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A Novel Non-model-based 6-DOF Electromagnetic Tracking Method Using Non-iterative Algorithm

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***Abstract*—Electromagnetic tracking, a non-fluoroscopic image navigation method most often used in minimally invasive therapy, has prominent advantages and features over the traditional X-ray radioscopy. Using two rotating coils and one 3-axis magnetic sensor, a novel 6 degree of freedom (DOF) electromagnetic tracking method is proposed in this paper. Two alternate rotating magnetic fields are generated in turns by these coils and the moving-around sensor simultaneously detects the magnetic filed flux density in 3 orthogonal directions. As the magnitude of a magnetic field comes to the maximum only when the rotating coil directly points toward the sensor, the spatial position and orientation of the sensor can be determined using triangulation measurement. An embodiment and the corresponding system framework of this method are developed and a non-model-based non-iterative algorithm is presented to calculate the 6-DOF of position and orientation. Moreover, simulation experiments are performed to validate the proposed method. The obtained results show that the averaged position error is 0.2365 cm and the averaged orientation error is below 1 degree away from low resolution area.**

I. Introduction

Minimally invasive therapy, with advantages of less trauma, less produce time, and less cost, is being widely used in recent clinic. During the medical procedures, the position and/or orientation of instruments (such as catheters, needles, and implanted devices) are important for operator and real-time monitoring of them is generally performed by different methods. One of the most often used methods in clinic is the X-ray radioscopy. However, many inevitable disadvantages, such as limited plane imaging, high radiation dose, and time cost, have brought it into less progress at present, especially on the modern minimally invasive procedures [1], [2]. Therefore, exploring and developing non-fluoroscopic tracking methods have attracted great interests of medical operators and researchers in recent decade.

Electromagnetic tracking is a kind of non-fluoroscopic method. Various methods [2]-[9] have already been developed to realize real-time spatial localizing or tracking.

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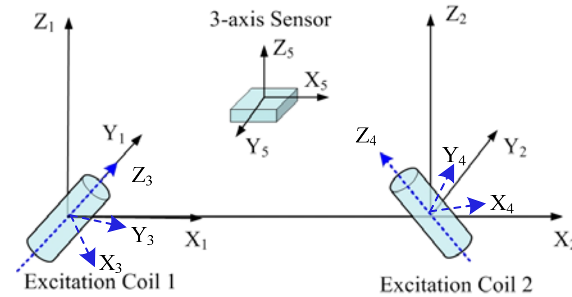


Fig. 1. Schematic of system embodiment: two coils rotating horizontally and vertically to search for the sensor (drivers are not shown).

However, most of the presented tracking methods in the prior art are based upon either the infinitesimal dipole model [4], [5] or other modified models [3].The infinitesimal dipole model is valid only when the distance between coil and sensor is much larger than the coil radius. Even though Schneider’s model [3] removes such limitation, there are still great differences between the real magnetic field and that calculated by the model. Furthermore, many of the methods in the prior arts use algorithms that are iterative [3], [5]. These iterative methods, needing lots of calculation, are usually greatly dependent on the selection of start point. Besides, there is no guarantee that they will converge to the correct solution. Therefore, a non-iterative method is also expected to have great advantages.

In this paper, a novel non-model-based 6-DOF electromagnetic tracking method is proposed using two rotating coils and one 3-axis magnetic sensor. An embodiment of this method is developed and a non-iterative algorithm is subsequently presented to calculate the position and orientation of 6-DOF. In order to validate the proposed method, a set of simulation experiments are carried out.

II. System Framework and Algorithm

A. Principle and Embodiment

As is known, the magnitude of a magnetic field comes to the maximum only when a rotating excitation coil directly points toward the sensor, the spatial position and orientation of the sensor can therefore be determined using triangulation measurement. Based on such a basic principle, a novel method of electromagnetic tracking is presented, as shown in Fig.1, which mainly comprises a 3-axis magnetic sensor and two electromagnetic coils. Each coil is mounted on a driver which can rotate horizontally and vertically. In addition, five Cartesian coordinates are defined in this paper to illustrate the

