Freehand ultrasound calibration: phantom versus tracked pointer

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ABSTRACT

PURPOSE: Ultrasound-guided tracked navigation requires spatial calibration between the ultrasound beam and the tracker. We examined the reproducibility and accuracy of two popular open source calibration methods[1] with a handheld linear ultrasound transducer. **METHODS**: A total of 10 calibrations were performed using (1) a double N-wire phantom with automatic image segmentation and registration; (2) and registration of landmark points collected with a tracked pointer. Reproducibility and accuracy were characterized by comparing the resulting transformation matrices, and by comparing ground truth landmark points. **RESULTS**: Transformation matrices calculated with an N-wire phantom showed a variance of X: 0.02 mm (in the direction of sound propagation), Y: 0.03 mm (in the direction of transducer elements) and Z: 0.21 mm (in the elevation direction). Transformation matrices obtained with tracked pointer showed a variance of X: 0.1 mm, Y: 0.10 mm and Z: 0.43 mm. Calibration accuracy was tested with ground truth cross wire points. The N-wire phantom provided a calibration with a distance from ground truth of X: 2.44 ± 1.44 mm, Y: 1.21 ± 0.88 mm, and Z: 1.12 ± 0.82 mm. Tracked pointer calibration had a distance from the ground truth of X: 0.23 ± 0.16 mm, Y: 0.62 ± 0.31 mm, and Z: 0.45 ± 0.33 mm. Distance from ground truth was significantly less ($p<0.01$) with the tracked pointer method in all directions. **CONCLUSION**: Calibration using a tracked pointer had a slightly greater variance; however it showed better accuracy over calibrations calculated with N-wire phantoms.

Keywords: Tracked ultrasound, calibration, wire phantom

1. INTRODUCTION

Freehand tracked ultrasound (US) imaging is an inexpensive, safe, non-invasive way to guide needle insertions during many different procedures, such as percutaneous biopsy and drug delivery (Chan *et al.* 2005). It requires an accurate and consistent spatial calibration between the tracking sensor and ultrasound beam. This calibration, which is specific to the US image and tracking field size, is essential for the accurate representation of the spatial relationship between the ultrasound image and the tracked tools required for the procedure.

1.1 Ultrasound Calibration Methods

Various calibration techniques have been proposed in the literature. Most calibration techniques require a specifically designed calibration phantom. Phantoms can range from single-bead and

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[1] Plus distribution website: https://www.assembla.com/spaces/plus/wiki and SlicerIGT distribution website: https://www.assembla.com/spaces/slicerigt/wiki

crosswire phantoms (Lindseth *et al*. 2003, Pranger R.W. *et al*. 1998), to multiple N-wire phantoms (Chen *et al*. 2009, Pagoulatos *et al*. 2001). A detailed review is available in Mercier *et al*. 2004. Calibration without a phantom has also been investigated (Muratore *et al*. 2001 and Boctor *et al.* 2006).

Double N-Wire Phantom Calibration

The double N-Wire phantom used during calibration is a variation of the stereotactic head frames originally used for neurological navigation with CT scans (Brown 1979). The double N-wire configuration intersects with the ultrasound beam in six locations. These intersection points define the spatial orientation of the plane intersecting with the phantom, and therefore the spatial orientation of the US beam. This information, along with the positioning of the US probe, defines the calibration transformation between the ultrasound image and the probe tracking sensor. Errors can arise when using these phantoms due to loosening of wires, inaccuracies in phantom manufacturing, altered speeds of sound in imaging mediums and inaccurate collection of images.

Tracked Pointer Calibration

Tracked pointer calibration does not require a phantom, and therefore removes the source of multiple errors. By not relying on a phantom this method is also more convenient for open source applications because it does not require the use of extra equipment. By tracking a pointer and linear US transducer, one can determine the position of a tracked pointer in both the tracker coordinate system and the image coordinate system. The calibration matrix can be calculated in a manner described in 2001 by Muratore *et al.* This generic and flexible calibration method may suffer from inconsistencies due to its reliance on the user in positioning and segmenting the pointer tip in the US beam.

