Ultrasound in Med. & Biol., Vol. 41, No. 4, pp. 1079–1094, 2015

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2014.11.020

● Original Contribution

A CLOSED-FORM DIFFERENTIAL FORMULATION FOR ULTRASOUND SPATIAL CALIBRATION: SINGLE WALL PHANTOM

Mohammad Najafi,* Narges Afsham,* Purang Abolmaesumi,* and Robert Rohling*†
*Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada; and †Department of Mechanical Engineering, University of British Columbia, Vancouver, British Columbia, Canada

(*Received* 23 *May* 2014; *revised* 17 *October* 2014; *in final form* 25 *November* 2014)

Abstract—Calibration is essential in freehand 3-D ultrasound to find the spatial transformation from the image coordinates to the sensor coordinate system. Ease of use, simplicity, precision and accuracy are among the most important factors in ultrasound calibration, especially when aiming to make calibration more reliable for day-to-day clinical use. We introduce a new mathematical framework for the simple and popular single-wall calibration phantom with a plane equation pre-determination step and the use of differential measurements to obtain accurate measurements. The proposed method provides a novel solution for ultrasound calibration that is accurate and easy to perform. This method is applicable to both radiofrequency (RF) and B-mode data, and both linear and curvilinear transducers. For a linear L14-5 transducer, the point reconstruction accuracy (PRA) of reconstructing 370 points is 0.73 ± 0.23 mm using 100 RF images, whereas the triple N-wire PRA is 0.67 ± 0.20 mm using 100 B-mode images. For a curvilinear C5-2 transducer, the PRA using the proposed method is 0.86 ± 0.28 mm on 400 points using 100 RF images, whereas N-wire calibration gives a PRA of 0.80 ± 0.46 mm using 100 B-mode images. Therefore, the accuracy of the proposed variation of the single-wall method using RF data is practically similar to the N-wire method while offering a simpler phantom with no need for accurate design and construction. (E-mail: rohling@ece.ubc.ca) © 2015 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Ultrasound, Calibration, Closed form, Single wall, Differential.**

INTRODUCTION

Ultrasound is a tolerable, portable, inexpensive and real-time modality that can produce 2-D and 3-D images, and therefore, it is a valuable intra-operative imaging modality to guide surgeons aiming to achieve higher accuracy in the intervention and improve patient outcomes. Specifically, there has been a surge of interest in integrating ultrasound imaging into a number of clinical procedures, such as laparoscopic procedures (Nakamoto et al. 2008), minimally invasive cardiac surgeries and therapies (Huang et al. 2010), spinal fusion surgeries (Yan et al. 2011), orthopedic surgeries (Paulius et al. 2008; Peters et al. 2010), guidance for breast biopsy (Cosio et al. 2010), tumor resection (Krekel et al. 2011), brain neurosurgery (Unsgård, 2009) and radiation therapy (Chinnaiyan et al. 2003).

In many such clinical procedures, there is a benefit in tracking the spatial location of the transducer while sweeping over the anatomy of interest. This "freehand" 3-D ultrasound imaging approach can be used for visualization and quantitative measurements such as 3-D locations, sizes and volumes of anatomic structures. Also, by tracking an ultrasound transducer, multiple ultrasound data sets can be mapped into the same coordinate system to construct larger volumes with an extended field of view. Ultrasound with positional information also facilitates registration to complementary image modalities such as magnetic resonance imaging (Melvær et al. 2012). In some applications, laparoscopic, biopsy and surgical tools are also tracked, and their positions should be converted to a common coordinate system as the ultrasound images. Augmented reality is yet another application that can benefit from tracked ultrasound transducers.

The accuracy of freehand-tracked ultrasound is an important factor in the overall accuracy of the aforementioned procedures (Peterhans et al. 2010). In many cases, high accuracy results in numerous clinical benefits. For example, intra-operative ultrasound imaging of the vertebrae, combined with automated registration to

---

Address correspondence to: Robert Rohling, Department of Electrical and Computer Engineering, University of British Columbia, 3059-2332 Main Mall, Vancouver, BC, V6T 1Z4, Canada. E-mail: rohling@ece.ubc.ca

pre-operative computed tomography, could improve spine surgery by improving accuracy, reducing operative time and decreasing invasiveness. The resulting benefits include lower surgical risk, increased possibility of performing more complex instrumentation, decreased post-operative complications, more confidence in the surgical procedures and better post-operative function (Yan et al. 2011). In performing neuronavigation based on intra-operative 3-D ultrasound, precise surgical planning and intervention are possible, resulting in the reduction of residual tumor volumes, reduced operation times and better patient outcomes (Lindseth et al. 2002). In ultrasound-guided liver tumor resection, the surgeon relies on ultrasound volumes for accurate orientation with respect to the tumor. High accuracy is needed to provide tumor-free resection margins and to preserve vessels close to the tumor (Gulati et al. 2009). For a breast tumor biopsy, the needle tip should be accurately located inside several positions of the tumor (Cosio et al. 2010). In real-time visualization of high-intensity focused ultrasound for prostate cancer treatment with 3-D ultrasound, precise knowledge of the size and location of the tumor and the treated areas can improve the outcome (Rouvire et al. 2007).

