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A Low-Cost Camera-Based Ultrasound Probe Tracking System: Design and Prototype

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***Abstract*—Real-time probe motion information may enhance the information gathered by ultrasound probes and permit the use of artificial intelligence or computer vision to reduce dependence upon a sonographers' knowledge and skill in the performance of ultrasound studies. Multiple types of tracking sensors and their combinations are integrated with ultrasound machines to provide real-time six degree of freedom (6-DOF) probe motion information. The accuracy and the precision of the tracking data are significant to the quality of obtained frames for all image dimensions. In this study, we proposed a system that integrates the camera-based tracking with an ultrasound device for obstetric ultrasound imaging. The tracking resolutions for position and orientation were evaluated to be less than 1 mm and 1°, respectively. Imaging tests with a fetus phantom was further conducted to verify the feasibility of camera-based probe tracking in obstetric ultrasound. The scanning frames were found to be repeatable with the aid of real-time probe motion.**

***Index Terms*—camera-based tracking, obstetric ultrasound, freehand ultrasound**

I. Introduction

Conventional 2D ultrasound imaging has been a commonly-used imaging modality for decades because it is portable, cost-effective and noninvasive. However, the image quality is highly dependent on the operators' skill. In addition, lack of 3D anatomical information prevents precise quantitative measurements and reproducibility in follow-up studies [1]. Recently, different techniques to address these limitations of conventional 2D ultrasound have been proposed in studies of clinical diagnostics and image guidance.

Accurate and precise real-time probe location may improve the imaging quality. For example, 3D freehand ultrasound acquires scanning geometries from 3D subjects and reconstructs the 3D volume based upon the scanned images and the tracked probe location. During the volume reconstruction, the real-time position and orientation of the probe at each moment will be related to each of the 2D ultrasound image. With the known probe trajectory, a 3D volume can then be reconstructed to enable more accurate and intuitive information about the subjects. In the obstetric ultrasound, the rendered 3D images can help improving the assessment of the fetal abnormalities [2].

Typical tracking devices include mechanical arms [3], [4], electromagnetic sensors [5], [6], inertia measurement units (IMU) [7], [8], optical sensors [9], [10], acoustic sensors [11], and their different combinations [12], [13]. Mechanical arms are used in robotic ultrasound systems, in which the probe is attached to a robotic arm. The robotic arm functions as an upper-limb to control the probe movement and permit accurate and consistent tracking of probe trajectory [4]. However, the mechanical arms are bulky to use and it is difficult for providers to ascertain the relative position between the probe and the strutures of interest in the clinical setting. Daoud et al. [6] integrated an electromagnetic position tracking system from NDI with an ultrasound machine for ultrasound volume reconstruction. However, the presences of metal objects degraded the tracking accuracy. Although IMU sensors can provide accurate orientation tracking information, they are unable to overcome the large drift resulting from the integration of the acceleration measurements. Therefore, IMU sensors can not provide accurate position tracking for daily data acquisition. Prevost et al. [8] incorporated an IMU sensor with the image-based tracking using a convolutional neural network (CNN), in which only the orientation information from IMU sensor was included in the network architecture. Optical sensors provides higher accuracy and more robust measurement if the line-of-sight is maintained during tracking. Ito et al. [10] attached a web camera to the probe for the feature tracking. The probe motion was estimated with an error of 2 mm for 150-200 mm probe travel distance. Acoustic sensors estimated position using the time-of-flight. Similar to optical sensors, acoustic sensors are prone to occlusion. Chen et al. [11] developed a 1-D array probe with five air-coupled ultrasound elements that estimated both the position and orientation by measuring the received acoustic signals.

The objective of this preliminary study is to investigate the accuracy and precision of the camera-based tracking with passive markers in the application of probe tracking in obstetric ultrasound. The feasibility of the proposed tracking system will be further discussed for its future use in 3D freehand ultrasound imaging applications.

II. Methods and Results

A. System Overview

Figure 1 shows the components of the integrated system. Details of each components are as follow.

