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An Accurate Calibration Method of Ultrasound Images by Center Positions of a Metal Ball

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Abstract— **This paper provides a novel method for three-dimensional tracking of ultrasound images. One of the issues to determine the position of a ultrasound image plane is the thickness of the image plane. The proposed methodology address the issue by the calibration phantom using a fiducial sphere with the diameter of 5.5 mm because comet-trail artifact can be observed in the image plane through the center of the sphere. Meanwhile, to measure the sphere center accurately by a tracking device, a pointer tool with the same sphere at the tip is also proposed. To validate the feasibility of the method, simulation and phantom tests were conducted. From the results of the phantom test, the accuracy of the calibration was 0.65, 0.40, and 0.42 mm in 10, 50, 100 points calibration. The results demonstrate that the proposed method has a great potential for accurate US probe calibration.**

I. INTRODUCTION

Medical imaging, like Magnetic Resonance Imaging (MRI), Computer Tomography (CT), and Ultrasound (US), is indispensable technology for clinical diagnosis and surgical procedure at present. Moreover, computer science and mechatronics technology have been applied to clinical settings for safer and more effective medical procedures. Especially, these research field is called Computer Assisted Diagnosis (CAD) and Computer Assisted Surgery (CAS).

In the CAS, intra-operative information such as positions and images are important for navigation of surgical procedures [1], [2]. While MRI and CT are 3D images modalities that provide many information to surgeons for their procedures, the modalities also have disadvantage of costs and portability in intra-operative use. Particularly, a specially designed operating room is needed to use CT and MRI intra-operatively. On the other hand, US has great potential in terms of the issues, because it is real-time, lower costs, and can be used in conventional operating room. Actually, significant amount of research has been conducted for a 3D real-time visualization by using US technology [3]. Meanwhile, recent US devices can acquire 3D images by mechanical or electrical sweeping. But US also has another technical issue that US does not have a peripheral frame. Therefore, US images/volumes can not be used for a surgical navigation directly. General approach of the issue is tracking an imaging probe with a tracking device. In this case, a transformation between the US image plane and the tracking device has to be determined, therefore measured image planes are integrated with a same coordinate system. In this paper, US calibration means the procedure to obtain the transformation between the probe and the tracker. Using the transformation, a 3D volume is able to reconstruct by some interpolation method. Therefore, the data is visualized by volume rendering, re-slicing, or surface rendering. The accuracy of the data are influenced by the calibration accuracy.

Geometrical designed phantoms are popular approach for US probe calibration [4]–[10]. The cross-wire and the Z-fiducial methods have been studied. However, it is difficult to detect the fiducial points accurately because the wire or the cross-point of wires is not imaged as a point or circle. Another approach is a method that uses a tracked needle without fiducial points. However, the method is also difficult to measure the tip position in an US image.

In this paper, we propose another calibration method using a calibration phantom with a fiducial sphere and a fiducial calibration tool in order to measure the center of the marker accurately. Feasibility of the method was evaluated by simulation and phantom tests.

II. MATERIALS AND METHODS

This section describes our system configuration and the proposed procedures. The system configuration is shown in Fig. 1. The system consists of an US imaging device (LOGIQ7, GE Healthcare UK Ltd., UK) with a 11 MHz linear probe, an optical tracking device (Polaris Spectra, NDI Inc., Canada) with several infrared markers, a calibration phantom with a metal sphere as a fiducial marker, and a workstation with a video capture board. Rigid-bodies with four infrared reflective markers (tracker) are attached to the phantom and the probe respectively (probe tracker and phantom tracker). The tracking device is connected to the workstation via a USB cable and tracks the rigid-bodies with 60 Hz rate. The details of the phantom and the calibration procedures are explained below.

A. The Calibration Phantom

The key of calibration phantom design is geometrical accuracy of fiducial points or markers. Our idea is a sphere marker and a pointer tool with the sphere tip which has the same size of the marker. Therefore, the center of the fiducial marker can be determined by pivot calibration using the pointer. The principle is illustrated in Fig. 2.