1.2 Objectives

The purpose of this study was to compare the consistency and accuracy of calibration with N-wire phantom and tracked pointer, for the purpose of freehand ultrasound-guided needle navigation during spinal needle insertions. We only compared methods that are readily available as an open-source application.

2. METHODS

N-wire phantom calibration and calibration using a tracked pointer were performed. The resulting image-to-probe transforms were assessed by determining the variation in the transformation matrices produced by each technique, as well as the image tracking accuracy.

2.1 Equipment used

A SonixTouch (UltraSonix, Richmond, BC, Canada) US machine with a SonixGPS (UltraSonix) electromagnetic tracking system was used during all experimental procedures. The double N-wire phantom calibration method required the use of a hard plastic phantom containing two parallel "N" wires wired into its centre. The phantom was tracked with a fixed 8 mm electromagnetic position sensor. The calibration with a tracked pointer method used a bevelled tip needle with a diameter of

0.5mm. The needle contained an electromagnetic position sensor in its tip; the exact position of the needle tip was determined using multiple pivot calibrations, a priori. The N-wire phantom calibration and tracked pointer calibration were both performed in a room temperature water bath with a linear US probe using a depth of 55mm, the depth typically used during spinal needle insertions. The imaging software of the US machine was adjusted to the sound velocity of room temperature water, so the images were not geometrically distorted.

2.2 Calibration with a double N-wire phantom

A double N-wire calibration phantom (Chen *et al*. 2009) with a distance of 10 mm between the "N" wires was used. In a previous experiment, it was found that a 10 mm distance provided the most consistent and accurate calibration. The N-wire phantom was used for a total of 5 calibrations, using an image depth of 55 mm, which is the typical depth for spinal needle insertions. The calibrations were calculated using an automatic segmentation and pattern registration algorithm (Chen *et al*. 2009).

2.3 Calibration with a tracked pointer

Five calibrations were calculated using the phantom-free method with tracked pointer (Muratore *et al*. 2001). A tracked pointer was imaged in the plane of a tracked linear US transducer (Figure 1). The coordinates of the tracked pointer tip and the US probe were recorded 20 times, placing the tracked pointer at the positions shown in Figure 2. The tracked pointer tip positions were distributed so that gravity center of the tracked pointer tip positions corresponded to the center of the anticipated target zone, the area of the US image in which greatest accuracy is needed. The tracked pointer tip positions were also distributed to give a wide variety of positions, while still being distributed evenly and symmetrically. The tracked pointer tip was manually picked from the US image and a similarity registration between the tracker and image coordinate systems was computed (Horn *et al*. 1987). The similarity registration produced the required transformation matrix and the root-mean-squares error for the registration.

