A Crawling Magnetic Robot Actuated and Steered via Oscillatory Rotating External Magnetic Fields in Tubular Environments

Bongjun Jang, Jaekwang Nam, Wonseo Lee, Student Member, IEEE, and Gunhee Jang, Member, IEEE

Abstract—We propose a novel crawling magnetic robot and a driving method utilizing an oscillatory rotating external magnetic field. The crawling magnetic robot is composed of an actuating body with a permanent magnet, two steering bodies with permanent magnets, and flexible legs. The proposed crawling magnetic robot can increase actuating torque with long cylindrical magnet to crawl in tubular environments and navigate in pulsatile flow more than conventional spiral robots. The rotating external magnetic field synchronizes the driving plane of the crawling magnetic robot with the oscillating external magnetic field, while the oscillating external magnetic field generates actuating motion in order to stably generate the crawling motion at any posture. Finally, we prototyped the crawling magnetic robot, and verified the effectiveness of the proposed crawling magnetic robot and driving method in various tubular environments.

Index Terms—Crawling magnetic robot (CMR), friction, medical robot, oscillatory rotating external magnetic field (OREMF), tubular environment.

I. INTRODUCTION

CATHETERS are widely used in various tubular environments of human body such as gastrointestinal tracts, blood vessels, urinary systems, intestines, and bronchial tubes [1]–[3]. The success rate of these catheterization process depends primarily upon the capability and experience of medical doctors [4]. Furthermore, they are continuously exposed to X-ray radiation during catheterization process, because continuous X-ray imaging is required to track the catheter. This radiation exposure has potential side effects including fatigue, headache, and increased risk of cancer [5], [6].

To overcome the disadvantages of the conventional catheterization process, robotic catheter systems actuated by motors or magnetic navigation system (MNS) have been developed to remotely control the catheters [7]–[9]. Recently, MNSs such as Niobe (Stereotaxis, USA) and CGCI (Magnetecs, USA) systems have been developed and commercialized and they increase the steering ability and controllability of the magnetic catheter and reduce the radiation exposure of medical doctors. These systems ensure safety via the remote control of the catheter. However, the use of tethered catheters still has the limitations such as risk of Bacteremia, which is the invasion of bacteria inside the tubular environment. The Bacteremia can cause sepsis in patients with low immunity and can even result in death [10], [11]. To overcome these limitations of the tethered catheters, various micro or millimeter-sized magnetic robots and their untethering driving methods have been widely investigated [12], [13]. Since the traditional electrically driven robots require batteries with limited operation times and limited opportunity for miniaturization, the magnetic robots manipulated by external magnetic fields (EMFs) generated by the MNS have great attention as promising alternatives of conventional approaches. [14], [15]. The MNS which controls various motions of wireless magnetic robots is generally required to generate various strength and driving frequency of uniform and gradient magnetic fields. Generally, MNS with electromagnets exhibits higher controllability than MNS with permanent magnets, because the operator has the flexibility to control various parameters in terms of the direction, strength, and driving frequency of the uniform and gradient magnetic field [16]. Several researchers have developed swimming magnetic robots manipulated by the MNS in tubular environments [17], [18]. These swimming magnetic robots generate effective navigating motions in narrow tubes that simulate blood vessels; however, the swimming magnetic robots are easily swept down the tube by pulsatile flow, and can accidentally cause dangerous drilling damage to the wall of a healthy blood vessel. Different from the swimming magnetic robots, some researchers developed a magnetic robot which navigates by utilizing friction force which enables the robot to support the environment [19]. However, their robot is developed to walk on planes, not to crawl in tubular environments. Other researchers have developed crawling magnetic robots (CMRs) which can maintain positions and stably navigate in tubular environments. The oscillatory magnetic field generated by the MNS is applied to generate asymmetric friction force between the wall of the
tube and the legs of the CMRs for propulsion [20], [21]. However, their crawling motion is degraded or stops entirely when the oscillating EMF is not parallel to the magnetized direction of the CMR’s permanent magnets. Their capacity for increases in propulsive force is also limited, because they cannot change the direction of movement when their permanent magnets are longer than the diameter of tube.

We developed a novel structure of the CMR and a driving method utilizing an oscillatory rotating external magnetic field (OREMF). The proposed CMR as shown in Fig. 1 is composed of actuating and steering bodies that are responsible for crawling and steering motions, respectively. In addition, it can have a long cylindrical magnet in the body to increase actuation magnetic torque. We mathematically developed a driving method utilizing OREMRF to synchronously and stably generate crawling motion in the proposed CMR at any posture. We prototyped the proposed CMR, and experimentally verified the actuating and steering capability of the proposed CMR in various tubular environments.

