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Three-Dimensional Electromagnetic Actuation System for Intravascular Locomotion

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***Abstract* - Various types of actuation methods for intravascular locomotive microrobot have been proposed and demonstrated. Among the actuation methods, electromagnetic based actuation (EMA) was considered as a promising mechanism. In generally, planar EMA systems for 2 dimensional movement of the microrobot were proposed and demonstrated. In this paper, we present 3 dimensional (D) EMA systems for the 3D space locomotion of the microrobot. The proposed system consists of a coil system and a robotic actuation system. The coil system has a pair of Helmholtz coils and a pair of Maxwell coils, and the robotic actuation system has a serial robot structure with roll-pitch-roll rotational axes which can rotate about three orthogonal axes (X, Y and Z). Finally, through experiments, we can demonstrate 3D movement of the microrobot by using the proposed EMA system. The proposed EMA system can be utilized for the 3D actuation of the intravascular microrobot.**

I. Introduction

OWING to a lack of exercise and an aging society, modern peoples suffer from cardiovascular diseases. Especially, coronary arteries which can supply heart with nutrients are very important vessels. Abnormal coronary arteries surround the heart causes cardioplegia and increase the death rate [1]. Drug therapy, coronary artery bypass graft (CABG) and catheterization is used for coronary arterial disease (CAD) treatments.

Drug therapy is restrictively used for dissolution and inhibitory actions of growth of thrombus in the coronary artery. And making a detour vessel method instead of blocked artery, CABG has a drawbacks which is long term recovery and hard to operate. Catheterization is comparatively simpler surgical operation than CABG method and largely used in a hospital. However, the medical treatment of chronic total occlusion (CTO) has the limitation of a delicate operation [2].

With these circumstances, operations of micro robot to treat injuries like a thrombus in a blood vessel is need to be developed [3]. It is very difficult to drive micro robot because of small size of vessels. For the solution of this problem, this paper investigates EMA system that can change position of micro robot using electromagnetic field.

Recently, many researches of MEMS and robot technologies are carried out. One of these researches is advanced with electromagnetic field acquiring mobile force of micro robot [4]. Using magnetic field, medical magnetic resonance imaging (MRI) gradient coils driving micro robot is one of the studies [5]. This method has advantages of vision acquisitions and migration paramagnetic micro robot. But it has limitations of MRI system because of fixed coils that restrict degree of freedom.

M. Sitti conducted experiment of permanent magnet millimeter size robot using five rectangle types' coils to move [6]. Micro robot in this method repeats stick-slip motion to move forward after sending a current at fixed coils. It is a good point to have a fixed structure, but the repeated stick-slip motion is not appropriate to medical treatment.

B. J. Nelson executed the movement of ferromagnetic microrobot in a plane with Helmholtz and Maxwell coil pairs which can be rotated by motor [7]. First of all, the rotation of Helmholtz coil can generate torque and rotate our microrobot. And the activation of Maxwell coils generates the movement of the microrobot in a straight line. Therefore, our microrobot can locomote in 2D plane. However, it is not possible that the microrobot moves in 3D space.

This paper proposes a new EMA system which can show the movement of the microrobot in 3D space. The proposed system consists of a pair of Helmholtz and Maxwell coils and 3D structure that can roll-pitch-roll motion. Through various experiments, the performances of the proposed EMA system are evaluated.

II. Theory

According to Biot-Savart theory, when an electrical current in a coil flow, the magnetic field is generated [8]. The magnitude of magnetic field is decided by current intensity. If the coil had a circular shape and the current had a magnitude of i, the magnetic field along the center of the coil was calculated as the following equation:

$$H = \frac{ir^2}{2(r^2+z^2)^{\frac{3}{2}}}\ , \qquad (1)$$

where i is current intensity at coil, r is radius of the circular shape of the coil and z is the distance from the coil center.