1) Camera and Marker Rigid Body: The key component of the optical tracking system utilized in this study was the OptiTrack V120: Trio (NaturalPoint, Inc.) camera bar, which integrated three lenses for the object tracking. User calibration was not required for this camera bar, which made it user-friendly for practical operation. Five reflective markers

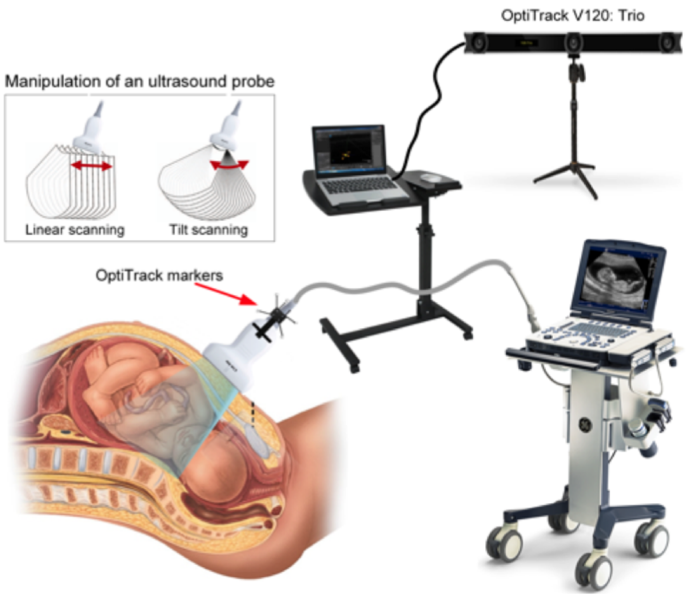

Fig. 1: Schematic of the integrated system

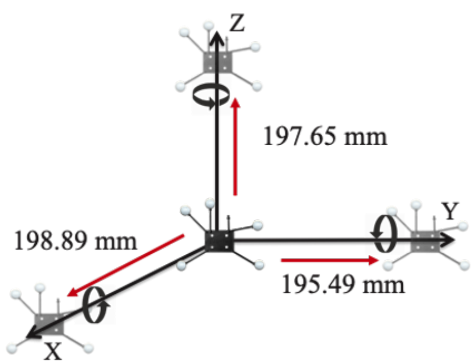

Fig. 2: Schematic of single axis positional and rotational tracking tests

attached asymmetrically to a rigid body were then fixed to the ultrasound probe to measure the position and orientation of the probe's viewpoint. The camera frame rate was 120 Hz.

2) Ultrasound Probe: In the experiment, a Butterfly iQ probe (Butterfly Network, Inc.) was used. The image depth was 7 cm and the probe frame rate was 33 Hz.

3) Portable Workstation: The workstation processor was Intel Core i7-8750H with a base frequency of 2.2 GHz. The RAM was 16 GB. The workstation was used for running the motion capture software and processing the tracking data.

4) Fetus Phantom: The phantom used in this test was a 3D printed fetus in the 4^{th} month of pregnancy. To improve the image quality, a 3D printed fetus phantom with the same modelling was created for the imaging tests. The phantom was made of ABS-M30 (Stratasys, Ltd.) with an acoustic impedance of 2.13 ± 0.08 MRayl [14].

B. Experiments and Results

1) Accuracy of Camera-Based Tracking: To evaluate the tracking accuracy of proposed system, the flat marker rigid body with five passive markers was attached to a 3-DOF motion stage and a 3-DOF stepping motor to test the single axis accuracy of both positional and rotational tracking. To test the positional tracking performance, the marker rigid body was translated along the three axes at a constant speed. Six tests were conducted for each axis (Figure 2).

TABLE I: Mean Error of Single Axis Tracking

	X-axis	Y-axis	Z-axis
Positional (mm)	0.19	0.08	0.69
Rotational (°)	0.56	0.62	0.33

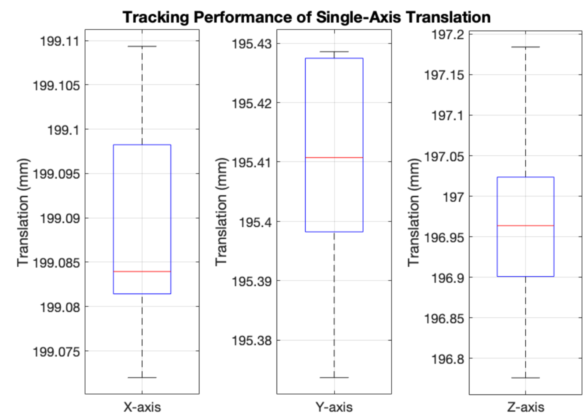

Fig. 3: Accuracy and precision of positional tracking

Table I demonstrates that the accuracy of positional tracking was sub-millimeter level. Figure 3 shows the precision of the measurements. Since low precision significantly degrades the quality of volume reconstruction [15], these results show the potential of the camera-based tracking for future construction.

