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Magnetic Localization Technology of Capsule Robot Based on Magnetic Sensor Array

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***Abstract* - Compared with traditional endoscopes, endoscopic capsule robots have been widely used in the medical field due to their small size, wireless transmission of internal images of digestive tract, and non-invasive and minimally invasive diagnosis and treatment. Therefore, when the capsule robot enters the human body, positioning it outside the human body becomes a key technology. Magnetic positioning technology has become the best method to realize capsule robot positioning with its high efficiency and high precision. In this paper, a magnetic positioning method is proposed, which measures the magnetic induction intensity through the magnetic sensor array platform built, and calculates the relative position of the capsule robot according to the magnetic dipole model derivation equation. In addition, this paper also carries out curve fitting for this method. The fitting results show that this method has higher positioning accuracy and shorter calculation time.**

Index Terms - Magnetic Positioning, Capsule Robot, Magnetic Dipole Model.

I. INTRODUCTION

In recent years, more and more attention has been paid to the magnetic positioning technology of medical capsule robots [1]-[2]. Because the accurate positioning of the capsule robot can not only find the lesion position for medical staff, but also prepare for future operations according to the information fed back by the capsule robot. Therefore, it is an efficient and convenient method to measure the magnetic induction intensity of the permanent magnet inside the capsule robot with magnetic sensors to provide real-time parameters for the positioning of the capsule robot. Based on the method of magnetic field positioning, there are many successful cases in China, such as the external magnetic tracking and positioning system based on Hall sensor array proposed by Ying Liao, Pingping Jiang and Guozheng Wang in 2012 [3]. The system establishes a new sensor array, through which the magnetic induction intensity of permanent magnet is measured, and the position and direction of capsule robot are obtained by using Levinberg-Maguire algorithm, and the absolute error is minimized when the number of sensors is 11. Although the method is simple to operate and has high accuracy, the system cannot effectively observe complex human intestinal tract. In 2015, Chao Hu, Yupeng Ren and their team proposed a compensation method for magnetic positioning interference of capsule endoscope caused by human body movement [4]. In this method, two perpendicular magnets are fixed on the surface of human body as reference targets to establish a suitable human body coordinate system, and the positioning result of capsule is converted from the sensor array coordinate system to the human body coordinate system. The method effectively solves the interference caused by the movement of the human body on the positioning of the capsule robot. In 2016, Hu Chao, Ren Pengyu and their team proposed a random complex number algorithm [5]. A large number of experiments have proved that the algorithm has higher accuracy than the traditional *L-M* algorithm. In 2019, Wang Min, Song Shuang, Hu Chao and their team proposed an algorithm combining absolute positioning and relative positioning [6]. Firstly, the absolute position of the capsule robot was measured by the sensor array built, and then the moving distance due to peristalsis of gastrointestinal tract was calculated by Bessel curve fitting method, thus realizing the positioning of the capsule robot.

Our laboratory has carried out relevant research on electromagnetic drive system. In this article, we have studied the magnetic positioning algorithm [7]-[11]. Through analyzing and studying various successful cases, this paper deduces the equation of magnetic dipole model carefully, and obtains that the position information of capsule robot is only related to the magnetic induction intensity measured by magnetic sensor. The experiment proves that the method is simple to operate and has high positioning accuracy, and is an applicable magnetic positioning algorithm.

The structure of this paper is as follows: Section II will introduce the mathematical model of magnetic positioning algorithm (Biot-Savart Law, magnetic dipole model and its transformation equation); In the third section, the sensors used in magnetic positioning and the positioning platform are proposed. The fourth section is the experimental part, which verifies the proposed algorithm. The last part is the conclusion.

II. Mathematical Model of Magnetic Positioning Algorithm

A. Biot-Savart Law

In magnetostatics, Biot-Savart law describes the magnetic field excited by a current element at any point P in space [12]. The magnitude of the magnetic induction intensity dB generated by the current element dl at a certain point P in space is proportional to the magnitude of the current element dl, proportional to the sine of the included angle between the position vector from the current element to the point P and the current element dl, and inversely proportional to the square of the distance from the current element dl to the point P [13].

