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A magnetic minirobot with anchoring and drilling ability in tubular environments actuated by external magnetic fields

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We propose a magnetic minirobot with anchoring and drilling ability (MMAD) controlled by an external magnetic field. The proposed MMAD can navigate through a tubular environment, such as human blood vessels, actuated by a magnetic gradient and uniform rotating magnetic field. It can also generate an anchoring motion, which stably holds the position of the MMAD under pulsatile flow, in order to drill and unblock obstructed blood vessels. The operating conditions of the MMAD were examined by investigating the magnetic torques, and the holding force of the MMAD was measured by a force sensing resistor. Finally, we performed various experiments in a tubular environment to verify the validity of the proposed MMAD.

A Vascular diseases such as angina pectoris and myocardial infarction are one of the main causes of human death in modern society.1,2 One of the traditional treatments is using a catheter composed of a flexible thin tube and wire to unblock the diseased blood vessels.3 Even though it is a simple surgery, the success of catheterization is mostly dependent on the maneuverability of the catheter and the experience of the medical doctors. Microrobots manipulated by a magnetic navigation system (MNS) have been extensively investigated as a possible alternative to traditional treatments. The treatment using a microrobot is a minimally invasive and highly efficient, compared to traditional treatments.3 Microrobots are composed of a permanent magnet, and they can be wirelessly manipulated by the magnetic field driven by coil currents in the MNS.4,5

Several researchers have developed various mechanisms of microrobots to release drugs or to generate drilling motion effectively.6,7 Yu et al. proposed a sphere-shaped microrobot with a drilling device with rough bumps for the effective microrobot actuated by rotating magnetic field.8 Pan et al. developed a spiral-type microrobot operated by a rotating magnetic field that generates thrust force to move the microrobot to the target position within fluid and to unblock the obstructed blood vessels through a drilling motion.9 However, conventional spiral microrobots risk damaging blood vessels due to spiral thread whirling navigating through blood vessels and they are unable to generate a drilling motion precisely under the pulsatile flow in human blood vessels. Thus, an anchoring ability holding its position against external disturbances such as the pulsatile flow in human blood vessels can effectively improve the accuracy and stability of the drilling motion.

In this research, we propose a magnetic minirobot with anchoring and drilling ability (MMAD) that navigates along tubular environments to verify novel concept for a future microrobot, as shown in Fig. 1. The proposed MMAD is composed of anchoring screws (AS1 and AS2) and drilling screw (DS), which are perpendicular to each other, and a rectangular parallelepiped magnet and a cylindrical magnet were inserted into anchoring screws and drilling screw, respectively. AS1 and AS2 have an opposite thread, which expand in the opposite direction under a same rotating magnetic field. The proposed MMAD can generate a linear propelling motion that moves back and forth, a drilling motion that unclogs the obstructed blood vessels, and an anchoring motion that supports the wall of the tube such as human blood vessels during drilling motion. We determine the operating condition of the MMAD by investigating the magnetic torques and measure the holding force of the anchoring motion using a force sensing resistor (FSR). Finally, we perform various experiments to verify the validity of the proposed MMAD.

The motions of the MMAD are controlled by the magnetic force and torque, generated from the interaction between the magnet of the MMAD, and the magnetic field applied by the MNS, and the magnetic force and torque can be expressed as follows:

\[ \mathbf{F} = (\mathbf{m} \cdot \nabla) \mathbf{B}, \]

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

where \( \mathbf{m} \) and \( \mathbf{B} \) are the magnetic moment of a magnet and the external magnetic flux density, respectively. The MMAD can generate screw motion of the ASs and the DS actuated.
by rotating uniform magnetic field. Figure 2 shows the rotating magnetic field that can be expressed as follows:

$$\mathbf{B}_{\text{rot}}(t) = B_0 (\cos \omega t \mathbf{U} + \sin \omega t \mathbf{N} \times \mathbf{U}),$$

(3)

where $B_0$, $\omega$, $\mathbf{N}$, and $\mathbf{U}$ are the magnitude and angular velocity of the rotating magnetic field, the unit vector of the rotating axis, and the unit vector normal to $\mathbf{N}$, respectively. An anchoring motion and drilling motion can be selectively generated by aligning the direction of $\mathbf{N}$ with the rotating axis of the screws, as shown in Fig. 2(a).

