Magnetic Tracking Inside Conducting Bores for Radiotherapy Tumor Localization Systems

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Abstract- We propose a unique magnetic tracking method that is applicable to tumor localization in radiotherapy gantry bores, where induced eddy currents distort magnetic source fields. Our method uses a specific configuration of sensors and an optimization method to reduce effects from the nearby gantry eddy currents, which are induced by the magnetic tracking source. We demonstrate the effectiveness of our method with numerical examples.

I. INTRODUCTION

Real-time, magnetic tracking is used in radiotherapy to localize tumor motion during treatment; however, there are no methods to track tumors inside gantry bores such as CT or Tomotherapy, both of which are vital for accurate treatment delivery [1]. Various tracking algorithms have been developed based different designs of tracking systems. Some of these algorithms use closed-form solution [2], while other algorithms develop more advanced procedures including nonlinear optimization [3]-[5]. However, these methods do not consider the interferences from eddy currents induced on nearby gantry and other metal objects. One of the localization systems [6] may handle the stationary eddy current effects by measuring a reference transponder, but it becomes invalid when the environment changes.

In this paper, a novel localization method is proposed to minimize the localization error caused by the eddy current on the gantry. Sensor arrangement and distortion minimization algorithm are discussed. Simulations are performed to evaluate localization performance.

II. INITIAL LOCALIZATION

The proposed localization system is composed of four groups of sensors installed under the sliding bed as shown in Fig.1. Each group consists of seven sensors. The center one measures the magnetic field B_x. The other six sensors are arranged along three orthogonal axes, to measure the gradient value of B_x.

Since the detection distance is much smaller than the wavelength of the operating frequency but much larger than the transponder's dimension, the magnetic field generated from the transponder can be approximated by the static dipole as:

$$B_x = \frac{\mu}{4\pi}\left\{\frac{3[\mathbf{m}\cdot(\mathbf{s}-\mathbf{p})](\mathbf{s}_x-\mathbf{p}_x)}{\|\mathbf{s}-\mathbf{p}\|^5} - \frac{\mathbf{m}_x}{\|\mathbf{s}-\mathbf{p}\|^3}\right\} \tag{1}$$

where **s** and **p** denotes the position vector of the transponder and the sensor, **m** is the magnetic moment, and μ is the permeability. The subscript x defines the projections of various quantities onto the x-axis in the Cartesian coordinate system and $\|\cdot\|$ defines l^2-norm. Considering the spatial gradients of the magnetic flux density, we have

$$\nabla B_x \cdot (\mathbf{s}-\mathbf{p}) = -3B_x\,. \tag{2}$$

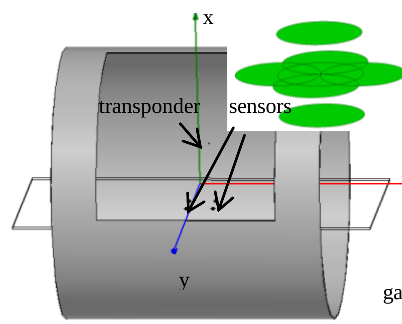

Fig. 1. Schematic diagram of the localization system

The measured magnetic field from four groups of sensors can form four equations following (2). Solving these four equations together leads to the estimated position of the transponder as:

$$\mathbf{p}_0 = \mathbf{G}^+(3\mathbf{b} + diag(\mathbf{GS})) \tag{3}$$

where

$$\mathbf{G} = [\nabla B_x^{(1)}, \nabla B_x^{(2)}, \nabla B_x^{(3)}, \nabla B_x^{(4)}]^T\,, \tag{4}$$

$$\mathbf{b} = [B_x^{(1)}, B_x^{(2)}, B_x^{(3)}, B_x^{(4)}]^T\,, \tag{5}$$

$$\mathbf{S} = [\mathbf{s}^{(1)}, \mathbf{s}^{(2)}, \mathbf{s}^{(3)}, \mathbf{s}^{(4)}]\,, \tag{6}$$

and $\mathbf{G}^+$ is the pseudo-inverse of $\mathbf{G}$. Then by instituting $\mathbf{p}_0$ to the dipole equation (1), we can derive an initial value of magnetic moment $\mathbf{m}_0$.

III. MINIMIZING EDDY CURRENT DISTORTION

Due to eddy current effects of the gantry and other metal objects of the detection system, distortions exist in the measured values of the magnetic flux density. It is difficult to measure and calibrate such effects in the tracking process because both the transponder position and the gantry may vary during medical treatments. Here we present a correction method without using any a priori information, which works well in the case of gantry rotating.

