A Real-time Tracking Method for Magnetism-driven Capsule Robot

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Abstract: In the last decade, significant progress has been made in applying passive capsule endoscopes (CE) to medical diagnostics. However, disadvantages still need to be overcome for better utilization. A major challenge is to actively control the movement of the CE and provide real-time location information. This paper proposes a magnetic tracking method for CE driven by an external magnetic field that is generated by four sets of electromagnetic coils around the CE. The tracking method is based on a magnetic sensor array. The magnetic actuation constitutes three steps. First, the driving current from each coil is obtained according to the control requirement for a certain position and orientation. Second, the magnetic field that is generated by the driving current in the tracking space is estimated according to the magnetic field model. It can also be measured by Hall-effect sensors embedded in the position system. Third, the magnetic field generated by the CE is subtracted from the total magnetic field measured by the sensors, and then the magnetic position algorithm is applied. In the experiments, the positioning error is found to be within 5.6 mm and the orientation error is under 8.5°. The proposed localization method would be used for closed-loop control of CE to achieve better and safer performance.

Key words: Capsule Robot, Magnetic Actuation, Magnetic Tracking, Magnetic field Separation.

1 Introduction

Wireless capsule endoscopes have become highly attractive for their low cost, minimally invasive characteristic and high-security. Research has increasingly focused on remote guidance and driving of the endoscope in the gastrointestinal (GI) tract [1-3]. Usually a small permanent magnet is installed inside the capsule, and its active movement is provided by the external magnetic force produced by coils or permanent magnet [4-7]. Carpi and Pappone conducted an animal experiment of a magnetic capsule endoscope using a commercial permanent magnet-based actuation system [8]. Petruska et al. proposed an electromagnet system for a CE with direct and rapid magnetic field control [9]. Moreover, CE can be remotely real-time controlled in an arbitrary position and orientated by a single external permanent magnet [10-12]. However, whether driven by an external permanent magnet or an external coil, magnetic actuation of CE requires that the location and the orientation to be accurately estimated in real time, which is still hard to achieve, especially when the CE is moving inside the GI track. It is necessary to provide real-time position and orientation information for accurate and effective remote control. There are several magnetic localization methods, as outlined in [13]. A universal positioning method for CE is to perceive the magnetic field of a small magnet inside the CE using an array of Hall-effect sensors [14-17]. However, these methods are difficult to use for locating a CE that is driven by a time-varying magnetic field, since the driving field will interact with the magnetic field for CE tracking. The previous study introduced a method of real-time tracking and navigation for CE [18], which used an active external magnet to control a small magnet. It considered the active driving magnet as the second tracking target and executed a multi-object tracking algorithm to achieve real-time tracking and actuation. [19] provided a method to locate a capsule when it is rotating in the applied field. However, the CE should be stationary to meet their desired performance. [20] and [21] provided a closed-loop control method for CE, which can locate the CE in real time when the capsule is dragged by magnetic force. But closed-loop propulsion by magnetic field using computer vision for localization, is not practical for clinical application because of the closed environment in gastrointestinal tract.

In this paper, an external localization strategy is introduced, which can provide real-time position and orientation information using an external magnetic sensor array when the CE is driven by external magnetic coils. The key point of the proposed method for localization is to decouple the magnetic field signal of CE from that of the whole magnetic field from sensors array, which contains geomagnetism, the magnetic field generated by the drive coils, and the interaction between magnetic fields. First, the current of each coil, according to the driving strategy, will be obtained. Then, the relationship between the current of the drive coils and the magnetic field generated by the drive coils will be estimated. Finally, the driving magnetic field strength and the geomagnetism will be removed from the sensing field, and the remaining field will be used to locate the CE in real time.

This paper is organized as follows. Section II introduces the actuation device and the localization system. Details of the analytical models of the driving system and the influence of the driving system on the positioning system is provided in Section III. Experimental results and data analysis are presented in section IV. A discussion and conclusion are given in Section V.