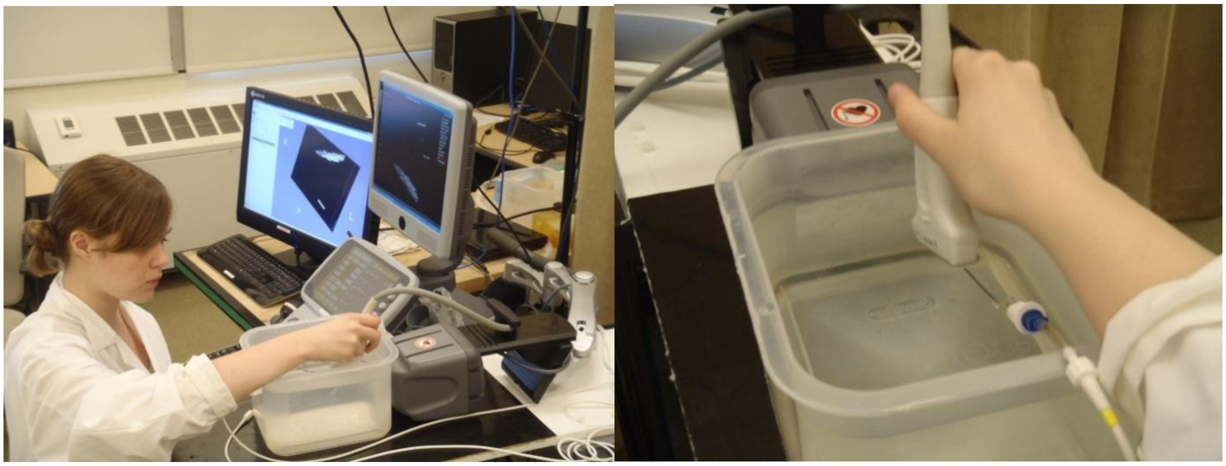

Figure 1. Calibration with tracked pointer: experimental system setup (left) and placement of the tracked pointer in the linear US beam (right).

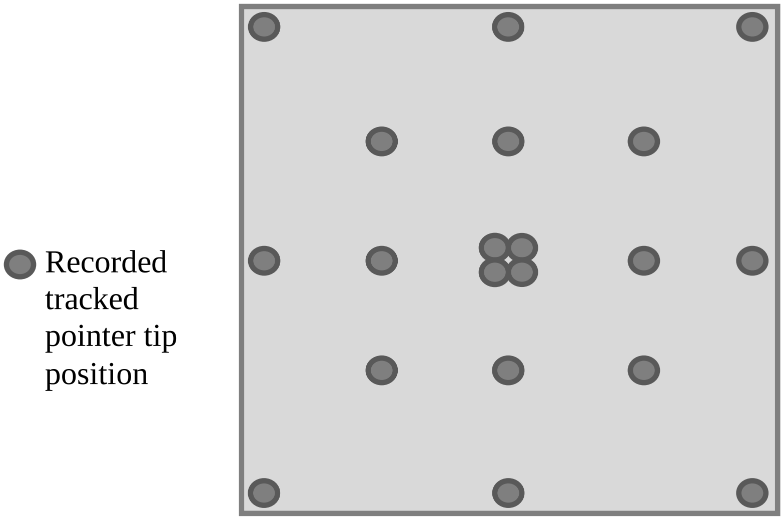

Figure 2. Approximate tracked pointer tip positions recorded during calibration with a tracked pointer.

2.4 Evaluation of variance

For both calibration methods, the variance was calculated by comparing a set of known landmark points transformed by each calibration matrix. The points used defined the corners of the US image at a depth of 55 mm. We repeated the transformation of the landmark points 5 times using different US transducer positions. The average squared distance of the points from their mean was considered the variance within the given set of transformations.

2.5 Evaluation of accuracy

In order to evaluate the accuracy of the calibrations, the transformation matrices with the least amount of error were used for testing the accuracy. A cross wire phantom, with a known (ground truth) wire cross position was used. A total of 20 images were collected with both calibration transformation matrices at a variety of different probe positions. The imaged position of the wire cross was then compared to the ground truth wire cross position in the coordinate system of the probe tracking sensor. The average distance between corresponding points was computed as the error.

3. RESULTS

The calibration variance with the double N-wire phantom was lower than with the tracked pointer as shown in Figure 3 (X: 0.02 mm, Y: 0.03 mm and Z: 0.21 mm versus X: 0.10 mm, Y: 0.07 mm, and Z: 0.43 mm).

