxwell coil for the microrobot 5 DOF locomotion in 3D space is built. The magnetic field analysis of the proposed 3D EMA system was analyzed by finite-element-method (FEM) with multi-physics COMSOL software. The proposed EMA system can produce magnetic field with different characteristics such as a controllable uniform gradient magnetic field, a rotating magnetic field and a oscillating magnetic field in a three-dimensional space by independently changing the current in each coil. In this paper the 3D motion dynamic equation model of microrobot was established. A novel control method for the gravity compensation for the wireless locomotive microrobot was proposed. The proposed method has the property that the direction of magnetic flux and the locomotion path of the microrobot are independent. Meanwhile, it can achieve the horizontal motions or nearly horizontal motions and overcome the gravity well at the same time. It has been verified by experiments in 3D liquid environment. With the proposed method, the microrobot shows good performance in horizontal motions as well as various motions in the 3D space.

INDEX TERMS Magnetic microrobot, 3D wireless locomotion, electromagnetic actuation system.

I. INTRODUCTION

In recent years, mechanical system has been widely concerned [1], [2]. Wirelesscontrollable microrobots have great

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potential application in the field of biomedicine [3]. These untethered, wireless controllable microrobots could lead to breakthroughs in traditional treatment such as minimally invasive therapies and diagnostics [4], [5]. Because the microrobot is very small, it is very difficult to integrate the traditional power source into the microrobot, the magnetic

field is applied to realize wireless actuation of the microrobot. Magnetic actuation of the microrobot shows good performance with easy controllability and good response, which makes it a good choice for biomedical applications. It is a good choice for biomedical applications because of its good performance with easy controllability and good response [6]. Several groups have carried out researches on electromagnetic actuation (EMA) of microrobot [7], [8]. The field of robotics has made great progress [9], [10].

Some nonuniform magnetic field methods have been proposed to actuate the microrobot. An EMA system which contains four electromagnetic coils was proposed. A microrobot can be controlled to move in a 2D space with the nonuniform magnetic field generated by the coils [11]. A precise closed-loop control of a microrobot in a 3D space by using a EMA system which consisted of 8 independent electromagnetic coils and vision feedback was achieved [12]. An OctoMag system which can achieve 5-DOF motion control of a microrobot was proposed [13]. It has eight electromagnet coils arranged in a certain relationship to produce complex nonuniform magnetic fields. Based on the nonuniform magnetic fields control method, they developed a smaller version of OctoMag, which is called MiniMag and had the similar functions compared to OctoMag [14].

Another magnetic actuation method is applied with the uniform magnetic field. Helmholtz coil can generate a uniform magnetic field, which can be used to align the robot to desired direction. If the structure of the microrobot is spiral structure, the microrobot can be actuated by Helmholtz coil. If the microrobot is other structure, the microrobot is aligned to the desired direction. while Maxwell coil can produce a uniform gradient magnetic field, which can drive the robot moving the aligned direction. In [15], a 2D EMA system has been proposed and designed. It contains a two-axis Helmholtz coil set and a two-axis Maxwell coils set. In [16], the authors proposed a 3D EMA system which consists of a 3-axis Helmholtz coil set, a fixed Maxwell coil and a rotating Maxwell coil. With gravity compensation control method, a microrobot can be moved in a 3D space and achieve 5DoF movement. However, the complexity of the EMA system has been increased with the rotating mechanism. Therefore, an improved 3D EMA system by using three fixed Helmholtz coils and one fixed Maxwell coil has been proposed in [17]. The proposed system had wider working space and less power consumption compared to the previous 3D EMA system [16]. However, the magnetic flux gradient produced by the proposed system was limited in the direction since there is only one pair of Maxwell coils. A locomotion method that used magnetic resonance imaging (MRI) device to drive a ferromagnetic microrobot was proposed in [7], [18]. With the uniform gradient magnetic field from the MRI, the microrobot can achieve 3DoF movement in liquid environment. The advantage of using MRI is that position of the microrobot can be estimated during the actuation, and therefore navigation can be achieved using a predictive control [19]. However, the microrobot can only be moved in

limited directions since that there is no additional coils to produce the desired magnetic field to align the microrobot in arbitrary directions.

In this paper, we design a holonomically-actuated system which can create magnetic forces in any direction with Helmholtz Coils and Maxwell Coils. A 3D EMA system with 3 pairs of Maxwell Coils and 3 pairs of Helmholtz Coils was built to verify the proposed method, which can be seen in Figure 1. It has the property that the direction of magnetic flux and the locomotion path of the microrobot are independent. With the proposed method, the microrobot shows good performance in horizontal motions as well as various motions in the 3D space. Experimental results show that the proposed method has good performance in horizontal motions as well as various motions in the 3D space. Compared with others' work, the novel control method achieves the horizontal motions or nearly horizontal motions and overcomes the gravity well at the same time.
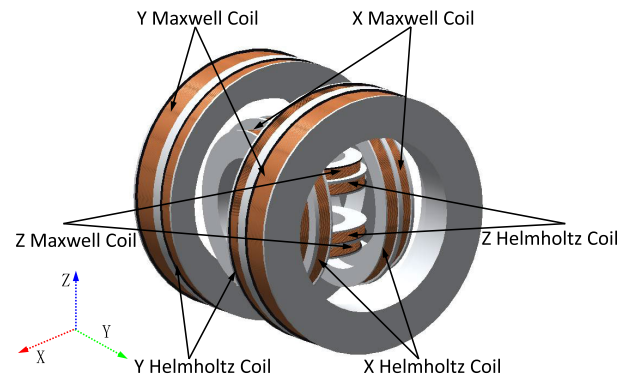

FIGURE 1. Model of the electromagnetic actuation system system.

