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3D Stereo Interactive Visualization for the TIPS Procedure

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Abstract

Transjugular intrahepatic portosystemic shunt formation (TIPS) is an effective treatment for portal hypertension [LaBerge 1995]. The procedure requires the insertion of a needle through the liver to connect the hepatic and portal veins. This operation is traditionally guided by fluoroscopic images that do not show the location of the target veins during needle insertion. We propose to provide the clinician an interactive, three-dimensional (3D), stereo display so that the position and orientation of the clinician's needle can be seen relative to the target vasculature intraoperatively. This paper describes the visualizations we are providing for intraoperative guidance.

Keywords

Image-guided surgery; minimally invasive surgery; augmented reality; quaternion; 3-D/2-D registration; medical imaging

Introduction

Endovascular operations involve guidance of a catheter through a vascular network with the goal of delivering therapy to a specific target. This form of minimally invasive surgery has undergone rapid growth over the last 10 years, and is now the procedure of choice for many patients who previously could be treated only by more invasive, open operation.

A primary difficulty with endovascular procedures is that they are typically guided only by flat projection images. To image the vasculature, the interventionalist injects small amounts of a contrast agent and obtains fluoroscopic images. These images generally show only the connected portions of the vasculature “downstream” of the catheter tip. The interventionalist thus cannot visualize other structures that are disconnected from the vascular anatomy shown in any particular image. Moreover, all three-dimensional (3D) information is collapsed into a projection view, making 3D perception of the vascular network difficult.

The purpose of this report is to describe a new method of guiding endovascular procedures using interactive 3D stereo visualizations. We use as an example application the TIPS procedure (Transjugular Intrahepatic Portosystemic Shunt). Our goal is to increase the speed and safety of endovascular procedures by providing the interventionalist with 3D information as the operation proceeds. The visualization methods employed are not themselves novel, but they have not been used for the guidance of endovascular surgery, and could change how these procedures are normally performed.

Why is the TIPS procedure difficult?

TIPS is an endovascular procedure used to treat the effects of severe liver disease. The goal of the operation is to create a direct conduit between the portal vein (the venous system that

supplies the liver) and the hepatic vein (the venous system that drains the liver). This connection allows decompression of elevated portal vein pressures and subsequent relief of many symptoms.

Needle insertion during the TIPS procedure has traditionally been guided by biplane fluoroscopic images that are acquired close to 90 degrees apart. A particular problem with TIPS, however, is that a needle must be inserted through the liver into the portal venous system, and these target vessels can only be visualized transiently by injection of CO₂. This static image is then applied to the real time fluoroscopic image as an overlay, to provide an estimate of the location of the portal vein during needle passage. During needle passage, however, the target veins cannot be seen directly, and both respiratory motion and needle pressure may displace the liver and its portal veins. The operation therefore involves insertion of a needle towards a target that cannot be seen and whose position changes as a result of the intervention! The left side of figure 1 shows a typical pair of fluoroscopic images during needle insertion where the target portal vein has been outlined in black on each image. An arrow indicates the projection of the needle on each view.

Our goal is to provide 3D image guidance of the TIPS procedure so that the interventionalist can readily adjust the needle position and trajectory to reach the target on the first pass (figure 1). We propose a 3D stereo display of the interventionalist's needle and target vessels. We also add interactivity by head tracking so that the interventionalist can gain a better 3D sense of the relationship between the target vessels and the needle during needle advancement.

Segmentation and registration

Our approach requires the preoperative creation of a 3D model of each patient's portal venous system. These vessels are extracted from a preoperative contrast enhanced computed tomographic scan (CTA) using the segmentation method of Aylward [Aylward 2002]. The segmented vessels are then post-processed to provide a set of connected vessel trees [Bullitt 2001].

At the beginning of each operation, the two fluoroscopic views are calibrated so that the relative positions and orientations of the two views are known [Faugeras 1996]. An 11 mm, contrast-filled balloon is also introduced endovascularly, and is firmly wedged into a branch of the liver's hepatic venous system. This balloon can be seen on each fluoroscopic image (Figure 2), and serves as a reference point that can be used later to indicate rigid-body motion of the liver (and its enclosed portal veins) during respiration, heartbeat, and needle insertion [Venkatraman 2004].

Prior to needle insertion, the portal venous system is visualized transiently by CO₂ injection. This injection provides a "snapshot" on each of the two fluoroscopic images of both the balloon and of the target veins. The 3D vessel model is then registered with this pair of fluoroscopic views, using an iterative closest point method that minimizes distance between the projections of 3D vessel skeleton curves and the skeleton curves of the 2D curves seen on the fluoroscopic images [Liu 1998]. Although the portal venous system be estimated during needle insertion by incorporating the changes in the position of the balloon, which can be tracked by fluoroscopy.