II. STRUCTURE OF THE CMR

The CMR has an actuating body and two steering bodies connected by connecting rods, as shown in Fig. 1(a). As shown in Fig. 1(b) and (c), the actuating body has guide tip and slot at the cylindrical magnet case and mid-housing, respectively. With the guide tip, a diametrically-magnetized cylindrical magnet can rotate 180° by the EMF along the slot in the mid-housing. As shown in Fig. 1(c), the steering body is composed of two diametrically-magnetized ring magnets, a spacer, two flexible legs, and end-housing. Two ring magnets magnetized in opposite directions are bonded to the spacer that maintains a constant distance between the ring magnets. Flexible legs are attached to the ring magnets and they stably support wall of the tubes with various diameters.

III. ACTUATING PRINCIPLE AND OREMRF

A. Moving Principle of the CMR and OREMRF

The magnetic torque exerted on a magnet by an EMF can be expressed as follows:

\[ \mathbf{T} = \mathbf{m} \times \mathbf{B} \]  

(1)

where \( \mathbf{m} \) and \( \mathbf{B} \) are the magnetic moment of a magnet and magnetic flux density of an EMF. While the cylindrical magnet experiences a magnetic torque under an EMF in (1), the ring magnets cannot experience a magnetic torque because the sum of the upper and lower magnetic moment is zero due to their opposite magnetized direction, as shown in Fig. 1(c). Fig. 2(a) shows the moving motion of the CMR under the counter clockwise uniform EMF. Since the cylindrical magnet experiences clockwise magnetic torque along the \( z \)-axis in (1), the upper legs slide to the negative \( x \)-direction and the lower legs slide to the positive \( x \)-direction. The sliding direction of the legs determines the amplitude of friction force due to the contact angles between the legs and the walls of the tube [22]. The smaller contact angle of the upper leg \( (A_u) \) generates the smaller positive friction force while the larger contact angle of the lower leg \( (A_l) \) generates the large negative friction force. Therefore, the sum of the friction force is negative \( x \)-direction which makes the CMR move toward as much as \( \Delta x \), as shown in Fig. 2(a). Likewise, the clockwise uniform EMF makes the CMR move toward, as shown in Fig. 2(b). This repeated oscillating magnetic field is referred to as the oscillating EMF, and it makes the CMR move forward via crawling motion [20]. We define the driving plane of the CMR as the plane that contains contact points between legs and wall (see xy-plane in Fig. 2). However, it is hard to keep the driving plane from rotating in real environment because the CMR can be easily rotated along the tube by pulsatile flow, error of the applied EMF, and geometry of curved tube. Due to these external disturbances, it is difficult...
to keep the driving plane to be parallel to the oscillating EMF, so the crawling motion of the CMR is degraded or comes to an end because the oscillating EMF under this situation does not maximize the propulsive friction force between the legs and the wall. To overcome these drawbacks, we propose a driving method which can always synchronize the oscillating EMF with the driving plane of the CMR, irrespective of the posture of the CMR in any tubular environment. This is accomplished by utilizing OREMF which combines oscillating EMF with rotating EMF. The oscillating EMF can be represented as follows:

$$B_{\text{oscillating}}(t) = B_0(\sin \delta N + \cos \delta U^*)$$

$$\delta = \alpha \sin 2\pi f_1 t$$

where $B_0$, $\delta$, $N$, and $U^*$ are the magnitude and oscillating angle of the magnetic flux density of oscillating EMF, unit vector of the rotating axis, and arbitrary unit vector normal to $N$, respectively, and $\alpha$ and $f_1$ are the magnitude of the oscillating angle and the oscillating frequency of the oscillating EMF, respectively. Although at first we set $U^*$ on the driving plane of the CMR, the driving plane is randomly rotated along $N$ by the external disturbance. However, if we rotate $U^*$, the driving plane is also rotated according to the $U^*$, and it is synchronized with the plane of the oscillating EMF including $N$ and $U^*$. The rotated $U^*$ can be expressed using unit vector of the rotating EMF as follows [23]:

$$U^*(t) = \cos 2\pi f_2 t U + \sin 2\pi f_2 t N \times U$$

where $f_2$ and $U$ are the rotating frequency of the rotating EMF, respectively. After substituting (4) into (2), the OREMF can be expressed as follows:

$$B_{\text{OREMF}}(t) = B_0(\sin \delta N + \cos \delta(\cos 2\pi f_2 t U + \sin 2\pi f_2 t N \times U))$$

(5)

With the proposed OREMF, the CMR can generate stable crawling motion at any posture.

