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Temporal and Spatial Calibration of a freehand 3D ultrasound reconstructions system by using an N-wire phantom

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Abstract— **Freehand three-dimensional (3D) ultrasound is a method for reconstructing a 3D volume from two-dimensional (2D) ultrasound (US) images. Indeed, the US scan is very common in the medical world; it is a noninvasive, fast and cheap exam. The objective is to enable the practitioner to have a 3D visualization inside the body, in real-time. The medical staff can rotate, move or scale it inside the 3D space. Another important possibility is a view inside the volume. In order to do so, we must move the US probe on the area of interest and the movement, the path is taken in by the Polaris Spectra System. The problem is that the system follows the probe and not the scan plane. The objective is to define the transformation between the US probe markers (rigid body) and the scan plan. For this, the system must be calibrate. During the calibration, the user must use a phantom with known dimensions. For this system, the method of improved N-wire phantom-based freehand ultrasound is used. We must make a temporal and a spatial calibration to obtain different matrixes which enable to know the different offset and transformation for having a good 3D reconstruction.**

Keywords— Temporal Calibration, Spatial Calibration, 3D Reconstruction, Freehand 3D Ultrasound Reconstruction, Improving N-wire, Phantom.

I. INTRODUCTION

Ultrasound imaging is a non-invasive exploration method based on the use of mechanical waves. Echoes reflected by the organs make possible to see what is invisible to the eye, or even to the X-ray. A system for 3D ultrasound representation can be used for medical doctors in order to have a better visualization of any pathology. The proposed system can be used, among others, in monitoring non-invasive or minimally invasive thermal therapies used in oncology. The applicators used in such therapies are waveguides, the microcoaxial antennas, ultrasound, HIFU, etc. For this type of therapy is necessary to have a display system which allows to perform the following tasks: to locate the target tissue (tumor), to guide the position of the applicator (e.g. microcoaxiales antenna) and monitoring the treatment.

The technique used in this work for building a 3D ultrasound system consists in tracking a position sensor attached to a conventional ultrasound probe. The probe is moved on the patient anatomy; the trajectory of the probe is recorded by the attached position sensor, in this case by the Polaris Spectra System. To reconstruct the 3d model, the 2d pictures are assembled and segmented. For each pixel of the 2D US pictures, a matrix with the precise orientation, rotation (the correct scale parameter) and positional parameters is used. This allows obtain the position in space of each pixel. The 3d reconstruction can have significant problems if there is an incorrect calibration of the system, significant variations in speed during scanning can lead to significant problems during the reconstruction.

The objective of this work is to improve the calibration method of the system with the software PLUS and a N-WIRE phantom. The steps for the calibration and the mathematical processing will be explained. The system presented in this article is a system that can still be improved. Up to now, this system can only generate an estimation of the surface of an object detected in a sequence of digital images that are received as input.

II. MATERIALS

A. *Optical Sensors*

The Polaris Spectra System is an optical system to measure the 3D positions of either active or passive markers affixed to application-specific tools. Using this information, the Polaris Spectra System is able to determine the position and orientation of tools within a specific measurement volume. The Polaris Spectra System volumetric accuracy is

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0.25mm. A 3D representation of the measurement volume is shown in Figure 1.

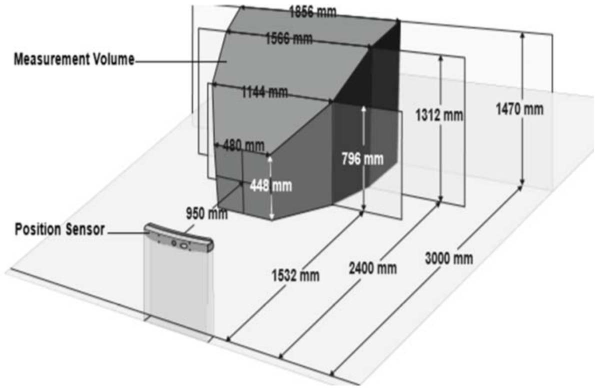


Figure 1: Polaris Spectra measurement volume.