TABLE I
COORDINATE FRAME DEFINITIONS

Symbol	Description
F_1	coordinate frame shown in Fig. 2
F_2	has the same orientation as F_1 but the origin at the center of coil 2
F_3	coordinate frame defined by current orientation of coil 1 with the coil along z-axis
F_4	coordinate frame defined by current orientation of coil 2,with the coil along z-axis
F_5	the frame defined by present orientation of the sensor

proposed method and subsequently describe the corresponding position and orientation algorithm, as described in Table I, and shown in Fig. 1.Once these two coils are excited by injecting pulsed DC current in turn, two alternate rotating DC magnetic fields will be built correspondingly and then detected by the 3-axis sensor synchronously in 3 orthogonal directions. So the coils can be rotated to search for the sensor. In order to track the freely moving sensor, two courses of tracking will be performed. The first is an initial searching course which may take a long time. Once the initial position of the sensor is caught, the subsequent tracking course can be realized quickly as the sensor might not move much far away in a short time interval. Once the direction of the sensor is found, the position of the sensor can be conveniently calculated by triangulation measurement. The orientation can also be calculated subsequently. Both the position and orientation calculation algorithms, to be discussed in detail below, are non-iterative and not dependent on any kind of magnetic model.

B. Position Calculation

When the coils are pointing toward the sensor, the geometric relationship between them can be illustrated in Fig. 2. The centers of both the coil 1 and coil 2 align along x axis, and the distance between them is d. The coordinate of sensor here is defined as (x, y, z), which is to be calculated. In this way, the orientation of the coils can be denoted by the inclinations (α_1, β_1) and (α_2, β_2) when the coils are pointing toward the sensor. Symbols a and b represent two borders of the triangular in the x - y plane:

$$a = \frac{d \tan\alpha_2}{\cos\alpha_1 \tan\alpha_2 - \sin\alpha_1} \tag{1}$$

$$b = \frac{d \tan\alpha_1}{\sin\alpha_2 - \cos\alpha_2 \tan\alpha_1} \tag{2}$$

Therefore, the position of sensor can be calculated as:

$$x = a\cos\alpha_1 = \frac{d \tan\alpha_2}{\tan\alpha_2 - \tan\alpha_1} \tag{3}$$

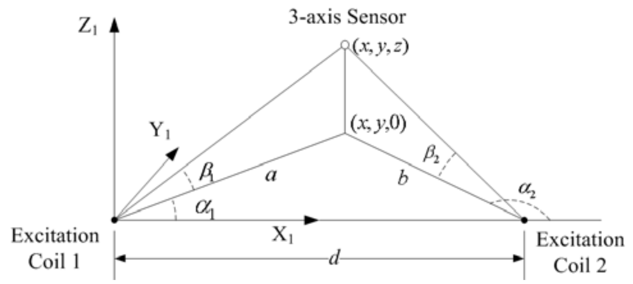


Fig. 2. Triangulation relationship between the two coils and the sensor.

$$y = a\sin\alpha_1 = \frac{d \tan\alpha_1 \tan\alpha_2}{\tan\alpha_2 - \tan\alpha_1} \tag{4}$$

$$z = \begin{cases} a\tan\beta_1 = \dfrac{d \tan\alpha_2 \tan\beta_1}{\cos\alpha 1 \tan\alpha_2 - \sin\alpha_1} & ,a < b \\ b\tan\beta_2 = \dfrac{d \tan\alpha_1 \tan\beta_2}{\sin\alpha_2 - \cos\alpha_2 \tan\alpha_1} & ,a \geq b \end{cases} \tag{5}$$

Both a and b can be used to solve z, the shorter one is selected to realize better precise. The algorithm is purely geometric, not dependant on magnetic model. The resolution of the angles (α_1, β_1) and (α_2, β_2) is a key factor that restricts the precise of the estimated position as well as the orientation.