The organization of this paper is as follows. The magnetic field model will be described in Section II. The motion control of the microrobot in the magnetic field and the proposed gravity compensation control algorithm will be analysed in Section III. The design of the EMA system and magnetic field analysis are discussed in Section IV. Experiments will be carried out in Section V. Finally, a discussion and conclusion will be drawn in Section VI.

II. MAGNETIC FILED MODELS

The microrobot can be controlled with magnetic torque and magnetic field force under the magnetic field. The magnetic field force and the magnetic torque can control the microrobot under the magnetic field. The force and the torque can be expressed as follows,

$$\mathbf{F} = V(\mathbf{M} \cdot \nabla)\mathbf{B} \tag{1}$$

$$\mathbf{T} = V\mathbf{M} \times \mathbf{B} \tag{2}$$

where $\mathbf{F}$ is the magnetic force, $\mathbf{T}$ is the magnetic torque, $\mathbf{B}$ is the magnetic flux, $\mathbf{M}$ is the magnetization of the microrobot and V is the volume of the microrobot. Equation (3) shows the magnetic field models of the Helmholtz coil. Equation (4)

shows the magnetic field models of the Maxwell coil.

$$\mathbf{B}_H(x, y, z) = \left[\left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 NI}{a} \quad 0 \quad 0\right]^T \tag{3}$$

$$\mathbf{B}_M(x, y, z) = [\, g_m x \quad -0.5 g_m y \quad -0.5 g_m z\,]^T \tag{4}$$

where μ_0 is the permeability of vacuum in free space, N is the turns of the coil, I is the current, and g_m is calculated as follows

$$g_m = \frac{16}{3}\left(\frac{3}{7}\right)^{\frac{5}{2}} \frac{\mu_0 NI}{a^2} \tag{5}$$

III. GRAVITY COMPENSATION CONTROL METHOD

Assuming that the microrobot moves in a plane π in the 3D space. The z-axis is in the plane π and the angle between the x-z plane and the π plane is α. The angle between the locomotion direction of the microrobot and the positive direction of z axis is β. Details can be seen in Figure 2.
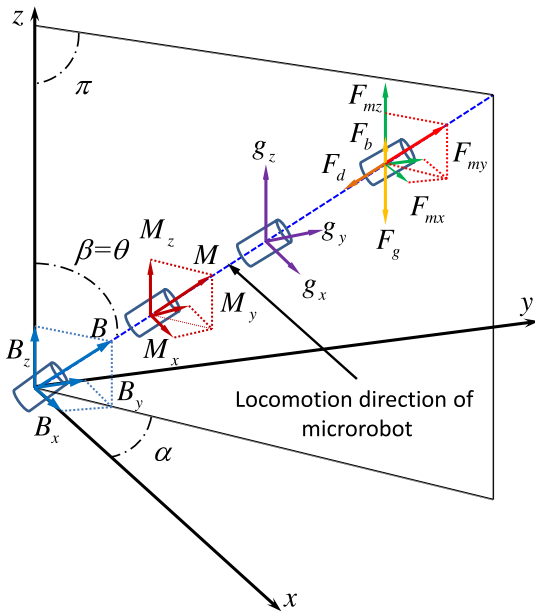

FIGURE 2. The previous microrobot locomotion control method in 3D space. The magnetic flux and the locomotion path share the same direction.

The goal is to determine the driven magnetic field if α and β are known. The angle between the magnetic flux density $\mathbf{B}$ produced by Helmholtz coils anf the positive direction of z axis is θ. If we set the magnitude of $\mathbf{B}$ as a constant, we can obtain the desired $\mathbf{B_d}$ as follows:

$$\begin{cases} B_{dx} = B \sin\theta \cos\alpha \\ B_{dy} = B \sin\theta \sin\alpha \\ B_{dz} = B \cos\theta \end{cases} \tag{6}$$

where $B = \|\mathbf{B}\|$ and $\mathbf{B_d} = (B_{dx}, B_{dy}, B_{dz})^T$. The magnitude of $\mathbf{M}$ also keeps constant and $M = \|\mathbf{M}\|$. The three

components can be expressed as follows:

$$\begin{cases} M_x = M \sin\theta \cos\alpha \\ M_y = M \sin\theta \sin\alpha \\ M_z = M \cos\theta \end{cases} \tag{7}$$

Since V and magnetization $\mathbf{M}$ of the microrobot can be known in advance, the magnetic force $\mathbf{F}$ can be described as follows

$$\begin{cases} F_{mx} = M_x V g_x = M \sin\theta \cos\alpha V g_x \\ F_{my} = M_y V g_y = M \sin\theta \sin\alpha V g_y \\ F_{mz} = M_z V g_z = M \cos\theta V g_z \end{cases} \tag{8}$$

where g_x, g_y and g_z are components of magnetic flux gradient. In order to control the microrobot following the desired path, $\mathbf{F}$ should meet the following equation

$$\frac{F_{mx}}{F_{my}} = \cot\alpha = \frac{M \sin\theta \cos\alpha V g_x}{M \sin\theta \sin\alpha V g_y} \tag{9}$$