Since the spacing among the seven sensors in each group is smaller than the distance from the locations of eddy currents (typically on the gantry), it is reasonable to assume that the secondary magnetic field generated by the eddy current are approximately equal to each other for the seven sensors. Thus, we can establish such a distortion model of the magnetic flux density measurements

$$B_{meas}^{(i,k)} = B_{true}^{(i,k)} + B_{eddy}^{(i)},\ i = 1,\ldots,4,\ k = 1,\ldots,7 \qquad (7)$$

where $B_{meas}^{(i,k)}$ is the measured magnetic field by the k-th sensor in the i-th group, and $B_{true}^{(i,k)}$ is the calculated magnetic field via the dipole equation (1). $B_{eddy}^{(i)}$ denotes the magnetic field induced by the eddy current in the i-th group, which is to be determined. There are 10 unknown quantities including the transponder position and magnetic moment. These values can be solved by minimizing an objective function

$$f(\mathbf{p},\mathbf{m},B_{eddy}^{(i)}) = \sum_{i=1}^{4}\sum_{j=1}^{7}\left|B_{meas}^{(i,k)} - B_{true}^{(i,k)} - B_{eddy}^{(i)}\right|^2. \qquad (8)$$

Many methods can be used to solve this minimization problem. Those traditional algorithms, such as Levenberg-Marquardt (L-M) algorithm, usually need a good initial guess to achieve accurate solution and converge rapidly. $\mathbf{p}_0$ and $\mathbf{m}_0$ estimated in the section (II) shall be used as the initial values for fast convergence.

IV. SIMULATION RESULTS

To evaluate the localization accuracy, we use Ansoft Maxwell to simulate the magnetic field distribution generated by the transponder inside the gantry system. Four sets of sensors are placed within the gantry. The geometry setup is shown in Fig. 1. The resulting values for both the magnetic field and the gradient of the magnetic field are exported to the proposed localization algorithm. The localization error is defined as

$$E = \left\|\mathbf{p}_{calc} - \mathbf{p}_{model}\right\| \qquad (9)$$

where $\mathbf{p}_{calc}$ is the position calculated from the output of sensors and $\mathbf{p}_{model}$ is the modeling transponder position.

Simulations were conducted for different positions and orientations of the transponder. For the purpose of comparison, the conventional optimization is also tested here. In the conventional approach, the following expression is used for optimization:

$$\min\ f(\mathbf{p},\mathbf{m}) = \sum_{i=1}^{4}\sum_{j=1}^{7}\left|B_{meas}^{(i,k)} - B_{true}^{(i,k)}\right|^2. \qquad (10)$$

Fig. 2-4 shows the results of localization with no optimization, conventional optimization, and proposed optimization approaches. As we can clearly see, the eddy current of the gantry causes large localization distortions if optimization procedure is not used. However, after correction as mentioned in section III, those errors are significantly reduced.

V. CONCLUSION

In this work, a magnetic localization method is proposed. It can significantly reduce the localization errors caused by the eddy current. The correction does not require any a priori information. The presented sensor arrangement can increase the converging speed of localization algorithm, which makes real-time tracking available.

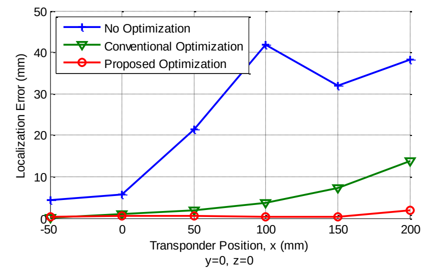

Fig. 2. Localization errors for transponder paralleling to X-axis

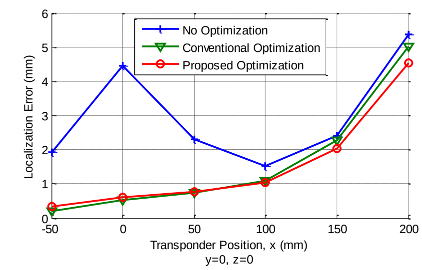

Fig. 3. Localization errors for transponder paralleling to Y-axis

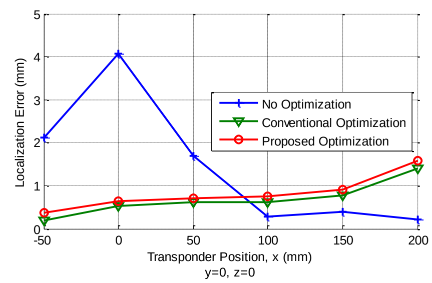

Fig. 4. Localization errors for transponder paralleling to Z-axis

VI. REFERENCES

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