Ultrasound Calibration for Unique 2.5D Conavi Images

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ABSTRACT

Intracardiac echocardiography (ICE) systems are routinely used in percutaneous cardiac interventions for interventional and surgical navigation. The Conavi Foresight is a new ICE system that uses a mechanically rotating transducer to generate a 2D conical surface image in 3D space, in contrast to the more typical side-firing phased array. When combined with magnetic tracking technology, this unique imaging geometry poses new calibration challenges and opportunities. The accuracy of tracked intracardiac image guidance is contingent on the accuracy of ultrasound probe calibration. Existing ultrasound calibration methods are designed for 2D planar images and cannot be applied to unique 2.5D conical surface images provided by the Conavi Foresight ICE system. In this work a calibration technique applied to the unique case of conical ultrasound image data is described and validated qualitatively. We report an overall calibration accuracy of 1.74 mm root-mean-square.

Keywords: Ultrasound calibration, intracardiac echocardiography, radial ultrasound, Conavi

1. INTRODUCTION

Image guidance is critical to percutaneous cardiac interventions because of the absence of the direct line of sight. Ultrasound imaging systems are an ideal fit for cardiac imaging due to their safety, relatively low cost, high soft tissue contrast and compatibility with surgical tools. Transthoracic and transesophageal ultrasound imaging is capable of providing high contrast 2D and 3D imaging of soft tissues in real-time, but they are constrained in their views as they are used from outside the heart. In contrast, intracardiac echocardiography (ICE) is often used to guide these minimally invasive cardiac procedures by advancing the probe inside the heart and providing real time imaging of the heart anatomy.[1,2] Conventional ICE images are 2D planar and limited in their resolution and field of view. The recently introduced Conavi Foresight ICE system[3] (Conavi Medical, North York, Canada) overcomes these challenges by generating high-resolution 3D ultrasound volumes in the order of milliseconds. The Conavi ICE probe acquires ultrasound data in spherical coordinates using a mechanically rotating transducer which rotates along the azimuthal angle θ at a specific polar angle or imaging angle ϕ to generate a hollow cone shaped image (Fig. 1). Each image frame acquired by the Conavi ICE is a 2D conical surface image in a 3D space. Therefore, we refer to this unique image configuration as 2.5D. Conavi ICE is also capable of generating 3D volume images by acquiring multiple 2.5D cone shaped images at varying imaging angles. Color Doppler imaging can also be obtained for side viewing images ($\phi \geq 70°$). These 3D reconstructions and 2.5D cone images offer new opportunities for improving existing ICE guidance as well as potentially new clinical applications.

The use of magnetic tracking with ultrasound imaging makes it possible to more easily register patient anatomy from ultrasound images to other imaging modalities such as preoperative CT and MRI, and even electrophysiology maps, for use in the actual intervention. Tracking also simplifies the navigation of catheters towards a surgical target, generating 3D models using volume stitching, and visualization of compound 3D volumes from 2D images. Tracking is achieved using sensors attached to the imaging probe. The tracking system generates a transformation between the sensor attached to an ultrasound device and the reference coordinate

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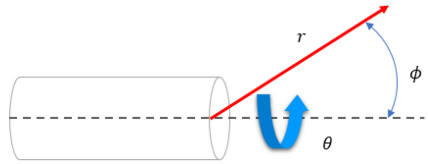