2 Platform Description

The proposed driving and tracking system consists of three main parts, as shown in Fig.1: a driving system containing four coils distributed around the capsule robot, a localization platform with a set of sensor array, and the capsule robot with am embedded cylindrical permanent magnet.

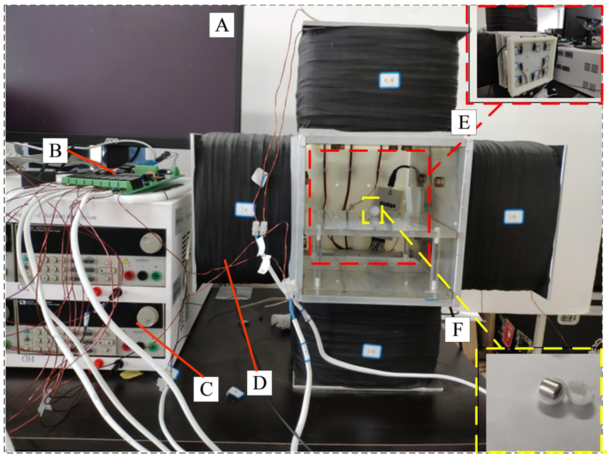

Fig. 1 The proposed driving and tracking system.
A: Desktop PC; B: Current control module;
C: DC power supply D: Electromagnetic coils;
E: Magnetic sensor array; F: Capsule robot.

As shown in Fig. 2, four sets of coils are controlled by four different power supplies. After each coil is powered up, a stable magnetic field is generated around the coils. Due to the vector superposition, the magnetic fields generated by the coils in four different directions will form a stable, directional magnetic field in the working area of the capsule robot, thereby actuating the capsule robot in different positions and orientations according to the driving demand of the capsule robot. The details are illustrated further in Section III.

According to the magnetic dipole model [22], the magnetic field strength of a magnet is inversely proportional to the cube of the distance. That is to say, when Hall-effect sensor is too close to the working area, the sensor will be saturated and then the measurement will be invalid. On the other hand, if the sensor array is too far from the working area, the magnetic field signal will be so weak to distinguish from the earth's magnetic field. Therefore, to achieve an accurate tracking result, the localization platform formed by eight sensors is arranged parallel to the line surface of the drive coils and the distance between the localization platform and the driving platform is set at 20 cm. It enables the sensor array to obtain the effective distance information of the robot without working in the saturated mode.

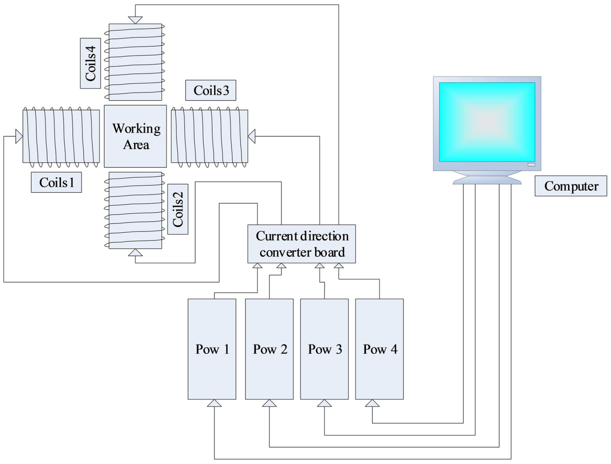

Fig. 2 Actuation of capsule robot.

3 Theoretical Approach

The capsule robot can be manipulated by the B-field generated by the external coils around the working area. In the present work, a rotating magnetic field is generated by four coils to control the CE rolling motion. Specific driving method is dicussed next.

The B-field measured by the sensor array constitutes three parts: geomagnetic field, driving magnetic field, and the magnetic field of the capsule robot, as given by

$$B_{sensor} = B_R + B_C + B_G \tag{1}$$

where B_{sensor} is the total magnetic field detected by the Hall-effect sensors, B_R is the magnetic field generated by the capsule robot, B_C is generated by drive coils, and B_G is the geomagnetic field.