From this equation, the magnitude of magnetic field generated by coil is directly proportional to the current

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intensity and the magnitude of magnetic field generated by coil is in inverse proportion to cubic *z.*

B.J Nelson introduced the EMA system by using a pair of Helmholtz coils and a pair of Maxwell coils. The Helmholtz coil pair can generate uniform magnetic field. And the Maxwell coil pair can generate gradient magnetic field.

The magnitude of magnetic field generated by a pair of Helmholtz coil base on the following equation:

$$H_{zh}=\frac{i\times n\times r^2}{2}\left(\frac{1}{\left[r^2+\left(\frac{d}{2}-z\right)\right]^{\frac{3}{2}}}+\frac{1}{\left[r^2+\left(\frac{d}{2}+z\right)\right]^{\frac{3}{2}}}\right) \quad , \tag{2}$$

where i is current intensity at coil, r is radius of the circular shape of the coil. n is the number of coil turns, d is the distance from the coil center.

Similarly, the magnitude of magnetic field generated by a pair of Maxwell coil base on following equation:

$$H_{zm}=\frac{i\times n\times r^2}{2}\left(\frac{1}{\left[r^2+\left(\frac{d}{2}-z\right)\right]^{\frac{3}{2}}}-\frac{1}{\left[r^2+\left(\frac{d}{2}+z\right)\right]^{\frac{3}{2}}}\right) \quad , \tag{3}$$

Then, the ferromagnetic microrobot is magentized and actuated by the Helmholtz coil and the torque(τ_m) is calculated as

$$\tau_m = v_m\vec{M}\times\vec{B} \quad , \tag{4}$$

Where v_m is volume of microrobot, $\vec{M}$ is the saturated magnetization, $\vec{B}$ is magnetic flux. According to principle of torque generation, microrobot can be rotated for the pair of Helmholtz coil's rotary motion.

And linear propulsion force (F_m) by Maxwell coils is calculated as

$$F_m = v_m(\vec{M}\bullet\nabla)\vec{B} \quad , \tag{5}$$

where v_m is volume of microrobot, $\vec{M}$ is the saturated magnetization, $\vec{B}$ is magnetic flux. $\vec{B}$ is defined as

$$\vec{B} = \mu_0(\vec{H}+\vec{M}) \quad , \tag{6}$$

Where μ_0 is permeability in vaccum environment, $\vec{H}$ is the magnitude of the magnetic field. Therefore, the magnetic flux is proportional to the magnitude of the magnetic field.

Finally, the magnetic field generated by Hemlholtz coil and Maxwell coil can locomote microrobot in 2D plane.

III. ELECTROMAGNETIC ACTUATION DESIGN AND FABRICATION

A. Design of 3D EMA system

For the 3D actuation of microrobot, we designed EMA system which consists of has a pair of Helmholtz coils, a pair of Maxwell coils, and robotic actuation system. Fig. 1 is a schematic diagram of 3D EMA system. The proposed 3D EMA system has three axes (roll-pitch-roll) [9]. And coil system is located at the end of three axes actuation system. A counterclockwise rotation is defined as the plus sign direction and the axes of $Roll_{(1)}$, Pitch and $Roll_{(2)}$ are defined as Fig. 1.

For the kinematic equation, the three axis (roll-pitch-roll) robotic system is described as links parameters (Table 1) by Denavita-Hartenberg (D-H) notation. From the D-H notation, the transfer matrixes of each axis are derived as follows:

