Paper Review Report

Fereshteh Aalamifar

Group 11: Enabling Technologies for Robot Assisted Ultrasound Tomography
Team members and mentors: Rishabh Khurana, Prof. Emad Boctor, Prof. Iulian Iordachita, Prof. Russell Taylor
Paper: L. Mercier, T. Lango, F. Lindseth, L. Collins, "A Review of Calibration Techniques for Freehand 3D Ultrasound Systems," Ultrasound Me. & Biol., Elsevier, Vol. 31, No. 2, pp. 143-165, 2005.

Summary of project

We are developing a prototype for robot assisted ultrasound tomography. This prototype includes a free hand ultrasound probe operated by a technician and a robot operated probe tracking the free hand one. This system can be used for more depth ultrasound imaging, faster scanning, and most importantly for soft tissue ultrasound tomography.

Paper selection Reason

I chose this paper because in our project we need to perform two ultrasound calibrations. On the free-hand probe we attach a marker which will be tracked by an optical tracker. This marker gives us the 3D position of probe in space. We need to find the transformation between the marker and origin of 2D ultrasound image. In addition, we will put the cameras of the optical tracker on the robot arm. The camera coordinate system should also be registered to the 2D ultrasound image of the robot operated probe. Since in the latter calibration, the camera is attached to the probe, calibration process can be challenging. Hence, we should first review all the calibration methods, to figure out the best way to perform this calibration.

This paper is a recent review on calibration techniques for 3D ultrasound. In addition, it covers many helpful topics related to our project including tracking technologies, calibration phantoms, temporal and spatial calibration methods and their comparisons, etc. This paper helped me become more familiar with the vocabulary of 3D ultrasound imaging, basic and some advanced concepts, current ultrasound technologies and calibration techniques. I could also infer a list of important issues that may come up in ultrasound tracking field.

Summary of problem & key result

In 3D ultrasound, the goal is to reconstruct 3D volumes from 2D ultrasound images. There are four techniques to construct a 3D ultrasound volume: 1. Constrained sweeping, 2. 3D probe, 3. Sensorless techniques, 4. Tracked 2D probe. The fourth method is more commonly used but the transformation between the tracking system and the 2D image needs to be found. Different techniques are used to find this transformation. The significance of this paper is the comprehensive review and classification of these techniques published between 1994-2004.

Background

The paper is very well written and covers almost all the required background. However, familiarity with ultrasound imaging and calibration techniques can be helpful to better understand and appreciate the significance of this paper.

Summary of the paper

1. Ultrasound Image Acquisition

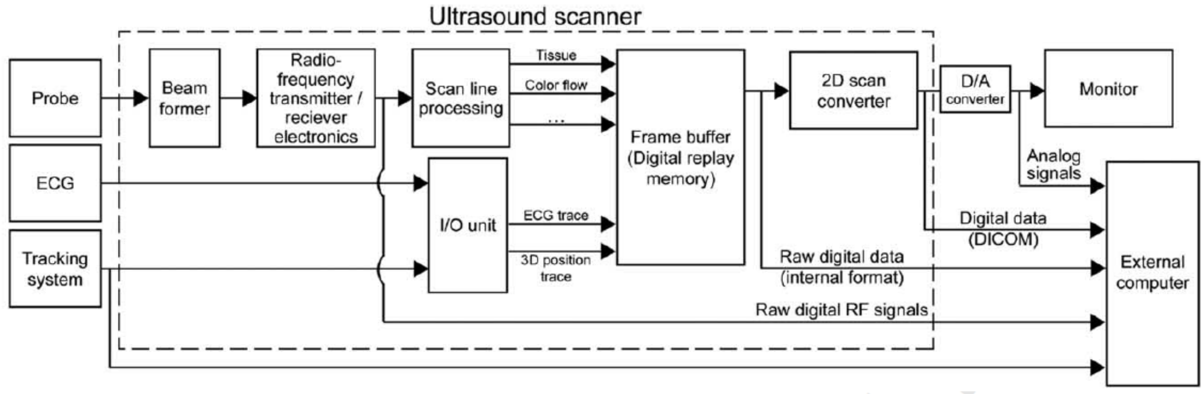

Figure 1. Image Acquisition modes; "Image from L. Mercier, et. al, A review of calibration techniques for freehand 3d ultrasound"