B. Turning Principle of the CMR

Fig. 4 shows a turning sequence of the moving direction by reversing the ring magnets with the legs. Because the moving direction is determined by the contact angle between the leg and wall, we can reverse the moving direction by reversing the ring magnets with the legs as shown in Fig. 4. However, the ring magnets cannot be rotated by an EMF because their total magnetic moment is zero. Instead, we rotate the cylindrical magnet $180^\circ$ around $x$-axis under $x$-directional rotating EMF as shown in Fig. 4(b). Then, the ring magnets rotate around $y$-axis because the same magnetic poles of the cylindrical magnet and ring magnets pull each other. We also introduce tilting angle $\chi$ around $z$-axis in addition to an $x$-directional rotating EMF as shown in Fig. 4(a). The tilting angle $\chi$ can increase the normal force at the legs, and it prevents whole body rotation of the CMR when cylindrical magnet is rotated under an $x$-directional rotating EMF. We also introduce tilting angle $\psi$ around $y$-axis in addition to an $x$-directional rotating EMF as shown in Fig. 4(b). The tilting angle $\psi$ can push the legs to generate the tilting angle $\gamma$ around $y$-axis. Without the tilting angle $\gamma$, we cannot rotate the ring magnets, because cylindrical magnet generates the same magnetic torque to the upper ring magnet and lower ring magnet in opposite direction. Finally, we apply the $x$-directional rotating EMF tilted by $\chi$ and $\psi$ around $z$- and $y$-axis, respectively. Then,
the cylindrical magnet is rotated around x-axis, and ring magnets with the legs are rotated around y-axis to reverse moving direction. After the turning motion, we remove the tilting angle of χ and ψ, and we apply an x-directional rotating EMF without χ and ψ to align the CMR along the tube because the angle of χ and ψ disturbs the moving motion.

IV. DESIGN AND FABRICATION OF THE CMR

A. Magnetic and Friction Torque Constraints

To change the moving direction of the CMR as shown in Fig. 4, magnetic and friction torque constraints should be satisfied. First, the external magnetic torque exerted on the cylindrical magnet generated by the EMF ($T_{m,ex}$) should overcome the internal magnetic torque generated by magnetic interaction between the cylindrical magnet and the ring magnets ($T_{m,in}$). The magnetic torque constraint can be expressed as follows:

$$T_{m,ex} - T_{m,in} > 0$$

(6)

We can determine $T_{m,ex}$ from (5) and $T_{m,in}$ by using a point-dipole model [24]. Since the upper and lower ring magnets inserted in the steering body have same geometry and arranged symmetrically, the upper and lower ring magnet apply same amount of internal magnetic torque to the cylindrical magnet. Therefore, the $T_{m,in}$ can be expressed as follows:

$$T_{m,in} = m_{cylinder} \times \frac{\mu_0}{2\pi} \left( \frac{3R(m_{ring} \cdot R)}{R^5} - \frac{m_{ring}}{R^3} \right)$$

(7)

where $m_{ring}$, $\mu_0$, $R$, and $R$ are the magnetic moment of the ring magnet, permeability of air, a vector from the ring magnet to the cylindrical magnet, and magnitude of $R$, respectively.

Second, the internal magnetic torque generated by the cylindrical magnet should overcome the friction torque generated by the friction between the legs and wall of the tubular environment ($T_f$). The friction torque constraint can be expressed as follows:

$$T_{m,in} - T_f > 0.$$  

(8)

However, it is difficult to theoretically determine $T_f$ between the legs and the wall of the tubular environment.