The current in the current source dl is I, the point P is an observation point in space, the angle θ between the direction of the current source and the connection line between the observation point P and the current source dl, and r is the distance between the current source and the observation point P. The direction of the magnetic flux dB generated by the current element at the point P can be obtained by the ampere's right-hand spiral rule, and the magnitude can be obtained by Biot-Savart's law as shown in Equation 1. Equation 2 is a vector expression of Biot-Savart's law [14]:

$$|\mathrm{dB}|=\frac{\mu_0}{4\pi}\frac{Idl\sin\theta}{r^2} \tag{1}$$

$$d\vec{B}=\frac{\mu_0}{4\pi}\frac{Idl\times\vec{r}}{r^3} \tag{2}$$

where, μ_0 is permeability of vacuum, and the value of which is $\mu_0=4\pi\times10^{-7}(H/m)$.

B. Magnetic dipole model

Magnetic dipole is a physical model established by analogy with electric dipole. The electric dipole model represents the electric field strength at any point in the electric field, and the magnetic dipole model represents the magnetic field strength at any point in the magnetic field [15]. The magnetic dipole model can be generally divided into two types. The first is the current loop model, which is mostly applied to the analysis of constant magnetic field. The second is an imaginary magnetic charge model, also known as magnetostatic model, which is mostly applied to magnetic field analysis in magnetostatic materials. In the magnetic positioning system I studied, the model used is the current loop model, because the magnet in the capsule robot is very small relative to the positioning system, which is equivalent to a small magnetic rod, and the magnetic field generated by the small magnetic rod can be regarded as the magnetic field generated by a small closed-loop circuit, so the current loop model is adopted. In essence, the magnetic dipole model is a positioning method, that is, the position and orientation of the magnet in the space magnetic field are obtained. In the positioning system, the position coordinate is (a,b,c), and the orientation coordinate is (n,p,q). The magnetic dipole model is shown in Figure 1.

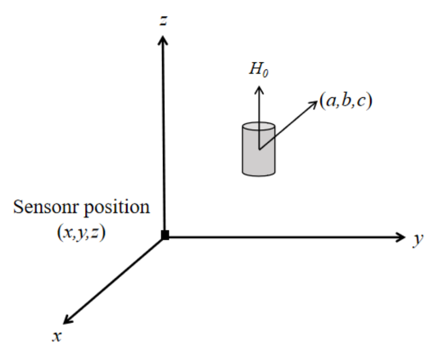

Fig. 1 Magnetic dipole model

According to Biot-Savart law, the magnetic induction intensity of the magnetic field $\vec{B}(\vec{B}_x,\vec{B}_y,\vec{B}_z)$ where the magnetic dipole model is located can be deduced as shown in Equation (3) [16]:

$$\begin{aligned}
B_x &= \frac{\mu_0}{4\pi}\left\{\frac{3[n(x-a)+p(y-b)+q(z-c)](x-a)}{r^5}-\frac{n}{r^3}\right\}\\
B_y &= \frac{\mu_0}{4\pi}\left\{\frac{3[n(x-a)+p(y-b)+q(z-c)](y-b)}{r^5}-\frac{p}{r^3}\right\}\\
B_z &= \frac{\mu_0}{4\pi}\left\{\frac{3[n(x-a)+p(y-b)+q(z-c)](z-c)}{r^5}-\frac{q}{r^3}\right\}
\end{aligned} \tag{3}$$

In Fig. 2, (a,b,c) is the position of the magnet, (n,p,q) is the magnetic dipole moment of the magnet, (x,y,z) is the position of the sensor.