In ultrasound imaging, RF signals are sent through the medium and the reflected RF signals, which correspond to the convolution integral between the spatial density of tissue and the point spread function (psf), are processed to form the image. Figure 1 shows four different data acquisition modes in ultrasound imaging:

1. Acquiring analog signal: The advantage is that this mode is available in almost all ultrasound machines. The disadvantage is that the frame rate is less than digital modes (less than 30 f/s) and also we need to convert it again to digital data to store on the external computer.
2. Three Digital modes: These digital data can be acquired at a faster speed (up to 100 f/s) and can be directly stored on the computer. These modes, however, need to be processed on the external computer to form a geometrical image.

2. Calibration Methods and Phantoms

There are four different coordinate systems present in an ultrasound calibration: image, sensor, tracker (or world), and phantom coordinate systems. Figure 2 shows these systems. Out of the three transformations, sensor to image is unknown and the goal is to calculate that. A least square minimization is used to find this transformation. The general conversion from a point in the kth image into the phantom coordinate system is as below:

$$\begin{pmatrix} x_k \\ y_k \\ z_k \\ 1 \end{pmatrix} = T_{p\leftarrow w}.T_{p\leftarrow w}.T_{p\leftarrow w}.\begin{pmatrix} s_x.u_k \\ s_y.v_k \\ 0 \\ 1 \end{pmatrix}$$

Where (u_k,v_k) is the position of feature point extracted from the image and (x_k,y_k,z_k) is the position of the point in the phantom coordinate system. s_x and s_y are scale factors representing the difference between real world dimensions and what is shown in the ultrasound image and can depend on the ultrasound depth settings. The scale factors may be provided by the digital setup or can be considered as an unknown and be calculated. The top center point of image is usually considered as origin because, for curved array probes, this point does not vary when the depth setting is changed.

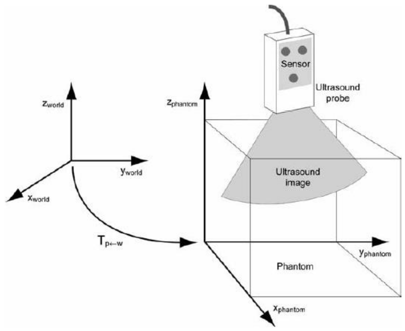

Figure 2. Coordinate systems present in calibration; "Image from L. Mercier, et. al, A review of calibration techniques for freehand 3d ultrasound"

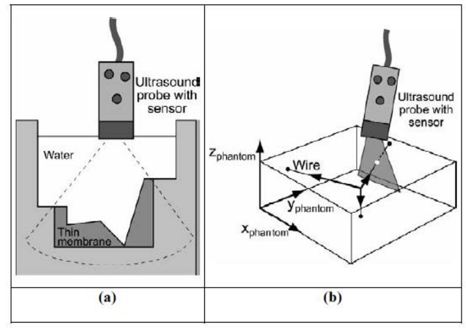

Figure 3. (a) 2D shaped phantom (b) three wire phantom; "Image from L. Mercier, et. al, A review of calibration techniques for freehand 3d ultrasound"

To do the calibration, usually some targets or a phantom containing targets are put inside the water and then the probe is put on top (or sometimes on other sides too) of the water tank to take images. There are several types of calibration phantoms introduced in this paper:

- Single point target: The point can be a spherical point or crossing of two wires. The point can also be the tip of a tracked pointer which does not require a phantom.
- Multiple point targets: multiple points can be created with several cross-wires, triangular wires, collinear points, or a combination of these. In addition, z- fiducial phantoms were developed in which the image always intersects with three points on the z-shape wires.
- 2D shaped phantoms: The idea is to align points of interest of a solid 2D geometric object in the ultrasound image.
- Three wire phantoms: The wires are orthogonal and their intersection is the origin of the phantom coordinate system and each wire represents one axis. This phantom does not require alignment of ultrasound image and make calibration easier because we always know that the feature in the image is on one of the axes.
- Wall phantoms: In this phantom, a line from the wall is present in the image and this makes segmentation easier than when the feature is a point.

