Tracking Three Dimensional Ultrasound with Immunity from Ferro-Magnetic Interference

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Abstract. Magnetic field tracking devices offer many advantages over other methods for tracking transducer location and orientation during ultrasound image acquisition. The disadvantage is sensitivity to ferromagnetic interference. We evaluated an "immune" tracking device that uses a flat plate magnetic field transmitter to shield the tracking volume from interference from the hospital bed. When we compared its accuracy with that of Ascension Technology, Inc.'s Flock of Birds™, we found that the immune device performed as well on a hospital bed as the Bird in a control environment. We conclude that the flat plate transmitter enables three-dimensional ultrasound by the freehand scanning approach in a clinical environment.

1 Introduction

The advantage of ultrasound is ability to visualize detailed anatomy by freehand scanning to obtain optimal definition of targeted structures and image quality. When the images are acquired with knowledge of their location and orientation in three-dimensional (3D) space, it is possible to reconstruct organ anatomy and quantify dimensions and inter-structural relationships with greater accuracy than any other imaging modality. During freehand scanning, image location and orientation are recorded by tracking the coordinates of the transducer (x, y, z, azimuth, elevation, roll). Transducer tracking is most commonly performed using a magnetic field tracking device due to ease of use and flexibility for internal as well as external applications. The disadvantage of magnetic field tracking devices is sensitivity to ferromagnetic interference in the vicinity, e.g., from the hospital bed.

Recently, Internav, Inc[1]. developed a novel design for the magnetic field transmitter that shields the tracking volume, which contains the target organ and the range of transducer manipulation during imaging, from ferromagnetic interference emanating from beneath the transmitter. Internav's transmitter tablet is flat enough (0.5 – 2 inches) to allow easy placement on a hospital stretcher, surgical bed, or motorized table in an x-ray or catheterization suite. Furthermore, Internav's transmitter provides an advantage over eddy current effects by spreading the

[1] Now owned by Ascension Technology, Inc., Burlington, VT

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transmitter antennas over more of the tracking volume. In previous electromagnetic tracking devices, a metallic object (e.g., an ultrasound probe) placed between the sensor and the transmitter affected all the magnetic field measurements. In Internav's immune tracking device, it is almost impossible to find a location where the ultrasound probe is between the sensor and all of the transmitter antennas. This inherently provides the device with better field measurements from which to calculate position and orientation.

The present study was performed to evaluate the performance and accuracy of this immune tracking device in comparison with the Flock of Birds™ (Bird, Ascension Technology, Inc., Burlington, VT).

2 Methods

2.1 Overview

Three-dimensional echocardiography by freehand scanning is performed using a commercial ultrasound machine and 3 or 5 MHz phased array transducer. The sensor of the magnetic field tracking device is attached to the transducer and the transmitter is positioned under the patient's chest in a fixed position. The transmitter sequentially generates three orthogonal magnetic fields that are detected by the sensor and used to compute the sensor's position (x, y, z) and orientation (azimuth, elevation, roll) in space with respect to the origin of the transmitter. The ultrasound images are recorded in digital format in files linked to the position data, scanning parameters such as image depth, and any hemodynamic parameters that may also be required. During image analysis, the borders of cardiac structures are traced, converted into x, y, z coordinates using the transducer position and orientation data, and then used to reconstruct these structures in 3D [1].

2.2 Calibration

The spatial relationship between the magnetic sensor and the image plane must be known in order to achieve accurate image registration in 3D space. This relationship, however, cannot be measured directly since the sensor packaging encloses its origin and there are no external reference points. Therefore a least-squares fitting technique is used to establish the relative position and orientation of the sensor and the image plane [2, 3]. The calibration software computes a transformation matrix that maps pixels in the ultrasound image into the sensor's coordinate system; the sensor measurements then map the image point locations to the 3D coordinate system of the transmitter.

We perform calibration by imaging a point target, a brass sphere 1.5 mm in diameter suspended by a thread inside a water-filled plastic sphere. This point target is imaged from a wide range of scanhead positions and orientations through the wall of the sphere. The transmitter is placed 20-30 cm beneath the target. Ferromagnetic materials were kept at least 1 m away from the device to avoid interference.

We collect 64 images during each of three calibration runs. The pixel coordinates (row, column) of the target are manually determined from each image, converted to mm using scanning depth, pixel aspect ratio, and correction for the speed of sound in water, and then input to the calibration software with the corresponding sensor measurements. The algorithm iteratively searches for the position and orientation of the sensor with respect to the imaging plane by minimizing the scatter of the calculated target position in the transmitter's coordinate system [2]. The output is a transformation matrix that includes the position offsets from the sensor origin to the image sector origin and a 2x3 matrix of angle cosines that defines the orientation of the image row and column axes with respect to the three sensor coordinate axes.