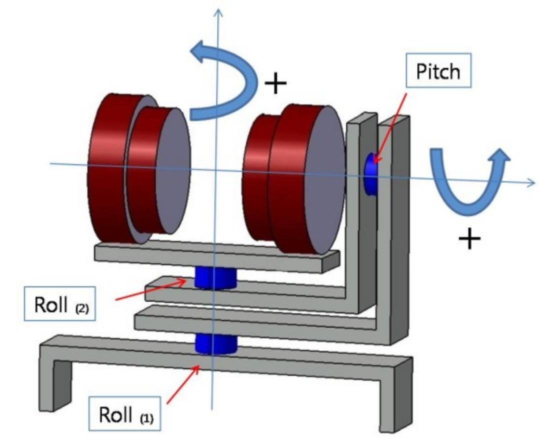

Fig. 1 Schematic of 3D EMA System

TABLE 1
LINK PARAMETER OF 3D EMA SYSTEM

i	$\alpha_i - 1$	$a_i - 1$	d_i	θ_i
1	0	0	0	θ_1
2	90°	0	0	θ_2
3	-90°	0	0	θ_3

$$ {}^{0}_{1}T=\begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0\\ s\theta_1 & c\theta_1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix},\ {}^{1}_{2}T=\begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 0\\ 0 & 0 & -1 & 0\\ s\theta_1 & c\theta_2 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix},$$

$$ {}^{2}_{3}T=\begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & 0\\ 0 & 0 & 1 & 0\\ -s\theta_3 & -c\theta_3 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}. \tag{7}$$

Therefore, the final transfer matrix (${}^{0}_{3}T$) is derived as

$$ {}^{0}_{3}T= \begin{bmatrix} c\theta_1c\theta_2c\theta_3-s\theta_1s\theta_3 & -c\theta_1c\theta_2s\theta_3-s\theta_1c\theta_3 & -c\theta_1s\theta_2 & 0\\ s\theta_1c\theta_2c\theta_3+c\theta_1s\theta_3 & -s\theta_1c\theta_2s\theta_3+c\theta_1c\theta_3 & -s\theta_1s\theta_2 & 0\\ s\theta_2c\theta_3 & -s\theta_2s\theta_3 & c\theta_2 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{8}$$

From the Eq. (8), the end position of the robot system (the center of coil system) does not have any linear displacement (p_x, p_y, p_z) but angular displacements (α, β, γ) by the rotation ($\theta_1\theta_2\theta_3$) of three axes.

When each axis of the proposed EMA system rotates, Fig. 2 shows the configurations of the system and the representative plane which the microrobot can move. And Table 2 means the axis coordinate values which are corresponding to the configurations of the 3D EMA system in Fig. 2. Firstly, when $roll_{(1)}$ and pitch axes are fixed at an angle of 0 degrees, the rotation of $roll_{(2)}$ axis shows the planar motion on XY plane. Therefore, the microrobot has the 2D locomotion on the XY plane. Similarly, when $roll_{(1)}$ and pitch axes are fixed at angles of 0 and 90 degrees, respectively, the rotation of $roll_{(2)}$ axis shows the motion on XZ plane and makes 2D locomotion of the microrobot on XZ plane. Lastly, when the $roll_{(1)}$ and pitch axes are set to an angle of 90 degrees, the $roll_{(2)}$ motion shows the movement on YZ plane and generates 2D locomotion of the microrobot on YZ plane. Based on this robotic roll-pitch-roll mechanism, 3D EMA system can realize the 3D locomotion of the microrobot.

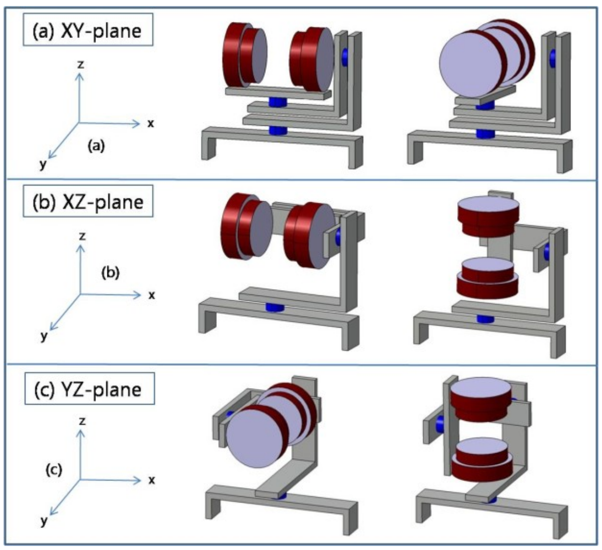

Fig. 2 3D Representative Configurations of 3D EMA System

TABLE 2
REPRESENTATIVE CONFIGURATION OF 3D EMA SYSTEM

Plane	Case 1	Case 2
XY	R_1PR_2(0° - 0° - 0°)	R_1PR_2(0° - 0° - 90°)
XZ	R_1PR_2(0° - 90° - 0°)	R_1PR_2(0° - 90° - 90°)
YZ	R_1PR_2(90° - 90° - 0°)	R_1PR_2(90° - 90° - 90°)