From equation (9), it can be seen that $g_x = g_y$. Therefore we use g_h instead of g_x and g_y. We divide F_{mz} into two parts, F_{mz_0} and $F_{mz'}$ because of constant gravity and buoyancy forces in the z direction. F_{mz_0} overcomes the gravity and buoyancy forces and $F_{mz'}$ donates the Z component of the driving force. g_z is also divided into two parts, g_{z_0} and $g_{z'}$. The following equations can be derived:

$$\frac{F_{mz'}}{\sqrt{F_{mx}^2 + F_{my}^2}} = \cot\beta = \frac{M \cos\theta V g_{z'}}{M \sin\theta V g_h} = \cot\theta \frac{g_{z'}}{g_h} \tag{10}$$

$$F_{mz_0} = M\cos\theta V g_{z_0} = V(\rho - \rho_f)g \tag{11}$$

where ρ is the density of the microrobot and ρ_f is the liquid. If the locomotion direction and the direction of $\mathbf{B}$ is the same, we set $\theta = \beta$. Thus $g_{z'} = g_h$ can be derived from equation (10). We can obtain g_{z_0} from equation (11)

$$g_{z_0} = \frac{(\rho - \rho_f)g}{M \cos\theta} \tag{12}$$

If we set suitable g_h according to the experimental environment of the locomotive microrobot, we can obtain the desired $\mathbf{F}$ by equation (8) after the path has been decided. Thus currents of each coils can be estimated and the microrobot can move along the desired path in the 3D ROI. However, if the locomotion direction parameter β is equal to 90° or nearly to 90°, which means that the microrobot moves in a horizontal or approximately horizontal plane, g_{z_0} will tend to infinity according to equation (12). The EMA system cannot produce infinite magnetic flux gradient, therefore the microrobot is unable to move in the horizontal or approximately horizontal plane using this actuation control method. To solve this problem, we propose a novel control method that keeps the angle θ formed by $\mathbf{B}$ and the positive direction of Z axis constant. The actuation method is shown in Figure 3. $g_{z'}$ in equation (10) can be derived as follows:

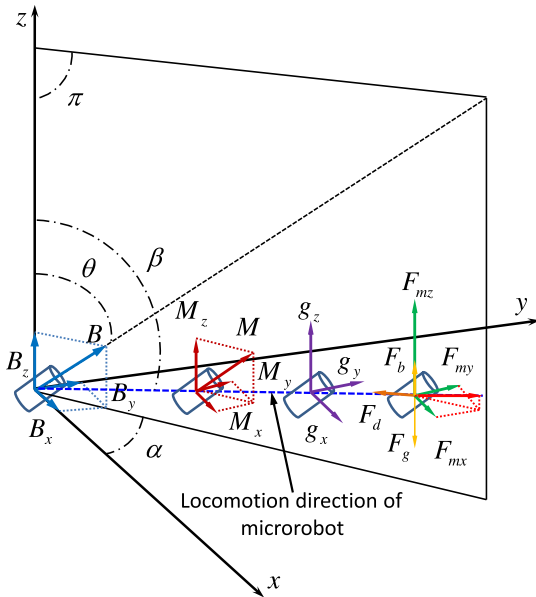$$g_{z'} = \frac{\cot\beta}{\cot\theta} g_h \tag{13}$$

FIGURE 3. The proposed microrobot locomotion control method in 3D space. The directions of the magnetic flux and the locomotion path are different.

And the equation (12) can be expressed as follows:

$$g_{z_0} = \frac{(\rho - \rho_f)g}{M \cos \theta} \leq \max \{g_{z_0}\} \qquad (14)$$

We can obtain the maximum value of θ from equation (14) and set the value of θ in the eligible range. g_{z_0} can then be determined. Finally, the currents of the six-pair coils can be calculated and the control of the microrobot moving in the 3D ROI can be achieved.

TABLE 1. Main parameters of the EMA system.

Coil	Radius $a(mm)$	Coil turns N
Maxwell X	76	289
Maxwell Y	120.7	729
Maxwell Z	49.2	121
Helmholtz X	88	196
Helmholtz Y	130	289
Helmholtz Z	54.4	121

IV. EMA SYSTEM DESIGN

To achieve the proposed actuation method, the EMA system will be built. We set the working space of the magnetic micro robot as $25 \times 25 \times 25mm^3$. The working space center coincides with coordinate origin. Basic parameters of the coils are shown in Table 1. In theoretical calculation, the default radius of each coil is the same. However, in actual machining, the wire is wound in a ring groove layer by layer. It is necessary to reduce the error between theoretical calculation and practical production in order to produce expected uniform magnetic field and uniform gradient magnetic field. In the

EMA magnetic system design, we follow the following three principles. Firstly, in order to improve the uniformity of the magnetic field, the cross section of the coil is square. This ensures that the number of radial layers of the coil is equal to the number of axial layers; Secondly, the radial layer coil radius on the axial coil of the same radial layer can be equivalent to the axial middle position; For coils with different radial layers, the coil radius of adjacent layers differs by the diameter d of one wire. According to equations (15) and (16), we can design the structure of the Helmholtz coil and the Maxwell coil, respectively.

$$\sum_{i=0}^{k-1} \frac{1}{a_0 + d/2 + d \times 1} = \frac{k}{a} \qquad (15)$$

$$\sum_{i=0}^{k-1} \frac{1}{(a_0 + d/2 + d \times 1)^2} = \frac{k}{a^2} \qquad (16)$$

where k is the number of axial and radial layers, a is the theoretical radius value, a_0 is the bottom radius of the groove.