2) Phantom Imaging: To verify the accuracy of the tracking system, a phantom imaging test was conducted. The 4-month fetus phantom was submerged in the degassed water. The

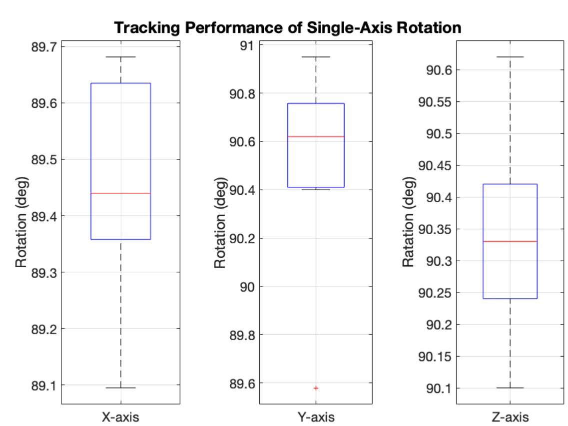

Fig. 4: Accuracy and precision of rotational tracking

TABLE II: Difference Between the Initial and Final Probe Position

	X-axis	Y-axis	Z-axis
Initial position (mm)	172.1	108.9	1267.8
Final positiona (mm)	172.3	108.6	1268.8
Difference (mm)	0.2	-0.3	1

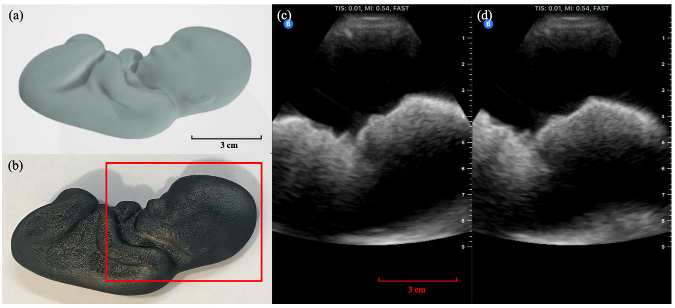

Fig. 5: Fetus phantom and comparison between the initial and final images

Butterfly probe with the attached marker rigid body was used for imaging purpose. Figure 5(a) is the 3D phantom model. Figure 5(b) indicates the area imaged in Figure 5(c) and Figure 5(d). The probe was placed at an initial fixed location and the position and orientation were recorded as the reference location. Then, the operator moved the probe within the operating region for 25 seconds, ending at the initial position. Figure 5(c) and Figure 5(d) are the initial and the final images, respectively. Initial and final probe positions with their differences are listed in Table II. Due to the error inherent to freehand scanning, the final position slightly shifted compared to the initial position. The two sub-figures showed very similar fetus head contour, indicating that with the accurate real-time probe motion information, the operator can collect repeat frames by repeating the probe location. With the repeatability, there is increased possibility to perform volume reconstruction based upon acquired 2D ultrasound frames.

III. Discussions

A camera-based tracking system integrated with the Butterfly iQ probe was tested in this study. All tests were conducted while the line-of-sight was well maintained. The overall tracking accuracy were less than 1 mm and 1°, respectively, and measurements were precise during testing. Extended experiments and analysis are required to evaluate the tracking performance in the event that visual occlusion happens during scanning. A possible way to resolve this issue maybe to further optimize the marker configuration. As tracking performance improves, future works will also include reconstructing the 3D/4D ultrasound images.

IV. Conclusion

In this paper, a freehand ultrasound imaging system was incorporated with the camera-based tracking. The pre-calibrated camera bar was shown to provide accurate and precise real-time tracking of ultrasound probe motion. Imaging testing was conducted by translating the probe back to the reference location during real-time probe motion. The results demonstrate a reliable tracking performance of the camera-based tracking and the feasibility of such system for use with 3D freehand obstetric ultrasound in clinical practice.

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