B. Fabrication of EMA coil and Robot actuation system

For the fabrication of 3D EMA system, firstly, EMA coil system is designed and fabricated. The key design parameters of coil system are the number of coil turns and the distance of two coil. Because of the restriction of space, it is difficult to design the two coil pairs (Helmholtz coils and Maxwll coils) with a same radius and a desired magnetic field intensity. Therefore, the two coil pairs with different radiuses are designed and they can generate a desired magnetic field in region of interest (ROI).

TABLE 3
SPECIFICATION OF EMA COIL SYSTEM

	Helmholtz Coil	Maxwell Coil
Radius	95mm	98mm
Coil turns	279	390
Wire Diameter	1mm	1.2mm

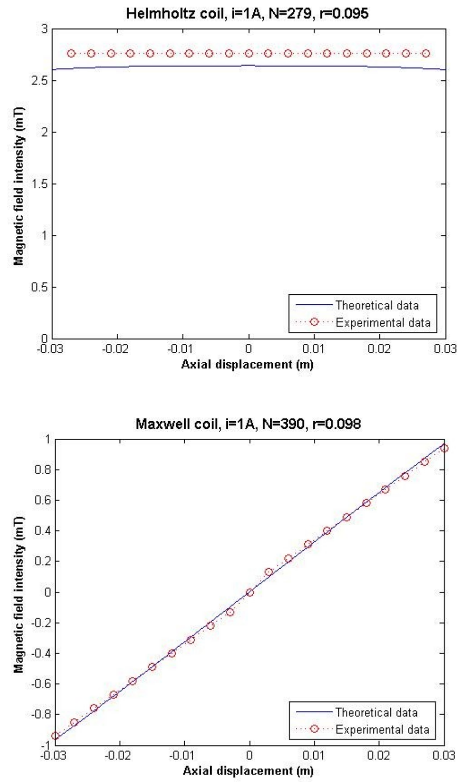

Fig. 3 Preliminary Test of the EMA coil System

Therefore, Helmholtz coil and Maxwell coil system are designed as follows. Firstly, we decided our ROI domain as a simple sphere with 60mm diameter. Based on the ROI domain, the radiuses of Helmholtz coil and Maxwell coil are designed as 95mm and 98mm, respectively. The numbers of coil turns are 279 times in Helmholtz coils and 390 times in Maxwell coils. Finally, for the fabrication of Helmholtz and Maxwell coil, the copper wires are used and the diameters of the copper wires are 1mm and 1.5mm, respectively. The specification of EMA coil system is described in Table 3.

For the preliminary test, the magnetic field measurements of EMA system are executed. That is, when constant currents are applied to Helmholtz coil and Maxwell coil, the magnetic fields of EMA system are measured. The magnetic flux can be measured by using Gaussmeter (SYPRIS, MODEL 6010) along the center line of the coils. In addition, the theoretical values are calculated from the Eq. (2) and Eq. (3) using MATLAB. Fig. 3 shows the measurement results and theoretical values of EMA system. From Fig. 3, we confirmed that Helmholtz coils pair generates a uniform magnetic flux density and Maxwell coils pair generates a uniform gradient magnetic flux density.

