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Modelling and solving the position tracking problem of remote-controlled gastrointestinal drug-delivery capsules

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ABSTRACT

A theoretical basis is presented to develop a real-time position tracking system for a remote-controlled drug-delivery capsule that would enable the targeted delivery of drugs to specific locations in the gastrointestinal tract. Tracking is accomplished by dual magnetic vector detection over time, using two separate sets of magnetic field sensing devices. One is used to detect the alternating magnetic field excited externally with certain frequencies, while the other is used to detect the geomagnetic field. A mathematical model of the magnetic flux density in space and time is constructed using the Biot–Savart law. Additionally, the earth's magnetic field and quaternion rotation theory are also used in the model to compensate for the constantly changing spatial orientation of the capsule as it travels through the gastrointestinal tract. Based on the model, an improved artificial bee colony algorithm is used to solve the inverse magnetic field problem. Firstly, chaotic sequencing improves the initial solution diversity, and a ranked selection strategy is applied. At later stages, the Levenberg-Marquardt algorithm is introduced in order to accelerate convergence. To verify the theoretical basis presented above, a prototype of the tracking system is developed. Calculations verification results in a convergence rate of 100% with an average of 179 iterations. The prototype testing shows that the dual magnetic vector detection method simplifies the solution of the inverse magnetic field problem, shortens the tracking time for each round of data, and increases the solution accuracy.

1. Introduction

Chronic digestive tract illnesses have become more common in recent years because of the accelerated pace and increased stress of modern life. These illnesses are difficult to treat with oral medications because such medications often do not reach the diseased tissue in sufficient doses. Therefore, if drugs could be delivered directly to the site of inflammation, wound, or lesion, absorption at the target area would increase, side effects would decrease, and in general the treatment would be much more effective.

Currently, images from inside the gastrointestinal tract are mainly acquired using capsule endoscopy [1,2]. A capsule containing remote-controlled drug-delivery equipment [3–5], rather than a camera, could be developed to enable the delivery of drugs to specific points along the gastrointestinal tract. Upon reaching the target site, external control equipment could command the capsule to deliver the drugs. Accordingly, the accurate and real-time tracking of the capsule's position within the gastrointestinal tract would be a key ability of such a system.

For some medical imaging techniques [6–8]—including X-ray, ultrasound, and magnetic resonance imaging—they can only supply visual information of the capsule location via images. However, these methods are impossible to obtain actual parameters of position and orientation to serve as feedback data for actuation systems. At present, a magnetic tracking method seems to be a promising solution [9–11]. According to this approach, a permanent magnet is enclosed in the in vivo micro-device, which results in a low-cost method that offers continuous tracking. However, this approach has limitations related to the solution speed and tracking range. In particular, the magnetic tracking method that employs static magnetic fields is restricted suffers from interference between the magnetic field produced by permanent magnets and the electromagnetic force used for driving drug release. Thus, the applicability of these tracking methods is similarly limited.

In particular, building upon our previous work [12,13], a dual magnetic vector detection system is proposed. This system

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consists of an alternating magnetic field detection device (AMFDD) and a geomagnetic field detection device. The AMFDD contains an external module that is fixed to the reference coordinate system, as well as an intra-capsule module that is fixed to the capsule's moving coordinate system. External alternating magnetic fields were provided by sequentially exciting four cylindrical coils at a certain frequency. The magnetic flux density was measured at the capsule's location. Using the Biot–Savart Law, a model of the magnetic flux density in space and time was constructed in the reference coordinate system $o-xyz$. Furthermore, the geomagnetic field vector was used to reduce the number of unknowns in the inverse magnetic field problem. More specifically, this vector was detected in the reference coordinate system $o-xyz$ and again in the capsule's moving coordinate system $o'-x'y'z'$. Quaternions were used to obtain the attitude angles of intra-capsule module, primarily owing to their utility in describing spatial rotations. Using the principle of quaternion rotation, the model of the magnetic flux density in space and time in the reference coordinate system was then rotated to the moving coordinate system. The transformed mathematical tracking model provided faster, more accurate solutions by decreasing the time required to collect each set of sample data. A chaotic bee colony algorithm, which combined a sequential selection strategy and the Levenberg-Marquardt (LM) algorithm in order to increase the speed and accuracy of the solution process, was also studied.

2. Dual magnetic vector detection tracking model

First, the reference coordinate system $o-xyz$ was constructed and fixed relative to the patient's body. Four cylindrical excitation coils were placed in the xoy plane. The axis of each excitation coil was parallel to the z-axis. The coordinates of the geometric center of each excitation coil were (b_i, c_i, d_i). Each excitation coil had n turns and an inner diameter of a. A sinusoidal excitation current I was used. The coordinates of the geometric center of the induction coil were (x_p, y_p, z_p), and μ_0 was the magnetic permeability of free space. According to the Biot–Savart Law [14], the variable magnetic flux density at the center of the induction coil excited by each excitation coil can be written as follows:

$$\vec{B}^{i}(x_p, y_p, z_p) = \frac{n\mu_0}{4\pi}\oint \frac{Id\vec{l}\times\vec{r}}{r^3} \tag{1}$$