B. Image Acquisition System

For the acquisition, conventional ultrasound system Prosound 6 Aloka, Japan was used (Figure 2).

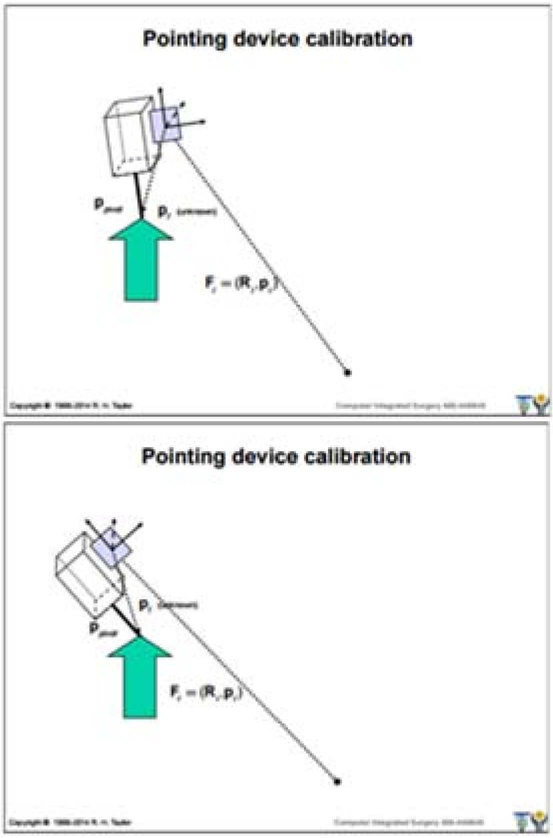
Figure 2: Ultrasound system Prosound 6.

A convex probe operated in a 3-6 MHz frequency range and a sweep angle of 82 ° was used.

III. METHOD

A. Pivot calibration

To perform the pivot calibration, a tool called stylus is used; it is composed of a rod (tip) of a rigid body and three reflective spheres (passive markers). This process is carried out to perform the transformation of the axis system coordinates of a set of markers (rigid body) to the tip of the stylus. The purpose of calibration is to determine the different movements, translation markers. The following schemes illustrate this [1], Figure 3.



3.

Figure 3: Pointing device calibration.

The way to perform calibration is critical. The calibration was made as follow:

- Determinate the translation *Pt* between the tip and the rigid body. *Pt* is the vector that transfers the system markers center towards the pen tip and *Ppivot* is a vector that transferred the coordinate system of axes of the positioner to the pen tip.
- Draw slow circle between 30 and 60° with the stylus.
- The vector *Ppivot* stays constant all time.
- The Stylus markers report the position and the orientation.
- The Polaris Spectra System obtains the marker coordinate system.
- This is to have *Fi(Ri,Ti)*; it is a vector including the position and orientation of the coordinate system. *i* is the position and orientation of the positioner.
- *Fi(Ri,Ti)* make the relation between *Pt* and *Ppivot,* indeed *Fi*Pt=Ppivot.*
- With the rotation *Ri* and the translation *Ti*: *Ri*Pt+Ti=Ppivot.*
- Obtain many positions to calculate *Pt.*

B. Temporal calibration

Temporal calibration estimates time offset between data streams acquired by different devices (scanner and the optical sensor). For the calibration, the probe must move in a periodical manner (period: 2s). Move the probe in a repeating up-and-down way while imaging the bottom of a water bath.

For each US image, a line is then fitted through the detected center of gravity (COG) points using the RANSAC algorithm (Fig. 4A and 4B). The signal amplitude of a given US image is then taken to be the distance from the midpoint of that image COG line to the midpoint of the mean COG line. The tracker and image position signals are aligned by finding the time shift that minimizes the sum-of-squared distance (SDD) between the two signals (Fig. 4C and 4D). The optimal time shift is computed using a multi-resolution search [2].

