Medical Image Analysis 19 (2015) 30–45

Contents lists available at ScienceDirect

Medical Image Analysis

journal homepage: www.elsevier.com/locate/media

Persistent and automatic intraoperative 3D digitization of surfaces under dynamic magnifications of an operating microscope

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ARTICLE INFO

Article history:
Received 28 October 2013
Received in revised form 22 July 2014
Accepted 23 July 2014
Available online 7 August 2014

Keywords:
Operating microscope
Magnification
Stereovision
Intraoperative digitization
Surface reconstruction

ABSTRACT

One of the major challenges impeding advancement in image-guided surgical (IGS) systems is the soft-tissue deformation during surgical procedures. These deformations reduce the utility of the patient's preoperative images and may produce inaccuracies in the application of preoperative surgical plans. Solutions to compensate for the tissue deformations include the acquisition of intraoperative tomographic images of the whole organ for direct displacement measurement and techniques that combines intraoperative organ surface measurements with computational biomechanical models to predict subsurface displacements. The later solution has the advantage of being less expensive and amenable to surgical workflow. Several modalities such as textured laser scanners, conoscopic holography, and stereo-pair cameras have been proposed for the intraoperative 3D estimation of organ surfaces to drive patient-specific biomechanical models for the intraoperative update of preoperative images. Though each modality has its respective advantages and disadvantages, stereo-pair camera approaches used within a standard operating microscope is the focus of this article. A new method that permits the automatic and near real-time estimation of 3D surfaces (at 1 Hz) under varying magnifications of the operating microscope is proposed. This method has been evaluated on a CAD phantom object and on full-length neurosurgery video sequences ($\sim$1 h) acquired intraoperatively by the proposed stereovision system. To the best of our knowledge, this type of validation study on full-length brain tumor surgery videos has not been done before. The method for estimating the unknown magnification factor of the operating microscope achieves accuracy within 0.02 of the theoretical value on a CAD phantom and within 0.06 on 4 clinical videos of the entire brain tumor surgery. When compared to a laser range scanner, the proposed method for reconstructing 3D surfaces intraoperatively achieves root mean square errors (surface-to-surface distance) in the 0.28–0.81 mm range on the phantom object and in the 0.54–1.35 mm range on 4 clinical cases. The digitization accuracy of the presented stereovision methods indicate that the operating microscope can be used to deliver the persistent intraoperative input required by computational biomechanical models to update the patient's preoperative images and facilitate active surgical guidance.

1. Introduction

Intraoperative soft tissue deformations or shift can produce inaccuracies in the preoperative plan within image-guided surgical (IGS) systems. For instance, in brain tumor surgery, brain shift can produce inaccuracies of 1–2.5 cm in the preoperative plan (Roberts et al., 1998a; Nimsky et al., 2000; Hartkens et al., 2003). Furthermore, such inaccuracies are compounded by surgical manipulation of the soft tissue. These real-time intraoperative issues make realizing accurate correspondence between the physical state of the patient and their preoperative images challenging in IGS systems. To address these intraoperative issues, several forms of intraoperative imaging modalities have been used as data to characterize soft tissue deformation in IGS systems. Based on the modality used, intraoperative tissue deformation compensation methods can be categorized as: (1) partial or complete volume tomographic intraoperative imaging of the organ undergoing deformation and (2) intraoperative 3D digitization of points on the organ surface, the primary focus of this article. Tomographic imaging modalities such as intraoperative computed tomography (iCT) (King et al., 2013), intraoperative MR (iMR), and intraoperative ultrasound (iUS) have been used to compensate for tissue

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http://dx.doi.org/10.1016/j.media.2014.07.004
1361-8415/

deformation and shift in hepatectomies (Lange et al., 2004; Bathe et al., 2006; Nakamoto et al., 2007) and neurosurgeries (Butler et al., 1998; Nabavi et al., 2001; Comeau et al., 2000; Letteboer et al., 2005). These types of volumetric imaging modalities provide direct access to the deformed 3D anatomy. However, these modalities are affected by surgical workflow disruption, engendered cost, or poor image contrast.

Employing 3D organ surface data to drive biomechanical models to compute 3D anatomical deformation is an alternative to the compensating for anatomical deformation using the above mentioned volumetric imaging based methods. Recent research has demonstrated that volumetric tissue deformation can be characterized and predicted with reasonable accuracy using organ surface data only (Dumpuri et al., 2010a; Chen et al., 2011; DeLorenzo et al., 2012; Rucker et al., 2013). These types of computational models rely on accurate correspondences between digitized 3D surfaces of the soft-tissue organ taken at various time points in the surgery. Certainly, persistent delivery of 3D organ surface measurements to this type of model-update framework can realize an active IGS system capable of delivering guidance in close to real time. Organ surface data and measurements to drive these computational models can be obtained using textured laser range scanners (tLRS), conoscopic holography (Simpson et al., 2012), and stereovision systems. All of these modalities deliver geometric measurements of the organ surfaces in the field of view (FOV) as 3D points or a point cloud. In the case of tLRS and stereovision, the point clouds carry color information making them textured. These modalities allow for an inexpensive alternative to 3D tomographic imaging modalities and provide an immediate non-contact method of digitizing 3D points in a FOV. With these types of 3D organ surface digitization and measurement techniques, the required input can be supplied to the patient-specific biomechanical computational framework to compensate for soft tissue deformations in IGS systems with minimal surgical workflow disruption. In this paper, we compare the point clouds obtained by the tLRS and the developed stereovision system capable of digitizing points under varying magnifications and movements of the operating microscope.

