Integration of Intra-operative 3D Ultrasound with Pre-operative MRI for Neurosurgical Guidance

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Abstract – When image-guided neurosurgery is used in procedures that require a craniotomy, targeting accuracy can often be compromised because of the brain shift that occurs due to pressure, gravitational and resection effects. Errors between the positions of homologous structures in the pre-operative images and within the brain itself, of up to 25mm have been reported. We have recently completed a study of the use of tracked 2D intra-operative ultrasound, integrated with 3D MRI as a means of visualizing and measuring the shift of the brain tissue during neurosurgical procedures, as well as correcting the pre-operative MR images on a slice-by-slice basis to conform with the intra-operative ultrasound images. More than 15 surgical cases have been performed thus far with the 2D system. We are extending this study to incorporate tracked 3D ultrasound. To date we have developed new tools for real-time overlay of the 3-D ultrasound volumes and with the pre-operative MRI volumes. These facilities include a stereoscopic virtual-reality view of the ultrasound probe with live ultrasound video superimposed over a 3D-rendered MRI of the brain, as well as 3D ultrasound/MRI transparency overlay views. In addition, algorithms to automatically extract homologous landmarks from MRI and 3D ultrasound images are under development. These landmarks will be used to automatically generate nonlinear warp transformations to correct the preoperative MRI as well as surgical target coordinates for brain shift.

***Key words* - image-guided surgery, 3D ultrasound, optical tracking system**

I. Introduction

Stereotactic surgery involves the registration of pre-operative medical images, typically from volumetric modalities such as MRI and CT, with a surgical coordinate system. For most operations, the surgical coordinates are defined by a set of x, y, and z graticules on a surgical frame that is affixed to the patient's skull.

In modern computer-aided surgery systems, the frame is replaced by a tracking system (usually optical, but possibly mechanical or magnetic) that the computer uses to track the surgical tools. Virtual representations of the tools are rendered over a pre-operative image volume in order to provide guidance for the surgeon. The registration of the patient to the image volume is accomplished via a set of fiducial markers that are affixed to the skull prior to the pre-operative imaging session.

In order for the surgeon to obtain the full benefit of stereotaxis, two criteria must be met: 1) the registration must be accurate and 2) the brain must not shift prior to or during surgery. The first criterion is guaranteed though quality assurance of all steps in the registration method. The second criterion can be met by using minimally invasive surgery, i.e. performing the operation through a small hole in the skull. For surgeries that require a craniotomy, however, there will be a brain shift of 10 mm on average and as large as 25 mm [1]. The brain shift is a nonlinear warping of the brain caused by gravity, loss of fluid from the cranial cavity, and tissue resection by the surgeon.

Our project involves the use of intra-operative ultrasound imaging to measure the brain shift. The measured shift can then be used as a nonlinear correction to the stereotactic transformation between pre-operative image coordinates and surgical coordinates. To make the measurement of brain shift possible, a set of infrared LEDs is mounted on the ultrasound probe to allow the surgical workstation to track the position and orientation of the probe. The computer uses this information to overlay the ultrasound images on the pre-operative MR volume, which allows direct measurement of the shift. Preliminary work in this area has been performed by several groups, and we have previously discussed the clinical utilization of our own system [2,3]. Fig. 1 is an ultrasound/MRI overlay that we acquired during a procedure at the Montreal Neurological Institute.

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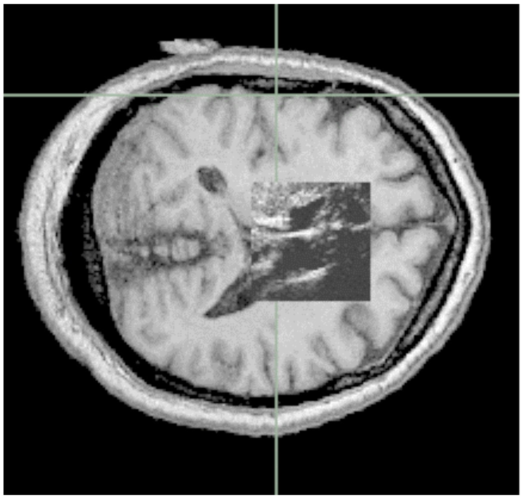

Fig 1: an overlay of an ultrasound image of the ventricles and falx on top of an MRI slice. This image was acquired during an amygdalohippocampotomy procedure at the MNI.

