Compact-design, Modeling and Simulation of the Internal Permanent Magnet of Magnetically Guided Capsule Endoscope

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Abstract. Miniaturization is a challenge for the magnetically guided capsule endoscope (MGCE), especially considering the multifunction of MGCE. This paper proposes a compact-design of internal permanent magnet (IPM), which contributes to the miniaturization of MGCE. The IPM is a complex of actuator and shell of the MGCE, which frees the occupation of conventional IPM. The IPM is for the first time designed with a streamline shape for good kinematics. A magnetic propulsion model of the proposed IPM is established and a magnetic propulsion simulation based on finite element (FE) and boundary element (BE) analysis for guaranteeing steady locomotion and navigation is conducted. The simulation is validated by comparison of the analytical model. At last, the locomotion modes and navigation of IPM are simulated based on the justified simulation. In conclusion, the compact-design of IPM can guarantee the locomotion and navigation of MGCE, and increase the available inner space of MGCE.

1. Introduction
The capsule endoscope (CE) has triggered a revolution for the medical screening and diagnosis of gastrointestinal (GI) tract in the past few years, and has become an alternatively method to conventional endoscope because of noninvasive process, low risk of infection and no perforation [1]. A CE captures the pictures of GI and then sends the data wirelessly to the external recorder after swallowed for future screening and diagnosis. However, current CE is passively actuated by its gravity and visceral peristalsis of GI, and the lack of active control leads to many problems to be solved. First, passive control may result in the negligence of areas of interest (AOI). Second, the accurate position and orientation of CEs are difficult to determine because of the random locomotion. Third, some additional functions based on precise localization such as drug-delivery and biopsy are difficult to realize.

Therefore, many possible solutions to endow the CE with active controllability have been proposed in some studies [2]. However, in these solutions, the size of capsule and the risk of scratch to the organs increase because the actuation of the capsule depends on the spatial motions of mechanical units embedded inside the capsule. Alternatively, the most promising solution to overcome these
shortcomings is to actuate MGCE by external magnetic (EM) field. Several researchers have designed and investigated MGCEs for GI and driving systems based on this solution [3-4]. This solution needs to place an IPM as an actuator inside the MGCE to coordinate the external magnetic field. However, the IPM increases the size of MGCE or weakens the multi-function of MGCE.

Miniaturization involving the hardware manufacturing, the elaborate layout and the compact-design of IPM is necessary for the MGCE. However, the hardware manufacturing and elaborate layout are limited by the state of the art of electronic components which are difficult to break through [5]. Several researchers have exerted efforts on the optimized compact-design of IPM. In G. Mingyuan’s work [6], the compact-design of IPM was a magnetic annular shell attaching to the surface of the MGCE, the replacement of inside IPM could save more inner space for other units, but the shell increases the risk of its fall-off. In F. Carpi’s work [7], an elastic shell as IPM fabricated with a mixture comprising of silicones and NdFeB powder by moulded method was proposed to reduce the risk of fall-off. In H. Yang’s work [8], a truncated IPM considering second central moment was proposed to obtain the optimized compact-design of IPM shape. Obviously, these compact-design of IPM have effective contributions to the miniaturization, but increase the size of MGCE more or less, which could be further optimized.

In this paper, we propose a novel compact-design of IPM, which is beneficial to the miniaturization of MGCE. The IPM is a biocompatible complex of actuator and shell of the MGCE rather than independent two parts. To guarantee sufficient magnetic force and torque of the proposed IPM during translation and locomotion, a magnetic propulsion model of the proposed IPM and a magnetic propulsion simulation are established based on MATLAB (MathWorks, Natick, Massachusetts, USA) and COMSOL Multiphysics 5.5 (COMSOL Inc. Stockholm, Sweden) The simulation is validated by comparison of the analytical model. The locomotion modes and navigation of IPM are simulated based on the simulation.

2. Modeling and simulation of the magnetic propulsion

2.1. Compact-design of IPM

The exterior shape of the IPM proposed in this paper can be modeled as equation (1):

\[
S(x) = \begin{cases} 
(R - r)(1 - \exp(-\alpha x)) + r, & 0 \leq x < \frac{L}{2} \\
(R - r)(1 - \exp(\alpha x - L)) + r, & \frac{L}{2} \leq x \leq L 
\end{cases}
\]

where \( r \) and \( R \) denote the inner and body radius respectively, \( \alpha \) denotes the index to determine the slope of the IPM, \( L \) denotes the total length of the IPM. As shown in figure 1, the two heads of the IPM are endowed with magnetic properties in longitudinal direction (\( \mu = 0.0303 \times 10^5 \)), and a transparent part is preserved in the middle for the embedded CCD. Using the proposed shape equation, the frictional resistance to which the IPM is subjected to can be minimized [9]. Since water is utilized to flatten out and extend the folds of stomach for complete screening and diagnosis, the proposed IPM works under a liquid-filled condition. Therefore, with the help of minimized frictional resistance and buoyancy of the IPM, a small magnitude of propulsion magnetic force and torque are usable for locomotion of IPM. Then we can assume that the IPM can easily follow with the magnetic force and torque.

2.2. Magnetic modeling of IPM and EM

An EM propulsion system based on Helmholtz coils and Maxwell coils are used for navigating and control of the IPM. As shown in figure 1, three-pair Helmholtz coils and three-pair Maxwell coils are respectively arranged orthogonally along three axes. When the input currents are in the same amplitude and direction, Helmholtz coils can generate the uniform magnetic flux density along the axis direction of two coils in the AOI. The magnetic flux density depends linearly on the value of the input current.
Similarly, when the input currents are in the same amplitude and opposite directions, Maxwell coils can generate the uniform gradient magnetic field along the axis direction of two coils in the AOI. The magnetic gradient field depends linearly on the value of the input current.