In this process, the magnetic dipole moment can be expressed as shown in Equation (4):

$$(\vec{n},\vec{p},\vec{q}) = k(\vec{n_0},\vec{p_0},\vec{q_0}) \tag{4}$$

where, k is constant, (n_0, p_0, q_0) is identity matrix.

$$\sqrt{n_0^2 + p_0^2 + q_0^2} = 1 \tag{5}$$

The pose parameter located by the magnetic dipole model can be called the expected target for location, and the error between the expected position parameter and the actual position parameter can be expressed by Equation (6) [17]:

$$E_P = \sqrt{(a_s - a_t)^2 + (b_s - b_t)^2 + (c_s - c_t)^2} \tag{6}$$

The error between the expected magnetic dipole moment and the actual magnetic dipole moment parameter is expressed by Equation (7):

$$E_o = \sqrt{(n_s - n_t)^2 + (p_s - p_t)^2 + (q_s - q_t)^2} \tag{7}$$

where, $(a_s, b_s, c_s, n_s, p_s, q_s)$ is the actual pose parameter and $(a_t, b_t, c_t, n_t, p_t, q_t)$ is the calculated pose parameter, the higher the positioning accuracy of the experiment, the lower the sum value.

C. *The Proposed Algorithm*

The polar coordinate representation of Equation (3) is as shown in Equation (8):

$$\vec{B}(\vec{m},\vec{r}) = \frac{\mu_0}{4\pi r^5}[3(\vec{r}.\vec{m})\vec{r} - r^2\vec{m}] \tag{8}$$

where, $\vec{B}$ is the magnetic field strength, $\vec{r}$ is the corresponding space vector, and $\vec{m}$ is the direction of the magnetic dipole moment. since the north pole faces upward, the direction of the magnetic dipole moment is in the positive direction along the z axis, and Equation (9) can be derived from (3) and (8):

$$\begin{cases} B_x = \dfrac{\mu_0 m}{4\pi r^5} 3zx \\ B_y = \dfrac{\mu_0 m}{4\pi r^5} 3zy \\ B_z = \dfrac{\mu_0 m}{4\pi r^5}(3z^2 - r^2) \end{cases} \tag{9}$$

Equation (10) can be obtained through a series of equation derivation:

$$\begin{cases} x = \dfrac{|10^{-7}m|^{\frac{1}{3}}}{\sqrt{3}} \dfrac{t^{\frac{4}{3}}B_x}{\sqrt{tB_z+1}} \\ y = \dfrac{|10^{-7}m|^{\frac{1}{3}}}{\sqrt{3}} \dfrac{t^{\frac{4}{3}}B_x}{\sqrt{tB_z+1}} \\ z = \dfrac{|10^{-7}m|^{\frac{1}{3}}}{\sqrt{3}} t^{\frac{1}{3}}\sqrt{tB_z+1} \end{cases} \tag{10}$$

t is given by the Equation (11):

$$t = (B_z + \sqrt{9B_z^2 + B_{xy}^2})/(2B_z^2 + 2B_{xy}^2) \tag{11}$$

Equation (10) is the derivation equation of the magnetic dipole model equation. According to Equation (10), the expected position of the permanent magnet is only related to $\vec{B}$. Since there is a certain error between the permanent magnet position calculated by Equation (10) and the actual position, this paper proposes a compensation method by which the error between the calculated position and the actual position can be reduced.

III. CONSTRUCTION OF EXPERIMENTAL PLATFORM

In order to verify the proposed algorithm, a sensor array platform is built as shown in Fig. 2.

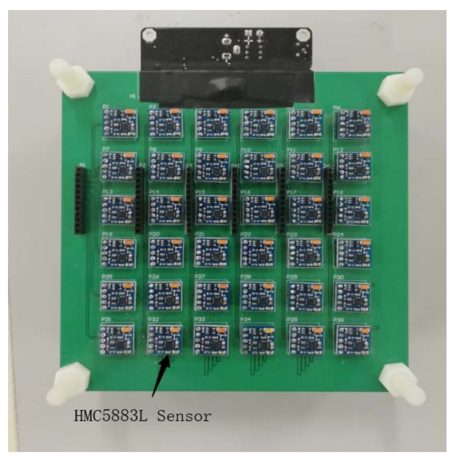

Fig. 2 Sensor Array Platform

The sensor we used is the Honeywell HMC5883L triaxial magnetic sensor. The HMC5883L sensors adopt I2C digital interface and Honeywell anisotropic magnetoresistance technology, so the HMC5883L sensor has the characteristics of high sensitivity and high linear accuracy in the axial direction. As the data measured by multiple sensors need to be displayed in the serial port and a switch-like device is needed to control the on-off of the sensors, the working state of the sensors is controlled by relays in this paper, as shown in Fig. 3.