The primary advancement of our current research over previous studies is the use of 3D ultrasound imaging as well as the use of sophisticated 3D visualization techniques. These facilitate the identification of landmarks in the images that can be used to measure the shift. The ultimate goal of this project is to use homologous landmarks in the ultrasound and MRI images to generate a nonlinear warp transformation from MR image coordinates to intra-operative surgical coordinates. This would allow the pre-operative MR images to be used for stereotactic guidance even in the presence of brain shift.

II. Materials and Methods

The primary components of our system are an Aloka SSD-2000 ultrasound scanner with a 5 MHz neuro ultrasound probe (Aloka Co., Ltd, Tokyo 181-8522, Japan), a POLARIS optical tracking system (Northern Digital Inc., Waterloo ON N2V 1C5, Canada, www.ndigital.com), and a 450 MHz Pentium II workstation with video input/output capabilities.

We calibrate the ultrasound probe for use with the tracking system by obtaining images of a string phantom submersed in a 9% glycerol solution, as shown in Fig. 2. A detailed description of the calibration procedure is provided in a previous document [4].

To test our system, we acquire MR and ultrasound images of poly vinyl alcohol cryogel (PVA-C) phantoms that we constructed for this project. PVA-C is a gel that cross-links as it thaws, and it is possible to construct the phantom from various pieces of PVA-C which have undergone different numbers of freeze-thaw cycles and hence provide good contrast for many imaging modalities. The mechanical properties of the gel can also be controlled, which make it ideal for deformation studies.

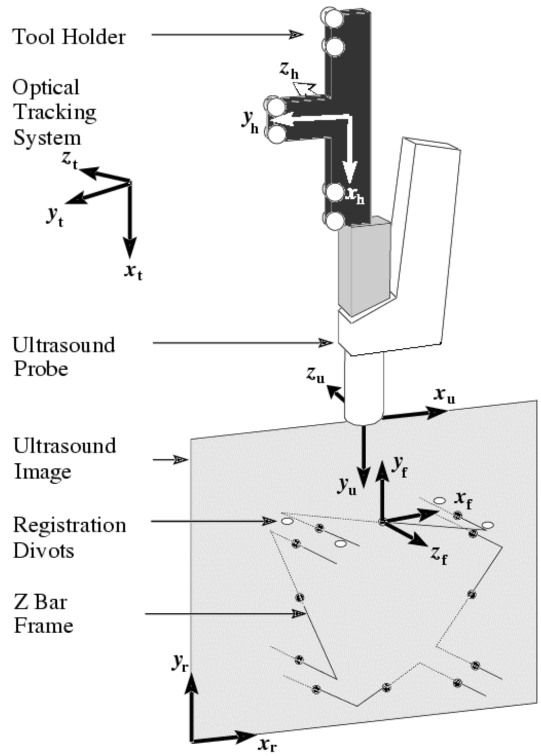

Fig. 2: the various coordinate systems involved in ultrasound probe calibration for stereotaxis.

The real-time overlay of ultrasound images on previously acquired MR image volumes is done by our in-house image guided surgery software, ASP. We are developing ASP within the framework of the open-source Visualization Toolkit (VTK) [5] (www.kitware.com/VTK.html) and using Python as a rapid application development language. Much of the C++ code we have developed is now part of VTK and available for free from Kitware.

