Proceedings on Automation in Medical Engineering
Proc AUTOMED, 2026, Vol. 3, No 1, Article ID 2517, 2 Pages

Infinite Science Publishing

Fast and portable phantom-based calibration for freehand 3D ultrasound

L. Ahrend[1,2*], J. Götz[3], S. Beirami[1], N. Esmaeili[1] and J. Hagenah[1,4]

[1] *Center for Digital Surgery, Department of General, Visceral and Pediatric Surgery, Universitätsmedizin Göttingen (UMG), Göttingen, Germany*
[2] *Student of Medical Engineering Science, Universität zu Lübeck, Lübeck, Germany*
[3] *Department of Trauma, Orthopedic and Plastic Surgery, UMG, Göttingen, Germany*
[4] *Fraunhofer Research Institution for Individualized and Cell-based Medical Engineering, Lübeck, Germany*
[*] *Corresponding author, email: Larissa.Ahrend@med.uni-goettingen.de*

Abstract: Freehand 3D ultrasound enables volumetric reconstruction by determining the spatial transformation between a tracked probe and the image plane. Portable probes require frequent recalibration due to limited battery life, demanding a fast and practical calibration method. We present an approach using a dual-purpose phantom as both a tracking tool and imaging target. Optical tracking combined with ultrasound imaging of the calibration pins establishes 2D–3D correspondences for least-squares estimation of the image-to-probe transformation. Leave-one-out evaluation showed high accuracy, with errors below the scanner's resolution. Calibration accuracy is limited by the ultrasound slice thickness.

I. Introduction

Freehand 3D ultrasound is performed by manually sweeping a 2D ultrasound probe over the region of interest while the probe's spatial location and orientation is tracked, e.g. utilizing a position sensor. To correctly place the acquired 2D images within a 3D coordinate system, the spatial transformation between the tracked probe and the ultrasound image plane must be determined. This calibration process estimates the rigid transformation matrix that defines the position and orientation of the image plane relative to the probe's coordinate system. Once this transformation is known, the tracked 2D images can be accurately reconstructed into a consistent 3D volume [1].

While numerous calibration methods have been proposed in the literature [1], most are not well suited for portable freehand 3D ultrasound setups. For the VScan Air CL used here [2], the tracking sensor must be detached during charging, requiring repeated calibration. Although not all portable probes have this constraint, the portable nature of these systems generally demands a calibration procedure that is easy to transport and relies on minimal additional equipment at the acquisition site. Therefore, a simple and rapid calibration method is required to reliably provide the necessary transformation under these constraints.

II. Material and methods

The calibration process uses an ultrasound probe with a tracking tool and a novel dual-purpose phantom for both tracking and imaging (see Figure 1). We utilize an optical tracking system (Polaris Vega XT, Northern Digital Inc. [2]) attached to a portable probe (VScan Air CL, GE Healthcare [3]). This probe requires the sensor to be temporarily removed during charging. Each charge provides approximately 50 minutes of active scanning time [3], so a new calibration is needed after every patient scan.

II.I. Calibration Phantom

Since the calibration phantom needs to fulfill this dual purpose, its design must comply with the tool requirements of the Polaris Vega XT and lie within the field of view of the probe (selected depth of 24 cm). Six tracking markers were therefore positioned across the ultrasound plane (Figure 1). A marker is a small sphere with a reflective coating that returns the infrared light from the camera to the position sensor. The geometry of the tracking system requires the markers to be spaced at least 50 mm apart, with a minimum difference of 3.5 mm between all possible distances, to ensure reliable tracking [2].

The calibration phantom can be attached directly to the probe using the probe holder. Its design ensures that the imaging plane intersects the center of the markers, which align with the tops of the mounting pins. During position recording in world coordinates, the markers must be attached (Figure 1, left). In imaging, the non-waterproof markers are removed, exposing the pins (Figure 1, right). In the image plane, their smaller diameter (2.3 mm) compared to the tracking markers (11.8 mm) provides more precise calibration targets.

Figure 1: Calibration phantom. Left: top view of tracked ultrasound probe and detached phantom; Right: side view of the probe attached to the phantom, markers removed.

II.II. Calibration Process

The goal of the calibration process is to estimate T_{Calib}, which maps 2D image coordinates into the 3D probe coordinate system as it is seen from the tracking camera. The process consists of two steps. In the first step (Figure 2, left), the tracked probe and the calibration phantom are rigidly attached to each other. Both tools are simultaneously tracked by the Polaris Vega XT, which records the transformations from world to probe coordinates (T_{Probe}) and from world to phantom coordinates ($T_{Phantom}$). From this measurement, the fixed rigid transformation between the phantom and the probe ($T_{Fix} = {T_{Probe}}^{-1} T_{Phantom}$) is computed. The 3D coordinates of the six calibration pins are known from the phantom's CAD model. Using T_{Fix}, the coordinates of all calibration pins are transformed into the probe coordinate system. In the second step (Figure 2, right), the calibration phantom is imaged using the ultrasound device in a water bath after the tracking markers have been removed, which is possible because the rigid attachment ensures that the pin positions remain fixed in the probe coordinate system. The tops of the mounting pins are visible in the ultrasound image (Figure 3). Following the 30 s video recording, six frames are uniformly selected over the entire acquisition period. The tops of the pins are manually selected in each frame. For each pin the average pixel position is used. This yields a set of 2D–3D correspondences between $(i,j)_{Image}$ and $(x,y,z)_{Probe}$. Using all point pairs, the following affine mapping is estimated via a least-squares approach:

