A robust electromagnetic tracking system for clinical applications

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Abstract:

Electromagnetic tracking systems (EMTS) are utilized to track surgical instruments during navigated interventions. Compared to optical tracking technologies, the non-line-of-sight feature is the biggest advantage of EMTS. However, significant distortions due to nearby metallic objects and a small working volume are serious drawbacks preventing ETMS from being widely used. We worked on developing new methods to improve the accuracy of EMTS even in the vicinity of large metal objects while speeding up the position estimation frame rate. Therefore, we proposed a method to realize frequency deviation multiplexing (FDM) for EMTS in order to speed up the frame rate, and a quadratic-rectangular (QR) excitation method to remove the distorted voltage induced by the nearby conductive distorter. The results show that the measurement speed and robustness to nearby metal objects of our EMTS were improved by the FDM and QR method.

Keyword: Electromagnetic Tracking, Image-guided Interventions, Navigation

1 Problem

Electromagnetic tracking is a growing technology for use in clinical applications[1]. Commercial available EMTS such as NDI Aurora (NDI Medical, Canada), Polhemus Fastrack (Polhemus, Canada) and Ascension MiniBIRD *(*Ascension Technology, USA*)* were used of clinical researches[2]. The following requirements of clinical EMTS are essential: high frame rate of position estimation, the number of sensors to be tracked in parallel, large working volume, small-sized sensors, high tracking accuracy and robustness with regard to metal objects[3].

Our work focuses on increasing the refresh rate and robustness of EMTS. Time division multiplexing (TDM) and frequency division multiplexing (FDM) are the common methods for electromagnetic tracking systems[4,5]. For TDM, the signals are sent to distinct transmitter coils sequentially in the time domain. Meanwhile, the sensor coil measures the voltage induced by the magnetic field generated by each transmitter coil. The FDM method separates the measured signals in the frequency domain in parallel that speeds up the measurements. By other research groups[6,7] and also in our previous studies[8] the digital signal processing (DSP) structure-based devices were used for signal generation and data acquisition in electromagnetic tracking. The DSP-based devices do not support the parallel executions of the FDM method. In this work, we propose a method to use a field-programmable gate array (FPGA) to realize the FDM method in EMTS.

The largest drawback of EMTS is its weak robustness due to nearby metallic distorters[9]. There are two types of metal distortions: conductive and/or ferromagnetic distortion. Ferromagnetic distorters interfere the shape of the generated magnetic field that is hard to be analytically characterized[10]. Calibrations compensate the static metallic distortions; however, they cannot correct the dynamic distortions in the operating room (OR) environment in real time[11]. We propose a method to remove the distorted voltage induced by the nearby conductive object so as to reduce the dynamic conductive distortions[12,13].