The proposed MMAD is composed of ASs and DS, which are perpendicularly installed in the robot body. A rectangular parallelepiped magnet and a cylindrical magnet were inserted into ASs and DS, respectively. ASs are expanded in the opposite direction under a same rotating magnetic field. ASs and DS are operated independently because external magnetic field is orthogonally applied to ASs and DS, respectively. Figure 3 shows the operating procedure of the MMAD. Assuming that the MMAD is initially placed on the xy-plane, while the magnetization direction of the permanent magnets is toward the y-direction, the z-directional uniform rotating magnetic field can synchronously turn the MMAD to clockwise direction, as shown in Fig. 3(a), because the permanent magnets are fixed to the MMAD. Once the direction of the MMAD is aligned toward the target point through this aligning motion, the x-directional magnetic gradient is applied to the MMAD so that the MMAD moves to the x-direction, as shown in Fig. 3(b). To move the MMAD in the opposite direction, magnets of MMAD should be rotated to the opposite direction or negative magnetic gradient should be applied.

To generate the anchoring motion and the drilling motion, the magnetic torque of each screw ($T_m^e$) of the MMAD generated by the external magnetic field, as shown in Eq. (2), should be greater than the resisting torque ($T_e^m$) between two magnets (A and B), which can be calculated by the following equation:

$$T_m = \mathbf{m} \times \mu_0 \left(\frac{3r(m_3 \cdot r)}{r^5} - \frac{m_1}{r^3}\right),$$

(4)

where $\mu_0$, $r$, and $\mathbf{m}$ are the permeability of the air, the distance between the permanent magnets, and the magnetizations of the permanent magnets A and B, respectively.

The MMAD should support the wall of the tube such as human blood vessels prior to drilling motion. When the y-directional rotating uniform magnetic field is exerted on ASs, both ASs can expand to anchor to the wall of the tube such as human blood vessels due to opposite thread of each screw, as shown in Fig. 3(c). Then, the x-directional rotating uniform magnetic field can expand the drilling screw, as shown in Fig. 3(d). Finally, DS generates the drilling motion under the z-directional rotating uniform magnetic field, as shown in Fig. 3(e). Both permanent magnets in ASs and DS are affected by the external rotating uniform magnetic field. Therefore, holding force of the anchoring motion should be greater than rotating torque of the MMAD by the external rotating uniform magnetic field.

We constructed a MNS to operate the MMAD, as shown in Fig. 4. A major component of the MNS is the coil system, as shown in Fig. 5, which is composed of Maxwell coil (MC), Helmholtz coil (HC), gradient saddle coil (GSC), and two uniform saddle coils (USCs). The MC and the GSC generate the magnetic gradient, while the HC and the USCs generate the uniform magnetic field. The major specifications of the MNS are shown in Table I. The combination of four coils (MC, GSC, HC, and USC(y)) can move the MMAD by selectively generating the magnetic gradient and the uniform magnetic field in two dimensional plane, and the combination of three coils (HC, USC(y), and USC(z)) can generate the anchoring motion and drilling motion by the rotating magnetic field in three dimensional space. Table II shows the maximum voltage, current, magnetic flux density, and magnetic gradient in the developed MNS.
As shown in Fig. 6, the proposed MMAD was prototyped by using a 3D printing technology. The width, height, and length of the MMAD were 20 mm, 15 mm, and 30 mm, respectively. A rectangular parallelepiped neodymium magnet with a length of 10 mm, a width of 5 mm, and a height of 2.6 mm was inserted between AS1 and AS2. And cylindrical neodymium magnet with diameter of 2.5 and a length of 10 mm was inserted into DS. ASs of the MMAD can expand to 5 mm by three rotating screw motion, and DS of the MMAD can expand to 7 mm by six rotating screw motion.