The calibration phantom consists of an acoustic board, a metal ball with the diameter of 11.0 mm. The acoustic board

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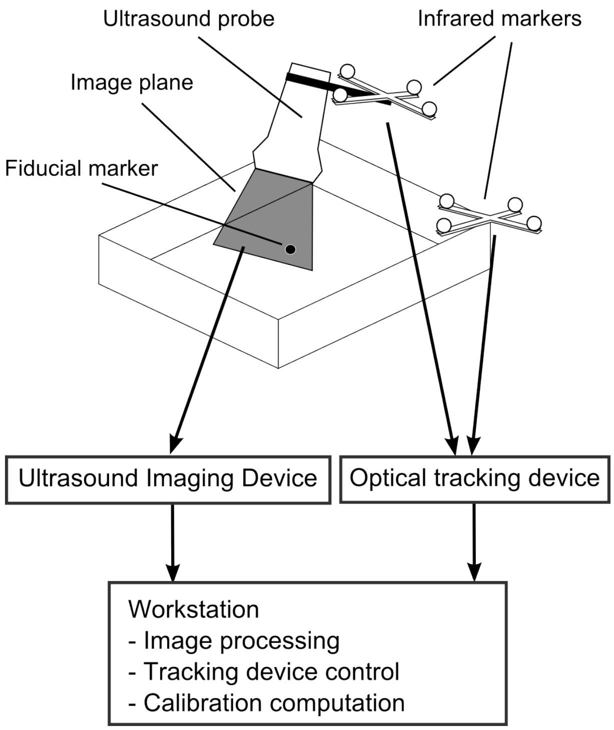

Fig. 1. System configuration

has a hole with 10.0 mm diameter in order to fix the sphere. As stated above, the phantom tracker was attached to the container of the phantom.

To determine the center of the sphere fixed on the hole, pivot calibration was conducted on the hole. Then, the fiducial marker was fixed on the hole. Next, the container was filled with hot water of $50°C$, where the wave propagation speed is equivalent to the average propagation speed among human tissues.

B. Calibration procedures

One of the difficult points of US probe calibration is the US image plane is not a thin plane with a couple of millimeter thickness corresponding to the US beam width. Meanwhile, the sphere marker shows comet-tail artifact when the sphere center is located in the image plane.

An US image with the fiducial marker is transfered to the workstation via a composite cable. The fiducial marker position is also measured by the tracking device at the same time, and its position in the probe tracker coordinates ${}^{Probe}p$ is obtained by following formula.

$$ {}^{Probe}p = {}^{Probe}T_G \, {}^{G}T_{Phantom} \, {}^{Phantom}p \tag{1} $$

where $Probe, G, Phantom$ are coordinate systems of the probe tracker, the tracking device, and the phantom tracker; and ${}^{Probe}T_G$ and ${}^{G}T_{Phantom}$ are the frame of the probe tracker and the phantom tracker, which are provided by the tracking device. ${}^{Phantom}p$ is the marker position from the phantom tracker by the phantom calibration procedures. The procedure is repeated several times by different postures of the probe

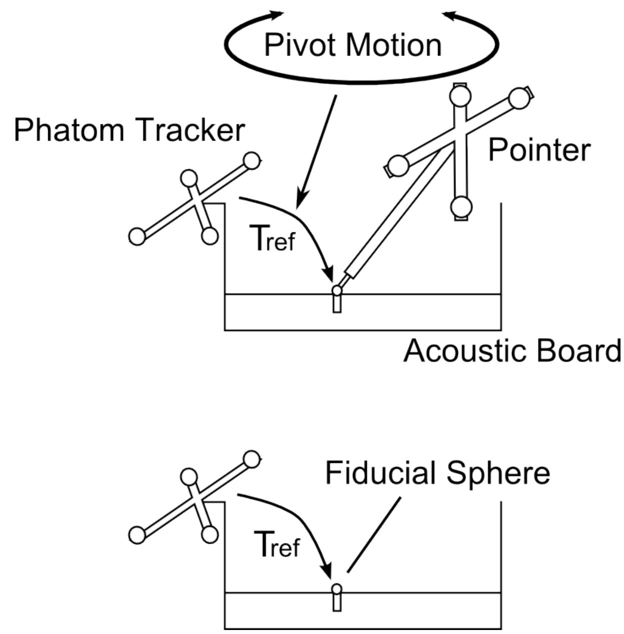

Fig. 2. The calibration phantom using a fiducial sphere.