2 Method

A. Experimental Setup

NDI Aurora 5-DOF catheter (NDI Medical, Canada) were selected as the EM sensors because they are widely used in clinical applications. Eight channels of voltage signals were generated and passed through eight current feedback amplifiers LT1210 (Linear Technology, USA) into the transmitter coils to produce magnetic fields. The voltage induced in the sensor coil were increased by a micropower amplifier LT1168a (Linear Technology, USA) and measured by the system. The core element of the EMTS experiment setup in our lab is the NI PXIe 8133 system (National Instrument, USA). It was used to program the FPGA board in NI PXI 7854R (National Instrument, USA) for signal generation and data acquisition. The PXI system also realizes direct memory access (DMA) communication between FPGA and the central processing unit (CPU). Figure 1 shows the experimental setup of the EMTS. As a standard testing platform, the experimental setup of EMTS allows us to use it for distinct research purposes.
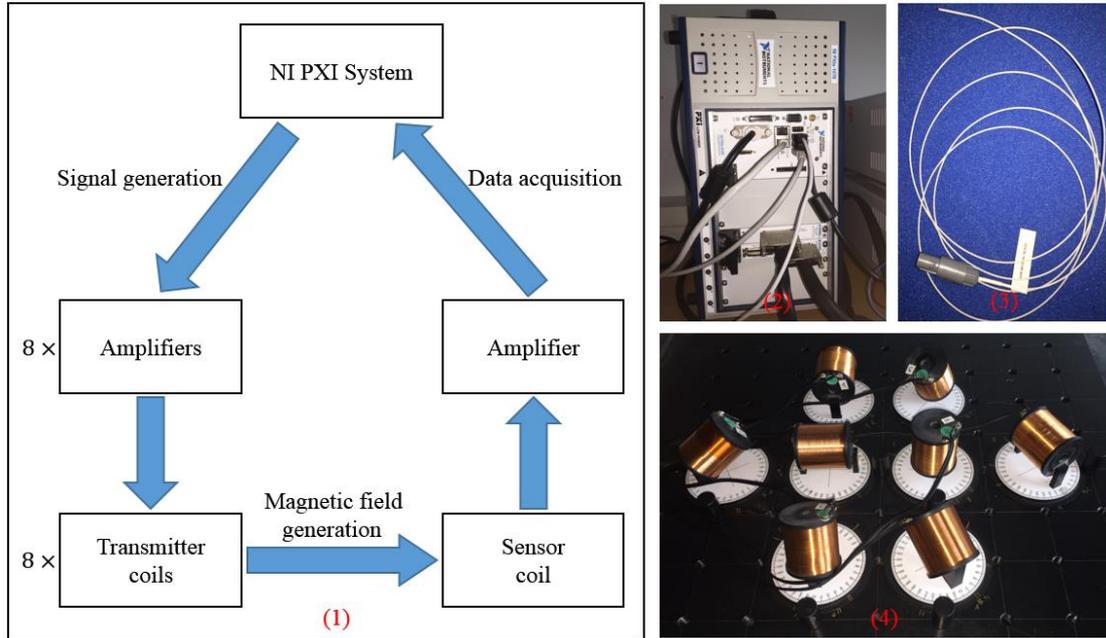
Figure 1. The experimental setup of the electromagnetic tracking system: (1) system block diagram, (2) NI PXI system, (3) NDI Aurora 5-DOF catheter, (4) Transmitter coils.

B. FDM Method

The NI PXI 7854R, including a Virtex-5-LX110 FPGA (*Xilinx, USA*) inside, was proposed to generate eight channels of sine-wave signals in parallel using direct digital synthesis (DDS). The generated signals were passed through the amplifiers into the eight transmitter coils to generate the magnetic field. In the meantime, the voltage induced across the sensor coil was measured by the FPGA. Each of the transmitter coils was supplied with signals at different frequencies from 1650 Hz up to 2000 Hz with an increasing step of 50 Hz. Eight FPGA IIR band-pass filters were designed and implemented to realize parallel filtering. A magnetic dipole model was commonly utilized to simulate the generated magnetic fields of EMTS[14,15]. The non-linear parameters describing the sensor's position and orientation (PO) are optimized using the Levenberg-Marquardt algorithm[16].

C. Quadratic-rectangular Excitation

The eddy current induced in a nearby electrically conductive object produces a secondary magnetic field adding on to the original magnetic field generated by the transmitter coils. The voltages induced by transmitter coils and distorter were simultaneously measured by the sensor coil. EMTS often use the sinusoidal waveform as system input signal[17,18]. However, according to sinusoidal excitation there is only a slight phase shift between the voltages induced in the sensor coil, with and without a proximate conductive distorter. It does not consist of adequate information to differentiate between distorted and non-distorted voltages. However, a quadratic-rectangular input waveform enables the differentiation of

the non-distorted voltages[12]. The mutual inductances between sensor and transmitters were calculated and lead to the sensor's PO estimation. The method was implemented by the NI PXI system to achieve faster measurement speed[13]. The constructed EMTS prototype applying quadratic-rectangular excitation was evaluated by experiments with static and dynamic sources of distortion.