3. Speed of sound Issue

During calibration we should note that the speed of sound is assumed 1540 m/s (speed of sound in human tissue) in ultrasound machines. So when we use another coupling medium, we need to adjust the measured distance as follows:

$$d = d_{measured} \times R \qquad \text{Where } d_{measured} = propagation\ time \times \frac{1540}{2} \qquad \text{and } R = \frac{1540}{s_{medium}}$$

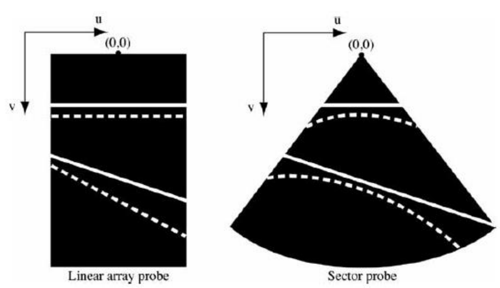

Figure 4. Effect of speed of sound; solid line is the real position of wire while dotted line is unadjusted distance in water; "Image from L. Mercier, et. al, A review of calibration techniques for freehand 3d ultrasound"

Figure 4 shows how speed of sound can change position of features if the adjustment is not considered. To make the speed of sound in water the same as in tissue, we can heat the water or add chemicals (e.g. ethanol) to it.

4. Least square minimization

As mentioned before, least square minimization is used to find the image-sensor transformation. There are two approaches to apply that: closed form, and iterative approach. Closed-form approach is used when we know the position of features in world's coordinate system (such as in single or multiple point targets) and we try to minimize the following least square error:

$$\sum_{j=1}^{N} \left|\left|b_j - sRa_j - T\right|\right|^2$$

Where b_j is the point in phantom, a_j is its position in image, and s is the scale factor. We want to calculate R and T which are the rotation and translation matrices that form the image-sensor transformation. Iterative approach is used when we do not know the position of features in world's coordinate system (such as in three wire or wall phantoms).

5. Comparison parameters

Many parameters can be considered when choosing a calibration method or comparing several methods. The parameters described by the authors can be summarized as: precision, accuracy, required time to perform calibration, complexity or price of the required software and hardware. However when choosing a method, we should take into account the specific requirements of the application. For example, in one application, the required time to perform calibration might be not so important in comparison with the accuracy or vice versa.

6. Other topics

This paper covers other topics such as temporal calibration and calibration evaluation which are not explained here for brevity.

My Assessment

Good points:

- The first review paper with conceptual description of almost all existing (before 2004) calibration methods
- Provides mathematics only if necessary and gives references for further details
- Provides comprehensive comparison tables
- Covers almost every important topic in the field

Bad points:

- Could have given some example applications appropriate for each method

Possible Future work:

- More recent advances in the field of ultrasound calibration can be reviewed. (After 2004)

Paper conclusion relevant to our project

In summary, in our project, we have to take the following steps for calibration:

- Choose an appropriate calibration method and, if needed, a calibration phantom
- Find sensor-world and world-phantom transformation. Sensor-world is just by reading the tracking information and for world-phantom we can put a pointer on the phantom's origin, or install markers on it.
- Put phantom or targets inside a water tank and take images; then extract features. Feature extraction can be done manually or automatically by calculating intensity centroids.

- Adjust measurements if needed based on medium’s speed of sound.
- Use least squares method to find the image to sensor transformation.

In addition, we will have in mind the role of temporal calibration and calibration evaluation to understand how good or bad our calibration is and how it can be improved.