FPGA based electromagnetic tracking system for fast catheter navigation

Mengfei Li, Tomasz Bien, Georg Rose

Abstract — an experimental setup of an electromagnetic tracking system (EMTS) has been developed to perform fast catheter navigation for minimally invasive surgery (MIS). The algorithm for the position and orientation (P&O) calculation is implemented in MATLAB while the whole EMTS is programmed and controlled by LabVIEW. The system utilizes a field programmable gate array (FPGA) for signal generation, acquisition and filtering. With the frequency division multiplexing (FDM) and FPGA infinite impulse response (IIR) filter technology, the developed system is able to track P&O of the catheter tip 35 times per second in five degrees of freedom (DOF). A phantom experiment has been performed to evaluate the performance of the EMTS. After calibration, the positional accuracy of the EMTS is 1.4mm inside the region of interest (ROI).

Keywords — Catheter Navigation, Electromagnetic Tracking, Filter, FPGA, Frequency Deviation Multiplexing, LabVIEW, Position and Orientation calculation.

1 Introduction

THE image-guided real-time (RT) surgical instrument navigation can be utilized for MIS. Instruments such as catheters and needles are target objects of the navigation systems [1]. There are currently four major modalities of tracking technologies used for MIS: mechanic, ultrasonic, optic and electromagnetic. The biggest advantage of an electromagnetic tracking system is that the EMTS does not need line-of-sight between the navigation tools and emitters. Therefore, EMTS allows the position of the surgical instrument to be tracked flexibly even inside the patient's body [2].

EMTS is able to calculate the three dimensional (3D) position and orientation of an electromagnetic sensor which is relative to the generated magnetic field from a field generator [3]. In computer-assisted surgery, the EMTS is applied to track the positions of the surgical instrument relative to the patient's body [4]. Before the tracking process begins, the coordinate system of the EMTS has to be registered with the coordinate system of the medical image. During the intervention, the tip of the catheter is tracked relative to the patient's anatomy [5].

There are two common technologies for electromagnetic tracking: alternating current (AC) EMTS and direct current (DC) EMTS. This paper focus on an AC EMTS with the FDM technology. The principle of the system is: to generate magnetic fields by supplying multiple emitting coils with signals of different frequencies and simultaneously measure the voltage induced in the sensing coil which is within the magnetic fields, filter out the measured signal at distinct frequencies and compare the measured voltages after filtering and the simulated voltages from each other in order to calculate the P&Os of the sensing coil.

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2 Method

The experimental setup of EMTS consists of a PXI system (*PXIe 8133 and PXI 7854R*, National Instruments, USA), a field generator with eight emitting coils, a sensing coil (*Aurora 5DOF Sensor*, Northern Digital, Canada) which is integrated inside a catheter (*Twin-Pass Dual Access catheter*, Vascular Solution, USA) and two types of amplifiers (*LT1210 and LT1168a*, Linear Technology, USA). The following figure illustrates the hardware of the whole system.

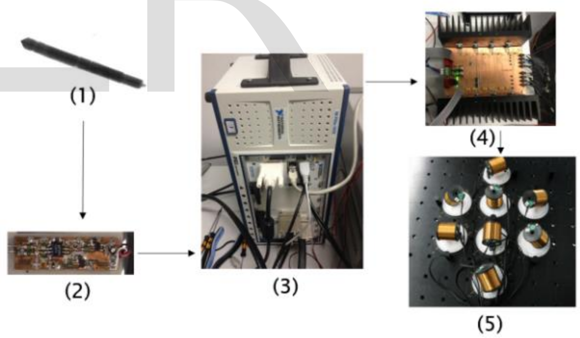

Fig.1 The experimental setup of an EMTS containing a sensing coil **(1)**, an amplifier for the sensing coil **(2)**, the NI PXI system **(3)**, eight amplifiers for the emitting coils **(4)** and a field generator with eight emitting coils **(5)**.