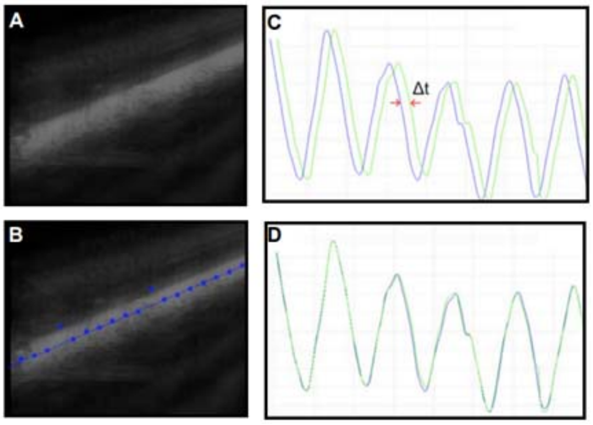


Figure 4: (A) US image of the bottom of a water tank and (B) the same image with COG points and a COG line. (C) Normalized tracker position signal (blue) and image position signal (green) before calibration, and (D) after calibration. x-axes are time, and y-axes are the normalized signal values; Δt is the temporal offset [2].

The process to define the offset between pictures acquisitions and captures the positions and orientations by the positioner is extremely important because the lag between data capture can introduce significant errors in procedures requiring high precision measurement when the probe moves fast.

C. US probe calibration

A complication of any system US Freehand 3D is that the positioning system sets the position 3D rigid body S instead of the position of the image plane I in relation to W as shown in Figure 5.

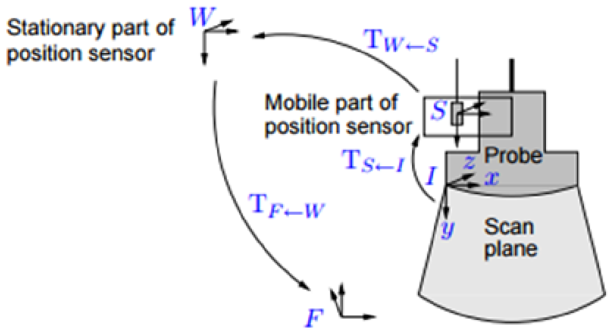


Figure 5: The coordinates associated with a freehand 3D ultrasound system and this different transformations (TF, TW and TS) [3].

Therefore, it is necessary to find the position and orientation of each scanning plane in relation to the rigid body coordinate system. The rigid body transformation matrix is:

Equation 1:

$$T_p = \begin{pmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix}$$

The matrix includes 6 parameters:

- 3 translations (axis x, y, z)
- 3 rotations (azimuth, elevation and roll)

With this information, it must be determined the scale of the images obtained by the ultrasound to be able to reconstruct a volume in space.

For this, an arbitrary point of the US picture was taken; we obtain a point $P^{I'} = (u, v, 0)^t$ *U* and *V* correspond to the columns and lines with a pixel unit rather than in millimeters.

A scaling factor *Ts* is:

Equation 2:

$$Ts = \begin{pmatrix} S_u & 0 & 0 \\ 0 & S_v & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Where S_u and S_v are the scales in millimeters by pixel; it is necessary for modifying the precedent equation and thus obtain a millimeters unit: $P^I = T_s P^{I'}$.

When calibration and scale are known, it is possible to place each point in 3D space using the following formula:

$$P^F = T_F \leftarrow W \quad T_W \leftarrow S \quad T_S \leftarrow T_s P^{I'}$$

1. *Phantom calibration*

The calibration phantom (Figure 6) is an object whose characteristics are known; it is specific to the PLUS software. It has holes in order to pass a wire which will be used for further calibration.

Figure 6: 3D establishment of a pattern of calibration phantom 2.0.