In addition to the radius of coils and turns of copper wires, other parameters of the electromagnetic coil structure can be obtained based on the three criteria of the coil system design. The details of the parameters of the coil structure was found in reference [20]. For the whole spatial magnetic field distribution, it is not enough to calculate the flux density along the Helmholtz coil axis and the flux density gradient along the Maxwell coil axis tightly. In order to ensure that the designed Helmholtz coil and Maxwell coil can achieve the desired results, we carry out three-dimensional simulation of the designed coil structure. Figure 1 shows the simulation model of designed EMA system. Using finite-element-method (FEM) by multi-physics COMSOL software, the magnetic filed values were analyzed to verify the performance of our proposed EMA system.

The magnetic flux density simulation results of the designed Helmholtz coil in the three axes are shown in Figure 4. In the simulation process, we set the current through the coil as 1A. The simulation results of our designed Helmholtz coils show that the magnetic field is almost uniform in the vicinity of position $(0, 0, 0)$. When the each Helmholtz coil passes 1A current, the magnetic flux density of X-axis, Y-axis and Z-axis Helmholtz coils are 1.713mT, 1.126mT, 1.911mT respectively. The results showed that the magnetic field produced by the Helmholtz coils in 3D space is uniform.

The gradient of magnetic flux density simulation results of the designed Maxwell coil in the three axes are shown in Figure 5. In the simulation process, we set the current through the Maxwell coils as 1A. When the each Maxwell coil passes 1A current, the gradient of magnetic flux density in the space near position $(0, 0, 0)$ produced by our designed Maxwell coils was shown in Table 2. The results showed that the magnetic field produced by the Maxwell coils in 3D space is uniform. According to the simulation results, the working space which is in the center of the coils system is
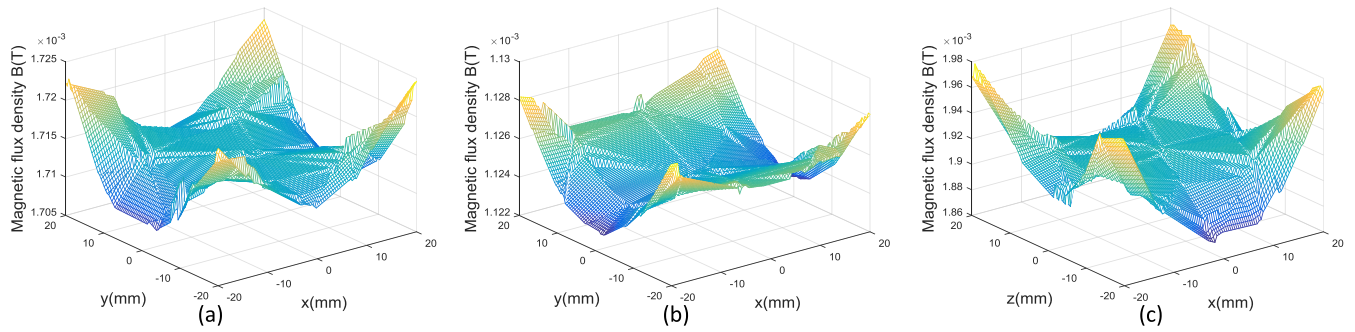
FIGURE 4. Magnetic flux density of the designed Helmholtz coil by FEM analysis. (*a*) *X*-axis Helmholtz coil, (*b*) *Y*-axis Helmholtz coil, (*c*) *Z*-axis Helmholtz coil.
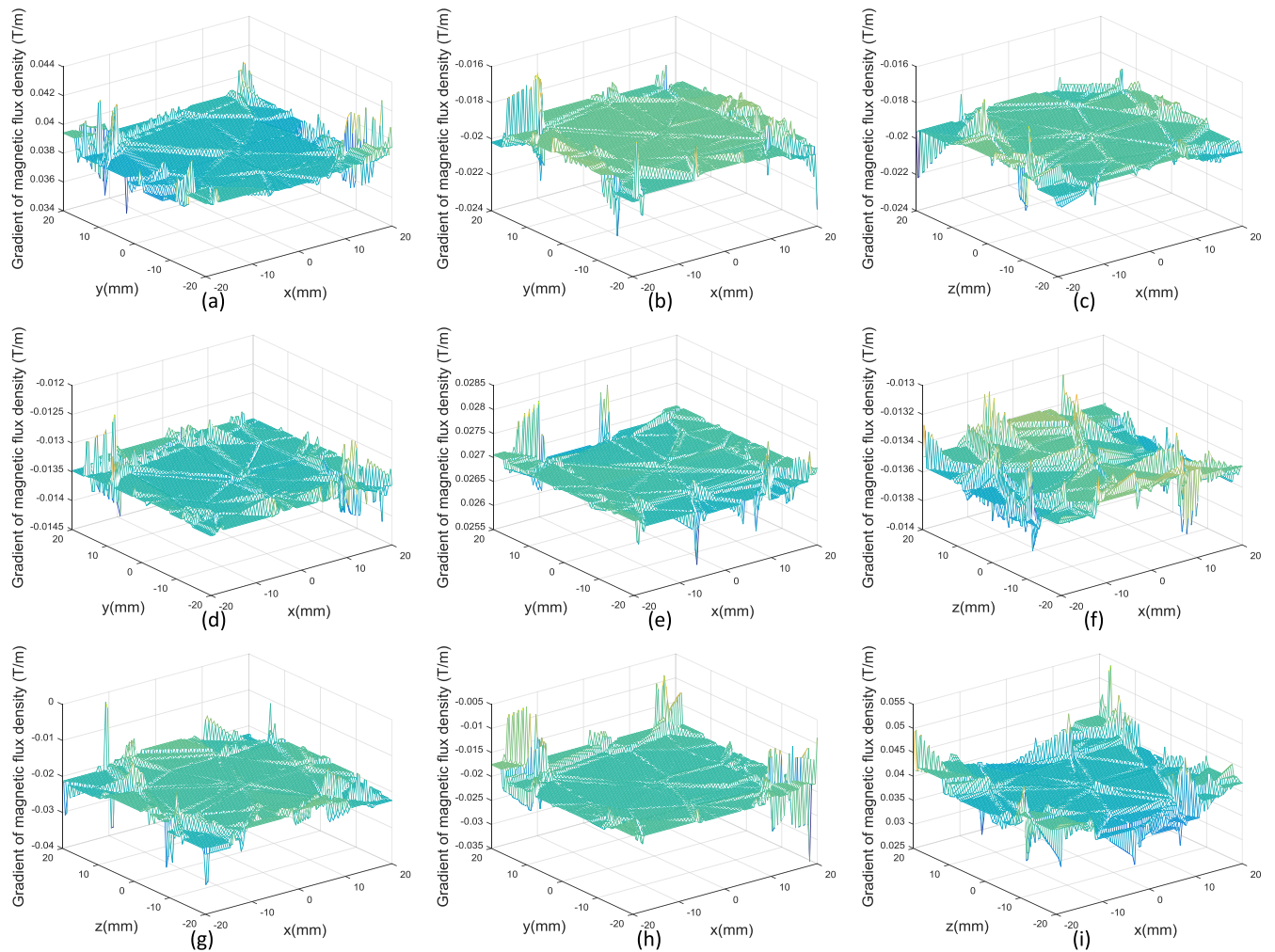