The FPGA inside the NI PXI system is the core component for the experimental setup of EMTS. FPGA technology is applied to replace the traditional digital signal processor (DSP) in order to increase the system speed by parallel processing. A DSP works sequentially while the FPGA is able to execute multiple processes simultaneously without slowing down its working speed [6]. In this experimental setup, the FPGA is utilized for signal generation, data acquisition and filtering. A sensing coil with a diameter of 0.5mm and a length of 8mm is used to measure the voltages induced in the magnetic fields generated by the field generator. The sensing coil is integrated in the tip of a catheter which has a diameter of 1.0mm. The amplifiers are used to amplify the signals supplied into the emitting coils and the signals measured by the sensing coil.

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The algorithm of position and orientation estimation of the sensing coil is based on the magnetic dipole model which is described in literature [7], [8] and [9]. The following equations represent the algorithm of P&O calculation applied for the developed experimental setup of EMTS.

$$U_i = -\omega \cdot A_s \cdot (\vec{B}_i \cdot \vec{n}_s) \quad (1)$$

$$\vec{B}_i = \frac{\mu}{4\pi} \cdot \left(\frac{3(\vec{x}_s - \vec{r}_{e,i}) \cdot (\vec{m}_{e,i} \cdot (\vec{x}_s - \vec{r}_{e,i}))}{|\vec{x}_s - \vec{r}_{e,i}|^5} - \frac{\vec{m}_{e,i}}{|\vec{x}_s - \vec{r}_{e,i}|^3}\right) \quad (2)$$

$$\vec{m}_{e,i} = \pi \cdot N_{e,i} \cdot I \cdot R_{e,i}^2 \cdot \begin{pmatrix} \sin\theta_{e,i} \cos\varphi_{e,i} \\ \sin\theta_{e,i} \sin\varphi_{e,i} \\ \cos\theta_{e,i} \end{pmatrix} \quad (3)$$

$$U_i - U_{m,i} = 0 \quad (4)$$

Equation (1) calculates the simulated voltage induced in the sensing coil in the magnetic field that is generated by each emitting coil respectively. In this equation, i is the number of emitting coils (1-8), A_s is the cross-sectional area of the sensing coil. The magnetic field in the cross-sectional area of the sensing coil can be assumed to be homogeneous, because of the small diameter of the sensing coil (0.5mm). The variable ω is the angular frequency of the currents which are fed into each emitting coil. The vector $\vec{B}_i$ represents the magnetic flux density in the sensing coil when the i-*th* emitting coil is generating a magnetic field. The variable $\vec{n}_s$ is the normal vector of the sensing coil. In Equation (2) the magnetic flux density $\vec{B}_i$ is calculated. In this equation, μ is the magnetic permeability of the vacuum. Vector $\vec{m}_{e,i}$ stands for the electromagnetic dipole moment and $\vec{r}_{e,i}$ is the position vector of distinct emitting coils in the coordinate system of the EMTS. $\vec{x}_s$ is the position vector of the sensing coil. The magnetic dipole moment $\vec{m}_{e,i}$ of the *i-th* emitting coil can be calculated in Equation (3). $N_{e,i}$ is the number of turns and $R_{e,i}$ is the radius of each emitting coil. Within equations (1), (2) and (3), the voltages induced in the sensing coil will be estimated basing on the known distribution of the electromagnetic field of the emitting coils. The P&O of the sensing coil will be estimated by minimizing the difference between the measured and estimated voltages on the sensing coil (4). In the experimental setup of EMTS, the FPGA is utilized to generate signals. The FPGA based direct digital synthesis (DDS) technology [10] is applied for the analog signal generation in this system. By DDS, the EMTS is able to generate multiple channels of signals with different characteristics simultaneously.

There are two methods to realize electromagnetic tracking: time division multiplexing (TDM) [11] and frequency division multiplexing (FDM) [12]. Both of the methods have been applied to the experimental setup and the results are compared. With the method of TDM, the generated sinusoidal signals are sequentially supplied to the eight emitting coils. When one of the emitting coils is working and the other seven are stopped, the voltages induced in the sensing coil is measured instantaneously. The chart below shows the working flow of the EMTS with TDM.