B. Measurement of Friction Torque

We conducted experiments to measure the friction torque between the legs and the wall of the tubular environment. We first fabricated a jig and a spacer by 3-D printing technology with an ultraviolet curable acrylic plastic material, and the legs were fabricated by thermoplastic polyurethane as shown in Fig. 5(a). The spacer is inserted in the jig, and the ring magnets with the flexible legs are attached to both sides to restrict the lateral movement, but to allow the rotation along the z-axis as shown in Fig. 5(b). A tip of each wire is attached to the ring magnets, and the other tip is fixed to a load cell (Model 31 of Honeywell, USA). Then, the assembled jig was placed in a fixed glass tube filled with water, and the load cell was fixed to the xyz-stage as shown in Fig. 5(c). To measure the friction torque, the xyz-stage was pulled along the positive x-direction. The movement of the xyz-stage makes rotation of the ring magnets, and the generated friction torque during the rotation is converted to the pulling force exerted on the wire which is fixed to the load cell. Therefore, $T_f$ is determined by multiplying the measured pulling force by outer radius of the ring magnet (2.5 mm). The measurements were performed 10 times to the glass tubes with the diameter of 10 and 12 mm. Fig. 5(d) shows measured friction torque for each case and it is the greatest one of 10 measurements each. Finally, the maximum friction torques in two glass tubes with the diameter of 10 and 12 mm were calculated as 0.0129 and 0.0035 m-N-m, respectively. By using $T_f$, we can specify the design constraint of the proposed CMR from (6) and (8).

C. CMR Design Considering Torque Constraints

The satisfaction of the torque constraints is dependent on the magnitude of $T_{m,in}$, which it can be determined by the
distance \((R)\) between the center of the cylindrical magnet and the ring magnet as shown in (7). As shown in Fig. 6(a), \(R\) can be expressed in terms of the distance \((d)\) between the actuating body and the steering body as follows:

\[
d = \sqrt{R^2 - \frac{1}{4}(h_{\text{ring}} + h_{\text{spacer}})^2} - \frac{1}{2}(L_{\text{cylinder}} + D_{\text{ring}}) \tag{9}
\]

where \(h_{\text{ring}}, h_{\text{spacer}}, L_{\text{cylinder}},\) and \(D_{\text{ring}}\) are the heights of the ring magnet and the spacer, the length of the cylindrical magnet, and the diameter of the ring magnet, respectively. Table I shows the geometric variables of the cylindrical magnet and the ring magnets, and they are selected in such a way that the proposed CMR can crawl along the tubes with the diameter ranging from 10 to 12 mm. The cylindrical magnets and ring magnets are NdFeB magnets which have N52 grade with a residual magnetic flux density of 1.4 T. To find \(d\) which satisfies the torque constraints for the given magnets and the spacer, (6) and (8) were calculated according to the rotating angle of the cylindrical magnet. As shown in Fig. 6(b) and (c), \(d\) should be larger than 2 mm and smaller than 11 mm to satisfy both the torque constraints. We set \(d\) to be 3 mm. Finally, we fabricated the parts of the CMR, and assembled the CMR as shown in Fig. 7(a) and (b).

**TABLE I**

<table>
<thead>
<tr>
<th>Design Variables of the CMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>Cylindrical magnet</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Ring magnet</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Spacer</td>
</tr>
<tr>
<td>CMR</td>
</tr>
</tbody>
</table>

**V. EXPERIMENTS**

**A. Magnetic Navigation System**

We used the MNS shown in Fig. 7(c) and (d) to effectively generate the OREM [23]. This MNS is composed of three coils (an \(x\)-directional Helmholtz coil, HC; a \(y\)-directional uniform saddle coil, USCy; and a \(z\)-directional uniform saddle coil, USCz) with an overall structure similar to that of a magnetic

---

---
resonance imaging system. The cylindrical shape of the MNS is quite effective for the application to human body. The magnetic field of the MNS can be expressed as in the following equations:

\[
B_{\text{OREMF}} = \mu_0 \left[ d_h, d_{uy}, d_{uz} \right]^T,
\]

\[
d_h = \left( \frac{4}{5} \right)^{3/2} \frac{i_k T_h}{r_h},
\]

\[
d_{uy} = 0.6004 \frac{i_{uy} T_{uy}}{r_{uy}},
\]

\[
d_{uz} = 0.6004 \frac{i_{uz} T_{uz}}{r_{uz}},
\]

where \(i_k, T_k, \) and \(r_k\) are the current, the number of turns, and the radius of the \(k\)th coil, respectively, and the subscripts \(h, uy, \) and \(uz\) represent the Helmholtz coil and the \(y\)- and \(z\)-directional uniform saddle coils, respectively. Each coil of the MNS can generate a uniform magnetic field along the respective central axes. Thus, the \(x\)-, \(y\)-, and \(z\)-directional components of the OREM in (4) can be easily generated and controlled by changing the input currents of the \(x\)-, \(y\)-, and \(z\)-directional coils of the MNS, respectively. Operators can monitor the position and orientation of the CMR via images displayed on the control panel; these are acquired from two biaxial cameras. The operators then manipulate the joystick controller to generate the appropriate motions of the CMR by controlling the OREM, such as the \(B_0, \alpha, f_1,\) and \(f_2.\) Information from the joystick controller is converted to current and applied to the power supplies.