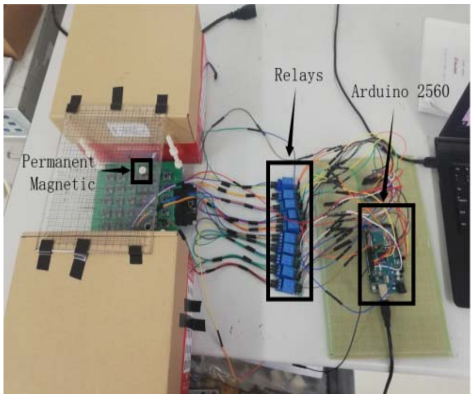

Fig. 3 Experimental Platform

As shown in Fig. 3, the control program is written by Arduino IDE software and burned to the development board, besides, the conduction state of the relay is controlled by arduino2560 development board to control the on-off of the sensors, thus reading the data measured by each sensor at the serial port.

IV. PERMANENT MAGNET POSITIONING EXPERIMENT

A. *Orientation experiments*

The experiment is to verify the accuracy of the proposed algorithm. Verification experiments control the coordinates of permanent magnets in any two directions in the three-dimensional space as fixed values. By gradually changing the coordinates of the third direction, the error between the actual value and the calculated value is obtained. In the *x*-axis orientation experiment, the *y*-axis and *z*-axis coordinates of the permanent magnet are fixed, a coordinate origin is calibrated, the *x*-axis coordinates are gradually changed at the same interval, the position of the permanent magnet is calculated through the proposed algorithm, and the image of the permanent magnet coordinates and errors is shown in Fig. 4.

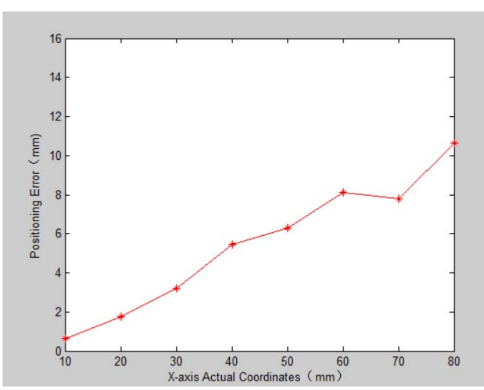

Fig. 4 *X*-Axis Direction Error

The experimental result in Fig. 4 shows that, as the distance between the permanent magnet and the origin increases, the positioning error also increases. from the calculation results, it can be concluded that the average positioning error increases by 1.12mm and the relative error is 11.2% for every 1cm increase in the distance between the permanent magnet and the origin in the x-axis direction.

B. *Curve fitting*

Due to the limited experimental platform, there are only a few specific points for the selection of permanent magnet positions. Therefore, errors obtained from the permanent magnet positioning are accidental to a certain extent. Therefore, curve fitting is needed to make the results more general. In this paper, there are two methods of curve fitting. The first is least square fitting and the other is interpolation fitting. Through comparison, it is found that the least square fitting has better fitting effect. Table 1 shows various data required to fit the curve using the least square method [18].

TABLE I

DATA REQUIRED FOR FITTING POSITIONING ERROR CURVES OF *X*-AXIS

i	$x_i(mm)$	$x_{ir}(mm)$	$y_i/error(mm)$	x_i^2	x_iy_i
1	10	9.38	0.62	100	6.15
2	20	18.23	1.77	400	35.47
3	30	26.81	3.19	900	95.56
4	40	34.57	5.43	1600	217.21
5	50	43.72	6.28	2500	314.20
6	60	51.90	8.10	3600	485.82
7	70	62.23	7.77	4900	543.87
8	80	69.35	10.65	6400	852.00
Σ	360	316.19	43.81	20400	2550.48

where, x_{ir} is the calculate position.

