A THREE DIMENSIONAL GUIDANCE SYSTEM FOR FRAMELESS STEREOTATIC NEUROSURGERY

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Abstract

We are using and developing a computer based tool to assist Neurosurgeons in both pre-operative planning and surgery. This tool is called the Stereotaxic Planning and Surgery System (SPSS). SPSS utilizes a localization device coupled with two and three-dimensional visualization techniques and it provides useful information to the surgeon when locating and removing diseased tissue. With SPSS, a new surgical technique, referred to as guided frameless stereotaxic surgery is also being developed.

Introduction

Prior to SPSS and its revolutionary surgical technique, there were two methods a Neurosurgeon could employ for removing diseased tissue. The first technique utilizes a frame which rigidly attaches to the patient’s head. This is a classical type of neurosurgery known as framed stereotactic surgery. The frame provides a reference coordinate system which results in a high degree of localization accuracy. The detriment of using a frame is the physical discomfort and mental stress to the patient. Neurosurgeons also find the frame cumbersome in the OR. For these reasons, frames are not used unless the operation demands a high degree of accuracy. The second type of neurosurgical technique is a free-hand approach where the Neurosurgeon examines images of the patient and guesses the location of the diseased tissue. To insure that the entire lesion is exposed, the surgeon removes a large portion of the calvarium. This technique is a more radical surgical technique and generally requires a longer hospital stay than surgery utilizing the stereotactic frame.

SPSS provides the same high degree of localization as framed stereotactic surgery without subjecting the patient to the stress associated with mounting and wearing a frame. SPSS couples this localization with two and three dimensional (2D and 3D) visualization during both a pre-operative planning phase and the actual surgery. In pre-operative planning, the surgeon views computerized tomography (CT) slices in sequence, identifies the diseased tissue in the appropriate CT scans, and views a 3D rendition of the image data. This visualization permits the surgeon to determine the location of the diseased tissue with respect to sensitive brain material and
provides a mechanism for experimenting with different approaches to remove the tissue. In surgery, SPSS activates the localization device and graphically displays the location of the device on various representations of the patients data including: a 3D rendering of the CT scans, an axial slice, a sagittal slice, a coronal slice, a Z-plane or trajectory view, and an arm’s-eye view. The trajectory view is defined as the plane which includes both the last link of the localization device (or the probe) and the Z-axis. The arm’s-eye view is defined as the plane perpendicular to the probe. The location of the probe tip is superimposed on all displayed views which shows where the device is relative to the patients data.

This paper describes some of the technical details of the SPSS system including: the transformations used in the system, the 2D and 3D visualization techniques, and the user interface which makes SPSS a useful and practical tool in the surgical environment.

Localization

Currently, SPSS uses a five jointed, passive, digitizing arm for localization in the Operating Room (OR). The arm is machined and assembled to very high precision to minimize localization errors. The arm consists of both joints and links. The joints are characterized by simple rotations about a single principle axis. Each joint is equipped with an encoder which relates joint movement to joint angle. Specifically, we can compute the relative angle of a joint given the number of counts and the encoder resolution with,

$$\omega = \frac{2\pi C}{R}$$  \hspace{1cm} (1)

where $\omega$ is the joint angle, $C$ is the number of encoder counts, and $R$ is the encoder resolution. The links which connect the joints are made of aluminum and have a know length.

The position of the tip of the probe is computed using a classical kinematic solution. For an introduction to kinematics refer to books by Synder [3] or Craig. [1] The arm is modeled as a rotation about a principle axis followed by a translation. Specifically, the location joint $i + 1$ relative to the previous joint $i$ is computed using:

$$i+1P = (i+1T) \cdot i+1P$$  \hspace{1cm} (2)

where $i+1P$ is the location of a point $P$ relative to the $i + 1$st joint, $i+1T$ is the transformation from joint $i$ to joint $i + 1$, and $iP$ is the location of a point $P$ relative to the $i$th joint. The transformation from joint $i$ to joint $i + 1$ is defined by a rotation followed by a translation. Specifically,

$$i+1T = (i+1R) \cdot (i+1T)$$  \hspace{1cm} (3)
where $i^{+1}R$ is the rotation between joint $i$ and joint $i+1$ and $i^{+1}T$ is the translation between the same two joints. The location of the probe is computed in this fashion, starting at one end and computing relative locations joint by joint.

**SPSS**

SPSS has a simple and easy to use interface which provides useful information to the surgeon in both a pre-operative planning phase and during the actual surgery. To make a useful tool for the sterile environment of the OR, we developed a graphics-interactive, surgeon-controlled interface. This interface permits the surgeon to control the program without using a computer keyboard or a mouse. Our interface is rapidly becoming the standard for all computer interacting neurological localization devices.

SPSS has a characteristic look and feel, which provides a simple and consistent interface. SPSS begins with a welcome screen which contains a label to introduce the system and three pushbuttons labeled Help, Continue, and Quit. Most users will press the continue button which brings the user to a utility choice screen. This screen permits the user to add new data to the system, perform system maintenance, or to pick a patient. Mousing on the Pick Patient button causes a patient browser to be activated. This browser contains the names of all the patients with imaging data on the system. When the user mouses on a patients name, a screen containing different imaging modalities appears. SPSS provides for MRI, CT and Angiogram data, however, only CT data can currently be used in our stereotactic system. We are working on an MRI distortion correction scheme which will permit us to localize using MRI data. Once the image modality is chosen, the patients data is loaded into the system and a side panel with control buttons including: Scout Browser, CT Browser, and Operate becomes active.

**Scout Browser**

A Scout image is GE's terminology for a standard X-ray radiograph produced using a CT scanner. Typically, the patient is supine on the scanner couch. The X-ray source is turned on and the patient is moved through the beam. During this time, the scanner array is strobed to form a (2D) projection image of the patient. The position of the X-ray source and detector array can be varied to produce different projection images.