D. Experimental Evaluation
Using LEGO bricks is a standard method to evaluate the accuracy of the EMTS due to the plastic feature and high precision[19,20]. In this work, an accuracy assessment protocol using LEGO bricks (*The Lego Group, Denmark*) is proposed to evaluate all EMTS methods.

Figure 2. Accuracy evaluation of EMTS setup

Figure 2 shows the setup of the EM tracker accuracy evaluation. The measurements were performed in a 3D volume of $25.6\,\text{cm} \times 25.6\,\text{cm} \times 18\,\text{cm}$. In each measurement, the tracker's position was measured at five layers with $8 \times 4 = 32$ points for each layer. Each step sensor movement towards x, y, z direction was $3.2\,\text{cm}, 6.4\,\text{cm}$, and $1.92\,\text{cm}$ respectively. The positions recorded by LEGO bricks were used as the reference positions to assess the accuracy of the EM tracker. Two metallic disks with different size and material were utilized as the worst case of nearby conductive distorters in the clinical environment. The same setup was also used to measure the standard deviations (SD) of the estimated sensors' PO for the TDM method in a metallic clean environment. In the experiment, each measurement of 160 positions was repeated 30 times to calculate the SD of the PO.

3 Results

A. Refresh Rate
By applying the FDM method, the system's refresh rate increased to 35.0 fps, which is approximately six times faster than the TDM method. The update rate of the QR method was 1.6 fps, which is much slower than the other two methods because the system needs much longer to measure the steady state response of a rectangular excitation.

B. Accuracy Assessment using LEGO Bricks
The tracker accuracy in six different scenarios: TDM, FDM and QR methods with and without nearby conductive distorter, was evaluated by LEGO bricks. Figure 3 shows the positional errors of the six measurements.

Figure 3. Error plot of the accuracy measurements. The horizontal axis represents the distance between the sensor and the middle point of the transmitter coils, and the vertical axis represents the positional error.

In a clean environment without metallic distortion, both TDM and FDM methods have a high precision. However, they are not able to track the sensor precisely when there are nearby conductive distorters. For the QR method, the results are similar with and without neighboring conductive distorters. The QR method works properly in a quite small 3D volume within the distance of approximate 11 cm between the sensor and the central point of the transmitter coils. The errors become larger with larger distances between sensor and transmitters.

The positional accuracy of the experimental EMTS decreases while the distance between sensor and transmitter is increasing. In a small working volume with a distance between sensor and center of field generator up to approximately 10 cm, the RMSE of the QR method was measured to be 1.7 mm and 2.0 mm in clean and distortion environment, respectively[12].
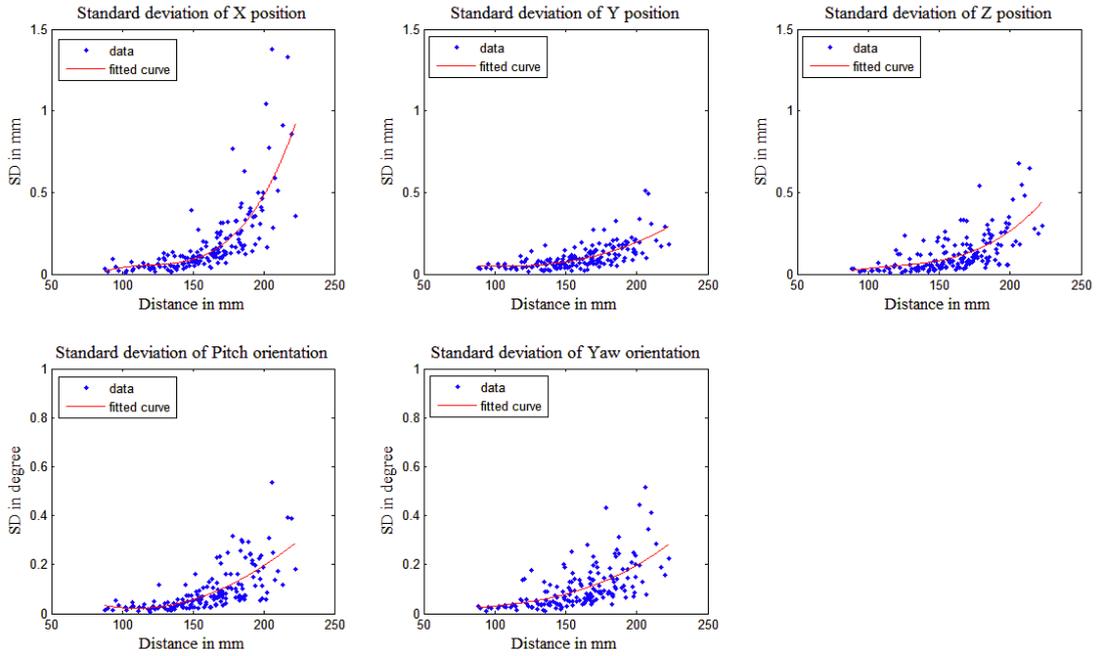
environment. The horizontal axis represents the distance between the sensor and the middle point of the transmitter coils, and the vertical axis represents the standard deviations.