### B. Experiment in Tubular Environments

We investigated the performance of the CMR moving in the straight watery tube according to changes of the diameter of the tubes and the oscillating angle, oscillating frequency, and rotating frequency of the uniform EMF (14 mT). We performed the same experiment five times for each case and averaged the results. Fig. 8(a) and (b) shows the velocity of the CMR in the 10 and 12 mm diameter tubes under an oscillating frequency of 10 Hz and a rotating frequency of 10 Hz according to changes in the oscillating angle. The velocity increases in conjunction with increases in the oscillating angle up to 45° for the 10 mm diameter tube and up to 60° for the 12 mm diameter tube, and then it becomes constant. This phenomenon can be explained in terms of the relationships between the friction force, contact angle, flexibility of the leg, and diameter of the tube. The CMR crawls forward due to the friction force between the leg and the wall, and this friction force increases with the increase in the contact angle, as shown in Fig. 2. This contact angle also increases with the increased oscillating angle up to a certain angle, and then becomes constant due to the flexibility of the leg and the diameter of the tube. Fig. 8(c) and (d) shows the velocity of the CMR in the 10 and 12 mm diameter tube under a rotating frequency of 10 Hz according to changes in the oscillating frequency and angle. The velocity increases, reaches a maximum value, and then decreases with increased oscillating frequency. The frequency corresponding to the maximum velocity is referred to as the step-out frequency, and beyond this step-out oscillating frequency, the crawling motion of the CMR cannot be synchronized with the applied OREM. Fig. 8(e) and (f) shows the velocity of the CMR in the 10 and 12 mm diameter tubes under an oscillating frequency of 10 Hz and an oscillating angle of 80° according to changes in the rotating frequency. This shows that the velocity of the CMR is almost constant.

**Table II**

<table>
<thead>
<tr>
<th>Diameter of tube</th>
<th>Variable</th>
<th>Value</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm</td>
<td>Oscillating angle</td>
<td>45°</td>
<td>4 mm/s</td>
</tr>
<tr>
<td></td>
<td>Oscillating frequency</td>
<td>9 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotating frequency</td>
<td>10 Hz</td>
<td></td>
</tr>
<tr>
<td>12 mm</td>
<td>Oscillating angle</td>
<td>60°</td>
<td>6 mm/s</td>
</tr>
<tr>
<td></td>
<td>Oscillating frequency</td>
<td>8 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotating frequency</td>
<td>10 Hz</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 8.** Measured velocities of the CMR according to the oscillating angle, oscillating frequency, and rotating frequency. (a) Velocity according to the oscillating angle in the 10 mm diameter tube \((f_1: 10 \text{ Hz}, f_2: 10 \text{ Hz})\). (b) Velocity according to the oscillating angle in the 12 mm diameter tube \((f_1: 10 \text{ Hz}, f_2: 10 \text{ Hz})\). (c) Velocity according to the oscillating frequency in the 10 mm diameter tube \((f_2: 10 \text{ Hz})\). (d) Velocity according to the oscillating frequency in the 12 mm diameter tube \((f_2: 10 \text{ Hz})\). (e) Velocity according to the rotating frequency in the 10 mm diameter tube \((\alpha: 80^\circ, f_1: 10 \text{ Hz})\). (f) Velocity according to the rotating frequency in the 12 mm diameter tube \((\alpha: 80^\circ, f_1: 10 \text{ Hz})\).
irrespective of the rotating frequency. With the application of rotating EMF, the rotational motion of the CMR synchronizes its driving plane with the oscillating plane of oscillating EMF, thus the rotational motion does not affect the velocity of the CMR. As shown in the case of the oscillating frequency, the velocity of the CMR is constant and decreases after the rotating frequency becomes larger than the step-out rotating frequency of 10 Hz. Table II shows the maximum speeds of the CMR, 4 and 6 mm/s in the 10 and 12 mm diameter tubes, respectively.