One of the most important processes in locating a capsule robot while driving is separating the magnetic field of the capsule robot from the compositive sensed magnetic field. The previous work [15-18] has separated B_R from B_R and B_G . Therefore, the existing major challenge is to accurately determine the magnetic field generated by the drive coils. B_G , generated by earth, is generally constant in a particular area, which means it can be measured in advance.

B_c is produced by the drive coils and is related to the current flowing through the coils and the position of four coils. The previous study [22] derived the magnetic field model of a rectangular coil. Therefore, The magnetic filed model of the coil with a specific current can be obtained according to the coordinate transformation between multiple coils and through superposition of the magnetic fields.

The overall magnetic field of the actuation system is

$$B(P) = \sum_{e=1}^{n} B_e(i_e)_P \tag{2}$$

where $B(P)$ is the overall magnetic field, and B_e is the magnetic generated by a rectangular coil, whose strength is proportional to the current.

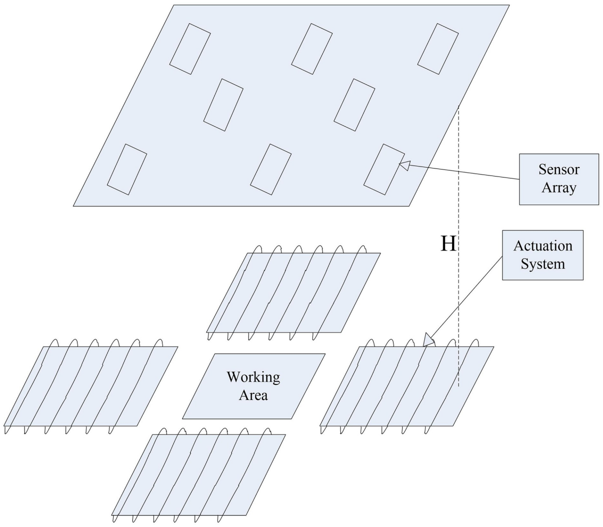

Fig. 3 Layout of the driving and localization system.

In this paper, the driving system consists of four rectangular coils, which means$n = 4$. The goal of driving the capsule robot to reacha certain point and orientation in the work space can be achieved by adjusting the current of each coil. Similarly, the magnetic field of the drive coils acting on the sensor array can also be expressed by equation (2). Obviously, B is proportional to the magnitude of the current while i is determined by the driving demand. Based on the input current i_e in different coils, the value of B_C can be acquired, and thereby achieving the purpose of separating B_R from B_R ,B_C and B_G .

The theoretical magnetic value B'_R of the capsule robot can be got using the magnetic dipole model.

(x_d, y_d, z_d) is the positional parameters of magnet, and $H_0 = (m, n, p)$ is the direction of the magnetic moment with $m^2 + n^2 + p^2 = 1$. At point (x_l, y_l, z_l) , the magnetic field can be calculated using

$$B_R' = B_T\left(\frac{3(H_0 ?\ P_l)\,P_l}{R_l^5} - \frac{H_0}{R_l^3}\right) \quad (3)$$

where B_T is a constant value related to the size and material of the magnet.

$$P_l = (x_l - x_d, y_l - y_d, z_l - z_d)$$

$$R_l = \sqrt{(x_l - x_d)^2 + (y_l - y_d)^2 + (z_l - z_d)^2} \quad (4)$$

Define the difference between the theoretical and measured values:

$$E = \sum_{l=1}^{n} (B_R' - B_R) \quad (5)$$

which is a nonlinear least squares problem. It can find the most suitable $[a, b, c]^T$ and $[m, n, p]^T$ to minimize the value of function (5) through Levenberg-Marquardt algorithm. $[a, b, c]^T$ denotes the location of the capsule robot, and $[m, n, p]^T$ denotes the orientation.

