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Analysis and visualization of rotation searching efficiency in two-round rotation based magnetic tracking

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ABSTRACT

A magnetic sensor attaching on the moving object will have a maximum intensity measurement when the rotating magnetic field is pointing at it. Before solving the position and orientation, the magnetic field could be rotated in two orthogonal planes to find the maximal pointing direction. In order to realize a real-time tracking, efficient searching strategies for this maximum-oriented magnetic field rotation must be provided. This paper sets up a novel rotation searching efficiency model to quantitatively evaluate the relationship between the rotation searching time and the rotation axis in the two-round rotation based magnetic field measurement. Based on this model, two searching strategies are proposed. Simulation results suggest that both searching strategies can realize full space tracking without any latency larger than 30 ms. Corresponding system platform is under development.

1. Introduction

Magnetic tracking systems are usually composed of three parts, i.e., magnetic source(s), magnetic sensor(s), and a computing and control module with a specific tracking algorithm. Permanent magnet [1–5], AC excited coil [6–13], and DC excited coil [13–15] are three major magnetic sources, all of which can generate a desired magnetic field. Magnetic tracking is thus an inverse problem based on the sensor measurement and certain field distribution model [16–18].

In some application, such as capsule endoscope [2,3] and underground drilling [4], rotating magnetic field is used to actuate the object as well as its tracking. Since the rotating magnetic field can produce a simple periodic flux density measurement at every point in space, quite a few papers and patents have been focused on the analysis of rotating field based magnetic tracking [1,6,7,9–11,13–15].

Paperno et al. [9] demonstrated that a rotating dipole forms an ellipse at any position in the near field region. And the relative position and orientation can be determined by four unique elliptical parameters: the aspect ratio, size, phase and orientation. The computation algorithm is analytic without any iteration. Henceforth, several modified tracking systems have been developed under the elliptical feature of the rotating field. Song et al. [7] proposed a modified method which uses only amplitude and phase of the sensing signal in calculation. Popek et al. [2] made a correction on the orientation algorithm of [9]. Schultze et al. [1] avoided the classic phase-lock technique of [9] in order to release the cable restrain of the object movement. Instead, a fast three-dimensional ellipse fitting algorithm is introduced.

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Nomenclature

$\boldsymbol{r}$	rotation axis, normal vector of rotation plane
$\boldsymbol{r_s}$	supplementary rotation axis in two-round rotation
$\boldsymbol{m}$	normal vector of motion plane
$\boldsymbol{l}$	intersecting line of rotation plane and motion plane
$\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}$	reference coordinate axes
$\overrightarrow{OP_0}$	previous pointing vector
$\overrightarrow{OP_1}$	current pointing vector
$\overrightarrow{OV}$	projecting vector of $\overrightarrow{OP_0}$ on rotation plane
$\overrightarrow{OV_1}$	projecting vector of $\overrightarrow{OP_1}$ on rotation plane
α	azimuth, direction angle of pointing vector relative to rotation plane
β	elevation, direction angle of pointing vector relative to rotation plane
$\Delta\alpha$	difference of α between $\overrightarrow{OP_0}$ and $\overrightarrow{OP_1}$
$\Delta\beta$	difference of β between $\overrightarrow{OP_0}$ and $\overrightarrow{OP_1}$
θ	dihedral angle between rotation plane and motion plane
φ	phase angle of pointing vector relative to intersecting line $\boldsymbol{l}$ on motion plane
$\Delta\varphi$	difference of φ between $\overrightarrow{OP_0}$ and $\overrightarrow{OP_1}$, one-round rotation angle, minimal rotation angle
(φ, θ)	direction coordinate of pointing vector in the rotation searching space
γ	total rotation angle of two-round rotation
R	rotation index

The above algorithms employ the vector information of the rotating magnetic flux density. Apart from that, the direction of the scalar flux density maximum can also be detected, so that the geometric relationship between the magnetic source and the sensor is simplified [6,14,15]. The corresponding algorithm is robust and non-iterative since it does not rely on dipole model or specific magnetic measurement for calculation.

As for the physical methods for producing a rotating magnetic field, the three kinds of magnetic sources have some difference. An electrical motor carrying a permanent magnet at a certain rotation frequency can generate a rotating field [1–4]. Particularly, step motor carrying a DC excited coil can accurately control the direction of the rotating field [14,15]. Two space and phase quadrature AC excited coils can also generate a quasi-static rotating magnetic field [7,9]. Additionally, Kuipers [13] added one DC excited coil which is orthogonal to the two AC excited coils. Thus the rotating magnetic field becomes a conically nutating magnetic field. A simplified two-dimensional nutating field is also proposed by using one AC coil and one DC coil. Gilboa [10] and Kasper et al. [11] employ three space quadrature AC excited coils so that the rotating field fluctuates spatially. The frequency in the third vertical coil should be different enough from the frequency in the two space and phase quadrature coils in the horizontal plane. Thus the distinguished signal from the third vertical coil can help determine the elevation angle of the sensor position, reducing tracking ambiguity. On the other hand, instead of rotating the magnetic source, rotating the sensor with a rotary stage is an equivalent way to capture a rotating field [6].

The above rotating manners can be classified into rotating field within one plane [1,2,7,9,13], and rotating field in three-dimensional space [6,10,11,13–15]. Almost all of them has a fixed rotation axis or being attached to the tracking object passively. However, it should be noted that whether the rotation axis of the rotating field has any influence on the tracking accuracy, sensitivity, as well as efficiency.

Kasper et al. [11] pointed out that the signal-to-noise ratio decreases with the increasing vertical direction due to the geometry of the magnetic field. Singularities exist at the north and south poles where the horizontal direction cannot be defined. Paperno and Keisar [19] has conducted a quantitative error analysis on their proposed method [9], in contrast to the patent method of Raab [12]. The location resolution of both methods rapidly degrades when the elevation coordinate approaches 0° or 90°, which is near and perpendicular to the rotation axis of the quasi-static field. From the perspective of sensing system, Fang and Son [20] have conducted a vivid description about the measurable tracking range based on their distributed multipole model [17]. They found the sensitivity changes with the rotation angles of the source. An optimal location configuration for the sensor and the source is obtained.

According to previous research of our laboratory, not only low resolution area is found [15], but also low searching efficiency area exists with vertical angle close to 90° in the rotating field based tracking system [14]. The low resolution area has been fully analysed and removed by an averaging position algorithm [21]. But the low searching efficiency problem remains unsolved. No peer research has been found concerning about the rotation searching efficiency due to the unique feature of our two-round rotation based tracking system.

The two-round spatial rotation can enable the magnetic field to be accurately pointing at the sensor, so that the geometric relationship between the source and the sensor is greatly simplified and allowing a fast non-iterative position and orientation algorithm to be adopted. Moreover, only the direction of the maximum measurement is needed, so the system does not depend on any field distribution model or the noise-sensitive field measurement value. Besides, a second rotation can provide additional information to reduce the ambiguity of possible locations. However, the main disadvantage is the need of an efficient searching strategy to guide the searching of maximum measurement so as to avoid the low searching efficiency