In all the clinical applications that use freehand-tracked ultrasound to reconstruct 3-D ultrasound volumes, such as those examples cited above, the challenge is to precisely locate the ultrasound image pixels with respect to a tracking sensor on the transducer. In a process called spatial calibration, the spatial transformation between the ultrasound image coordinates and the transducer's coordinate system is determined.

Many methods have been proposed for ultrasound calibration over the last two decades. Most methods are based on imaging an artificial object with known geometric parameters called a phantom. To calculate the calibration parameters, the phantom geometry, the ultrasound image features and usually a mathematical model are used. Calibration methods can thus be categorized according to the phantom shape.

Point-based phantoms can be constructed as a bead (Amin et al. 2001; Detmer et al. 1994), crossed-wires (Melvær et al. 2012; Trobaugh et al. 1994; Yaniv et al. 2011) or the center of a sphere (Brendel et al. 2004). Wire-based phantoms usually have N- or Z-shaped patterns, but other configurations can also be used (Boctor et al. 2004; Chen et al. 2009; Hsu et al. 2008b; Pagoulatos et al. 2001; Peterhans et al. 2010). The method of Chen et al. (2009) is used in the open-source PLUS ultrasound software employed by several research groups (Lasso et al. 2012). In plane-based methods, the phantom can be a fixed plane, as in the single-wall method (Najafi et al. 2012b; Prager et al. 1998; Yaniv et al. 2011) or its variant the Cambridge phantom (Prager et al. 1998), or multiple planes (Najafi et al. 2012a). Another approach is based on registration of 2-D ultrasound images with the 3-D model of the phantom (Bergmeir et al. 2009; Blackall et al. 2000; Lange et al. 2011). Some calibration methods do not require a phantom and use a calibrated stylus (Hsu et al. 2008a; Khamene and Sauer 2005; Muratore and Galloway 2001) or use changes in speckle from transducer movements (Boctor et al. 2006).

Calibration methods can also be categorized according to their mathematical solution technique. Some of the calibration methods solve the calibration parameters by iteratively minimizing a cost function based on the mathematical geometry of the problem (Detmer et al. 1994; Melvær et al. 2012; Prager et al. 1998). Iterative methods are subject to suboptimal local minima and are sensitive to initial estimates; therefore, they are less robust in general than closed-form solutions (Eggert et al. 1997). Some methods use a closed-form solution derived from the geometry of the phantom to determine calibration parameters (Boctor et al. 2004; Chen et al. 2009; Najafi et al. 2012b). Not all methods use a mathematical solver to calculate calibration parameters. For example, there are methods that are based on iterative manual alignment of the ultrasound image with a thin planar phantom (Gee et al. 2005; Lindseth et al. 2003). Detailed reviews, comparison of different calibration methods and a summary of various validation techniques can be found in survey papers (Hsu et al. 2009; Mercier et al. 2005).

Ease of use, simplicity, precision (repeatability) and accuracy are among the most important factors in ultrasound calibration, especially when the aim is to make calibration more reliable for day-to-day clinical use. Phantoms that must be built with a specific geometry, or from specific material, or with a specific scanning or alignment protocol or phantoms that use complicated segmentation or registration algorithms are barriers to simplicity and ease of use for a user. The single-wall method uses perhaps the simplest phantom among other calibration methods. It merely requires a planar object such as the flat bottom surface of the water tank. Such a phantom is part of the popular Stradwin freehand ultrasound system freely available and used by many research groups (Prager et al. 1999).

One of the most important limiting factors in increasing the accuracy of calibration is accurate, absolute localization of phantom features in ultrasound images (Lange et al. 2011). One reason for this is the blurry appearance of features resulting from the finite resolution of the ultrasound images and the presence of noise. Moreover, image formation errors arise from speed of sound variations, refraction and a finite beam width, all of which contribute to distortions in the shape of the depicted features.