C. Orientation Calculation

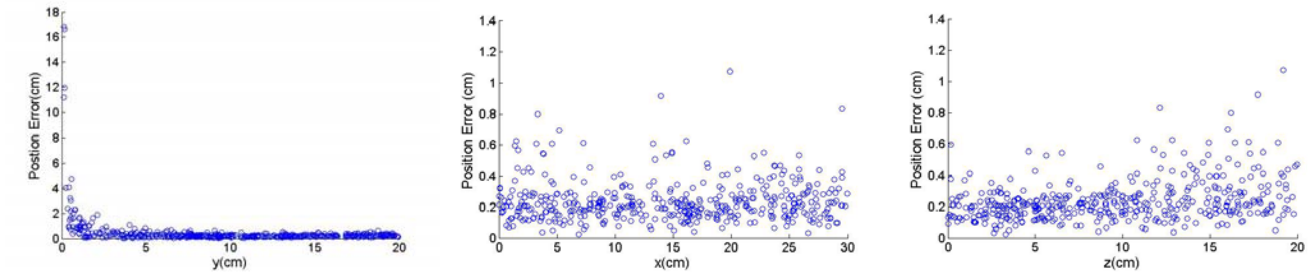
Based on the determined position of the sensor, the orientation can be subsequently calculated.

The magnetic flux density detected by the sensor, when the coil 1 or the coil 2 is stimulated and pointing toward the sensor, is denoted as $B_1 = [B_{1x}, B_{1y}, B_{1z}]^T$ or $B_2 = [B_{2x}, B_{2y}, B_{2z}]^T$, which are both in coordinate frame F_5. When rotated to F_3, the vector of B_1 changes to be $B_1' = [B_{1x}', B_{1y}', B_{1z}']^T$. Due to the vector of the magnetic flux density along the axis of the coil when the test position is along this axis, it is expected that both B_{1x}' and B_{1y}' approach zero and B_{1z}' reaches the maximum value. The angles of φ, θ and ψ represent the three Z-X-Z Euler angles from coordinate frame F_5 to F_3. Therefore, angles φ and θ can be calculated:

$$\varphi = \begin{cases} \arctan(B_{1y}/B_{1x}) - \pi/2, & B_{1x} \geq 0 \\ \arctan(B_{1y}/B_{1x}) + \pi/2, & B_{1x} < 0 \end{cases} \tag{6}$$

$$\theta = \arctan\left(B_{1z} \Big/ \sqrt{{B_{1x}}^2 + {B_{1y}}^2}\right) - \pi/2 \tag{7}$$

Rotating B_2 from F_5 to F_4, the result is denoted as $B_2' = [B_{2x}', B_{2y}', B_{2z}']^T$. Similarly, the vector of B_2' is expected to be along z -axis, so ψ can be calculated as follows:



(a) (b) (c)

Fig. 3. Simulation results of position localization: (a) position Error vs. y, (b) position Error vs. x (y>2.5cm), (c) position Error vs. z (y>2.5cm).

$$T_1 = \begin{bmatrix} \sin\alpha_1 & \cos\alpha_1 & 0 \\ -\cos\alpha_1 & \sin\alpha_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\beta_1 & \cos\beta_1 \\ 0 & -\cos\beta_1 & \sin\beta_1 \end{bmatrix} \quad (8)$$

$$T_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\beta_2 & -\cos\beta_2 \\ 0 & \cos\beta_2 & \sin\beta_2 \end{bmatrix} \begin{bmatrix} \sin\alpha_2 & -\cos\alpha_2 & 0 \\ \cos\alpha_2 & \sin\alpha_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (9)$$

$$T_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi \\ 0 & \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix} \quad (10)$$

$$B_2' = T_2 T_1 T_3 B_2 \quad (11)$$

Matrix T_1 is the transformation matrix from F_3 to F_1, T_2 is the matrix from F_1 to F_4, and T_3 is that from F_5 to F_3. B_2' can be expressed as a function of ψ using (11). As B_{2x}' and B_{2y}' approach zero, ψ can be calculated non-iteratively. Once the angles of φ, θ and ψ are all determined, the direction cosine matrix from F_1 to F_5 (orientation of sensor) O can be calculated using (12). The three Euler angles can be further calculated.

$$O = (T_1 T_3)^{-1} \quad (12)$$

III. Simulation and Results

A. Simulation Method

In order to validate the proposed method, simulation experiments are performed. The equations (13) to (15) describe the magnetic flux density produced by a circle with current [3]. Adding up the flux density produced by *n* turns of circle equidistantly aligned along z-axis, the magnetic field generated by a coil at a given position can be calculated.