![Figure 1. The EM and IPM system. Red coils are Helmholtz coils and blue coils are Maxwell coils. The geometry of IPM is: \( L = 23\text{mm}, R = 4.5\text{mm}, r = 0 \).](image)

For a point in AOI, the overlaying magnetic flux density \( B \) can be described by the Biot-Savart law. By the superposition of these coils, \( \nabla \times B \) is a diagonal and trace-free matrix. The magnetic field can be regarded as a magneto-static case, where the divergence and rotation of magnetic flux density \( B \) are zero. When the IPM works in the magnetic field generated by the EM system, it can be aligned by the uniform magnetic field and driven by the magnetic gradient field, the magnetic propulsion torque and force can follow as equation:

\[
T = V M \times B
\]

\[
F = V (M \cdot \nabla) B
\]

where \( T \) and \( F \) denote the magnetic propulsion torque and force, \( V \) and \( M \) denote the magnetic volume and magnetization of the IPM. Thanks to the no-rotation of the magnetic field, the IPM can be controlled and navigated easily in the AOI due to the decoupling of the gradient field.

When the \( B_{\text{desired}} \) and \( F_{\text{desired}} \) are determined, the input current of six-pair coils can be obtained as follows:

\[
\begin{bmatrix}
    B_{\text{desired}} \\
    F_{\text{desired}}
\end{bmatrix} =
\begin{bmatrix}
    e(p) \\
    \frac{\partial e(p)}{\partial (x,y,z)}
\end{bmatrix}
\begin{bmatrix}
    I_1 \\
    \vdots \\
    I_6
\end{bmatrix}
\]

(4)

Where \( p \) denotes a static point in the AOI, \( e(p) \) is the mapping matrix between \( B \) and input current \( I \) in per unit of six-pair coils.

2.3. Simulation of IPM navigation

A FE simulation based on COMSOL for EM system is conducted. In COMSOL, AC/DC module is selected to simulate the magnetic field distribution generated by the EM system. The geometry model of EM system is established as shown in figure 2. The blocks represent the air domain, and a square perpendicular to the axis \( z \) is introduced to demonstrate the magnetic field distribution of the AOI. To improve the accuracy and reduce the computational costs of the simulation, the grids of air domain are relative harsh but the grids of coils are fine. The results are obtained and then used as boundary conditions for the magnetic propulsion model of IPM as shown in figure 3. In the magnetic propulsion
model, FEM and BEM are combined to simulate the magnetic force and torque of IPM. The force on the IPM is calculated internally as an integral of the surface stress tensor over all boundaries of the IPM as equation (5):

$$n_i T_n = -\frac{1}{2} (H \cdot B) n_i + (n_i \cdot H) B^T$$

(5)

where $n_i$ and $T_n$ denote the boundary normal pointing out from the IPM and the stress tensor of air. An auxiliary tensor-analysis plane is established to guarantee good numerical accuracy.

3. Validations and results

3.1. Simulation of EM system

The AOI of the EM system is selected as a square region with $30mm \times 30mm$. Figure 4 shows the AOI magnetic field distribution of the Helmholtz coil when the desired magnetic flux density is $5mT$ along the axis x, the non-uniformity is 0.24%. Figure 5 shows the AOI magnetic field distribution of the Helmholtz coil when the desired magnetic gradient field is $0.04T/m$ along the axis x. The black arrows represent the direction of magnetic flux density.
The results demonstrate that the magnetic field in the AOI generated by the EM is uniform enough. By adjusting the values of the input current, the generated magnetic field can satisfy various navigation and locomotion of the IPM.

3.2. Validation of magnetic propulsion simulation

Four types of MGCE (1: \( L = 23 \text{ mm}, \alpha = 0.5, r = 2 \text{ mm} \), 2: \( L = 24 \text{ mm}, \alpha = 1.5, r = 2 \text{ mm} \), \( L = 23 \text{ mm}, \alpha = 0.5, r = 3 \text{ mm} \), \( L = 24 \text{ mm}, \alpha = 1.5, r = 3 \text{ mm} \) ) are selected to validate the magnetic propulsion simulation. Figure 6 shows the comparison of the calculated magnetic torque based on the analytical model and the simulated magnetic torque based on FE and BE analysis. Figure 7 shows the comparison of force. The results show that the calculated values and simulated values match well.

3.3. Locomotion mode and navigation of the IPM

In a specific case of IPM navigation, figure 8 to figure 10 show the navigation maps of the uniform magnetic field, the gradient magnetic field and the magnetic force. When the IPM is placed at one point of the AOI, it will first be aligned by the uniform magnetic field. And then a gradient magnetic field \( B_v = [0.01 \text{ T/m}, 0.02 \text{ T/m}, -0.03 \text{ T/m}] \) will exert on the IPM and the IPM can be driven by it. The magnetic force generated is shown in Figure 10. Figure 11 shows the simulation of a helical locomotion mode[10]. The simulation results show that desired locomotion and navigation can be achieved by different combinations of input currents.
4. Conclusion and discussion
This paper proposes a compact-design of the IPM for MGCE system, and the IPM is a complex of the actuator and shell of the MGCE. The proposed IPM frees the occupation of conventional IPM, so it can increase the available inner space, which is beneficial to the miniaturization of the MGCE. The simulated values obtained by the magnetic propulsion simulation proposed in this paper matches well with the calculated values based on the magnetic propulsion analytical model, so the simulation can guarantee sufficient magnetic torque and force of the IPM during locomotion and navigation.

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