Intraoperative Ultrasound Probe Calibration in 
a Sterile Environment

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Abstract. Strict sterility requirements impose restrictions on the type 
of equipment and its handling in an operating room (OR). This paper 
proposes three methods for intraoperative calibration of a tracked ultrasound 
probe under sterile conditions. We categorically call these methods 
air calibration to contrast them with the common phantom-based cali-
bration methods that employ a coupling medium (e.g., a water-bath). 
The methods each consist of a preoperative and an intraoperative cali-
bration stage. The preoperative stage is performed once in a non-sterile 
environment where any of the existing calibration methods can be used. 
The intraoperative stage is performed before each intervention in the 
OR. To minimize impact on the interventional work-flow, we required 
that the intraoperative calibration took less than 10 minutes, produced 
a robust result and was easy to perform.

1 Introduction

We have developed and demonstrated navigation systems for laparoscopic [1, 2] 
and endoscopic [3] transgastric interventions. The system has been validated in 
vivo on porcine models with a non-survival protocol [4] where sterility of the 
operating room (OR) is not a requirement. In moving from porcine to human 
subjects, sterility of the experimental equipment became a primary concern. This 
imposed limitations on the type of equipment and its handling in the sterile field 
(and during the disinfection process for endoscopy). As we have found, introduc-
tion of new material and practices into an OR is complex; it requires extensive 
iterative development of appropriate protocols and eventual certification. The 
process can postpone experiments for months. In this paper, we discuss one spe-
cific challenge that we encountered with the calibration of ultrasound and new 
methods that were devised around these practical limitations.

The navigation system consists of a laparoscopic ultrasound (LUS) or an 
endoscopic ultrasound (EUS) probe. An electromagnetic (EM) sensor (Ascension 
Technology) is attached close to the transducer on the probe where the relative 
position of the sensor w.r.t. the ultrasound plane can be maintained. In our

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prior porcine experiments, we used Polyolefin tubes (shrink wrap) to secure the EM sensor. We then performed a standard single-wall phantom calibration [5] in a water-bath prior to the operation. The calibration procedure need not be repeated as long as the EM sensor is not removed.

In human subjects, however, there is a concern that biological sediments may not be properly removed by the disinfection or sterilization process, if the sensor is not detached from the instrument. This means that the EM sensor may not be configured permanently, but rather is attached after the components are sterilized separately and supplied in the sterile field of the OR. As such, there is a need for intraoperative calibration of the instrument in the sterile field.

An intraoperative calibration method has been proposed by Chen et al. in [6], who designed a double-N phantom that can be disassembled for sterilization and reassembled for the operation. Sub-millimeter accuracy is reported in conjunction with an optical tracking system.

There are good arguments against ultrasound calibration in the OR with phantoms and liquids. Sterilization, phantom construction, and phantom assembly issues aside, accurate calibration is time-consuming and a delicate task. For example, correction for the speed of sound [7] may involve controlling the water temperature or creating water-glycerol or water-ethanol solutions. The more complicated an engineering solution, the less likely it is to be integrated into a clinical work-flow.

A phantom-less method for quality-control of calibration parameters is given by Boctor et al. [8]. The method can recover a sub-set of calibration parameters. In [9], Wein and Khamene propose a method that employs spatial consistency of two orthogonal freehand ultrasound sweeps of a region of interest to determine calibration parameters. The method is suitable for transcutaneous ultrasound probes and cannot be readily applied to the calibration of endoscopic or laparoscopic ultrasound.

2 Air Calibration

We propose three calibration methods (Mold Calibration, Funnel Calibration, and the Closest Point Calibration) that do not involve use of a phantom or a coupling medium (such as a water-bath) and can be performed easily by technicians in the OR. The third method has the added advantage that it uses only material already available in the OR and thus does not require an approval process. We categorically call these techniques air calibration methods.