If all measurements were perfect, the calculated 3D location of the point target would be the same for all images. However, variability is introduced by such factors as noise in the 3D position measurements, the limits of ultrasound image resolution, and manual identification of the point target on the images. The overall root mean square (RMS) uncertainty in locating the point target is calculated as the vector sum of the standard deviations of the x, y, and z components. This represents the precision of the combined magnetic sensor and ultrasound imaging system. The two matrices that produce the lowest RMS uncertainty are averaged to produce the final transformation matrix [4].

2.3 Test Procedure

The precision of repeatedly locating a single point in space from images acquired at any arbitrary position surrounding it reflects not only error in the magnetic field sensor, but also uncertainty in the location of a point in an ultrasound image due to such factors as lateral and range resolution, beam thickness, and manual identification of the point. We tested precision by acquiring at least 20 images of the point target using the same protocol as for calibration, reconstructing the target's 3D location using the final transformation matrix, and calculating the RMS uncertainty.

We also tested the accuracy of each tracking device for measuring distance between two points.

Precision and accuracy were measured *in vitro* by mounting the sensor on a stylus with a ball tip. We used the ball tip to locate two sockets positioned 10 cm apart on a Plexiglas box (Fig. 1). We then measured each magnetic field tracking device's precision in repeatedly locating each socket, and each device's accuracy in measuring distance between two sockets, at baseline (without ferromagnetic interference), and on top of a hospital stretcher such as used for echocardiography. For the stretcher studies, a 25.5 cm thick foam mattress designed for ultrasound imaging of the heart was placed onto the stretcher and the back rail was raised. The mattress cutout was removed as if to facilitate heart imaging. A pegboard holding the transmitter and box in the same positions as for the baseline study was placed on the mattress with the box over the mattress cut-out to simulate the heart of a patient lying on the mattress in the left lateral position.

We also tested whether suspending the transmitter above the stretcher can reduce the stretcher's interference on the magnetic tracking device.

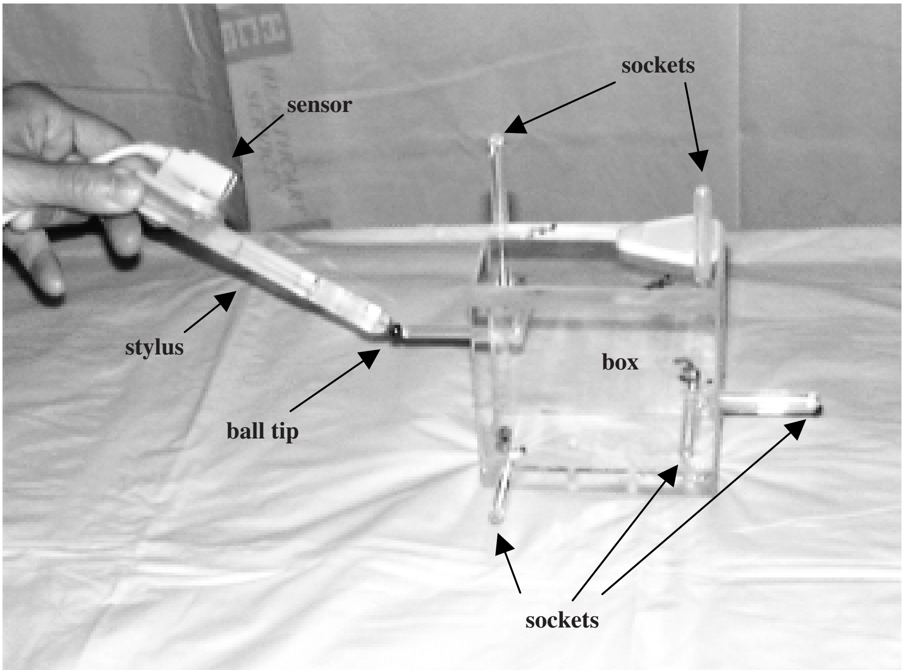

Fig. 1. In vitro system used for testing the precision and accuracy of the tracking device. The stylus simulates the transducer. The plexiglass box simulates the ultrasound target. The magnetic field sensor is mounted on the stylus. After calibration the stylus is used to locate the x,y,z positions of the sockets. For static testing, socket location is recorded with the stylus in a stable position; for dynamic testing, socket location is sampled frequently while the stylus is angulated or rotated in the manner of freehand scanning

2.4 Statistical Analysis

Error in inter-socket distance was calculated as the difference between measurements at baseline vs. on a hospital stretcher. Error was compared between tracking devices using t test.