From the *x*-axis positioning error, it can be figured out that the selected 8 points are located on both sides of a straight line, so the linear function can be used to fit this set of experimental data, as shown in Equation (13):

$$E(x) = a + bx \tag{13}$$

Equation (13) is a first-order fitting formula of the least square method, in which the unknown parameters are *a* and *b*. The corresponding equations for the first-order polynomial fitting problem are established as Equation (14) [19]:

$$\begin{bmatrix} 8 & \sum_{i=1}^{8} x_i \\ \sum_{i=1}^{8} x_i & \sum_{i=1}^{8} x_i^2 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{8} y_i \\ \sum_{i=1}^{8} x_i y_i \end{bmatrix} \tag{14}$$

Equation (14) figures out the unknowns in equation (13) in the form of matrix. The equations of undetermined coefficients obtained from Table. 1 are:

$$\begin{cases} 8a + 360b = 43.81 \\ 360a + 20400b = 2550.48 \end{cases} \quad (15)$$

The obtained result is brought into equation (13) to obtain Equation (16):

$$E(x) = 0.14x - 0.73 \quad (16)$$

The curve fitted by the least square method is shown in Fig. 5.

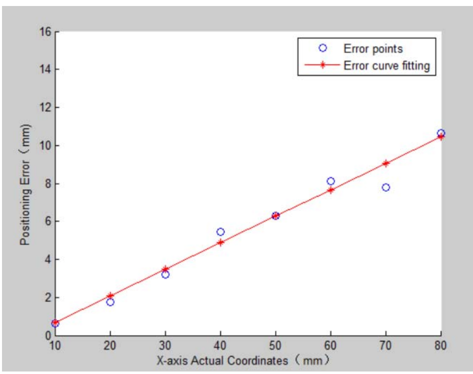

Fig. 5 Error curve fitting

The curve equation fitted by known data is called empirical equation. The quality of an empirical equation is usually measured by mean square error and maximum deviation. The fitting quality indexes of the x-axis errors are 1.55 for the mean square error and 1.30 for the maximum deviation.

The new compensated calculated position can be obtained by fitting the error curves in x-axis directions. The error between the compensated calculated position and the actual position is obviously reduced. The curve of permanent magnet positioning error obtained after compensation and positioning error before compensation is shown in Fig. 6.

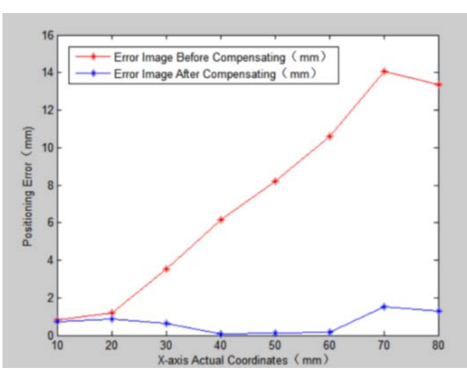

Fig. 6 Positioning error curve before and after triaxial compensation

It can be figured out from Fig. 6 that the positioning error of the permanent magnet is obviously reduced after error compensation, thus proving that the compensation method has better effect on reducing the positioning error of the permanent magnet.

V. Conclusions

This paper proposes a derivation algorithm for the positioning of capsule robots. The algorithm is verified to be able to realize the positioning of the robots. The compensation calculation is carried out for the positioning of permanent magnets through the least square curve fitting and the fitting equation, which improves the positioning accuracy and has better real-time performance. However, the algorithm also has some shortcomings, that is, it is not combined with a specific capsule robot. Therefore, in future research, I will find a way to reduce the positioning error and combine it with the capsule robot in the laboratory to make the experimental results more convincing.

Acknowledgment

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