These methods partition the process into preoperative and intraoperative calibration steps. Preoperatively, the ultrasound probe can be calibrated using any phantom-based method such as the single-wall phantom, Cambridge phantom, 3-wire phantom [5], or Hopkins phantom [10]. In a conventional calibration setup the following coordinate systems are defined, the tracker (world) coordinates $C_T$, the sensor coordinates $C_S$, and the ultrasound image coordinates $C_U$ as shown in Fig. 1(a). The conventional calibration problem determines $^S T_U$ the transformation matrix from the ultrasound image’s coordinate system to the sensor’s coordinate system.
For air calibration, we introduce an extra coordinate system \( (C_F) \) whose position remains fixed w.r.t. the ultrasound transducer. This coordinate system is attached to a physical (mold and funnel calibration) or virtual (the closest point calibration) object that maintains its relative position to the ultrasound plane.

We postulate that we can specify a stable coordinate system that remains fixed w.r.t. to the ultrasound coordinate system. The transformation matrix from the ultrasound plane to this coordinate system is denoted by \( F_T^U \). The purpose of the preoperative calibration is to determine this transformation. We first perform a conventional calibration and determine \( S_T^U \). Then, the position of \( C_F \) is determined w.r.t. the tracker \( (T_T^F = F_T^U^{-1}) \) and we can now determine \( F_T^U \) based on known relationships

\[
F_T^U = F_T^T T_T^T S_T^U. \tag{1}
\]

During the intraoperative phase, the position of the EM sensor has changed (the sensor has been detached and reinstalled) and \( S_T^U \) from the preoperative stage is no longer valid and a new calibration is required. The intraoperative calibration stage consists of measuring the position of \( C_F \) w.r.t. the tracker with the same method used in the preoperative step to determine \( T_T^F \) and then compute the calibration matrix \( S_T^U \) using known matrices

\[
S_T^U = T_T^S F_T^{-1} F_T^U. \tag{2}
\]

So far we have not been specific in setting the fixed coordinate system and its position and orientation in the coordinate frame of the tracking device. In the next sections, we discuss three air calibration methods to achieve this. The first two that require a device to be built are briefly discussed; the third method that uses point-to-surface registration will be explained in detail.
2.1 Mold Calibration

The tip of the ultrasound probe is cast to create a mold. We built a mold that fits the inflexible tip of the ultrasound probe. The asymmetries in the probe’s shape ensure that the probe fits in the mold in a unique position. A second sensor is attached to the exterior of the mold. During the preoperative calibration stage, the ultrasound plane is calibrated relative to the mold sensor. The position of the mold sensor defines our fixed coordinate system, as the sensor does not have to be removed for sterilization (it does not directly touch the probe). During the intraoperative phase, a sensor is also attached to the probe and the probe is inserted in the mold. Probe calibration matrix is then computed using (2).

2.2 Funnel Calibration

This method is a variation of the mold calibration process, in which the mold is built with a sharp pointed end, like a funnel. Preoperatively, the ultrasound plane is calibrated against the tip of the funnel in a manner similar to calibration of a stylus. Since the position of the funnel tip does not change w.r.t. the ultrasound plane, the same process can be repeated intraoperatively to recover the calibration matrix. The funnel calibration requires a single sensor.

2.3 Closest Point Calibration

The previous methods require purpose-built appliances. Even when the appliances are built using approved material and are sterilizable, they must pass the approval process before they can be used. To further simplify the calibration process, we developed a third method that relies solely on material and devices already approved for use in the OR.

We use the same principle that the ultrasound probe must be calibrated w.r.t. a fixed point in space in relation to the ultrasound plane. We then create a model of the ultrasound probe by imaging the probe in a CT scanner and extracting a surface model by segmenting the image. Fig. 1(b) shows a laparoscopic probe and the surface model of its tip derived from a CT scan of the probe. Three easy-to-identify landmarks (e.g. for laparoscopic probe: tip of the probe, entrance of the biopsy channel and lower exit of biopsy channel) are approximately identified in the model. The user is later instructed to touch these landmarks to initialize the registration process. We inserted a needle in the biopsy channel to give the model more spatial extent. We segmented the needle and the probe separately. The model with the needle inserted is used to guide the registration algorithm in the initial phase of the calibration process.