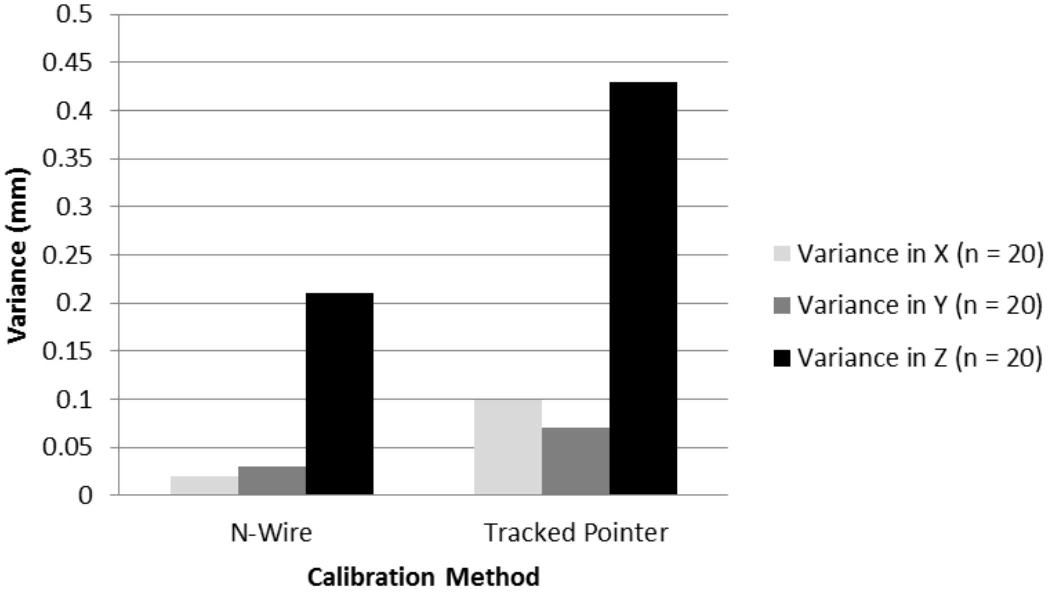

Figure 3. Comparison of variance in X, Y, and Z for both calibration methods.

The accuracy, defined as the distance between an imaged point and its ground truth point, was found to be X: 2.44 ± 1.44 mm, Y: 1.21 ± 0.88 mm, and Z: 1.12 ± 0.82 mm (average ± SD) with the N-wire phantom. The accuracy for calibration with tracked pointer was X: 0.23 ± 0.16 mm, Y: 0.62 ± 0.31 mm, and Z: 0.45 ± 0.33 mm. Figure 4 shows the average distance between the ground truth points and the imaged points in millimetres. Independent samples T-test revealed significantly less (p<0.01) distance from the ground truth with the tracked pointer method in all directions.