Fig. 9 shows a bifurcated tube with a diameter of 12 mm; the navigating and steering capability of the proposed CMR were verified in this complex tube using the control variables of the OREMIF in Table II. Initially, the CMR moved forward via OREMIF (Step 1) and steered to enter the right branch of the tube (Step 2). The CMR then reversed its moving direction using the steering motion and moved back to a junction point in the tube using OREMIF (Step 3). To enter the left branch of the tube, the CMR changed again its moving direction, and moved forward (Step 4). As in Step 3, the CMR turned back to the junction point and the initial point (Steps 5 and 6). This experiment shows that the proposed OREMIF successfully controls the fine locomotion of the proposed CMR in a complex tubular environment.

We performed a comparative experiment between the proposed CMR and a conventional spiral robot [23] in a straight watery tube with diameter of 12 mm to compare their motion under pulsatile flow, as shown in Fig. 10(a). The pulsatile flow was generated via peristaltic pump (WT600-1F of Longer Precision Pump, China), and its flow rate was measured by the flowmeter (MF200 of NURITECH, Korea). The diameter, length, pitch, and magnetic moment of the spiral robot are 7.2 mm, 25 mm, 8 mm, and 18.13 A·m², respectively. Fig. 10(b) shows the flow rate of the applied pulsatile flow which is similar with the flow rate of the blood vessel in human heart [25]. During the first 2.3 s, the EMF was not applied to either CMR or spiral robot, and after 2.3 s, the EMF was applied to the CMR and spiral robots for up to 17 s. The CMR was controlled using the control variables of the OREMIF shown in Table II, and the spiral robot was controlled by the rotating EMF with a rotating frequency of 9 Hz. Both EMFs have maximum magnetic flux densities of 14 mT. Using the EMFs, both robots can move with the almost same speed (3.4 mm/s). Fig. 10(c) shows that the proposed CMR can anchor its position stably even without EMF and move forward with less oscillation than the spiral robot under pulsatile flow.

**VI. CONCLUSION**

We developed a novel structure of the CMR and its driving method utilizing the OREMIF. The proposed CMR can increase the actuating torque with the long cylindrical magnet to crawl in tubular environments and navigate in pulsatile flow more stable than the conventional spiral robots. Also, the proposed OREMIF enables the CMR to generate the propulsive force at any posture.
by synchronizing the driving plane of the CMR with the oscillating EMF. We described the structures of the CMR, its driving methods, and its design process with fabrication. Finally, we verified locomotion of the CMR in tubular environments with the diameter of 10 and 12 mm. It shows that the CMR can navigate and change its direction in Y-shaped glass tube and that it can navigate more stably in the pulsatile flow environment. Once the application tubular environment is specified, structure improvement and optimization including the miniaturization can be performed with the help of proposed design process in this paper. This paper can contribute to developing multifunctional CMR with various medical applications such as drug and stent delivery via the proposed EMFs.

References


Bongjun Jang received the B.S. degree in mechanical engineering from Gachon University, Gyeonggi-do, South Korea, in 2015. He is currently working toward the M.S. degree in mechanical convergence engineering at Hanyang University, Seoul, South Korea. His current research interests include design, analysis, and control of magnetic robots and electromagnetic systems for biomedical applications.

Jaekwang Nam received the B.S. degree in mechanical engineering from Hanyang University, Seoul, South Korea, in 2011, where he is currently working toward the Ph.D. degree in mechanical convergence engineering. His research interests include various structures of microrobots performing multifunctions in human blood vessels by magnetic navigation systems.

Wonseo Lee (S’16) received the B.S. degree in mechanical engineering from Hanyang University, Seoul, South Korea, in 2014, where he is currently working toward the Ph.D. degree in mechanical convergence engineering. His current research interests include design, analysis, and control of magnetic robots and magnetic catheters with electromagnetic systems for biomedical applications.

Gunhee Jang (M’00) received the B.S. degree in mechanical engineering from Hanyang University, Seoul, South Korea, in 1984; the M.S. degree in mechanical engineering from the Korea Advanced Institute of Science and Technology, Seoul, South Korea, in 1986; and the Ph.D. degree in mechanical engineering from the University of California, Berkeley, CA, USA, in 1993. He is currently a Professor with the Department of Mechanical Engineering and the Diretor of the Precision Rotating Electromechanical Machine Laboratory, Hanyang University. His current research is focused on microrobots actuated by magnetic navigation systems, and electromagnetic systems, such as motors and actuators. He has authored or co-authored more than 280 articles published in journals and conference proceedings in his field, and more than 29 patents including several international patents.