to obtain the marker position at the various positions on the images.

When sufficient points are collected, the calibration is performed by following algorithm (Fig. 3). First, the center of the marker in each image is detected by image processing: Edge filtering and circle fitting. For edge filtering, Hough filter was used. Next, five points on the edge are selected manually and the best fit circle is predicted. After the image processing, the transformation between the coordinate systems of the US image plane and the probe tracker is computed by using a point-based registration technique (Fig. 4) [11]. The Open Computer Vision library (OpenCV) and the Visualization Toolkit (VTK, Kitware Inc., USA) were used for the implementation of the software.

III. Validations

This section shows that the validation of the proposed method. First, the method was evaluated by simulation. Next, the phantom test using a developed calibration phantom was conducted. The performance of the method was evaluated by residue of point-based registration and errors of the fiducial positions derived from the image and the tracking device with obtained calibration matrix.

A. Simulation

In the simulation, both an image point set and a tracked point set were generated by following methods.

First, we defined a calibration matrix T = RotX(10.0) RotY(20.0) RotZ(30.0) Trans(10.0, 20.0, 30.0), with RotX, RotY, RotZ rotational matrices around x, y, z axis, respectively, and Trans a translation matrix. Then, a set of image points was randomly generated within the rage x[0.0:100.0]; y[0.0:100.0]; z[-3.0:3.0]. Next, we defined corresponding set of tracked points by multiplying each image points by the

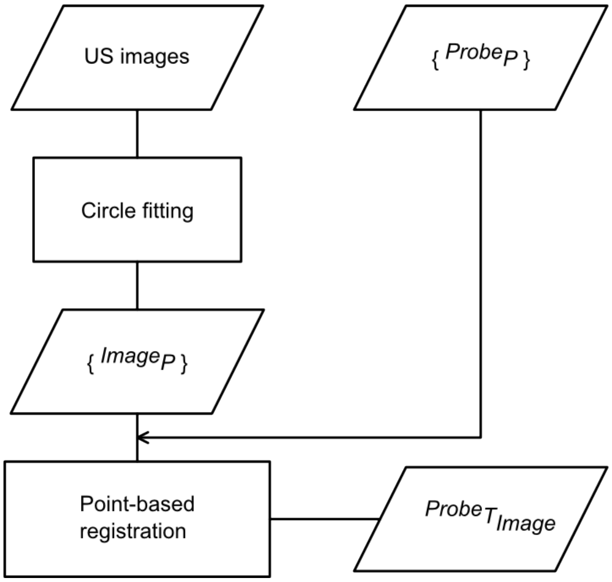

Fig. 3. Flowchart of the calibration procedures.

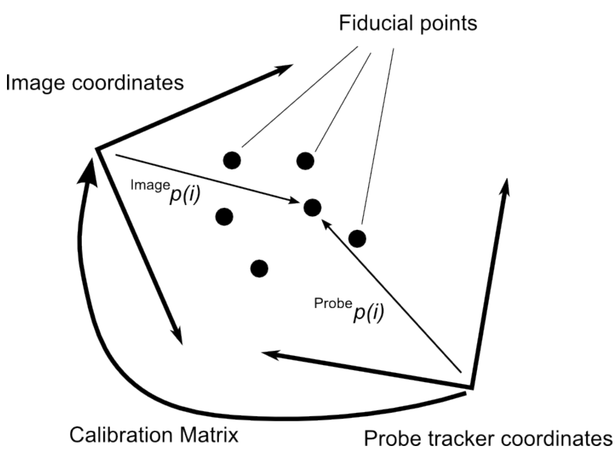

Fig. 4. Point-based registration between coordinates of the image plane and the probe tracker.