This calibration allows computing transformation between a phantom object coordinate system (Phantom) and the coordinate system of tracking marker attached to the object (Reference) by point matching. Point coordinates are defined in the Phantom coordinate system and coordinates of the same points are also acquired in the Reference coordinate system by using a tracked stylus (StylusTip). To detect and select points in the Reference coordinate system the landmark detection algorithm can be used by detecting the stylus tip point when the tracked stylus is swiveling. [4]

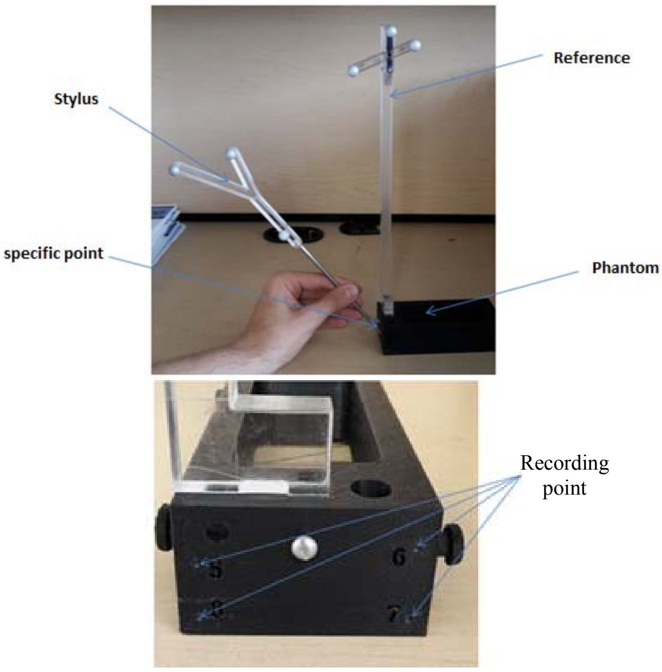


Figure 7: Recording 8 calibration points of the phantom with the stylus.

2. *Improving N-Wire Phantom*

The US probe calibration was carried out with the Plus software which is based on the calibration method called Improving N-wire phantom. The transformations used in the calibration method Improving N-wire phantom described in Figure 8:

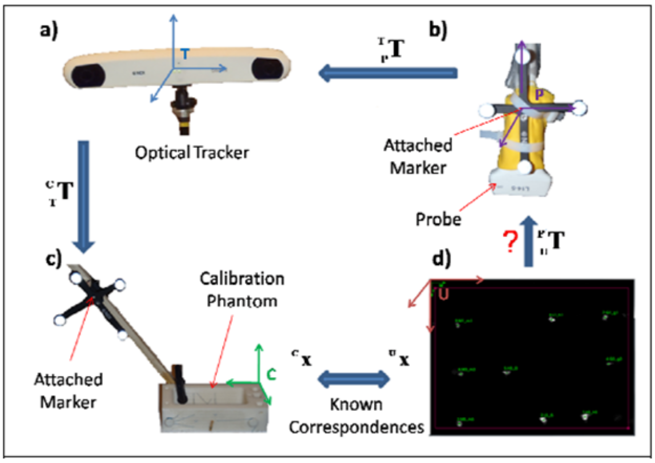


Figure 8: Transformations involved in the image to probe calibration procedure: a) sensor of the optical tracking device b) probe with an attached marker c) calibration phantom with an attached marker d) N-wire intersection points visible in the ultrasound image. [5]

This method use a specific phantom with a known geometry like that shown in the Figure 6.

This procedure is ideal to calibrating the probe US for two reasons: the insertion of wire, N-wire in the phantom and the images appear as bright spots, which in turn can be detected and segmented in a precisely manner, robust and automatically in real time. The points appear in green when they are detected. (Figure 8d).