FIGURE 5. Resutls of gradient of the Magnetic flux density of the designed Maxwell coil using FEM analysis. (*a*) Magnetic gradient of *X* direction in *X* − *Y* plane produced by *X* Maxwell coil, (*b*) Magnetic gradient of *Y* direction in *X* − *Y* plane produced by *X* Maxwell coil, (*c*) Magnetic gradient of *Z* direction in *X* − *Z* plane produced by *X* Maxwell coil, (*d*) Magnetic gradient of *X* direction in *X* − *Y* plane produced by *Y* Maxwell coil, (*e*) Magnetic gradient of *Y* direction in *X* − *Y* plane produced by *Y*Maxwell coil, (*f*) Magnetic gradient of *Z* direction in *X* − *Z* plane produced by *Y* Maxwell coil, (*g*) Magnetic gradient of *X* direction in *X* − *Z* plane produced by *Z* Maxwell coil, (*h*) Magnetic gradient of *Y* direction in *X* − *Y* plane produced by *Z* Maxwell coil, (*i*) Magnetic gradient of *Z* direction in *X* − *Z* plane produced by *Z* Maxwell coil.

$25 \times 25 \times 25 mm^3$. In the working space the magnetic filed produced by the Helmholtz coils and the Maxwell coils is uniform at the same time. The values of uniform magnetic flux density and the uniform gradient can then be calculated, and the expression of the $\Lambda_{B,F}(\mathbf{M}, \mathbf{p})$ matrix can be obtained.
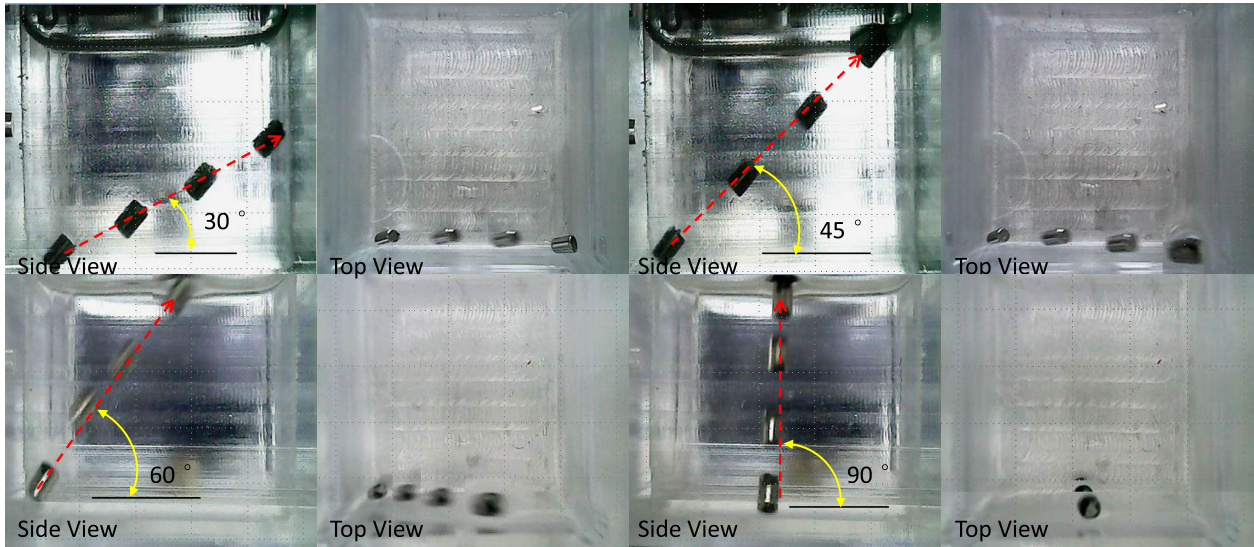
FIGURE 6. Motions of the microrobot with gravity compensation in the *X-Z* plane using the first control method.