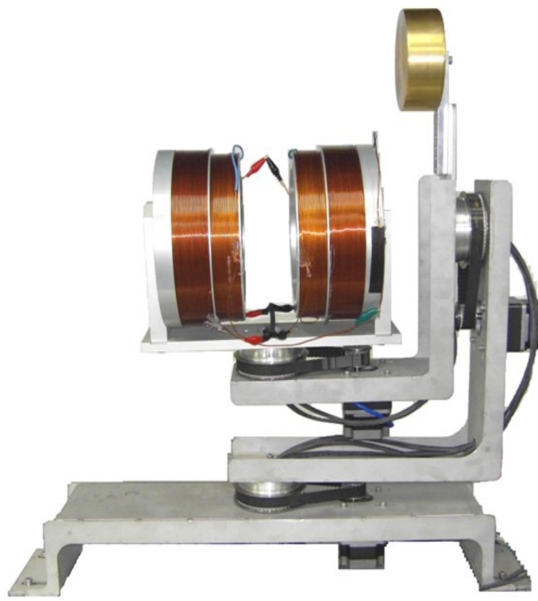

Fig. 4 Prototype of 3D EMA System

Based on the schematic (Fig. 1) of 3D EMA system, a prototype was fabricated as shown in Fig. 4. The size of the system has 60cm of width, 60cm of height, and 15cm of depth. The weight of the system is about 30kg. This system consists of EMA coil system, roll-pitch-roll axis rotational mechanism, and three stepping motor. The step motors and the rotational axes are connected by belts and for the compromising of the gravitation effect, a count balance mass is introduced. For the roll-pitch-roll motions of the proposed mechanism, conventional stepping motors (pk264A1-SG36, Oriental Motor Company) are used.

IV. Experiment

A. Experimental Setup for 3D Locomotion test

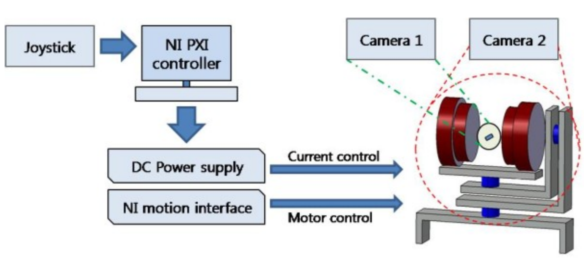

Fig. 5 Schematic of Experimental Setup for 3D Locomotion Test

Through various experiments, we want to verify that the proposed system can show 3D locomotion of microrobot. As a microrobot, cylindrical (diameter 2mm, height 2mm) neodymium magnet is used in these experiments. Fig. 5 shows the schematics of experimental setup for 3D locomotion tests of our EMA system. Firstly, the proposed 3D EMA system was installed on the optical table. For the

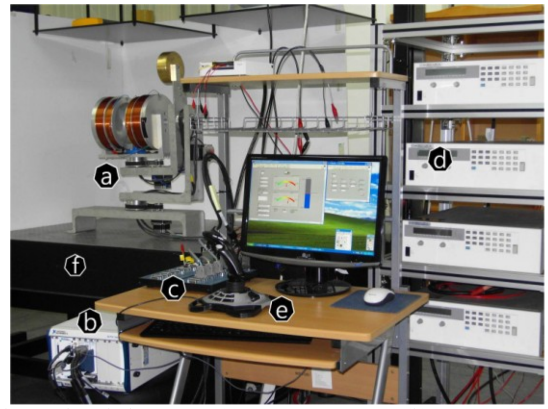

Fig. 6 The whole system. (a) 3D EMA System, (b) NI PXI, (c) NI motion interface, (d) Power supplier, (e) Joystick, (f) Optical table.

measurement of the movement of the microrobot, two camera systems (camera 1 and camera 2) were used. In detail, camera 2 monitors the configuration of the whole 3D EMA system and camera 1 precisely observes the motion of the microrobot. The coil current of the EMA system could be adjusted by the programmable power supplier (Agilent 6652A) and the motors of the roll-pitch-roll axes were controlled by the motor drivers. The power supply and the motor drivers were controlled by NI-PXI (National Instruments) system. For the control of EMA system, we adopted a conventional joystick. The rotation angles of EMA system were controlled by the steering of the joystick and the current intensities were adjusted by the throttle lever of joystick. The experimental setup is shown in Fig. 6.

