Swimming microrobot actuated by two pairs of Helmholtz coils system

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1. Introduction

Worldwide research on medical microrobots has shown much progress and developments in the ongoing efforts to decrease damage to a human body during an operation and to reduce operation time. Especially, microrobots that can move along blood vessels and treat specific parts of body have received much attention. The ultimate objective of the microrobot is to approach its destination accurately and quickly. Generally, small motors and smart materials, such as IPMC and SMA, are known used as actuators for the microrobot. However, they sometimes occupy most of volume of the microrobot, and thus they cannot be practically applied to a microrobot.

To solve this problem, electromagnetic based actuation (EMA) systems for microrobot were used, and the driving mechanisms of biomedical microrobot using EMA systems were studied [1,2]. Kosa et al. suggested a movable microrobot in the body using an external magnetic field of MRI [3,4]. In the microrobot, coil patterns generate current through external electromagnetic induction. The microrobot can move by the interaction between the external magnetic field and the magnetic field generated from the induced current. Because the microrobot drives in MRI, the position of the microrobot and the target destination can be estimated from MRI image. In addition, such a system does not need other external coil systems. However, owing to its complicated structure, it is very difficult to realize a small microrobot whose moving direction can be controlled by using only the MRI system.

Guo et al. suggested a simple swimming microrobot [5–7] which has a magnet and a fin attached the magnet directly. The microrobot moves along a pipe, which is surrounded by a coil. Current flowing through this coil generates a magnetic field along the pipe. In this system, the microrobot has a simple structure and has fast moving speed. However, the microrobot can move only inside the coiled pipe and cannot be applied to the human body. In addition, it is difficult steer the microrobot in a certain direction and to control the swing angle of the fin.

Masahiro et al. suggested a turning fish type microrobot using an NdFeB magnet. Its movement is very similar to the real swimming motion of a fish [8]. An external magnetic field is generated by a coil. When both the basic input offset and frequency of the sinusuous function current or modifying wave form are changed, the robot moves either straight or turns. A magnet in the fish type robot is wire-connected with the fin so that the robot can turn naturally. But this type of robot cannot be made small due to the wire connection, and it is also difficult to control precisely because the robot is controlled by a coil.

In this paper, a tadpole shaped swimming microrobot is proposed. The tadpole microrobot has a simple structure and simple parts, but it can be controlled precisely because EMA system with two pairs of Helmholtz coils was used. Therefore, the tadpole microrobot can freely swim with various motions in a water bath in the region of interest (ROI) of the EMA system. The swimming motion of the microrobot can be changed by controlling the swing angle of the fin and the frequency of the swing motion. Through various experiments, the control parameters such as the swing...
angle and the frequency were optimized, and the actuation performance of the microrobot was demonstrated.

2. Fabrication of EMA coil structure and swimming microrobot

2.1. EMA coil system

Generally, a pair of Helmholtz coils is used to generate a uniform magnetic field in the region of interest (ROI) [9]. When a permanent magnet is located in the uniform magnetic field generated by a Helmholtz coil, it rotates to align in the direction of the generated uniform magnetic field and the following torque ($\tau$) is generated as:

$$\tau = VM \times B$$  \hspace{1cm} (1)

where $V$ and $M$ are the volume and the magnetization of the permanent magnet, respectively and $B$ denotes the magnetic flux of the external magnetic field [10]. Enough torque for the small volume of the magnet in ROI can be generated by increasing the magnetic flux of generated external magnetic field by Helmholtz coils. This

![Fig. 1. Schematic diagram of two pairs of Helmholtz coils.](image)

![Fig. 2. Square type, two pair Helmholtz coils system.](image)
means that the current flow in the Helmholtz coils should be increased.

A pair of Helmholtz coils generates the uniform magnetic flux intensity along the axis between the coils. In addition, the magnetic field generated by two pairs of Helmholtz coils positioned perpendicularly to each other can be defined as the vector sum of the magnetic fields of the pair of Helmholtz coils. Therefore, along the desired direction, a uniform magnetic flux can be generated and the permanent magnet can be aligned in the desired direction in ROI. Fig. 1 shows the schematic diagram of the two pairs of Helmholtz coils in this study.

Two pairs of square type Helmholtz coils [11] were fabricated and setup, as shown in Fig. 2. Compared with the circular type Helmholtz coils, the square type Helmholtz coils has larger ROI. The area of ROI of our EMA system was about 150 mm × 200 mm.

2.2. Swimming microrobot

Generally, because a microrobot has an actuator, power element, and control electronic circuits, the volume of the microrobot is increased. A large microrobot is difficult to apply to a human body in medical applications. Furthermore, a large microrobot is affected by its surrounding environments, such as the digestive organs, blood vessel, and brain tissue. However, the microrobot using the EMA system can be miniaturized because the microrobot could be driven by a small size permanent magnet, which is located in the microrobot’s body. In addition, the microrobot can be simply designed and fabricated. As shown in Fig. 3, we propose a simple swimming microrobot with a simple propulsion mechanism in the form of a swing fin attached at the rotating magnetic element.