Preoperative Calibration: The preoperative calibration involves a calibration phantom, two EM sensors, and the probe to be calibrated. One of the sensors is mounted on the probe and the second one is used to scan the surface of the probe. In addition to the coordinate systems defined at the beginning of Section 2 we also have the coordinate system of the scanning sensor which we denote by $C_S$. The fixed coordinate system $C_F$, in this setup is defined at an arbitrary (but fixed) position in the segmented CT volume.
We first determine the calibration matrix between the probe sensor and the ultrasound plane $S_U$ using the single-wall phantom. We then scan the surface of the probe by moving the second sensor slowly against the surface of the probe. The scanning sensor is attached to a stylus for easy handling.

The precise location of the coordinate system attached to the scanning sensor is not known. The offset between the location of the coordinate system and the tip of the sensor can be described by a translation. The position of the tip of the sensor $x_t$ based on the sensor measurements $x_s'$ is given by

$$x_t = x_s' + [v_x \ v_y \ v_z]^T,$$  \hspace{1cm} (3)

where the unknown translation vector $v = [v_x \ v_y \ v_z]^T$ is computed as part of our calibration/registration process.

The set of points measured on the surface of the probe $\{x_t\}$ are related to corresponding surface points in the model $\{x_m\}$ by a rigid transformation. The iterative closest point (ICP) algorithm can be used to register the two point sets as long as $v$ is given. The adaptation of ICP to solve for $v$ in addition to the rigid registration parameters is not trivial. One could install the sensor on a stylus and calibrate the stylus to retrieve $v$. We did not find this option convenient nor particular helpful for overall accuracy. The error is further compounded by the stylus calibration. Alternatively, we solve for $v$ and the rigid registration together using a 9-parameter local optimization algorithm with a closest point cost function (a suitable optimization algorithm such as Powell, Simplex, or Gradient Descent variants can be used). The outcome of the closest point optimization is the transformation matrix from the tracker coordinates to the model (fixed) coordinates $F_T$. We also measure the position of the sensor attached to the probe and can now compute $F_T$ using (1). Note that the probe must remain stationary during the scanning process for this method to work. However, it is more convenient to have the flexibility to move the probe to gain access to the surface. The ability to move the probe has the added advantage that one does not have to worry about securing the probe in position and errors due to pressure against the tip of the probe which may cause small movements. To this end, we record the position of the scanning sensor and the probe sensor simultaneously, and compute the position of the surface points in the coordinate system of the probe sensor:

$$x_s = T_{S}^{-1} x_t$$  \hspace{1cm} (4)

Using $\{x_s\}$ instead of $\{x_t\}$ means that the outcome of the registration process is $F_T$ and (1) can be simplified to

$$F_T = F_S S_U.$$  \hspace{1cm} (5)

**Intraoperative Calibration:** The intraoperative calibration involves two EM sensors and the probe to be calibrated. The calibration process is similar to the preoperative calibration except that no phantom-based calibration is involved. The surface of the probe is scanned using a sensor and the resulting object
measurements are registered against the model to determine $F_T S$, as before. Since $F_T U$ is known, the calibration matrix is computed using:

$$S_T U = F_T S^{-1} F_T U.$$  \hspace{1cm} (6)

**Object to Model Registration:** To ensure convergence, a three-stage registration is performed for object to model registration. Each stage is designed to improve the registration accuracy and is initialized from the solution returned by the previous stage.

1. **3-point registration:** the user is requested to identify 3 previously selected landmarks in a pre-defined order by touching the corresponding points on the object by the sensor. An approximate rigid transformation from the object to the model is computed and used for initializing the registration optimization algorithm.

2. **9-parameter registration - initial:** a 9-parameter registration consisting of rigid object-to-model alignment parameters (6 parameters) and position of the sensor’s tip in the coordinate system of the sensor (3 parameters) is performed. The results are used to initialize the next registration stage.

3. **9-parameter registration - final:** data points that belong to the needle are removed from both the object samples and the model and a constrained 9-parameter optimization is performed to determine the registration parameters more accurately.

Fig. 2 illustrates incremental improvement in registration of a point of clouds measured from the surface of a laparoscopic probe (shown in red) to a model of the probe (shown in blue). Fig. 2(b) shows the result of a 6-parameter registration which does not include the calibration parameters of the sensor. This is shown for comparison with 9-parameter registrations only and is not part of our registration algorithm.