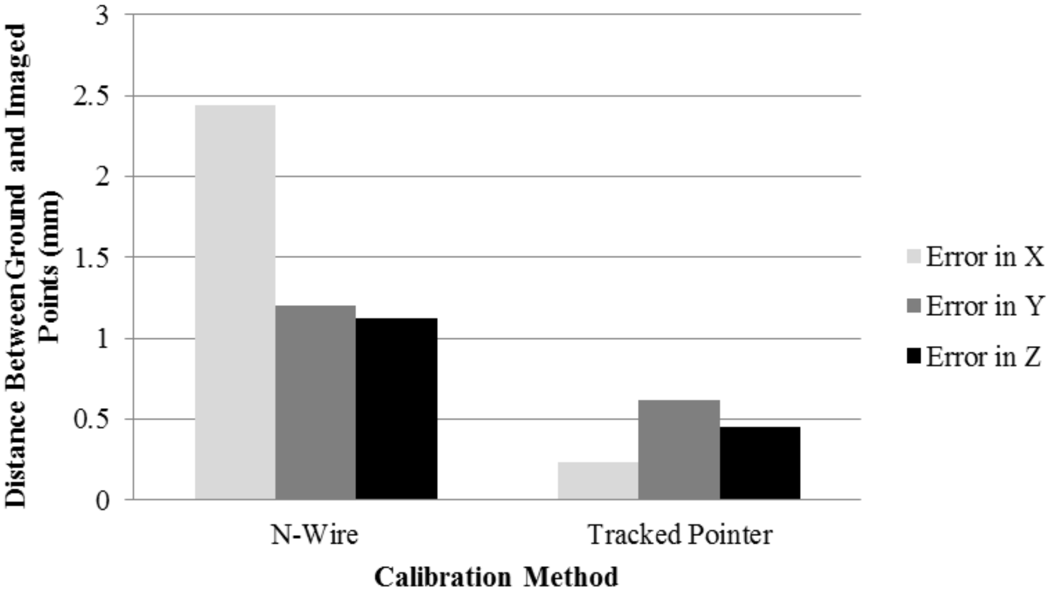

Figure 4. Average distance between ground truth and imaged points for both calibration matrices.

4. DISCUSSION

4.1 Variance Comparison

The greater variance seen during tracked pointer calibration may be related to various issues regarding calibration point collection. The number of points collected during each calibration for a tracked pointer calibration varies between 5 and 20 points, and their distribution and placement is determined by the operator. As opposed to the double N-wire phantom calibration which uses 1200 optimally placed and distributed points. During point collection for the tracked pointer calibration it is possible that the points are not distributed evenly and symmetrically around the target zone, whose centre of gravity should be in the centre of the collected points. We also know that the ultrasound beam has a thickness of several millimetres and that the thickness varies with depth. This means that the operator may fail to place the tracked pointer in the centre of the beam. However, these issues do not arise when using the N-wire phantom because the positioning and distribution of the points are predetermined based on the wire placements within the phantom. This ensures that the points collected are optimal and lead us to assume that the number, placement, and distribution of the points greatly affect the consistency of the resulting calibration.

4.2 Accuracy Comparison

The accuracies reported here show that the tracked pointer method of calibration is significantly more accurate than the double N-wire phantom method of calibration. Although manual picking of the tracked points is not as precise as the automatic segmentation of N-wires, the tracked pointer method involves less workflow steps for error propagation. The N-wire phantom may have geometry inaccuracies for different reasons. Systematic errors involving the geometry of all wires remain undetected during N-wire calibration, since the algorithm uses similar images for validation to what it uses for calibration. Phantom manufacturing and tracking registration of the phantom is not involved in the pointer-based method, so errors of these do not affect the final accuracy.

4.3 Tool Comparison

Calibrations performed using tracked pointers are also advantageous because, unlike double N-wire calibrations, they do not use single purpose equipment. The calibration phantom used during double N-wire calibration is only used for calibration, whereas the tracked pointer used in this experiment was a needle with an attached EM sensor which could easily be used for multiple purposes. Furthermore, decreasing the amount of highly specific pieces of equipment needed increases the ability of other researchers to reproduce these results for experimentation.

The software platform used in the experiment is open-source. The Public software Library for UltraSound imaging research (PLUS) is a software package containing functions and applications for tracked ultrasound acquisition, calibration, and processing. On the PLUS website, users can download source code, released applications, documentation, example configurations, and models for rapid prototyping phantoms. PLUS also provides a server application (PlusServer) to stream tracking and imaging information to 3D Slicer. All software modules we used in 3D Slicer are accessible through the Extension Manager of 3D Slicer.

In addition, use of a tracked pointer instead of a calibration phantom reduces the cost of the calibration method, as a tracked pointer is a relatively simple instrument to produce if a tracked needle is not required for other experimentation, as opposed to a phantom with highly specific features. Reducing the cost of materials and equipment needed to replicate a procedure also assists in increasing the reproducibility of the method for further research.

In conclusion, calibration with a tracked pointer had a slightly greater variance, but it showed greater accuracy over calibration with N-wire phantoms. Also of importance, calibration with the tracked pointer is flexible with respect to transducer size and ultrasound imaging parameter settings. Its ability to be performed without special equipment appeals to open source turn-key applications due to its decreased complexity and price. In freehand tracked ultrasound-guided needle navigation systems, despite its reliance on the operator, calibration with tracked pointer is preferable over calibration with N-wire phantoms.

5. ACKNOWLEDGMENTS

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