The interventionalist's needle is tracked on both fluoroscopic views throughout the procedure [Jolly 2003] and is reconstructed into 3D [Hartley 2000] using the principles of epipolar geometry [Bullitt 1997]. The interventionalist's needle can then be shown in 3D and relative to the 3D portal veins throughout the procedure.

3D Stereo display creation

We propose providing the clinician with a 3D stereo display of both the target portal veins and of the needle. Our goal is to provide a lightweight, inexpensive, easy-to-use system that will allow effective 3D visualization without impeding the clinician's ability to manipulate a catheter or to observe the actual fluoroscopic images.

Image creation

The stereo display provides each eye with a slightly different image at a high rate. To generate the 3D images we use OpenGL and its ability to draw into two buffers: in our case a right and a left buffer. The 3D information displayed includes the 3D vasculature and the clinician's needle reconstructed into 3D. A separate view is generated for each eye using the two OpenGL functions `gluLookAt` and `glFrustum`. The `gluLookAt` method sets the position of the camera. The `glFrustum` method sets the field of view of the camera. We successively display 3D objects in the left and right buffers, with synchronization between the left buffer and the stereo hardware controlled by the graphics card.

The function `glFrustum` requires 6 settings: *left*, *right*, *bottom*, *top*, *near*, *far*. Parameters *near* and *far* specify the distances to the near and far depth clipping planes. Both distances must be positive. Parameters *left* and *right* specify the coordinates for the left and right vertical near clipping plane. The parameters *bottom* and *top* specify the coordinates for the bottom and top horizontal near clipping planes. The function `glFrustum` produces a perspective projection matrix. The points (*left*, *bottom*, *near*) and (*right*, *top*, *near*) specify the points on the near clipping plane that are mapped to the lower left and upper right corners of the window.

The correct way to set the left and right eye's cameras is to use parallel axis asymmetric frustum perspective projection [Bourke 1999], in which the view vectors for each eye remain parallel. From a virtual camera placed between the two eyes one can set the left and right eyes `glFrustum`. The only information needed is the focal distance, the eye separation, the aspect ratio (width:height, 4:3 was chosen to match the screen dimensions) and the field of view, plus near and far clipping planes. Then the settings of the `gluLookAt` and `glFrustum` can be derived using similar triangles.

For purposes of clarity, we provide more detail about the left eye's camera. The parameters *near* and *far* are the same as in our virtual camera. The parameters *top* and *bottom* are also the same.

$$top = near * \tan(FieldOfView/2) \text{ and } bottom = -top$$

The only difficulty is to compute the *left* and *right* parameters, which are labeled on figure 4 as d_{left} and d_{right} . Here is how we process. From the camera setting one can find the distance a :

$$a = ratio * \tan(FieldOfView/2) * FocalLength$$

From this the distances b and c are derived

$$b = a - EyeSep/2 \text{ and } c = a + EyeSep/2$$

The link between b , c and respectively d_{left} and d_{right} is given by the similar triangles.

$$\frac{d_{left}}{b} = \frac{d_{right}}{c} = \frac{near}{FocalLength}$$

One therefore derives the parameters *left* and *right* for the left eye. Similar computations are made for the right eye.

Stereo Hardware

The hardware used to create the 3D stereo display includes a StereoGraphics ZScreen 2000i polarized screen with passive glasses, a ViewSonic P95F 19" CRT monitor, and an NVIDIA Quadro 4 graphics card. The ZScreen is a polarized screen, which is sold together with a lightweight pair of passive polarized glasses. The screen can be polarized in each of two directions. Each direction corresponds to the polarization of one of the eyes of the glasses. Each eye of the glasses alternately becomes opaque and allows visual input along the correct polarization. By synchronizing the ZScreen polarization with the image displayed at a high refresh rate (120 Hz for the screen, 60 images/second for each eye) a stereo image is generated. The ZScreen is mounted on the front of the monitor and the user. Synchronization is provided by the NVIDIA graphics card through a 3-pin mini-DIN connector.

This particular set of hardware was selected for the guidance of endovascular surgery for several reasons. First, the system is wireless, so the physician is not "tethered" by wiring which might hamper movement around the operative field. Second, the glasses are lightweight and comfortable. Because of the low optical density of the lenses, the physician's vision of the operating field and fluoroscopic images is relatively unaffected. Finally, we chose to use relatively inexpensive, COTS (commercial off-the-shelf) components. The total cost of the system, not including the PC, is less than \$5500.

Adding interactivity

Vessel display

It is important to add interactivity to the software so that the interventionalist can make changes to the display. The software allows the user to rotate the vasculature in any direction within a fixed coordinate system. This is very useful because the clinician's intuitive sense of object movement is preserved.

Another option is the ability to display the vessel as a surface, as a wire frame or only as a skeleton. This can provide helpful information during 2D-3D vessel registration when the doctor either needs to see through some vessels in order to perceive the underlying fluoroscopic view, or to observe the curves of the vasculature, which is easy to do by displaying the skeleton.