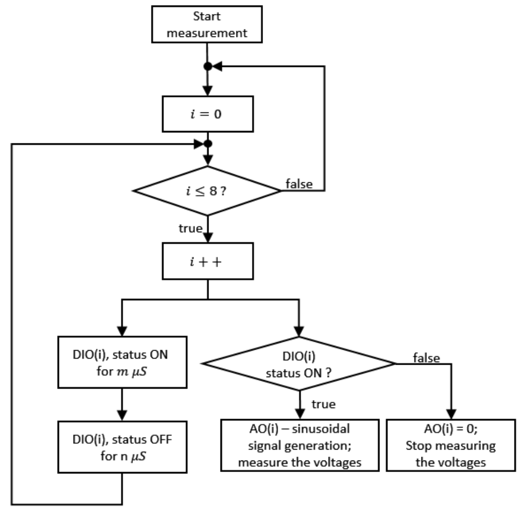

Fig.2 Flow diagram of voltage measurement with TDM

As is shown in Fig. 2, the generated signals are sequentially outputted from analog output terminals of the FPGA AO1 to AO8. The digital output signals DIO1 to DIO8 are used to turn on and off the amplifier of the emitting coils. When one of the amplifiers is turned on, relatively, one of the emitting coils is fed with the sinusoidal current. On the other hand, when all of the amplifiers are turned off, there are not any analog output signals. With TDM, the speed of catheter tracking is highly dependent on the speed of the voltage measurement. The frequency of the signals fed to the emitting coils is equal to 1 kHz. Twenty periods of the voltage signals induced in the sensing coil are measured when one of the eight emitting coil generates a magnetic field, which means 160 periods of the signals are measured during one complete voltage measurement (eight emitting coils). Therefore, the system requires 160ms for a whole voltage measurement.

FDM technology makes the voltage measurement eight times faster. For each measurement, instead of 160, only 20 periods of the signals are required.

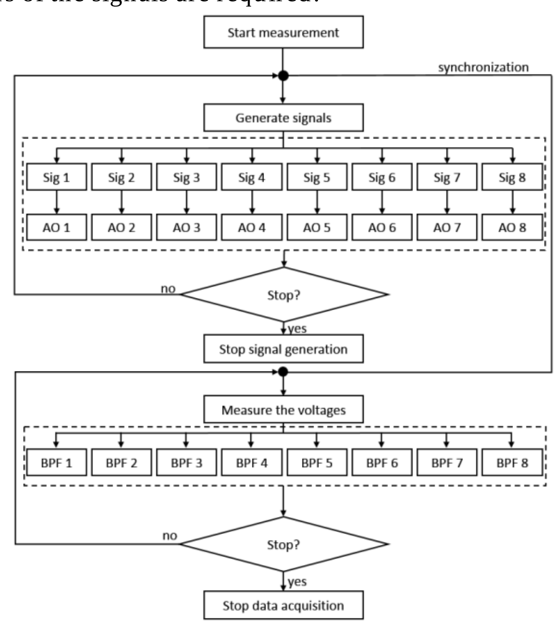

Fig.3 Flow diagram of voltage measurement with FDM

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Fig. 3 illustrates the work flow of the EMTS by applying FDM method. After the measurement begins, the generated signals with different frequencies for eight emitting coils are parallel fed into the amplifier. Meanwhile, the voltages on the sensing coil are measured. The measured voltages consisting of the signals of distinct frequencies, are sent to eight band-pass filters to restore the voltages induced in the magnetic field generated by each emitting coil individually. These filtered voltages are compared with the simulated voltages for P&O calculation. The FPGA is utilized to run all of these processes in parallel, including the eight IIR band-pass filters. Compared to sequential execution of eight band-pass filters by a DSP processor (i.e. by MATLAB in PC), parallel executions of FPGA make the filtering processes significantly faster.