The whole isometric view of the swimming microrobot is shown in Fig. 4. The microrobot consists of an acrylic body, rotating axis, a cylinder type magnet and a silicone fin. The cylindrical neodymium magnet (diameter 1 mm, height 2 mm) with a high magnetic flux density was used. The acrylic main body and the rotating axis are fabricated by conventional mechanical machining. To convert the rotation of the magnet to the propulsion of the swimming microrobot, a silicone fin was attached at the rotation part installed on the permanent magnet. The PDMS (polydimethylsiloxane) silicone fin with 0.2 mm of thickness was fabricated by spin coating and cutting using a surgical knife.

Firstly, the fin of the microrobot was aligned to the swimming direction. The magnetic axis is perpendicular to the swimming direction. In addition, because the density of acrylic is higher than that of water, the microrobot needs a buoyant part and a triangular shape buoyant part using urethane was attached at the head of the
main body with consideration of the center of mass of the micro-robot. The total size of the microrobot was $1.44 \text{ mm} \times 3 \text{ mm} \times 11.3$–$19.3 \text{ mm}$, excluding the buoyant part, and the length of the acrylic body was $3.3 \text{ mm}$. The length of fin used in experiment was varied from $8 \text{ mm}$ to $16 \text{ mm}$. The total assembled swimming microrobot is shown in Fig. 5. Finally, similar to a tadpole, the microrobot including the buoyant part has a larger head than the fin and displayed an undulation motion.
3. Propulsion mechanism using EMA system

The currents of the EMA coil system should be controlled to generate a magnetic field in the desired direction in ROI. The magnetic field generated by the two pairs of Helmholtz coils, which are positioned perpendicularly with each other, can be defined as the vector sum of the magnetic fields of the pair of Helmholtz coils. Along the desired direction, the uniform magnetic flux can be generated, and the permanent magnet can be aligned with the desired direction in ROI.

Fig. 6 shows the moving mechanism of the swimming microrobot. The blue\(^1\) arrow means the desired moving direction of the swimming microrobot and the red arrows mean the direction of the uniform magnetic field generated by the EMA coil system. Initially, the uniform magnetic field (a) is perpendicular with the desired moving direction and thus the permanent magnet of the microrobot is aligned with the uniform magnetic field (a). Secondly, the uniform magnetic field is changed to direction (b), and the permanent magnet is aligned with direction (b). Similarly, the uniform magnetic field is changed to direction (c) and the permanent magnet is also aligned with direction (c). When the permanent magnet of the microrobot is switched from (b) to (c), the fin attached with the magnet also swings with the magnet, and thus, the microrobot shows swimming motion.

In detail, firstly, to generate the desired magnetic field of direction (a), the currents of two pairs of Helmholtz coils \(I_{x,a}, I_{y,a}\) are set to \(I_{x,a} = I_{\text{max}} \cos \theta, I_{y,a} = I_{\text{max}} \sin \theta\), where \(I_{\text{max}}\) is the maximum input current. Secondly, when the magnetic field is aligned to direction (b), the currents of the two pairs of Helmholtz coils are described as:

\[
I_{x,b} = I_{\text{max}} \cos(\theta + \alpha) \\
I_{y,b} = I_{\text{max}} \sin(\theta + \alpha)
\]

Finally, in the aligned direction (c), the currents of the two pairs of Helmholtz coils are described as:

\[
I_{x,c} = I_{\text{max}} \cos(\theta - \alpha) \\
I_{y,c} = I_{\text{max}} \sin(\theta - \alpha)
\]

To change the direction of the magnetic fields from (b) to (c) continuously, the term of \(\alpha\) should be defined by the sinusoidal function \(\alpha(t) = \pm \frac{x_{\text{max}}}{C_{176}} \sin(\omega t)\), where \(x_{\text{max}}\) is half the switching angle of the fin and \(\omega\) is the switching velocity of the swing fin.

Therefore, finally, to generate a continuously switching magnetic field in the \(\pm x_{\text{max}}\) direction, the currents of the two pairs of Helmholtz coils are defined as:

\[
I_{x} = I_{\text{max}} \cos(\theta + \alpha(t)) \\
I_{y} = I_{\text{max}} \sin(\theta + \alpha(t))
\]

For directional variable \(\theta\) and \(x_{\text{max}}\) of 40° and 30°, respectively, the aligned magnetic field directions (a, b and c) are found by numerical analysis, as shown in Fig. 7. The magnetic field produced by the two pair Helmholtz coil system aligned well to the desired directions.

4. Experiments

4.1. Experimental setup

Fig. 8 shows the schematics of the experimental setup in this study. The swimming microrobot was positioned in a water tank in ROI of EMA system. For observation of the motion of the microrobot, a Camscope (Somotech Vision) was installed. To interface with a joystick and the current control of the EMA system, PXI controller and LabVIEW software (National Instrument) were used. Two DC power supplies (Agilent) were adopted, and a relay circuit was installed to change the sign of the current. The final, constructed experimental setup is shown in Fig. 9.