III. Results

Fig. 3 shows an image from a tracked ultrasound probe superimposed on a 3D view of an MRI image volume. The image can be viewed in stereo on the computer monitor through the use of liquid-crystal shutter glasses. The scene is rendered in real time (5 frames per second) as the ultrasound probe is moved. When 3D ultrasound acquisition is done, a volumetric

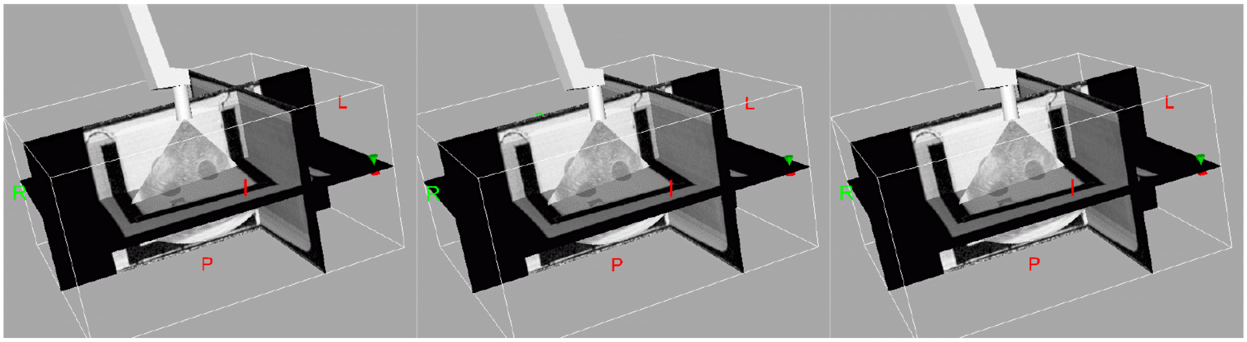

Fig. 3: Stereo images of an ultrasound image rendered with a triplanar view of an MRI volume. The ultrasound image is registered to the MRI: Features such as the cylindrical cavities in the phantom (dark circles) appear in at the same location in both modalities. To view in stereo, either cross your eyes while looking at the left two images until the images are superimposed, or focus beyond the page while looking at the right two images.

overlay of the ultrasound and MR images is achieved as shown in Fig. 4. The ultrasound volume represents 6 seconds of ultrasound video acquisition, which can then be resliced from any orientation for comparison to the MRI.

IV. Discussion and Conclusion

Our goal is to provide the surgeon with the means to rapidly assess brain shift, and furthermore to allow the pre-operative images to be used for accurate surgical guidance even in the presence of brain shift. To facilitate the latter, we are developing tools to deform the pre-operative image in real time to match landmarks between it and the 3D intra-operative ultrasound volume.

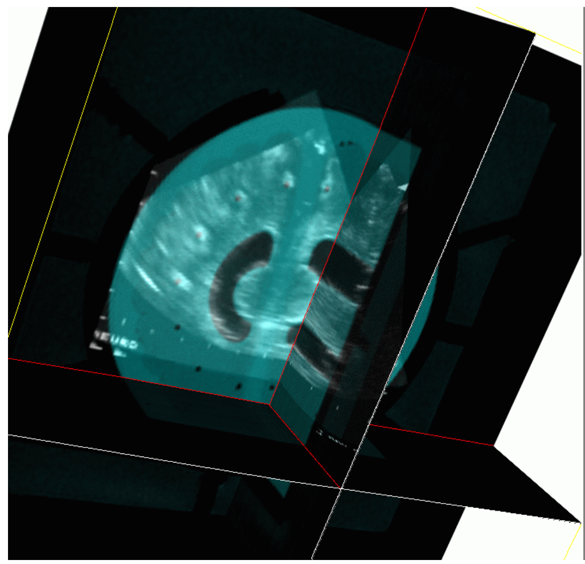

Fig. 4: Overlay of a 3D ultrasound volume (white) on a registered MRI volume (blue).

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