In each step, 2000×8 (eight emitting coils) samples of the filtered signals are sent to the host machine from FPGA periodically by direct memory access (DMA) technology. DMA data transfers are accomplished by first-in-first-out (FIFO) architecture. There are two FIFOs used for the DMA process. One FIFO uses the block RAM is in the FPGA and the other FIFO is the DMA FIFO in the host machine. A DMA engine transfers the data from the FPGA device RAM to the host machine memory automatically in the NI PXI system [13]. With the FIFO technology, the developed EMTS is able to work in real-time.

3 Results

In the experimental setup of the EMTS, the calculated positions and orientations of the sensing coil (in the tip of the catheter) are described as numbers. In the interventions, the P&Os of the surgical instrument have to be directly visualized relative to the patient's anatomy image. The EMTS which has been developed is aimed to realize computer assisted endovascular interventions. Instead of clinical experiments, an experiment with an aneurysm phantom has been performed in order to evaluate the applicability of the developed the electromagnetic tracking system in the clinical condition. In this experiment, the P&Os of the catheter's tip in the aneurysm phantom is visualized by 3D Slicer.

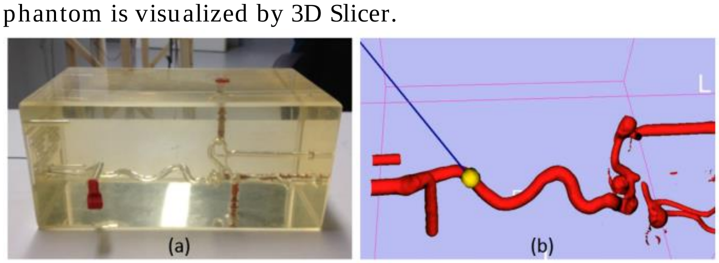

Fig.4 Aneurysm phantom and its model in 3D Slicer

The aneurysm phantom is shown in Fig. 4(a). Before the experiment, a set of the CT scans of the aneurysm phantom has been transformed into the surface-model in 3D slicer. The coordinate system of the CT images was registered with the coordinate system of the EMTS. During the experiment, the catheter (with the sensing coil in the tip of it) is pushed in and pulled out in the vascular system of the phantom. The position of the sensing coil is presented as a yellow point. Its orientation is illustrated as a blue line in Fig. 4(b). The P&Os of the catheter tip are tracked and visualized in 3D slicer.

The results of the phantom experiments with the TDM system and FDM system are compared. Both of the two systems are able to track the P&Os of the catheter tip stably. The main difference between the two systems is the tracking speed. By applying TDM, the EMTS only measures the P&Os approximately 6 times per second. However, by applying FDM, the system enables the P&Os of the catheter's tip with a measuring rate of 35 times per second. It means, with this experimental setup, the FDM system runs approximately 6 times faster than the TDM system.

The visualization of the P&Os of the catheter tip relative to the patient's vascular system enables the interventions with reduced doses of the contrast agent and decreased doses of x-ray radiation. Before the intervention, the patient will be scanned by CT once. After registration, during the entire intervention processes, no more CT scans are required.

The accuracy of the image-guided surgery system is dependent on the accuracy of the tracking system [14]. For the accurate navigation, the electromagnetic tracking system needs to be calibrated. The algorithm for tracker calibration of the EMTS is described in [9]. An accuracy evaluation of the experimental setup with FDM has been performed both before and after calibration.

Fig.5 The measurement setup of accuracy evaluation consists an optical tracking system (*Polaris Spectra*, Northern Digital, Canada) **(1)**, the tip of the catheter **(2)**, optical tracker **(3)**, field generator **(4)** and the Lego Mindstorms robot system on a wooden frame **(5)**.

As is seen in Fig. 5, in this measurement setup, the catheter tip (2) which consists of a sensing coil inside, is rigidly fixed at one position and orientation relative to the optical marker. The robot moves the optical marker to 350 different positions inside the ROI ($25cm \times 25cm \times 25cm$). For each movement, the positions of the sensing coil and the positions of the optical marker are measured by EMTS and the optical tracking system respectively. The mean error of the Polaris Spectra optical tracking system is 0.25mm, which is much smaller than the expected mean error of an electromagnetic tracking system [9]. Because of its high accuracy, the optical system is utilized as a reference position measuring system to evaluate the accuracy of the EMTS. Assuming the position errors of the sensing coil are E_x, E_y, E_z in x, y and z axis respectively, the total error is calculated as $E = \sqrt{E_x^{\ 2} + E_y^{\ 2} + E_z^{\ 2}}$. The following figures indicate the difference of the accuracy of the EMTS before and after calibration.