As shown in Figure 4, the SD of the measured PO in all x, y, z positions and pitch, yaw orientations increase while the distance between sensor and transmitter is becoming larger. The maximum SD of the x direction within the testing volume is measured to be 1.4 mm, which is too large and requires to be reduced for clinical applications.

4   Discussion

In this work, we presented the FDM and QR method developed to enhance the EMTS performances. The results show that the PO estimation frame rate and the robustness to nearby conductive distortions of the EMTS were improved. Compared to the TDM method with the refresh rate of 6 fps, the FDM method increased the refresh rate of the EMTS experimental setup up to 35 fps. The positional accuracy of the EMTS by applying both methods was similar. For both the TDM and FDM method of the experimental EMTS, 20 periods of voltage signals induced in the sensor coil were measured and averaged. The measurement speed has the room to be increased by acquiring fewer signal periods. To reduce the conductive distortion, the QR method currently only works properly in a small testing volume with a distance between the sensor and the center point of the field generator of up to 11 cm. In larger working volume, the performance of QR method is poor because the measured steady-state signal of the system response to the rectangular excitation is weak. Increasing the generated signal amplitude and using amplifiers with larger gains are the potential ways to improve the QR method. The current refresh rate of the QR method is 1.6 fps that is too low for real-time clinical navigation. Therefore, we are investigating a new method to increase the system speed. The SD of the estimated position and orientation of the sensor becomes larger when the distance between the sensor and transmitter increases. By increasing the distance, the measured voltage induced in the sensor coil has a smaller signal to noise ratio (SNR). The averaging process can be applied to increase the accuracy of the measured PO of the sensor[22]. However, it takes more time to run the averaging algorithm. Therefore, we will investigate if Kalman filtering could reduce the SD of the tracked PO of the sensor without slowing down the measurement speed. Furthermore, the evaluation of the self-built EMTS setup in clinical environment, e.g. in angiographic laboratory, and a systematic comparison between with commercially available EMTS is part of future research.

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6 References

[1] A. M. Franz, T. Haidegger, W. Birkfellner, K. Cleary, T. M. Peters, and L. Maier-Hein, "Electromagnetic tracking in medicine--a review of technology, validation, and applications," IEEE Trans Med Imaging 33 (8), 1702–1725 (2014).

[2] G. S. Fischer and R. H. Taylor, "Electromagnetic Tracker Measurement Error Simulation and Tool Design," in Medical Image Computing and Computer-Assisted Intervention – MICCAI, 73–80 (2015).

[3] Z. Yaniv, E. Wilson, D. Lindisch, and K. Cleary, "Electromagnetic tracking in the clinical environment," Med. Phys. 36 (3), 876 (2009).

[4] R. F. Higgins, AC magnetic tracking with phase disambiguation, US Patent, US8121812 B2, (2012).

[5] A. Govari, Electromagnetic position single axis system, US Patent, US6484118 B1, (2002).