transformation matrix T. Finally, to simulate measurement errors, small random vectors (x_e, y_e, z_e) were added to each image and tracked point. Precisely, for tracked points we set $-0.1 \leq x_e, y_e, z_e \leq 0.1$ and for image points we set $-0.15 \leq x_e, y_e \leq 0.15$. Note that the z coordinate of image points is subsequently ignored as they are projected on the image plane.

Table I shows the registration residue and the error of obtained transformation matrix. The test was executed with 100 times in respective number of points: 10, 50, and 100. The results suggests 10 points are not sufficient for stable and correct US probe calibration.

B. Phantom Test

To validate the proposed method in actual condition, phantom tests were conducted. The developed phantom and tool (5.5 mm diameter sphere tip) are shown in Fig. 5. To measure the marker position from the phantom tracker, the phantom calibration was performed by careful pivot motion.

TABLE I
RESULT OF SIMULATION TEST

Num.	Residue [mm]	Position Err. [mm]	Rotation Err. [deg]
10	0.80 ± 0.30	1.36 ± 1.05	2.64 ± 3.09
50	0.35 ± 0.13	0.49 ± 0.37	0.65 ± 0.34
100	0.26 ± 0.09	0.41 ± 0.32	0.45 ± 0.23

Next, the fiducial sphere (5.5 mm diameter) was fixed to the hole by bond. Then, the container was filled with $50°C$ water.

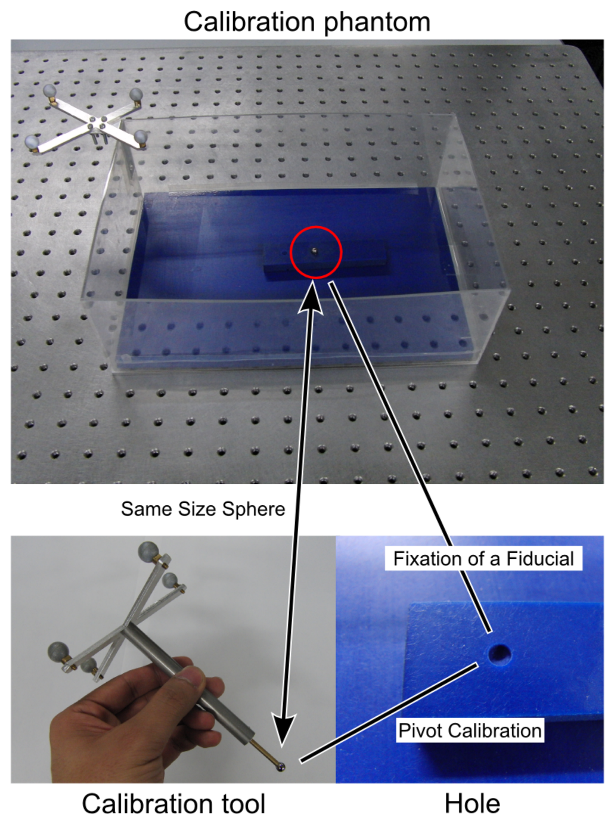

Fig. 5. The calibration phantom and tool.

150 US images were collected manually. Then, the center positions of the markers were detected by image processing. At the time, the marker position from the probe tracker was measured by the tracking device. Next, the set of the image points was obtained by circle fitting of the US images. One of the pre/post-processed images is shown in Fig. 6.