### 3 Results

An LUS probe was calibrated preoperatively using the single-wall phantom. The probe was then registered to its 3D segmented model to compute the calibration matrix w.r.t. a fixed point in the model. For the intraoperative calibration we used a different sensor which was placed at a different location on the surface of the probe. The calibration was determined by the closest point calibration algorithm. Table 1 shows air calibration precision for 6 experiments. The first three rows show the mean registration error for each registration step. The registration error is reduced by each step. To validate the air calibration method, the intraoperative sensor was also independently calibrated using the single-wall phantom so that the air calibration results can be compared with the single-wall phantom. Single-wall calibration was also performed several times. The results are summarized in Table 2. The precision of the calibration methods was computed for a point in the center of the ultrasound image. This makes sense as the operators tend to keep objects of interests in the center of the field of view. We also report the preoperative calibration precision with the single-wall phantom for completeness.
Fig. 2. Incremental improvement in the alignment of a scanned probe (red cloud) with the model (blue): (a) the registration is initialized with a 3-point rigid alignment first; (b) a 6-parameter registration is unable to register the point cloud to the surface of the model due to the distance of the origin of the sensor’s coordinate system from its tip, (c) a 9-parameter optimization algorithm retrieves rigid registration parameters together with the sensor’s calibration, (d) starting from the results of the previous run, a second 9-parameter optimization is performed with the needle points removed for improved alignment.

4 Discussion

This study demonstrates a fast, easy-to-use method for instrument calibration suitable for intraoperative use. It uses equipment and material already available in the OR. Our experiments were not directed toward reconstruction of 3D freehand ultrasound volumes but with approximate alignment of the B-mode ultrasound with a preoperative CT. The reformatted CT were shown side-by-side with the ultrasound stream to provide anatomical context for interpreting the ultrasound and improving the navigation of laparoscopic and endoscopic ultrasound [3]. For this application, the highest calibration accuracy was not the primary concern and we limited ourselves to qualitative assessment of the resulting calibration. It will be interesting to investigate the limits of the proposed methods for freehand ultrasound and to provide accuracy results in addition to precision in the future work. Single-wall phantom preoperative calibration is easy to perform but not the most accurate method. We expect the overall precision and accuracy to improve with a better preoperative calibration method.
Table 1. Registration error and the calibration precision for a number of experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean reg. err. (step 1)</td>
<td>2.14</td>
<td>1.60</td>
<td>1.97</td>
<td>3.20</td>
<td>1.88</td>
<td>2.81</td>
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<tr>
<td>Mean reg. err. (step 2)</td>
<td>0.53</td>
<td>0.48</td>
<td>0.59</td>
<td>0.60</td>
<td>0.81</td>
<td>0.64</td>
</tr>
<tr>
<td>Mean reg. err. (step 3)</td>
<td>0.50</td>
<td>0.48</td>
<td>0.59</td>
<td>0.54</td>
<td>0.73</td>
<td>0.63</td>
</tr>
<tr>
<td>Air calibration error</td>
<td>2.07</td>
<td>2.33</td>
<td>0.37</td>
<td>2.18</td>
<td>2.27</td>
<td>2.20</td>
</tr>
</tbody>
</table>

Table 2. Precision of the single-wall phantom and the closest point calibration methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Err. Mean</th>
<th>Err. Std</th>
<th>Err. Min</th>
<th>Err. Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall-phantom calib., pre-op. sensor</td>
<td>1.26 mm</td>
<td>0.44 mm</td>
<td>0.79 mm</td>
<td>1.85 mm</td>
</tr>
<tr>
<td>Wall-phantom calib., intra-op sensor</td>
<td>1.17 mm</td>
<td>0.40 mm</td>
<td>0.66 mm</td>
<td>1.71 mm</td>
</tr>
<tr>
<td>Air calib., intra-op sensor</td>
<td>1.90 mm</td>
<td>0.76 mm</td>
<td>0.37 mm</td>
<td>2.33 mm</td>
</tr>
</tbody>
</table>

References