[6] Z. Zhang and G. Liu, "The Design and Analysis of Electromagnetic Tracking System," JEMAA 05 (02), 85–89 (2013).

[7] K. O'Donoghue and P. Cantillon-Murphy, "Low Cost Super-Nyquist Asynchronous Demodulation for Use in EM Tracking Systems," IEEE Trans. Instrum. Meas. 64 (2), 458–466 (2015).

[8] T. Bien and G. Rose, "Algorithm for calibration of the electromagnetic tracking system," in IEEE-EMBS International Conference on Biomedical and Health Informatics (BHI) , pp. 85–88 (2012).

[9] J. Hummel, M. Figl, C. Kollmann, H. Bergmann, and W. Birkfellner, "Evaluation of a miniature electromagnetic position tracker," Med. Phys. 29 (10), 2205 (2002).

[10] S. LaScalza, J. Arico, and R. Hughes, "Effect of metal and sampling rate on accuracy of Flock of Birds electromagnetic tracking system," Journal of Biomechanics 36 (1), 141–144 (2003).

[11] W. Birkfellner, F. Watzinger, F. Wanschitz, R. Ewers, and H. Bergmann, "Calibration of tracking systems in a surgical environment," IEEE Trans Med Imaging 17 (5), 737–742 (1998).

[12] T. Bien, M. Li, Z. Salah, and G. Rose, "Electromagnetic tracking system with reduced distortion using quadratic excitation," Int J Comput Assist Radiol Surg 9 (2), 323–332 (2014).

[13] M. Li, T. Bien, and G. Rose, "Construction of a conductive distortion reduced electromagnetic tracking system for computer assisted image-guided interventions," Med Eng Phys 36 (11), 1496–1501 (2014).

[14] Jianfeng Xie, Cheng Qin, Xin Zhou, Langtao Huang, Xiaotao Han, Min Wang, and Liang Li, "The Simulations and Experiments of the Electromagnetic Tracking System Based on Magnetic Dipole Model," IEEE Trans. Appl. Supercond. 24 (3), 1–4 (2014).

[15] S. Song, C. Hu, B. Li, X. Li, and M. Q.-H. Meng, "An Electromagnetic Localization and Orientation Method Based on Rotating Magnetic Dipole," IEEE Trans. Magn. 49 (3), 1274–1277 (2013).

[16] J. T. Sherman, J. K. Lubkert, R. S. Popovic, and M. R. DiSilvestro, "Characterization of a Novel Magnetic Tracking System," IEEE Trans. Magn. 43 (6), 2725–2727 (2007).

[17] K. O'Donoghue, D. Eustace, J. Griffiths, M. O'Shea, T. Power, H. Mansfield, and P. Cantillon-Murphy, "Catheter Position Tracking System Using Planar Magnetics and Closed Loop Current Control," IEEE Trans. Magn. 50 (7), 1–9 (2014).

[18] E. Paperno, I. Sasada, and E. Leonovich, "A new method for magnetic position and orientation tracking," IEEE Trans. Magn. 37 (4), 1938–1940 (2001).

[19] K. O'Donoghue and P. Cantillon-Murphy, "Planar Magnetic Shielding for Use With Electromagnetic Tracking Systems," IEEE Trans. Magn. 51 (2), 1–12 (2015).

[20] T. Haidegger, G. Fenyvesi, B. Sirokai, M. Kelemen, M. Nagy, B. Takács, L. Kovács, B. Benyó, and Z. Benyó, "Towards unified electromagnetic tracking system assessment-static errors," Conf Proc IEEE Eng Med Biol Soc, 1905–1908 (2011).

[21]   M. Li, T. Bien, and G. Rose, "FPGA based electromagnetic tracking system for fast catheter navigation," IJSER 4 (9), 2566–2570 (2013).

[22]   J. Cui, Y. Zhang, and J. Wu, "Averaging position algorithm of an independent rotating coils based electromagnetic tracking system," Proceedings of 2013 IEEE 11th International Conference on Electronic Measurement & Instruments, (2013).