The software also allows user-selected culling of the displayed 3D vasculature. An individual vessel may be selected and then either recolored or deleted from display. Similarly, since our data structures order each parent vessel's children according to the direction of flow in the parent vessel, one may delete all vessels downstream of a particular vessel or a selected vessel point. This capacity is particularly useful for guidance of endovascular surgery, since fluoroscopic images obtained during the early angiographic fill phase will not contain small terminal branches.

Head tracking

Another enhancement provided by our display system is tracking the position of the user's head. As the doctor's head moves, images are redrawn from the new point of view. With such tracking the doctor can "move around" the 3D model, making it easier to visualize 3D relationships.

To track head movement we selected the Origin Instruments DynaSight infrared tracker. The program queries the tracker 60 times per second and determines the position of the target. The

target is a lightweight, 0.7 cm diameter passive reflective sticker. We put such a marker between the eyes of the glasses we use for 3D Stereo display. This tracking solution is inexpensive, is sufficiently accurate for our purposes, is not confounded by radio or electromagnetic signals in the operating room, and since it is wireless, does not restrict the physician's movement.

The view refreshes using the information provided by the tracker. Rather than moving the camera or eye position while the head moves around the 3D object, the 3D object is rotated on the screen. The scene can be rotated in software as well as by head motion. When the tracker reports a new head position, the camera information is updated with `gluLookAt` and `glFrustum`. These changes occur if the user moves closer to or farther from the screen. Rotations are computed using quaternions. For example, at time t_0 , the tracker reports a position, which can be represented as a normalized quaternion, q_0 . At time t_1 , we receive another position that we express again as a normalized quaternion, q_1 . The relationship between these is also quaternion that represents rotation by an angle θ around an axis.

$$q_1 = q_{rot} * q_0 \text{ and so : } q_{rot} = q_1 * q_0^{-1}$$

The quaternion q_{rot} give us the head movement as a rotation that we then apply to the scene. Given q_{rot} , the axis and angle of rotation can be computed [Glassner 1990, Shoemake 1985].

Future work: Simulation

The visualization methods described above have been implemented, and initial reaction of the clinicians involved has been highly positive. However, before using the proposed approach to guide clinical procedures directly, we require simulation tests to ensure that our method will be useful, accurate, and easy to use, and to formally assess which visualizations will be most useful (e.g., an external view of the vessels and needle, as currently implemented, or a "needle eye's view"). We have already performed accuracy tests on many of the components involved in the overall system (vessel segmentation [Aylward 2002], 3D curve reconstruction [Bullitt 1997], 2D-3D registration [Liu 1998], and balloon tracking [Venkatraman 2004]). Formal clinical trials involving several radiologists are planned to compare the speed and accuracy of the traditional methods with the new visualization scheme. However, this requires modifying the system to allow direct input from the fluoroscopic units, and increasing the speed of the current image processing algorithms to allow real-time processing of the image streams. We estimate that we will begin such trials in approximately one year. We believe that the proposed visualizations will prove useful not only for the TIPS procedure, but also for a wide range of endovascular operations.

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Biographies

Damien Maupu is finishing his “Diplôme d’ingénieur” from CPE Lyon, France. From 2003–2004, he served an internship in the Department of Surgery at the University of North at Carolina Chapel Hill, USA. He is currently at the Swiss Federal Institute of Technology Lausanne, Switzerland. His interests include computer graphics and computer vision.

Mark H. Van Horn received the PhD degree from North Carolina State University. He is a Research Assistant Professor in the Department of Surgery at the University of North Carolina. His current research interests include medical image analysis and image-guided surgery. He is a member of the IEEE, Eta Kappa Nu, and Tau Beta Pi.

Susan Weeks received her MD degree from the University of North Carolina at Chapel Hill and completed a residency in Radiology and Fellowship in Vascular and Interventional Radiology at the same institution. She currently practices at UNC as an associate professor. Her professional interests include image-guided surgery, local tumor therapy, and abdominal transplantation.

Elizabeth Bullitt is a board-certified neurosurgeon (BA Harvard 1971; MD U. Colorado 1976; Residency Duke 1981) and Professor of Neurosurgery at UNC. She directs the multidisciplinary CASILab (<http://casilab.med.unc.edu/>), which focuses upon image-guided surgery and computer-assisted diagnosis. Research has centered upon vascular applications. Dr. Bullitt is an affiliate member of IEEE.

Figure 1.
Comparison between the normal procedure and the TIPS project

Figure 2.
 Overview of TIPS procedure

Figure 3.
OpenGL Frustum camera settings: `glFrustum(left, right, bottom, top, near, far)`

Figure 4.
Parallel axis asymmetric frustum perspective projection

Figure 5.
3D vessels can be displayed either as a surface, as a wire frame or as skeleton

Fig. 6.
Vessel selection

Figure 7.
Head tracker