4 Experiment and Analysis

To verify the proposed method, the capsule robot is placed in several positions with the driving magnetic field on. According to the magnetic field model of the rectangular coil, the driving demand of the robot in a fixed position can determine the driving current i_e of each coil. Then the capsule robot can be located since the magnetic field working on the sensor array is proportional to i_e .

Experiments are conducted to evaluate the accuracy and reliability of the proposed localization methods. The experiment is divided into three steps after setting up the experimental equipment. First, in the case where the drive coil is not energized and the capsule robot is not placed, several sets of geomagnetic field values are measured and averaged in order to reduce the error. Then, each coil is connected to a plurality of sets of appropriate currents according to the driving demand, and the relationship between the current and the generated magnetic field is estimated. Finally, the capsule robot is placed at a fixed point and the coil is flowed through driving currents. By comparing the magnetic field values generated by a single capsule robot with that generated by the capsule robot after separation, the range of positioning accuracy of the capsule robot can be estimated.

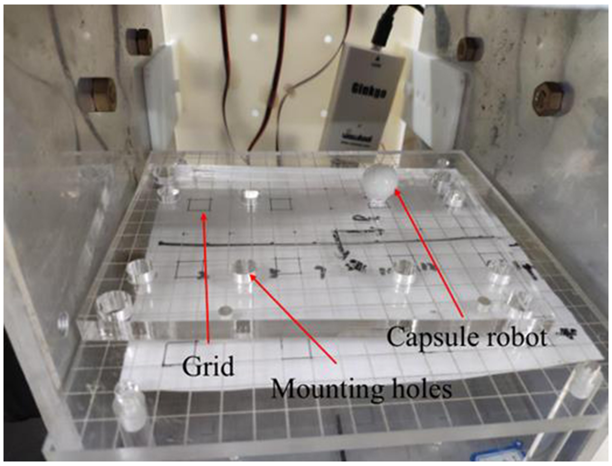

Fig. 4 The Workspace.

In the experiment, eight three-axis magnetometers HMC5883L sensing magnetic fields are placed on the positioning platform. In order to prevent the spherical capsule robot from rolling in the workspace under the action of gravity without current, the capsule robot is trapped on a flat plate with fixing holes, as shown in Fig. 4.

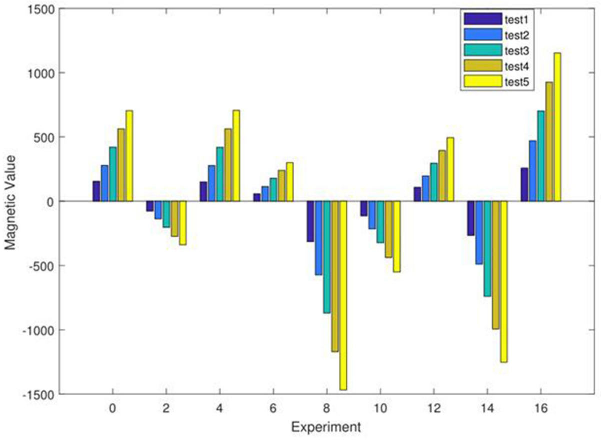

Fig. 5 The magnetic field value measured by the sensors when different currents are applied to the coil. When the current is applied to the coil, the magnetic field value is measured by the sensor. Each color represents the same current value. The five currents in the figure are 1I, 2I, 3I, 4I, and 5I. The nine sets of data in the figure are the measured values of 9 randomly selected directions from 24 directions (obtained from eight sensors).

Fig.5 shows the magnitude of the magnetic field measured by the sensors when a proportional current is applied. A constrain of uniform magnetic field is set in the workspace. The driving effect of the capsule robot is the same under proportional current as long as the driving torque can rotate the capsule robot. The unit current *I* shown in the figure is equal to (0.05A, 0.17A, -0.05A, -0.17A), which is a requisite current to actuate the capsule robot in the orientation (1, 0, 0) at the location (0, 0, 0) based on equation (2). It can be seen that the magnetic value is proportional to the current.