B. Fundamental Experiments of 3D Locomotion

Before the evaluation of the 3D locomotion of the microrobot by 3D EMA system, two kind of simple experiments were executed. The locomotion tests of the microrobot by 3D EMA system were performed along the horizon path and the vertical path, respectively. These two types of experiments could be regarded as the representative basic locomotion tests. For the tests, we introduced a straight path made by hollow plain glass tube with 60mm of length and 5mm of diameter and this tube is filled with silicone oil. The silicone oil has the viscosity of 100cp and reduces the abrupt motion of the microrobot by its drag force.

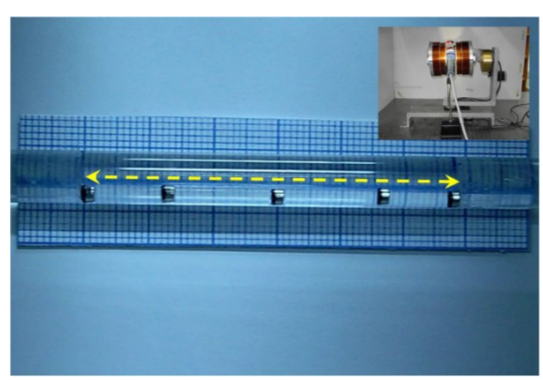

Fig. 7 Locomotion of Microrobot along Horizontal Path

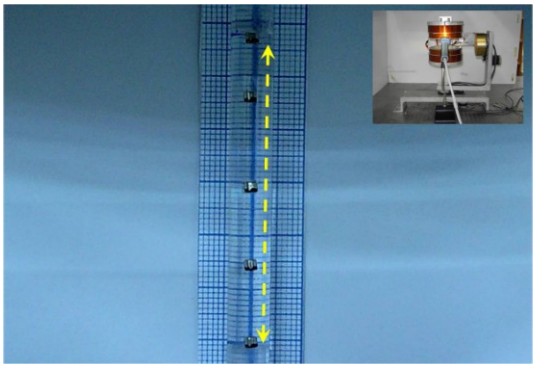

Fig. 8 Locomotion of Microrobot along Vertical Path

Fig. 7 shows the locomotion result of the microrobot along the horizontal path. We could observe that the microrobot moved from side to side of the horizontal path. For the direction switch of the microrobot, the current direction of Maxwell coils should be changed. By the adjusting of the current intensity of Maxwell coils, the velocity of the microrobot could be controlled.

Similarly, the vertical movement of the microrobot was tested as shown in Fig. 8. The microrobot shows the up and down motion along the vertical path. In this experiment, it is confirm that the proposed 3D EMA system overcomes the effect of the gravitation force of the microrobot.

For the detail comparison, the slops of the path for the locomotion were varied from 0 to 90 degree and the fine motions of the microrobot were investigated. The motions of the microrobot were recorded by video camera with 30 frames/sec and the speed of the microrobot was analyzed by the image frame of the video clip.

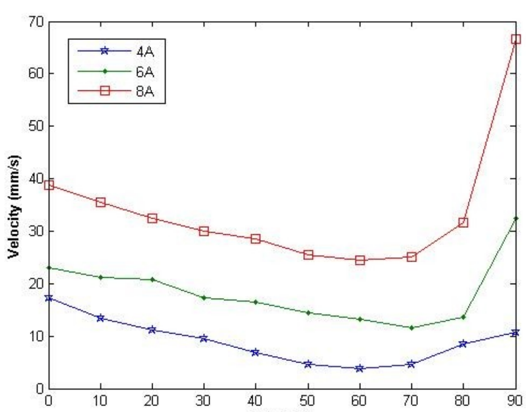

Fig. 9 Velocity of Microrobot by Path's Angle

Generally, owing to the effect of the gravitational force, as the angle of the path increases, the speed of the microrobot will decrease. However, the experimental results showed the different phenomena, as shown in Fig. 9. For the path with the slope from 0 to 70 degree, as the slopes increased, the velocity of the microrobot decreased. However, on the contrary, the velocities of the microrobot rapidly increased in case of 80 and 90 degrees. From these results, we could estimate that the microrobot is influenced by the gravitation force and the friction force. And the effect of the friction force between the microrobot and the surface of the path could be different phenomena compared with the friction in macro objects. When the constant currents (4A, 6A, and 8A) were applied to Maxwell coils, the microrobot showed the high velocity at high input current.