TABLE 2. Gradient of magnetic flux density produced by Maxwell coils.

Coil	Gradient in x direction(T/m)	Gradient in y direction(T/m)	Gradient in z direction(T/m)
X	0.0386	-0.0194	-0.0193
Y	-0.0136	0.0270	-0.0135
Z	-0.0199	-0.0199	0.0399

Based on the above simulation and analysis, the EMA system has been set up, which can be seen in Figure 9. It combines a 3-axis Helmholtz coil set and a 3-axis Maxwell coil set. Current fed on coils are generated with DC motor driving device (AQMD3620NS), which can be controlled with a computer program written by VS2010. Two USB digital microscopes(supereyes B005) are used to record the three-dimensional motion of the magnetic microrobot. The purpose of the magnetic actuation control system is to actuate the microrobot from the current position to the target position. Due to the inertia of the mechanical system itself, it will cause time lag in the transmission of energy and information. At the same time, due to the external noise, it will cause the magnetic microrobot movement deviation. In order to control the stable movement of the magnetic microrobot, the position of the microrobot was obtained by the two cameras. The difference between the expected position information and the actual position information can be used as the input of the control end signal. PID algorithm is used to control the output current of the driving device and realize the control of space magnetic field. In this way, the motion of microrobot can be closed-loop controlled. Figure 10 shows the block diagram of control principle of the magnetic microrobot. P is the actual position and Pd is the expected position in the Figure.

V. EXPERIMENT
For further evaluation of the performance of the proposed control method, experiments have been carried out based on the EMA system. The microrobot is a cylindrical NdFeB (N42) magnet with a 2mm diameter and 3mm height. The working space is filled with silicone oil of kinematic viscosity(350cs). The camera views are shown in Figure 11. After the experimental platform has been set up, several experiments have been conducted to further verification of the performance of the proposed control method.

Firstly, in order to verify the proposed two gravity compensation control methods, the 2D microrobot actuation experiments in the x-z plane were done. The results of the locomotions of the magnetic microrobot in the x-z plane using the first control method are shown in Figure 6. The magnetic microrobot can be moved in the various desired directions (30°, 45°, 60°, 90°). Using this control method, firstly, the microrobot was aligned to the desired direction by the uniform magnetic produced by the Helmholtz coils. Then, the magnetic microrobot was actuated in the desired direction by the the uniform magnetic flux gradient produced by the Maxwell coils. Using the second improved control method, we only keep the value of θ constant which means the ratio of B_x and B_z is set to $tan\theta$. The locomotion direction of microrobot β depends on the magnetic flux gradients produced by Maxwell coils. The locomotion results are shown in Figure 7.