Using a Taylor series expansion and simplification, the magnetic flux density components ${B_x}^i$, ${B_y}^i$and ${B_z}^i$ along each axis can be written as follows:

$$\begin{aligned}
{B_x}^i &= \frac{n\mu_0 I a^2}{4({x_0}^2+{y_0}^2+{z_0}^2+a^2)^{3/2}}\left(\frac{3x_0z_0}{{x_0}^2+{y_0}^2+{z_0}^2+a^2}+\frac{105a^2{x_0}^3z_0}{8({x_0}^2+{y_0}^2+{z_0}^2+a^2)^3}+\frac{105a^2x_0{y_0}^2z_0}{8({x_0}^2+{y_0}^2+{z_0}^2+a^2)^3}\right)\\
{B_y}^i &= \frac{n\mu_0 I a^2}{4({x_0}^2+{y_0}^2+{z_0}^2+a^2)^{3/2}}\left(\frac{3y_0z_0}{{x_0}^2+{y_0}^2+{z_0}^2+a^2}+\frac{105a^2{y_0}^3z_0}{8({x_0}^2+{y_0}^2+{z_0}^2+a^2)^3}+\frac{105a^2{x_0}^2y_0z_0}{8({x_0}^2+{y_0}^2+{z_0}^2+a^2)^3}\right)\\
{B_z}^i &= \frac{n\mu_0 I a^2}{4({x_0}^2+{y_0}^2+{z_0}^2+a^2)^{3/2}}\left(2-\frac{3({x_0}^2+{y_0}^2)}{{x_0}^2+{y_0}^2+{z_0}^2+a^2}+\frac{15a^2({x_0}^2+{y_0}^2)}{2({x_0}^2+{y_0}^2+{z_0}^2+a^2)^2}-\frac{105a^2({x_0}^2+{y_0}^2)^2}{8({x_0}^2+{y_0}^2+{z_0}^2+a^2)^3}\right)
\end{aligned} \tag{2}$$

where $x_0 = x_p - b_i$, $y_0 = y_p - c_i$ and $z_0 = z_p - d_i$.

In order to obtain the attitude of the drug-delivery capsule in space, a 3-axis geomagnetic field transducer was placed outside the patient with its coordinate axes parallel to the three axes of the reference coordinate system $o-xyz$. The transducer output was $\vec{B_0} = [B_{x0}, B_{y0}, B_{z0}]^T$. Another 3-axis geomagnetic field transducer was fixed inside the capsule with its axes parallel to the axes of the capsule's moving coordinate system $o'-x'y'z'$. The output from the transducer inside the capsule was $\vec{B_1} = [B_{x1}, B_{y1}, B_{z1}]^T$. The induction coil's axis of rotation was parallel to the z'-axis.

At this stage, the quaternion rotation principle was applied. Representing rotations using quaternions is a more compact and rapid method of computing compared to representing using matrices. The magnetic field vectors $\vec{B_0}$ and $\vec{B_1}$ in quaternion representation are:

$$q_{B_0} = \left[0, B_{x0}, B_{y0}, B_{z0}\right]^T \tag{3}$$

$$q_{B_1} = \left[0, B_{x1}, B_{y1}, B_{z1}\right]^T \tag{4}$$

Moreover, the rotation quaternion q is:

$$q = \left[\cos\left(\frac{\theta}{2}\right), w_i\cdot\sin\left(\frac{\theta}{2}\right), w_j\cdot\sin\left(\frac{\theta}{2}\right), w_k\cdot\sin\left(\frac{\theta}{2}\right)\right]^T \tag{5}$$

where

$$\vec{w} = \frac{\vec{B_0}\times\vec{B_1}}{|\vec{B_0}\times\vec{B_1}|} \tag{6}$$

and

$$\theta = a\quad\tan 2\left(|\vec{B_0}\times\vec{B_1}|,\ \vec{B_0}\cdot\vec{B_1}\right) \tag{7}$$

According to the quaternion rotation principle, the relationship between the magnetic flux density components in the reference coordinate system and the magnetic flux density components in the moving coordinate system is:

$$\begin{bmatrix} 0 \\ B_{x'} \\ B_{y'} \\ B_{z'} \end{bmatrix} = q\cdot\begin{bmatrix} 0 \\ B_x \\ B_y \\ B_z \end{bmatrix}\cdot q^{-1}. \tag{8}$$

Eqs. (2) and (5) can be substituted into Eq. (8), and the magnetic flux density component $B_{z'}$ in the moving coordinate system can thereby be obtained. The vector normal to the cross-section of the induction coil is:

$$\vec{s_{z'}} = s\cdot\vec{z'} \tag{9}$$

where $\vec{z'}$ is a unit vector on the z'-axis of the moving coordinate system. From this, the output electromotive force E is:

$$E = -\frac{d(B_{z'}\cdot s_{z'})}{dt} \tag{10}$$

When each coil was excited, the electromotive force E outputted from the induction coil could be measured. The tracking model was derived in relation to the positional vectors and the three attitude angles of the induction coil inside the capsule. Using the geomagnetic vector detection in the reference coordinate system and again in the moving coordinate system, the three attitude angles of the capsule were thus obtained based on the principle of quaternion rotation. In all, only three positional parameters as unknowns were included in the group of nonlinear equations. Based on Eq. (10), there were four equations corresponding to four excitation coils. This simplified the solution of the tracking model and increased the accuracy of solutions.