We performed various experiments of the MMAD to verify the validity of the proposed MMAD. First, we examined the operating conditions of the MMAD by investigating the magnetic torques. Fig. 7 shows the magnetic torques by the angular difference of the magnetization direction between the permanent magnets in the ASs and DS. The magnetic torques of each magnet can be calculated using Eq. (4). While the external rotating magnetic field for the MMAD without DS increases gradually, it starts the anchoring motion when the rotating magnetic flux density becomes 3.7 mT. The corresponding magnetic torque of 590 mN mm is calculated from Eq. (1). It shows that the MMAD requires at least 590 mN mm of magnetic torque by rotating uniform magnetic field to generate the anchoring motion. The total magnetic torque of the ASs equals to the summation of the friction torque and the magnetic torque interfering from DS, and it repeats every 360° expressed as a blue line in Fig. 7. Furthermore, it shows that the MMAD requires at least 110 mN mm of magnetic torque by rotating uniform magnetic field to generate the drilling motion. The maximum magnetic torques of ASs and DS by the external magnetic field of 14 mT are 1800 mN mm and 670 mN mm.

Second, we constructed an experimental apparatus to measure the holding force of the anchoring motion in silicon tube, as shown in Fig. 8. FSR was adhered to the MMAD in a silicone tube with a diameter of 22 mm and a rotating magnetic field was applied to anchor the MMAD to the wall of the silicone tube. Then, the FSR was manually pushed until it moves and loses anchoring ability. The average holding force of the MMAD was measured to be about 0.2 N in dry condition and 0.1 N in wet condition, which is four times and two times larger than the weight of the MMAD.

Finally, we demonstrated the navigating, anchoring, and drilling motions of the MMAD in a y-shape silicone tube, as shown in Fig. 9. The magnetic fields used in each step were listed in Table III. Step I shows an x-directional propelling motion of the MMAD to reach the bifurcated point. The maximum propelling force of the MMAD was calculated to be 11.9 mN, and maximum velocity was measured to be 19.62 cm/s. The minimum magnetic gradient to start the propelling motion was 20 mT/m. Therefore, the resisting friction force can be calculated to be 3.6 mN in this environment. In step II, a uniform magnetic field was applied to the MMAD in order to align the MMAD toward the upper branch. And a magnetic gradient was applied to the MMAD in step III to generate a linear propelling magnetic force to reach the upper branch. Then, the MMAD moved back to the bifurcated point in step IV. In steps V and VI, the MMAD was aligned along the lower branch and moved to the blocked...
area. After the MMAD reached the blocked area, a uniform rotating magnetic field was applied to the MMAD to expand ASs to anchor to the wall of the tube in step VII. Then, in step VIII, another uniform rotating magnetic field rotating along the axis of DS was applied to expand DS. The drilling motion of the MMAD was finally generated in step IX by a uniform rotating magnetic field rotating along the axis of drill tip. This experiment demonstrates the possibility that the proposed MMAD can precisely and stably generate a drilling motion while anchoring to the wall of the tube.

We proposed a novel MMAD that can navigate along tubular environment and have anchoring and drilling abilities controlled by the external magnetic field effectively. We determined the operating condition of the MMAD by investigating the magnetic torques and investigated the holding force of the anchoring motion mathematically and experimentally. We performed various experiments to verify the validity of the proposed MMAD, and the results show that the MMAD can be used to stably and precisely generate a drilling motion overcoming external disturbances. The proposed MMAD could be miniaturized and further researched through clinical demonstration in order to be applied in human blood vessel, but this research could contribute to the development of a microrobot with multi-functions to treat human coronary artery diseases efficiently.

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TABLE III. Magnetic fields used to generate the navigating motion, anchoring motion, and drilling motion of the MMAD.

<table>
<thead>
<tr>
<th>Magnetic field type</th>
<th>Magnitude</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step I</td>
<td>Gradient</td>
<td>68.37 mT/m</td>
</tr>
<tr>
<td>Step II</td>
<td>Uniform</td>
<td>14 mT</td>
</tr>
<tr>
<td>Step III</td>
<td>Gradient</td>
<td>68.37 mT/m</td>
</tr>
<tr>
<td>Step IV</td>
<td>Gradient</td>
<td>68.37 mT/m</td>
</tr>
<tr>
<td>Step V</td>
<td>Uniform</td>
<td>14 mT</td>
</tr>
<tr>
<td>Step VI</td>
<td>Gradient</td>
<td>68.37 mT/m</td>
</tr>
<tr>
<td>Step VII</td>
<td>Rotating</td>
<td>14 mT</td>
</tr>
<tr>
<td>Step VIII</td>
<td>Rotating</td>
<td>10 mT</td>
</tr>
<tr>
<td>Step IX</td>
<td>Rotating</td>
<td>10 mT</td>
</tr>
</tbody>
</table>