The localization and orientation error are shown in Fig. 6. Overall, the proposed position method is acceptable since the maximum errors are 9.4 mm and 14.9° . Its total average error is 5.6 mm for position and 8.5° for orientation, respectively. The result indicates that the error increases with the current, because of the error in the used mathematical model. These errors are related to the manufacturing accuracy and the material of the driving system. Since we calculate the magnitude of the magnetic field in the mathematical model by integrating the current generated by the current in the unit coil, which strictly assumes that the size of the coil is the same, and the winding is identical and evenly distributed. In fact, it is difficult to be absolutely consistent with these devices. When the current is magnified, the error is amplified. But in the real driving process, less than half of the current can drive the robot effectively.

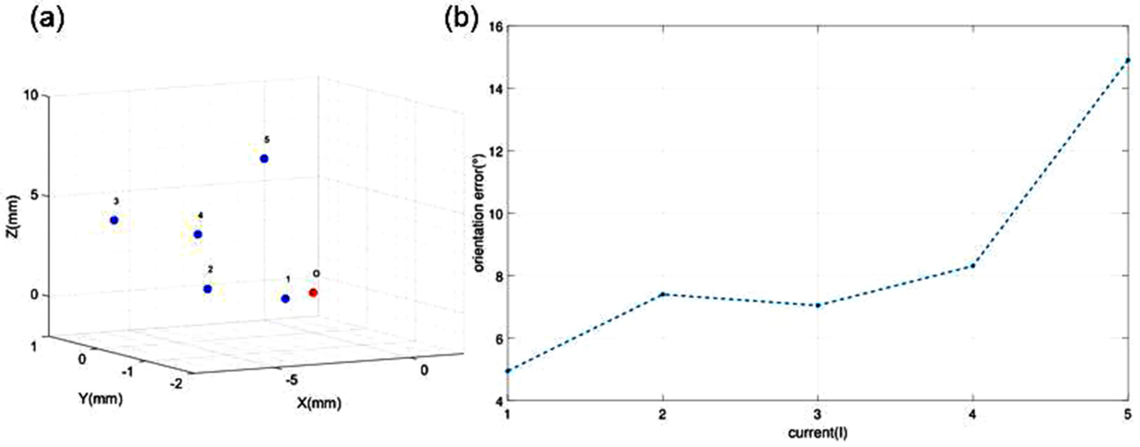

Fig. 6 Positioning results and orientation error with different drive currents.

a) The red point is ground truth position and orientation. Five blue points are position results in 5 different currents.
(b) Orientation error with five different currents. unit *I* = (0.05A, 0.17A, -0.05A, -0.17A).

5 Conclusion

This paper was motivated by the limitation of simultaneously driving andtracking a capsule robot. To overcome these limitations caused by mutual interference between complex magnetic fields, a new method was proposed by establishing a mathematical model between the driving current and the magnetic field. Also an experimental platform was developed for localization and actuation. Funally, by separating the driving magnetic field and the geomagnetic field, the value of the magnetic field which can be used for positioning the capsule robot can be obtained. Five experiments were carried out to verify the performance of the proposed method. The result showed an acceptable estimation of position and orientation with the external driving magnetic field. However, there are some shortcomings in the experiments. For example, the positioning error will become slightly larger as the current becomes larger. Planned future work will improve the manufacturing precision of the equipment to reduce the error. Also, closed-loop control of the capsule robot will be achieved based on the results of simultaneously driving and tracking the capsule robot.

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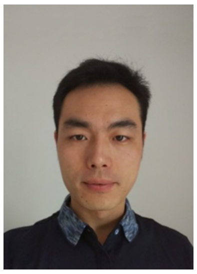

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