It is possible to calculate the intersection of wires in the image planes of the US probe if the geometry is accurate and the insert positions of wires are known. The intersection of the middle wire with the image plane in the calibration phantom coordinate system is computed by using: [6]

Equation 3:

$$C_{x2} = C_a + \frac{||U_{x3} - U_{x2}||}{||U_{x3} - U_{x1}||}(C_d - C_a)$$

Parameters of the equation are illustrated in Figure 9:

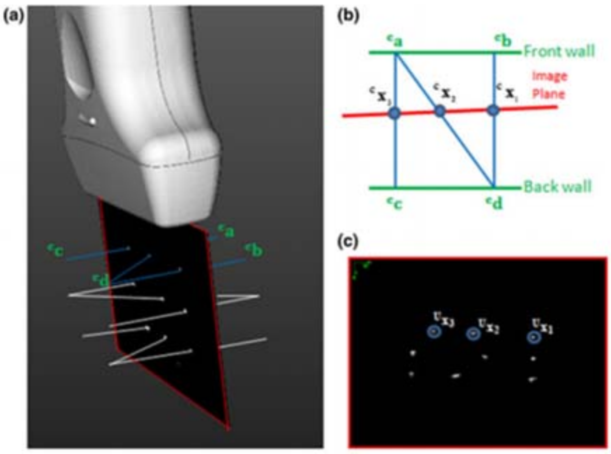


Figure 9: a) Phantom Calibration uses three layers of wire. The red frame is the image plane. b) Sketch of the top N-wire in the calibration phantom. *Cx1*, *Cx2* and *Cx3* are the coordinates of the intersection between the wires and the image plane, in the calibration phantom coordinate system. *Ca* and *Cd* are the coordinates of the intersection points of the middle wire (between *a* and *d* points) with the parallel side wires, in the calibration phantom coordinate system. c) Intersection of the N-wires and the US image plane are automatically segmented. *Ux1, Ux2,* and *Ux3* are the coordinates of the intersection between the top N-wire and the US image. Ratio of the *x3 – x1* distance and the *x3 – x2* distance is the same in the calibration phantom coordinate system as in the US image coordinate system; therefore, from the *Ux1, Ux2,* and *Ux3* coordinates, the position of *x2* point along the *Ca – Cd* line can be determined, i.e. *Cx2* coordinates can be computed. [5]

The objective of a US probe calibration is to determine the transformation that brings a position of the US picture frame (U), in the US probe pictures (P). This is actually a 4 × 4 matrix that encodes eight calibration parameters (three rotation parameters, two scale factors and the three translation parameters); we obtain the following equation [6]:

Equation 4:

$${}^{P}_{U}T\,{}^{U}X = {}^{P}X$$

${}^{U}X$ corresponds to the segmented coordinate all intersections between the wire and the image plane of the ultrasound probe. ${}^{P}X$ is the average coordinates of the wire in the probe coordinate system. The resulting matrix is not perfect; for this reason, the software uses two different methods to minimize the error.

3. Probe calibration with software PLUS

To calibrate the probe we used: a calibration phantom, the probe US with a rigid body fixed, a container with water and a anechoic plate on the bottom to prevent the US reflection and thus to avoid maximum noise.

To calibrate, you must move the US probe on the calibration phantom in different directions to collect the necessary information and replace in the equation:

$$p^{F} = T_{P} \leftarrow w \quad T_{W} \leftarrow s \quad T_{s} \leftarrow T_{s} P^{t}$$

Figure 10: US probe calibration.

IV. Results

The rigid body transformation for the stylus is obtained during the pivot calibration; this transformation is characterized by the following matrice:

Equation 5:

$$Pt = \begin{bmatrix} 0.988048 & 0.002660 & 0.154241 & 191.3130 \\ -0.002693 & 0.999996 & 0 & -0.052144 \\ -0.154123 & -0.000415 & 0.988052 & -29.84240 \end{bmatrix}$$

To accurately calculate the transformation of the coordinate system of axes of a set of markers to the Stylus tip is very important. Indeed, after this step, the recording calibration phantom is realized. This indicate at the program the correctly dimension of the calibration phantom. Phantom calibration record depends mainly on the accuracy with which the pivot calibration was performed.
During the temporal calibration, an offset of 0.0147s is obtained.