$$(x,y,z)^T = A\,(i,j)^T + t. \qquad (1)$$

The resulting homogeneous transformation matrix composed of A and t represents the final calibration.

III. Results and discussion

The calibration procedure was evaluated using a leave-one-out approach. To minimize the influence of point selection variability, the point selection and transformation calculation was repeated five times. The resulting distances between the selected pin top and its projected position had a mean of 0.68 mm with a standard deviation of 0.15 mm. The calibration errors remained smaller than the scanner's inherent resolution [3], confirming the method's high accuracy.

In the calibration process, the tops of the pins are assumed to lie at the center of the ultrasound image plane. To verify this assumption, larger cylinders were temporarily mounted

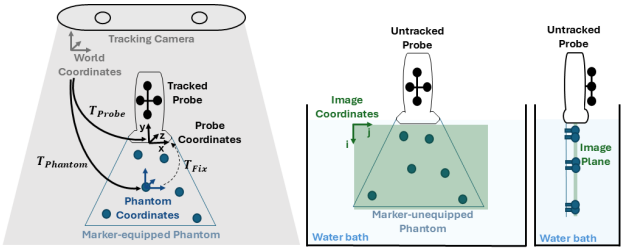

Figure 2: Calibration process consisting of two steps. Step 1 (left): Scanning the probe with the attached probe tool and calibration tool using the optical tracking system. Step 2 (right): Acquiring an untracked ultrasound scan of the phantom.

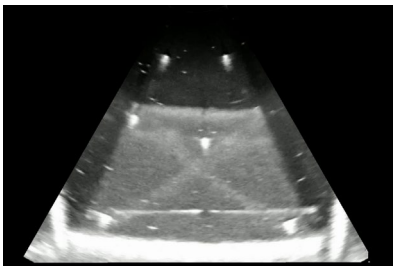

Figure 3: Ultrasound image of the calibration phantom.

on top of the pins. If both the larger cylinders and the original pins were visible in the image, the pin tops could be considered to lie within the image plane. This was consistently observed across three independent measurements. Assuming the pin tops lie at the center of the imaging plane is the main limitation of the calibration, as their exact in-plane position cannot be directly measured. Consequently, the calibration error is constrained by the slice thickness, which for the used transducer is approximately 1.8–2.1 mm [4].

Given the intended use case of the 3D ultrasound system, the calibration procedure prioritizes speed and practicality. The complete process, including retrieving the probe from the charger, attaching the tracking tool, mounting the calibration phantom, placing the tracking markers, recording the tracking data, connecting the probe to the application interface, acquiring the ultrasound video, selecting the pin tops, computing the transformation matrix, and removing the phantom, takes approximately 10 minutes in total. Notably, the ultrasound imaging requires only 30 seconds, which is roughly 1% of the probe's battery life. This shows that the method is sufficiently fast and feasible for repeated, on-site calibration between patient scans, supporting the intended portable workflow.

IV. Conclusions

We present a fast, practical calibration procedure for freehand 3D ultrasound using a tracked probe and a novel dual-purpose phantom. The method supports on-site calibration in portable workflows. Evaluation using a leave-one-out approach demonstrated high accuracy, with errors below the scanner's resolution. Future work will examine the resulting 3D reconstructions to determine whether the achieved calibration translates into high-quality volumetric imaging and to detect systematic errors not captured by the leave-one-out test. Additionally, automation of marker detection could be explored to reduce manual input and inter-operator variability.

Author's Statement

Research funding: This study was supported by the Ministry of Science and Culture (Ministerium für Wissenschaft und Kultur - MWK) of Lower Saxony (grant number ZN4094). Conflict of interest: Authors state no conflict of interest.

References

[1] C. Wu et al., "Automatic spatial calibration of freehand ultrasound probe with a multilayer N-wire phantom," Ultrasonics, vol. 128, p. 106862, 2023, doi: 10.1016/j.ultras.2022.106862.
[2] NDI., Polaris Tool Design Guide, 10005896 R04, Jan. 2025.
[3] GE Healthcare, VScan Air CL User Manual, 2025.
[4] H. J. Scholten et al., "Differences in ultrasound elevational beam width (slice thickness) between popular handheld devices," WFUMB Ultrasound Open, vol. 1, no. 2, p. 100009, 2023, doi: 10.1016/j.wfumbo.2023.100009.