Secondly, we choose an arbitrary plane in the 3D ROI to verify the 3D motion of the microrobot. We use the improved control method to carry out the gravity compensation actuation of the microrobot since some motions in the horizontal or approximately horizontal plane request huge magnetic flux gradient in the Z direction when using the first control method, while the magnetic flux gradients produced by coils have limitations. We conduct microrobot actuation
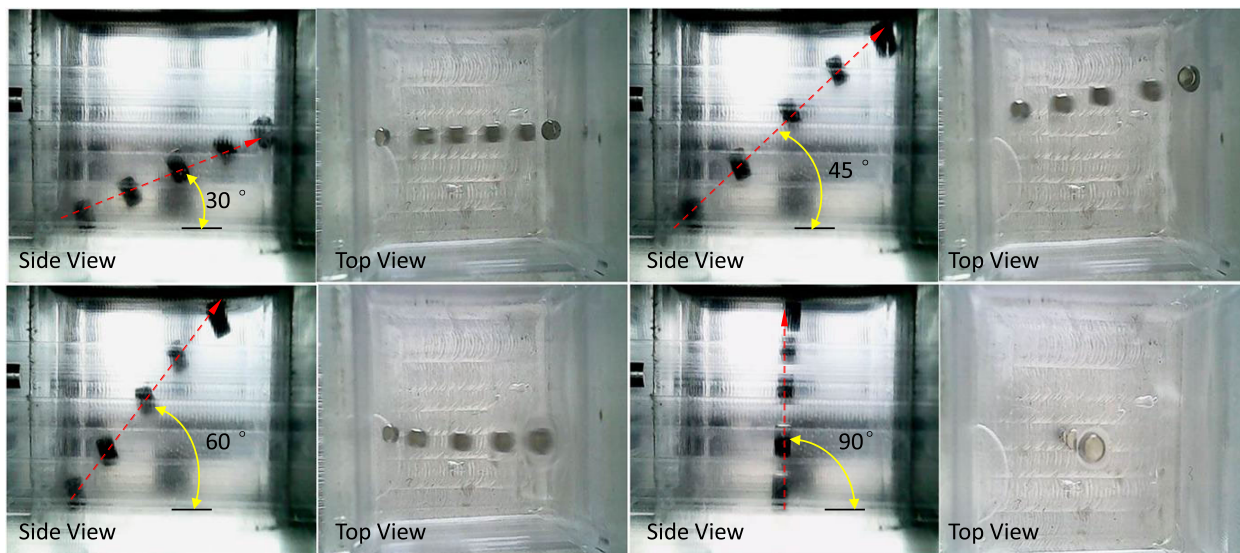
FIGURE 7. Motions of the microrobot with gravity compensation in the *X-Z* plane using the second control method.
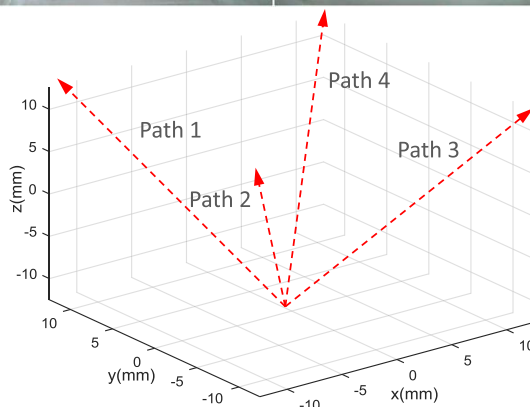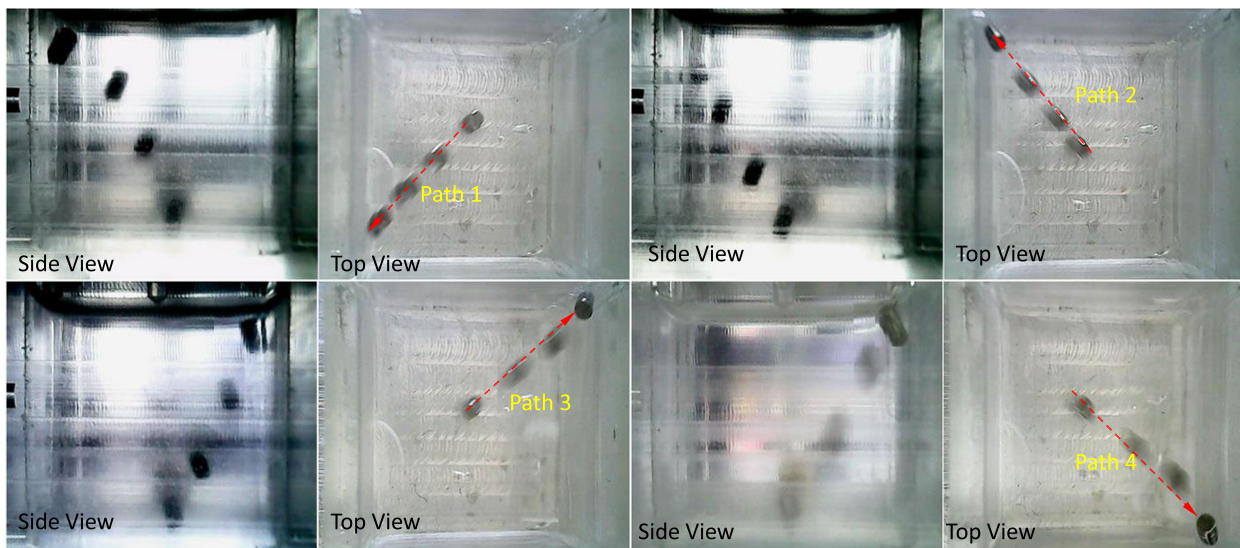

FIGURE 8. Motions of the microrobot with gravity compensation in the 3D ROI.

tests along four planning paths, in which α is $-135°$, $135°$, $45°$ and $-45°$, respectively. β is $35°$. Those two parameters determine the locomotion directions of microrobot.