5. Experimental results

The performance of the swimming microrobot was evaluated by various experiments measuring the velocities of the microrobot according to variables such as the swing angle, the swing frequency, and the fin length. To verify the effect of the swing angle and the swing frequency on the performance of the microrobot, one of the variables was fixed as a constant value, and the other variable was changed as the microrobot swam, with the fin of the microrobot showing undulation motion like a tadpole.

Firstly, when the swimming velocity according to the swing frequency of the fin was measured, the swing angle was fixed as

\[
I_{x,a} = I_{\text{max}} \cos(\theta + \alpha) \\
I_{y,a} = I_{\text{max}} \sin(\theta + \alpha)
\]

\[
I_{x,c} = I_{\text{max}} \cos(\theta - \alpha) \\
I_{y,c} = I_{\text{max}} \sin(\theta - \alpha)
\]

\[
I_{x} = I_{\text{max}} \cos(\theta + \alpha(t)) \\
I_{y} = I_{\text{max}} \sin(\theta + \alpha(t))
\]

\[
I_{x} = I_{\text{max}} \cos(\theta - \alpha) \\
I_{y} = I_{\text{max}} \sin(\theta - \alpha)
\]

\[
I_{x} = I_{\text{max}} \cos(\theta + \alpha(t)) \\
I_{y} = I_{\text{max}} \sin(\theta + \alpha(t))
\]
On the contrary, the swing frequency of the fin was set to 5 Hz to verify the effect of the swimming velocity according to the swing angle. For the measurement of the swimming velocity, the swimming distance of the microrobot was set to 100 mm, and \( I_{\text{max}} \) was set to 3.5 A in the experiments. And all experiments were repeated three times and all experimental results were summarized using the averaged values. In addition, we verified the effect of the fin length on the swimming performance by the changing of the fin length from 8 mm to 16 mm.

Fig. 10 shows the experimental data on the swimming velocities according to the swing frequency. When the fin length is shorter than 12 mm, the swimming microrobot shows fast and stable velocities in range of high frequencies (over 5 Hz). On the contrary, the microrobot which has a longer fin length than 12 mm shows fast swimming velocities in the range of low frequencies (under 4 Hz). Generally, the maximum swimming velocities of the microrobots appear in the frequency range between 4 Hz and 6 Hz and the significant decreases of the swimming velocity are shown after 8 Hz. The microrobots with the short fin have fast and stable swimming motions in the range of high swing frequencies because their short fins decrease the effect of the momentum of the rotating parts including its fin under the same magnetic condition. However, when the fin was too short, the microrobot showed unstable swimming and no undulation motion.

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The swimming velocities according to the swing angle \( (\alpha_{\text{max}}) \) are shown in Fig. 11. The experimental data showed that the swimming velocity increased with the swing angle of the magnetic flux. In addition, the gradients of swimming velocities are almost the same regardless of the length of fin. However, when the fin length
of the microrobot was too short or too long, the locomotion performance of the microrobot deteriorated.

These experimental results showed that the locomotion of the swimming robot was seriously affected by the swing angle because the swing angle of the fin could not follow to the desired swing angle at the high swing frequencies. In addition, the fin length of the microrobot had a strong influence on the swimming motion and the velocity. Therefore, the microrobot with about 12 mm of the fin length shows the best velocity and stable swimming motion, as in Figs. 10 and 11. In addition, the variation of swimming velocity was very small as less than 3.5%. Finally, the straight and turning performance of the swimming microrobot were demonstrated, as shown in Fig. 12, where we adopted the optimized values \( I_{\text{max}} = 3.5A \), Swing frequency = 5 Hz, and Swing angle \( \alpha_{\text{max}} = 80^\circ \) and 12 mm of the fin length. From these results, the proposed microrobot showed very similar swimming motion to that of a tadpole.

6. Conclusions

In this paper, a tadpole type swimming microrobot on the free surface of a fluid has been proposed. Firstly, we proposed the design and the structure of the microrobot using EMA system and derived the control mechanism for the swimming microrobot. The
The total size of the fabricated microrobot was 1.44 mm × 3 mm × 11.3–19.3 mm. In addition, we carried out numerical analysis using MATLAB to verify if the two pairs of Helmholtz coils were suitable to generate a uniform magnetic field in the desired direction for the actuation of the microrobot. By various locomotion experiments, the tadpole type microrobot was shown to display natural swimming motion as well as controllability of the swimming motion on the free surface of the water via a joystick. Especially, we selected three variables to modify the swimming performance of the microrobot in the control mechanism. Based on the locomotion experiments, the three variables can be optimized so that the tadpole type microrobot can swim properly in the fluid. In addition, we expected that the microrobot can be applied to various fluidic surroundings by adjusting the variables of the microrobot.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.mechatronics.2010.09.001.

References