During surgery SPSS activates a digitizing arm and graphically displays the position of the tip of the probe relative to the patients CT scans. To relate an OR tip position to CT scans, a transformation between these two spaces must be established. SPSS computes this transformation by identifying three corresponding points each space, and solving for the transformation which maps the three points in one space to the corresponding three points in the other space. Foley [2] describes a formal treatment of this solution. Currently, we implant three metallic scalp staples in the patients head prior to the CT scans. The staples appear
very bright in the images because the density is much greater than that of human anatomy.

Scout images are used to determine the 3D location of the three scalp staples because, the staples are usually positioned away from the tumor and it is unlikely that the staples will appear in any CT slices. Even if the staples were to appear in a CT slice, the location accuracy is questionable because of the slice spacing. At least two, 2D projections of a point are needed to determine the 3D location of that point. In SPSS, the surgeon identifies the same staple in two orthogonal scout views, specifically an anterior/posterior (AP) and lateral (LAT) view. Using these locations, the 3D location is determined by solving a set of simultaneous equations.

**Visualization**

During both pre-operative planning and surgery, SPSS graphically displays the position of the tumor relative to the probe of the localizing device using both 2D and 3D visualization techniques. The 3D rendering graphically shows the location of the probe with respect to the patients CT data. The surgeons find this 3D view useful in maintaining their orientation. The 2D visualization shows different orthogonal and oblique slices through the patients image data with the probe superimposed on each image.

There are three different techniques for rendering 3D data. The first technique is to displays a wire frame of the object. The CT slices are first thresholded with an appropriate value for extracting the external skin. A contour detector is then applied to determine the contour of the bounding skin. Most contour detectors require a seed point on the contour of interest and are highly interactive to allow hand editing of the automatically detected contour. Finally, the edited contours are displayed on the screen using a perspective viewing technique. This technique is useful because of the the small amount of data needed to generate a three dimensional rendering of the object. In fact, most personal computers can display a wire frame in real time. The detriment of this approach is the amount of interactive editing required and a wire-frame does not provide a realistic rendering of the object.

A second approach to 3D rendering is referred to as surface rendering which is an extension and improvement of the wire-frame technique just described. Surface rendering displays the surface of objects using the detected contours by determining a triangular mesh covering the surface. The mesh fills in the gaps between contours of adjacent slices. Several computer manufactures provide hardware to render these triangular meshes very quickly, for example, Silicon Graphics and Hewlett Packard. Surface rendering displays a much more realistic object compared to the wire frame, however, this approach suffers from the highly interactive contour detection drawback of the wire-frame approach and the process of determining the
triangular mesh is very computationally expensive and highly interactive.

The third approach of rendering 3D data is referred to as volume rendering. In this technique, the 2D CT pixels on each slice are treated as 3D voxels. The detriment of using this approach is the large number of voxels that must be rendered. The objects we render typically contain 3.5 million voxels which take approximately 30 seconds to display on our commercially available graphics workstation.

SPSS uses a modified volume rendering approach which exercises the special purpose hardware of our graphics workstation. Using our technique, we render a 3D view of the head in a preset orientation in approximately 4 seconds. This update time is responsive enough for the surgeons in the OR. In the 3D display we show a wedge cutout of that part of the patients data between the probe and the viewer. The sides of the wedge show the surgeon the actual CT data at the corresponding location. This is useful because usually there are sufficient external landmarks visible to keep the surgeon oriented.

SPSS provides a variety of 2D images corresponding to the location of the probe of the digitizing arm. Specifically, SPSS displays the axial, sagittal, and coronal slice at the probe tip location. A cross is superimposed at the location of the tip in each image plane. In addition to these orthogonal slice planes, SPSS provides two unique oblique slice planes. We refer to one of these planes as the arms eye view and the other is called the Z-plane or trajectory view. The arms eye view is defined as the 2D plane which is perpendicular to the probe. The arms-eye view is useful because it shows the tissue around the probe tip. For example, if the surgeon is removing a tumor this view shows how much more tissue must be removed. The trajectory view is defined as the 2D plane which includes the probe and the Z-axis. This view is useful because it shows the trajectory of the probe. Typically, a surgeon uses this view to determine the best approach and location of the opening to remove diseased tissue.

Since the computer screen is limited in size and is located some distance away from the surgeon, SPSS provides a menu system so the surgeon can choose a desired display. The physical environment of the OR makes it impossible for the surgeon to operate the computer in a conventional sense. To overcome these environmental problems, SPSS uses a foot pedal in place of the return key and turns the localizing device into a mouse which can traverse the menu system during the operation. This surgeon controlled interface permits the surgeon to display different information at various time during the operation and does not require additional personnel to operate the system.

Conclusions
In this paper, a new computer based tool (SPSS) to assist Neurosurgeons in both pre-operative planning and surgery is described. SPSS utilizes a localization device
coupled with two and three dimensional visualization techniques to provide useful information to the Neurosurgeon when locating and removing diseased tissue. Although the current localization device is a passive, digitizing arm, the system is not limited to this type of input device and can use any device capable of determining its three dimensional position. The current version of the system has successfully been used in the Operating Room several times.

SPSS has a simple and easy to use interface which is rapidly becoming the standard for all computer interacting neurosurgical localization devices. The interface can be used in the sterile environment of the Operating Room by the Neurosurgeon during the operation. This is accomplished by providing a foot-pedal which functions as the return or enter key, and by using the digitizing arm as a mouse to control which graphical representations of the patients image data are displayed at different times during the operation. This graphics-interactive, surgeon-controlled interface is unique and does not require additional personnel to operate the system.

References