While the spatial calibration, the rigid body transformation matrix is obtained:

Equation 6:

$$T_{P} \leftarrow_{U} = \begin{bmatrix} 0.263928 & -0.331233 & -0.905885 & 298.696 \\ 0.852388 & -0.359453 & 0.379775 & -87.7383 \\ -0.451417 & -0.872398 & 0.187469 & -79.8204 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

And a scale factor of:
Equation 7:

$$Ts = \begin{bmatrix} 0.160474 \\ 0.368895 \\ 0.229438 \end{bmatrix}$$

The problem of calibration of the US probe consists essentially of obtaining the 3D position of a pixel of an image 2D US. As mentioned above, the precision with which the process is implemented is very important for the US 3D Freehand system. Indeed it is commonly an error is present in the 3D reconstruction process. If the probe is incorrectly calibrated the system will produce inaccurate measurements and images.

With Matlab, we can reconstruct a breast tumor for example; with our program after the calibration and the scan of the area of interest we obtain this result:

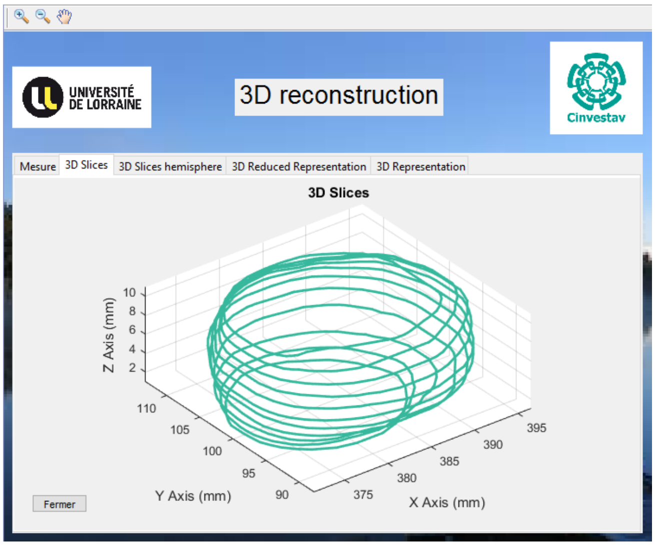


Figure 11: 3D slice hemisphere of breast tumor phantom reconstruct with Matlab

V. Discussion and Conclusion

The obtained results show that the calibration is functional. A functional calibration provides a good 3D reconstruction quality. In this part, we are trying to explain the problems that we encounter and the solutions to resolve the problems. The experimentation was repeated several times in order to improve our system and to correct errors.

A. *Problems encountered*

1. *Phantom calibration*

There are a lot of noises caused by wave reflection when you check the image on the Ultrasound system. An ultrasound wave is reflected in all the directions, one part of this wave is used to see the region of interest and another one is noise. The objective is to reduce the noise to have a good image quality.

2. *Calibration phantom geometry*

In the phantom geometry part, the code should match to the phantom coordinate points we use. We tried several configurations with different coordinates. If the coordinates does not match to the code, it is impossible to see the green points (Like depicted in figure 8d) when we do the spatial calibration. The US probe does not locate the points and the wire, so you have a high calibration error.

B. *Solutions provided*

1. *Waves reflection*

To eliminate all the wave reflection, we used different methods. At the beginning, we change the water because in this there were a lot of bubbles. We think it is better to replace the water by degasified water. After this operation we can better see the region of interest on the Ultrasound scan. Then, we add an anechoic material at the bottom of the container to stop the wave reflection. Another solution to limit the reflection is to change the wire material and add an anti-reflect paste on the phantom.

2. *Calibration phantom geometry*

To obtain a good calibration, we must change the phantom geometry, in a part of the code in the file Plus. The code depends on the way you pass the wire on the phantom.

This article has addressed the issue of freehand 3D ultrasound calibration. Ultrasound is a relatively cheap and easy to integrate imaging, mix with the Polaris Spectra System it is a good and relative reliable method for visualize inside the body in 3D. The freehand 3D ultrasound calibration is a reliable method and rather fast for allows a good 3D reconstruction.

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