Figure 8 shows the results of the 3D wireless actuation of the microrobot along the different paths. The EMA system we designed is capable of wirelessly actuating the microrobot
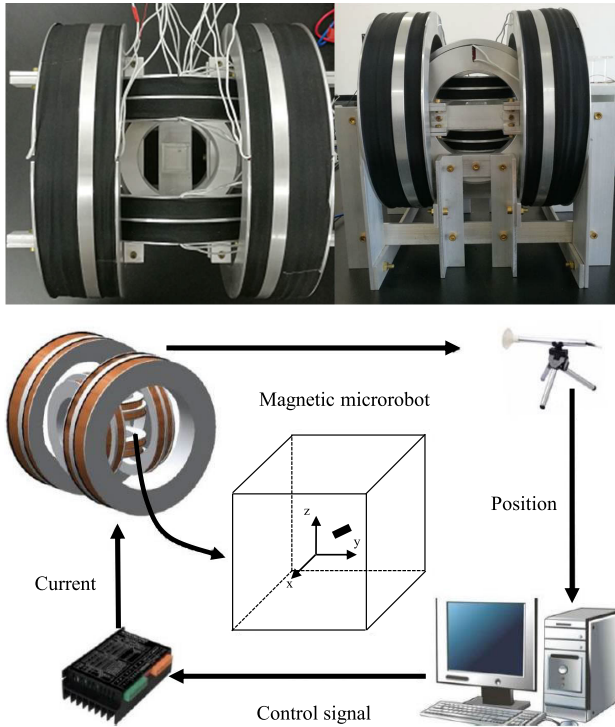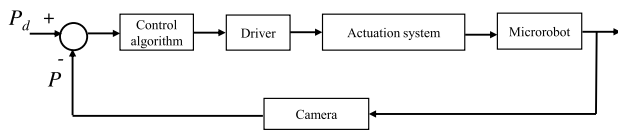
FIGURE 9. Experimental platform of the EMA system.

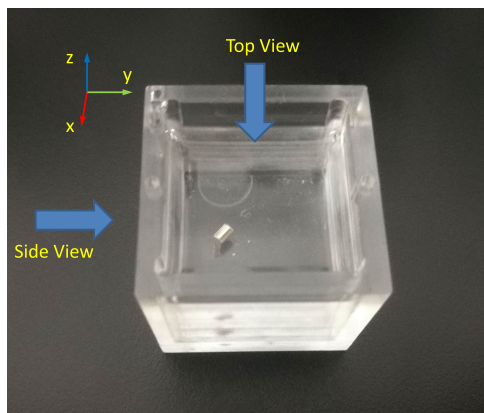**FIGURE 10.** Diagram of visual position feedback control of EMA system.

FIGURE 11. The camera views when recording the 3D motions of the microrobot.

in the 3D space. The proposed control method is also verified.

Lastly, we conduct an experiment to verify the ability to achieve horizontal actuation motions of microrobot by using the second control method. Figure 12 shows the result of a rectangular path motion of the microrobot in the 3D space.
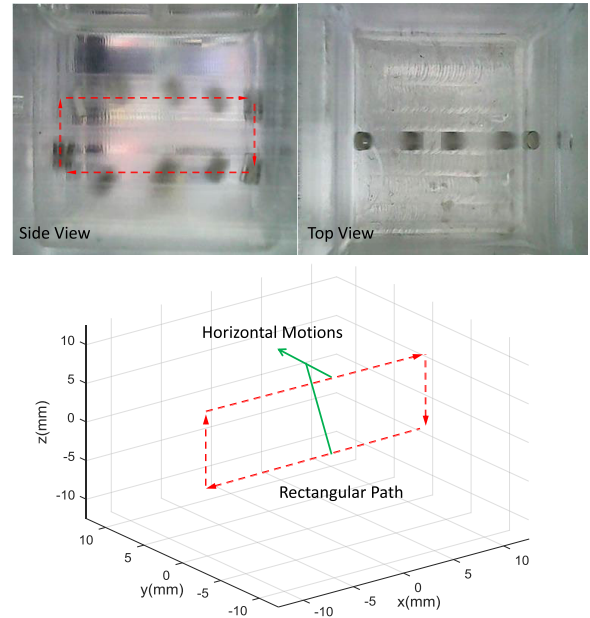

FIGURE 12. Motions of the microrobot when following a rectangular path.

In order to achieve the rectangular path motion in the space, the microrobot needs to accomplish twice the horizontal vertical motions. The result shows that the microrobot can be actuated in a horizontal plane with gravity compensation to achieve the rectangular path motion in the 3D ROI. Since there are some errors between the ideal horizontal motions and the actual experiments while the actual experiment achieves, strictly speaking, the approximately horizontal motions, we can still think that the second method we proposed shows good performance in solving the horizontal motions of wireless actuation microrobot and overcoming the gravity at the same time.

VI. CONCLUSION

In this paper we built an electromagnetic actuation system (EMA) which combined with Helmholtz coil and Maxwell coil to control the magnetic microrobot. The three-dimensional configuration is imported into the physical field COMSOL software. The magnetic field of the coil is simulated by the finite element method and the relevant mathematical model is verified. The structural parameters of the coil are optimized and the design criteria from the ideal coil model to the actual coil model are proposed. The control algorithm of 3D driving gravity compensation for micro robot is proposed. And the closed-loop control algorithm based on position information feedback was proposed. The proposed control method was demonstrated to be capable of solving difficulties in horizontal or approximately horizontal motions. At last, a variety of experiments were done to verify the performance of proposed system and the control method. The experimental results show that the proposed EMA system can wirelessly actuate the magnetic microrobot in the 3D space along the planning path. The microrobot can be

actuated in various paths including the horizontal or approximately horizontal motions by using the proposed control method.

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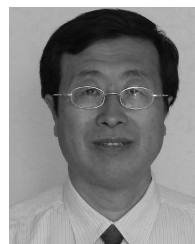
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