The calibration transformation between the sets of the image points and tracked points was computed in 10, 50, and 100 points respectively. To validate the obtained matrix, other 50 points in the phantom coordinates were transformed to the image coordinates using the obtained calibration matrix. Then, the transformed positions were compared with the positions by the US images. The results were shown in Table II. The error norms of each condition were 0.65, 0.40, and 0.42 mm, respectively. From the results, the mean errors depends on the number of collected points slightly, meanwhile the standard deviations did not have difference

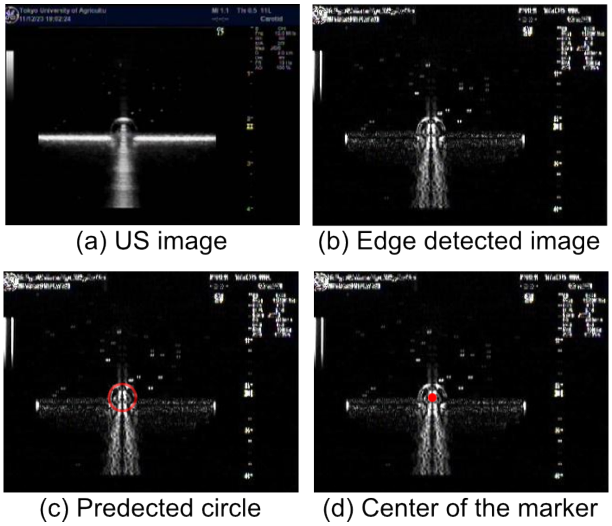

Fig. 6. Image processing to detect the center of the marker.

between the number of points.

TABLE II
CALIBRATION RESULTS (N=50)

Num.	x [mm]	y [mm]	z [mm]
10	-0.34 ± 1.02	-0.48 ± 0.49	-0.27 ± 0.99
50	-0.16 ± 1.01	-0.36 ± 0.50	-0.08 ± 0.98
100	0.32 ± 1.01	-0.26 ± 0.50	-0.11 ± 0.98

IV. CONCLUSIONS

In this study, we proposed that the US probe calibration method consisting of the phantom with a fiducial sphere and the pointer tool with the same sphere at the tip. The center of the marker can be determined by pivot motion. Also, the center can be detected easily in US images because comet-tail artifact is observed when the center is located on the image plane. Several geometrical phantoms have been reported, however some of them are difficult to implement the phantoms because of complex designs. The proposed phantom and tool is not complex structure, therefore the method is easy to implement and use.

Comparing with a wire phantom [4]–[9], measurement of the wire position in the US image is very difficult and inaccurate because the wire is not shown as a dot or circle. A tracked needle [10] has the same issue, detection of the tip position in an image is difficult. Our method addresses the issue by using the sphere fiducial that can be shown as circle in an image. Thus, the center of the sphere can be detected accurately. Meanwhile, the geometrical position of the wire or the cross-point of wires also has to be measured accurately. To measure the cross-point accurately, a cross-wire phantom with motion constraint was proposed [9]. In the phantom, the cross-wire is contained in a glass sphere, and the cross point can be measure by the rotation motion of the sphere since the cross point is located at the center of the sphere. Our phantom consisting of the sphere fiducial and the pointer tool provides more convenience to make the phantom with the same accuracy of phantom calibration.

As for the accuracy assessment, the accuracy of the phantom test is better than the simulation in 10 points calibration. A possible reason is that the given errors are greater than the actual errors. Particularly z, slice thickness direction errors were different between the simulation and the phantom test. That means that the sphere fiducial enables detect that it is located on the image plane accurately.

Meanwhile, the detection of the fiducial center has not been automated fully yet. Several methods for circle detection have been reported. We are planning to apply an algorithm of the following image processing for full automatic calibration; noise removal, edge detection, and circle detection. Moreover, the material of the fiducial should be considered for accurate and automatic processing. We are also planning to investigate the artifact and the performance of the circle detection by other fiducial markers made of different materials.

In conclusions, we proposed that the US probe calibration using a sphere fiducial and a pointer tool. The calibration accuracy was 0.65 mm in 10 points and 0.4 mm by 50 points. The results demonstrates that the proposed method has great potential for accurate and convenient US probe calibration.

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