Optically tracked tLRS have been used to reliably digitize surfaces or point clouds to drive biomechanical models for compensation of intraoperative brain shift and intraoperative liver tissue deformation (Cash et al., 2007; Dumpuri et al., 2010a, 2010b; Chen et al., 2011; Rucker et al., 2013). The tLRS can digitize points with sub-millimetric accuracy within a root mean square (RMS) error of 0.47 mm (Pheiffer et al., 2012). While the tLRS provides valuable intraoperative information for brain tumor surgery, establishing correspondences between temporally sparse digitized organ surfaces is challenging and makes computing intermediate updates for brain tumor surgery even more challenging (Ding et al., 2011).

Stereovision systems of operating microscopes can remedy the deficiencies of the tLRS by providing temporally dense 3D digitization of organ surfaces to drive the patient-specific biomechanical soft-tissue compensation models. Initial work in a similar vein has been done with respect to using an operating microscope for visualizing critical anatomy virtually in the surgical FOV for neurosurgery and otolaryngology surgery (King et al., 1999; Edwards et al., 2000). In this augmented reality microscope-assisted guided intervention platform, bivariate polynomials for camera calibration (Willson, 1994) are used with a given zoom and focus input setting for establishing the correct 3D position of critical anatomies overlays. Figl et al. (2005) developed a fully automatic calibration method for an optical see-through head-mounted operating microscope for the full range of zoom and focal length settings, where a special calibration pattern is used. In this presented work, we use standard camera calibration techniques (Zhang, 2000) with a content-based approach and do not separate the zoom and focal length settings of the microscope's optics as done in Willson (1994) and Figl et al. (2005). Our method is based on estimating the magnification being used by neurosurgeons. This magnification is the result of a combination of using the zoom and/or focal length adjustment functions on the operating microscope.

Although stereovision techniques are often used for surface reconstruction in computer-assisted laparoscopic surgeries (Maier-Hein et al., 2013, in press), in this paper, we focus on three stereovision systems that have been used for brain shift correction using biomechanical models. These stereovision systems are housed externally or internally within the operating microscope, which is used routinely in neurosurgeries. The 3D digitization of the organ surface present in the operating microscope's FOV can be accomplished using stereovision theory. The first system uses stereo-pair cameras attached externally to the operating microscope optics (Sun et al., 2005a, 2005b; Ji et al., 2010). This setup renders the assistant ocular arm unusable when the cameras are powered on. Often, the assistant ocular arm of the microscope is used as a teaching tool. This limits the acquisition of temporally dense cortical surface measurements. The second stereovision system also uses an external stereo-pair camera system attached to the operating microscope. This system relies on a game-theoretic approach for combining intensity information in the operating microscope's FOV to digitize 3D points (DeLorenzo et al., 2007, 2010). The system relies on manually delineated sulcal features on the cortical surface for computing 3D surfaces or point clouds using the developed game-theoretic framework. Similar to the disadvantages shouldered by the tLRS, the temporally sparse data from these two stereovision systems make establishing correspondence for driving the model-update framework challenging. Paul et al. (2005) developed the third stereovision system. This system uses external cameras and is capable of displaying 3D reconstructed cortical surfaces registered to the patient's preoperative images for surgical visualization. In Paul et al. (2009), the stereovision aspect of this system has been extended for registering 3D cortical surfaces acquired by the stereo-pair cameras for computing cortical deformations. One of the major unaddressed issues in these three stereovision systems is the acquisition of reliable and accurate point clouds from the microscope under varying magnifications and microscope movements for the duration of a typical brain tumor surgery, approximately 1 h.

During neurosurgery, the surgeon frequently moves the head of the operating microscope and zooms in and out of the surgical site to effectively manipulate the organ surface to perform the surgery. The magnification function of the operating microscope is a combination of changes in zooms and focal lengths of the complex optical system housed inside the head of the operating microscope. The unknown head movements and magnification changes alter the determined camera calibration parameters at the pixel level, cause calibration drift, and consequently, result in inaccurate point clouds. Several popular methods for self-calibration of cameras have been developed (Hemayed, 2003), where an initial camera calibration is not performed.

In published methods, the stereo-pair cameras are either recalibrated or the operating microscope's optics are readjusted to the initial calibration state for the stereo-pair cameras when a point cloud needs to be obtained during the surgery. Overall, the inability to persistently and robustly digitize points on the organ surface accurately for the duration of the neurosurgery has been one of the considerable barriers to widespread adoption of the operating microscope as a temporally dense intraoperative digitization platform. As a result, the development of an active IGS system capable of soft tissue surgical guidance to the clinical armamentarium has been slowed.