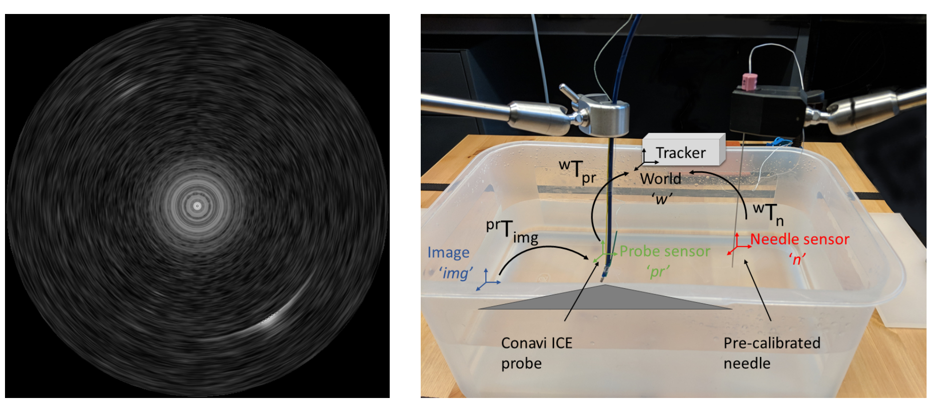
Figure 1: Scanning method for Conavi Foresight ICE probe - a single element, mechanically rotating transducer acquires data along the radial vector in a spherical coordinate system

system, but the position of the ultrasound image with respect to the reference is unknown. Therefore, ultrasound calibration is required to determine the transformation between the the coordinate system of the image volume and the sensor attached to the probe. The combined accuracy of the tracking system and the calibration affects the overall accuracy of the image guidance system. Many calibration techniques have been described in the literature for ultrasound probes.[4] Ultrasound calibration methods for 2D planar ICE probes have been described and evaluated to provide image guidance during surgical procedures such as left atrial ablation therapy.[5] However, all such calibration methods are designed for 2D planar ICE images. The Conavi Foresight ICE system, being unique in its image acquisition technique and 2.5D conical images, has not yet included methods tracking and calibration in the commercially available version of the technology.

We present an intracardiac ultrasound calibration method designed for 2.5D conical ICE. A magnetic tracking system and a pre-calibrated needle are used to calibrate the Conavi ICE probe and define the relation between the sensor attached to the probe and the 2.5D conical images. We validate our calibration by performing a qualitative analysis in virtual space.

2. METHODS

Owing to the unique 2.5D conical configuration of the images taken by Conavi Foresight ICE system, standard cross-wire phantoms or Z-fiducial phantoms[4] cannot be used as they are designed for conventional 2D planar images. We formulate ultrasound probe calibration as a registration problem between homologous point-line registration,[6] using a tracked needle (a line) and its hyperechoic reflection in ultrasound image (a point) as the basis for calibration. While the Conavi ICE generates a conical ultrasound image in real time, it is displayed on a conventional 2D monitor as a disc-shaped image in 2D polar coordinate system (Fig. 2a). Given the imaging depth and the imaging angle ϕ, the 2D pixel location in the original disc image can be converted to a 3D coordinate system. In this manner, the point-line based calibration[6] is directly applicable to the Conavi probe calibration, where efficient solutions exist.[7]



(a) (b)

Figure 2: (a) Screen capture of Conavi ICE image as seen from the front and (b) experimental set up for data acquisition

A Conavi ICE probe was augmented with a magnetic tracking system (Aurora, NDI, Canada),[8] with a magnetic tracking sensor rigidly attached to the outer sheath close to the probe tip. A water bath was scanned at room temperature using tracked Conavi ICE probe. A pre-calibrated needle (Aurora Needle, 18G/150 mm, NDI, Canada)[9] was used to model a line. The needle has a 5 degrees-of-freedom magnetic sensor built in. The pose of the needle is defined by a point of origin and a direction vector. The needle was oriented at multiple positions and angles to produce point fiducials on the cone shaped 2.5D images, along the radius and at varying azimuthal angles θ. For this initial assessment, the imaging angle ϕ was kept constant at 80°. Clamps were used to minimize jitter and overcome accuracies caused by temporal misalignment. 15 point fiducials were recorded using screen-capture of the Conavi console, along with the tracking information for both the probe and the needle.