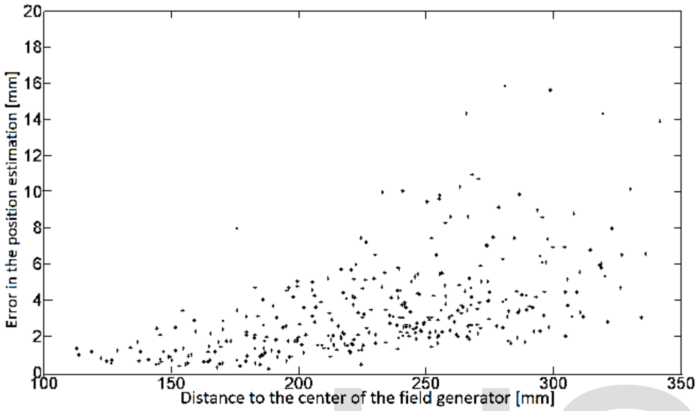

Fig.6 Position errors of EMTS with FDM before calibration

As is shown in Fig. 6, before calibration the maximum error of the EMTS is approximately 16mm and the mean error for is 3.5mm.This figure clearly demonstrates that increasing the distance of the sensing coil from the center of the field generator decreases the accuracy. After calibration, the EMTS has considerably higher accuracy, which is illustrated in the graph below.

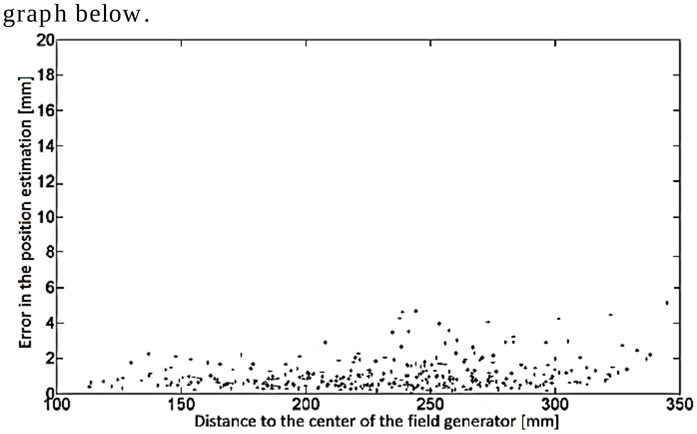

Fig. 7 Position errors of EMTS with FDM after calibration

The results after calibration is shown in Fig. 7. The maximum error in position estimation of the sensing coil reduces from 16mm to 5mm. Meanwhile, the root mean square (RMS) error is correspondingly much smaller, which decreases from 4.4mm to 1.4mm. The accuracy of the system is comparable to the commercial electromagnetic tracking systems, e.g., the NDI AURORA has a positional accuracy (RMS error) of 0.7mm, the accuracy of Ascension microBird is 1.4mm and the accuracy of Polhemus Fastrak is 0.76mm [15].

4 Discussion

This paper introduces an experimental setup of the FPGA based electromagnetic tracking system. Two methods for configuring the system are introduced: time division multiplexing and frequency division multiplexing. With the same experimental setup, the FDM system tracks the P&Os of the catheter approximately six times faster than the TDM system with achieving the same precision. The EMTS utilizes a FPGA as the core component to run multiple processes in parallel, which makes the system significantly faster than using traditional DSP devices. In the future, the experiments of catheter tracking should be performed in real patients' anatomy to evaluate the EMTS for actual medical applications. The working volume of the EMTS could be enlarged by increasing the frequencies and amplitudes of the signals which are supplied to the emitting coils. Furthermore, this experimental setup of the EMTS is able to be used as a testing platform for novel researches in minimal invasive surgery.

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