Fig. 10 Cross Path for Locomotion Test

C. *Experimental Results for 3D Locomotion*

In order to show the locomotion of the microrobot by 3D EMA system, a straight cross path was designed and fabricated, as shown in Fig. 10. The path is made by hollow plain glass and has 80 x 80 x 80mm of size and 5mm of inner diameter. For the exclusion of the sudden motion of the microrobot and the consideration of the effect of drag force, the path was filled with silicone oil of high viscosity (1000cp). By using the cross path, we could confirm the possibility of the 3D locomotion of the microrobot and estimate the feasibility of the locomotion of the microrobot in the blood vessel of human body.

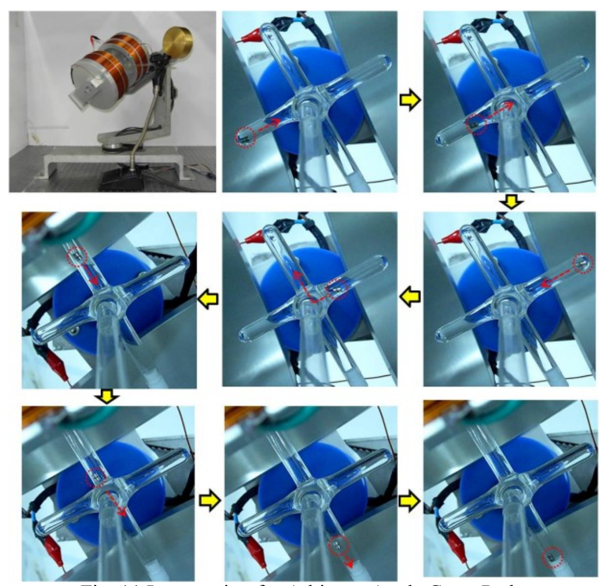

Fig. 11 Locomotion for Arbitrary Angle Cross Path

Finally, for the 3D movement of the microrobot, the path is adjusted to have arbitrary angles and the locomotion of the microrobot was tested as shown in Fig. 11. The $roll_{(1)}$-pitch axes were set to be an angle of (45,45) degree and the $roll_{(2)}$ axis was controlled. From the experiments, we could find that the microrobot can move freely in the arbitrary path and maintain the position. Through these experiments, we realized that the motions of microrobot in arbitrary 3D plane are possible.

However, the 3D EMA system has some restriction of the positioning of the target object, such as human body and the position recognition of the microrobot and the path. That is, the proposed 3D EMA system is able to locomote the microrobot in 3D space. But, the structure of 3D EMA system is not reasonable for the human's medical application.

V. CONCLUSION

For the locomotion of the microrobot, the method using electromagnetic system was studied. In previous study, 2D plane EMA system was proposed and the system consists of a pair of Helmholtz coil and Maxwell coil and a rotational motor. In this paper, 3D EMA system was proposed for the 3D locomotion of the microrobot. Similar with 2D plane EMA system, 3D EMA system has a pair of Helmholtz coil and Maxwell coil. In addition, for the 3D spatial motion of 3D EMA system, our proposed system has adopted a roll-pitch-roll robotic system. Firstly, the proposed 3D EMA system was analyzed and fundamentally tested. For the evaluation of the 3D locomotion, the various experiments were executed. Through these various experiments, we could confirm that the proposed 3D EMA system can be a feasible solution of the locomotion of the microrobot. However, owing to their some restriction, such as the positioning of the target object and the position recognition, the 3D EMA system should be improved. Also there are still some problems that we need to solve, such as the EMA system size and the coating of the robot with biocompatible material, the positioning precision of the microrobot, and the actuation in the real blood vessel. This is the point of the question which we must consider. In the future, we will propose a new 3D EMA system which can be applied to human body.

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