The coordinate systems are represented in Fig. 2b, with the coordinate system defined by the magnetic tracking system being considered as the world coordinate system. Let w, n, pr and img represent coordinate systems as defined by the tracker, needle, Conavi probe and ultrasound image volume, respectively. As the needle is precalibrated, the transform P_1 from needle tip to the sensor on the needle is known. The pose of the line fiducials can be defined in coordinate system of the ultrasound probe using:

$$P_2 = {}^{pr}T_{img} = ({}^{w}T_{pr})^{-1}({}^{w}T_n)P_1 \tag{1}$$

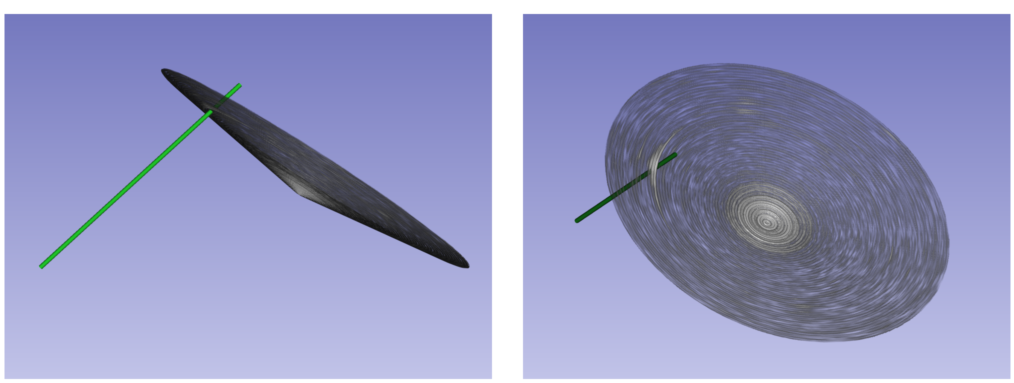
Since the 2.5D Conavi data are acquired using a screen-capture, an additional step is required to convert the fiducial points from the coordinates of a planar 2D image to that of 3D space in which the ultrasound is acquired. Eqn. 2 is used to represent the relationship between the two image coordinate systems,

$$\begin{bmatrix} x_{3D} \\ y_{3D} \\ z_{3D} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \|(x_{2D}, y_{2D}) - \boldsymbol{o}\| tan(90 - \phi) \end{bmatrix} \begin{bmatrix} x_{2D} \\ y_{2D} \\ 1 \end{bmatrix} \tag{2}$$

where $\boldsymbol{o} = (ox, oy)$ represents the center of the planar image or the apex of the conical image. Fiducial point coordinates in 3D space and pose information of the line fiducials (P_2) are used to solve for the affine calibration transformation comprising of anisotropic scaled, followed by rotation and translation.

3. RESULTS

Preliminary results depict an overall calibration accuracy (fiducial registration error, or FRE) of 1.74 mm. For initial validation, a qualitative assessment was performed. The 2.5D images were reconstructed from the screen captures. Transformations were applied to a virtual needle model and the reconstructed volume. Figure 3 shows that the needle passing through the needle reflection or point fiducial seen in the image, thus validating the calibration method.



(a) (b)

Figure 3: Qualitative validation of calibration method in virtual space. Needle passes through the reconstructed 2.5D ICE image: (a) side view, and (b) top view.

4. NEW AND BREAKTHROUGH WORK TO BE PRESENTED

In this work, a calibration method for the unique 2.5D cone-geometry images acquired using a single-element, intracardiac ultrasound probe was presented and evaluated. Qualitative analysis in a virtual environment shows that the needle intersects with the point fiducial in the 2.5D conical images after calibration. The FRE of the calibration was 1.74 mm in this initial study.

5. CONCLUSION

Intracardiac ultrasound probes and their tracking is a vital part of interventional cardiology and cardiac surgery. The accuracy of such a tracking system is dependent on the quality of ultrasound calibration. We describe a proof of concept study towards developing a calibration technique for 2.5D cone shaped images acquired using Conavi Foresight ICE system. Our prior work on the point-to-line ultrasound calibration technique[6] naturally extends to the unique scenario of 2.5D Conavi probe system, achieving an FRE of 1.74 mm. For the full manuscript, temporal calibration will be incorporated and accuracy assessment in forms of target registration error of the calibration technique will be reported.

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