When the coil is rotating, the magnetic flux density of a fixed position can be calculated by rotating the coordinate from F_1 or F_2 to F_3 or F_4. The flux density sampled by the sensor can then be got by further rotating of the flux density vector from F_3 or F_4 to F_5.

$$B = \frac{N\mu_0 I}{2\pi}\frac{1}{\sqrt{(a+\sqrt{x^2+y^2})^2+z^2}} \bullet \begin{bmatrix} \frac{xz}{x^2+y^2}\left(-K(\alpha)+E(\alpha)\frac{a^2+x^2+y^2+z^2}{(a-\sqrt{x^2+y^2})^2+z^2}\right) \\ \frac{yz}{x^2+y^2}\left(-K(\alpha)+E(\alpha)\frac{a^2+x^2+y^2+z^2}{(a-\sqrt{x^2+y^2})^2+z^2}\right) \\ K(\alpha)+E(\alpha)\frac{a^2-x^2-y^2-z^2}{(a-\sqrt{x^2+y^2})^2+z^2} \end{bmatrix} \quad (13)$$

$$K(\alpha) = \int_0^{\pi/2} \frac{d\theta}{\sqrt{(1-\alpha^2\sin^2\theta)}}$$
$$E(\alpha) = \int_0^{\pi/2} \sqrt{(1-\alpha^2\sin^2\theta)}\,d\theta \quad (14)$$

where α is defined as following,

$$\alpha = \sqrt{4a\sqrt{x^2+y^2} \Big/ ((a+\sqrt{x^2+y^2})^2+z^2)} \quad (15)$$

B. Position Error

Using the simulation method described above, 500 random positions and orientations were tested in turns. The distance d between the two coils was chosen as 30cm and all tested positions were with x from 0 to 30cm and y and z from 0 to 20cm in F_1. The tracking angle resolutions of two coils are both 1 degree. Position error was given by the distances between the estimated position and the real position, which is, the vector sum of the error in 3 orientations.

Fig. 3(a) shows position error distribution with postion along y axis. The system has a low resolution area near x-z plane. That is because the triangle in the x-y plane becomes very flat and the length of borders a and b in (3) and (4) might be solved with great error. As a result, it is suggested the tracking area to be away from the x-z plane in practice.

As shown in Fig. 3(a), when y is larger than 2cm, the condition became better. Fig. 3(b) and Fig. 3(c) position error distribution along x and z axes when y >2.5cm. When z became lager, the error range gradually became larger. The error range didn't show significant changes along x axis.

TABLE II
STATISTIC DATA OF POSITION ERROR‡

Max(cm)	Mean(cm)	Min(cm)	Std(cm)	90%(cm)
1.0745	0.2365	0.0244	0.1324	0.3965

‡. Max for maximum error, min for minimum error. Std for standard deviation, 90% for the upper boundary of 90% confident level

TABLE III
STATISTIC DATA OF ORIENTATION ERROR‡

Angle	Max(°)	Mean(°)	Min(°)	Std(°)	90%(°)
φ	2.7813	0.6845	0.0004	0.5651	1.4571
θ	1.9418	0.4108	0.0006	0.2981	0.8034
ψ	3.3132	0.7074	0.0052	0.6117	1.5283

‡. Max for maximum error, min for minimum error. Std for standard deviation, 90% for the upper boundary of 90% confident level

Table II gives the statistic data of position error with y >2.5cm. The mean error is 0.2365cm. If the track angle resolution is increased, the system may get a better performance.

C. Orientation Error

Using the same experiments procedure, the orientation estimation performance of the method was evaluated. The error was shown by the difference between estimated Euler angles and real angles. As the orientation calculation is based on the position calculation, only points at y >2.5cm were selected. The result is shown in Table III.The mean error is below 1 degree and the maximum error is below 5 degree.

IV. CONCLUSIONS

In this paper, a novel non-model-based 6-DOF electromagnetic tracking method is proposed to overcome disadvantages of the previous infinitesimal dipole model. An embodiment of this method is developed with two rotating coils and one 3-axis magnetic sensor. By using the proposed non-iterative algorithm, the 6-DOF position and orientation is subsequently calculated. Simulate results show that the position and the orientation error of the system could be acceptable for localization and real-time tracking of medical instruments during the minimally invasive producers.

It should be noted that there is a low resolution area of the system near the x - z plane, and the position to be tracked should be away from this area. Besides, errors induced by the noise and error of the sensor are not considered in this preliminary simulation. Future investigations and further works should be conducted to overcome these limitations and develop this method to clinical applications.

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