3 Results

When the Bird transmitter was placed on top of the hospital stretcher the precision worsened about fivefold compared to values obtained at baseline (Table 1). Elevating the transmitter 50 cm above the sockets reduced the interference of the stretcher on the magnetic field. However the RMS remained double its baseline value and the error in measuring distance was still significant.

Table 1. Precision (RMS, mm) in Repeatedly Locating a Point Target

Tracking Device	Transmitter Location	Baseline		On Hospital Stretcher	
		Socket a	Socket b	Socket a	Socket b
Bird	on mattress	0.99	1.25	4.90	6.04
Bird	50 cm above mattress	1.87	1.72	2.97	2.76
Immune	on mattress	0.94, 0.93, 0.91*		1.22, 1.21*	

* multiple measurements were made at each test condition

When the immune transmitter was placed on stretcher, neither precision nor distance was altered significantly from baseline values (Tables 1, 2). The distance error of the immune tracking device was just 0.07 cm for the static test and 0.08 cm for the dynamic test.

Table 2. Error in Measuring Distance

Magnetic Field Tracking Device	Number	Error, mm
Bird	17	2.6 ± 1.1
Immune	2	0.1 ± 0.0*

* p<0.0001

4 Discussion

Previous studies have demonstrated the inaccuracy of the magnetic tracking device when operated in the proximity of ferromagnetic materials typical of a hospital environment [5]. The results of the present study confirm that interference from a hospital stretcher reduces precision and accuracy in tracking. A solution reported anecdotally by a colleague to be effective, elevating the transmitter 50 cm above the ultrasound target, also had disappointing results.

The magnitude of error induced by ferromagnetic interference in measuring distance may appear to be small. However it is unacceptably large when compared with the intracardiac structures whose dimensions are being analyzed. For example left ventricular end diastolic wall thickness is 7-8 mm in adults.

In contrast, the immune tracking device utilized a flat transmitter design to provide accuracy and precision comparable to that of the Bird both at baseline and in the presence of ferromagnetic interference. We further verified that the immune device's performance was maintained during dynamic testing, which simulates the clinical application of this technology to freehand scanning. These results indicate that transducer tracking can be performed accurately and reproducibly on a regular hospital stretcher using the immune magnetic tracking technology. Consequently 3D ultrasound by freehand scan technique need no longer be restricted to a research laboratory or non-ferromagnetic bed.

4.1 Clinical Implications

Magnetic tracking devices offer a number of advantages in acquiring 3D ultrasound scans of the heart [4]. Unlike acoustic and optical tracking devices, there is no necessity to maintain a line of sight between the transducer and its tracking device. Unlike mechanical tracking, the magnetic tracking device permits freehand scanning so that images can be recorded in whatever combination of acoustic windows and views provides optimal image quality in each individual patient. The results of the present study indicate that an important limitation of magnetic tracking devices has now been eliminated: employment of the immune device enables 3D ultrasound by the freehand scan method to be performed in a clinical environment.

The significance of this finding lies in enabling of 3D ultrasound by freehand scanning. Freehand scanning enables delineation of anatomic detail because the transducer can be manipulated to obtain image planes orthogonal to the structure. For example, we have been able to obtain images displaying principal chordae tendineae along at least 70% of their length or defining the aberrant location of papillary muscle insertion on the left ventricular endocardium [6]. Such detail is unlikely to be visualized by ultrasound using fixed volumetric acquisitions, in which the entire data set is recorded from a single transducer position. Such detail also cannot be captured by magnetic resonance due to the need to predefine the acquisition protocol. As a consequence, immune tracking provides clinical feasibility to the mode of 3D ultrasound that retains the superior spatial definition of this imaging modality.

There are many potential applications of 3D ultrasound technology. These are not limited to reconstruction of cardiac structures and quantitative analysis of their dimensions, function, and geometry, although ventricular volume and mass have been the main focus of 3D echocardiography. We recently developed methods for visual guidance, a visual interface that assists inexperienced observers in acquiring images in anatomically accurate planes [7]. This technology could also be applied as an educational tool to facilitate the training of sonographers and physicians in ultrasound scanning, and as in telemedicine to assist rural health care providers acquire images of diagnostic quality for transmission to a medical center for expert interpretation. Immune tracking technology also facilitates ultrasound-guided intervention procedures.

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