We are now working to expand the capabilities of the system in several ways. We intend to integrate localization equipment in the operating room in order to use the system as a navigation aid during surgery. The high performance networking infrastructure already in place supports moving a completed planning session to a second machine in the operating room for use in subsequent image-guided surgery. We are also in the process of enhancing the system so that it will be capable of supporting frameless stereotactic procedures.

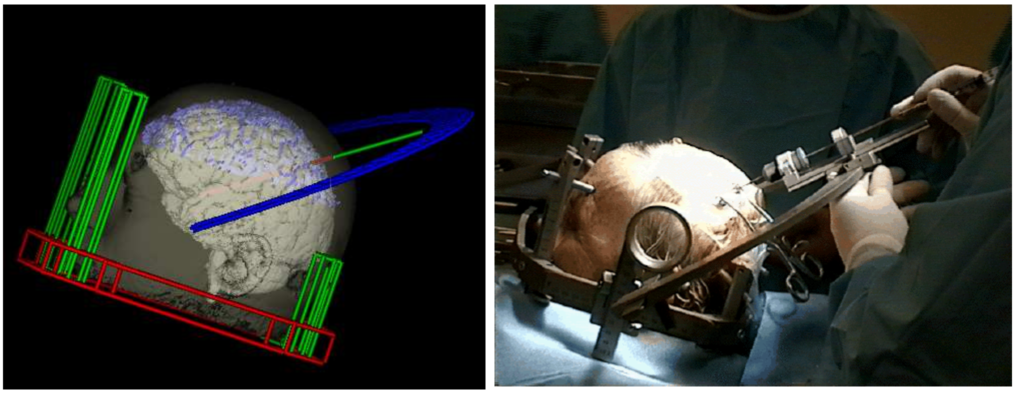

Figure 8 - Comparison of a simulated image (left) and actual trajectory photograph(right).

7. REFERENCES

1. Mugler, III, J.P. and J.R. Brookeman, "Three-Dimensional Magnetization-Prepared Rapid Gradient-Echo Imaging (3D MP-RAGE)," *Mag Res Med*, **15**, 152-157, 1990.
2. Mullikin, JC., "The Vector Distance Transform in Two and Three Dimensions," *CVGIP*, **53**, 76-87, 1991.
3. Talairach J and P. Tournoux , *Co-Planar Stereotaxic Atlas of the Human Brain*. New York: Georg Thieme Verlag, 1988.
4. Terzopoulos, D., A. Witkin, and M. Kass., "Constraints on Deformable Models: Recovering 3D Shape and Nonrigid Motion," *Artificial Intelligence*, **36**, 91-123, 1988a.
5. Vincent L. and P. Soille, "Watersheds in Digital Spaces: An Efficient Algorithm Based on Immersion Simulations." *IEEE Trans Pattern Anal Machine Intell*, **13**: 583-598, 1991.
6. Snell, J.W., M.B. Merickel, J.M. Ortega, J.C. Goble, J.R. Brookeman and N.F. Kassell, "Model-Based Boundary Estimation of Complex Objects Using Active Surface Templates," *Pattern Recognition*, In press.
7. Goble, J.C., K. Hinckley, J.W. Snell, R. Pausch, N. Kassell, "Two-handed Spatial Interface Tools for Neurosurgical Planning", *IEEE Computer* (to appear).
8. Siddon, R.L. and N.H. Barth, "Stereotactic localization of intracranial targets," *Int J Radiation Oncology Biol Phys* **13**: 1241-1246, 1987.

Polhemus Navigation Systems, Inc. to monitor the location of interface “props”. Each prop is instrumented with a small magnetic receiver which generates a signal in response to pulsed magnetic waves sent out by a nearby magnetic field transmitting box. The FASTRAK system processes the signals generated by the receiver to determine the location (x, y, z) and orientation (yaw, pitch, roll) of each receiver relative to the transmitting box, and returns this information to the host computer via an RS232 serial port connection.

When the user picks up the head prop (a doll head) and rotates it, the computer-generated 3D image of the individual patient’s head seen on the screen is automatically updated to match the orientation of the doll’s head. The surgeon can also control the image zoom factor by moving the doll’s head towards or away from his or her body. Since moving the head left-right or up-down is typically not useful, we have found it helpful to constrain the (x, y) position of the polygonal brain to the center of the screen. This simplifies the task and surgeons find it natural.

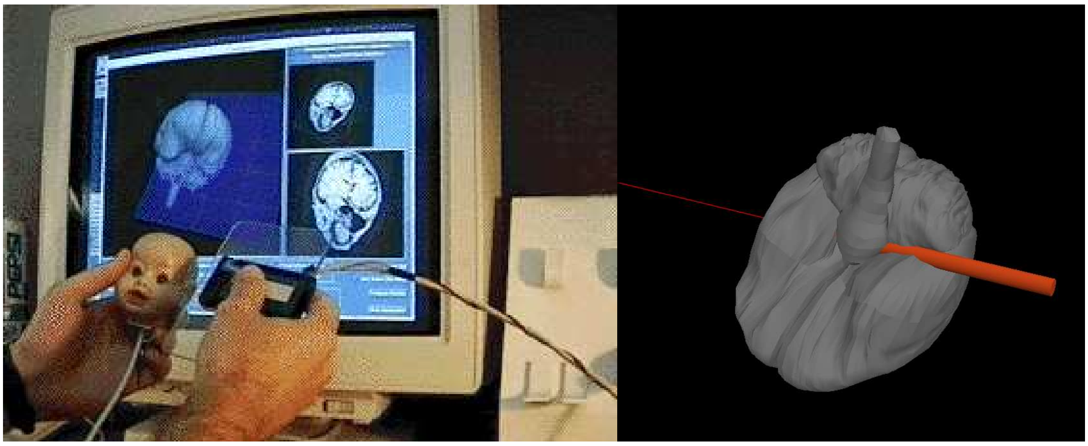

Figure 7 - Physician using two-handed interface tools (left). Close-up of surface model being manipulated (right).

The on-screen image or “virtual head” is actually updated approximately 15 times per second, so from the user’s perspective, the motion of the doll’s head and the motion of the virtual head appear to be tightly coupled. Ideally, as the surgeon rotates the doll’s head, he or she would like to see a detailed volume-rendered image of the individual patient’s head (Figure 7). The two-handed interface techniques permit fast, intuitive interaction between the neurosurgeon and complex planning software. These techniques form a basis for surgical planning software that is well accepted by the surgical community.[7]

6. DISCUSSION

We have implemented a 3D computerized stereotactic planning system which integrates many recent developments in computer workstation, graphics and networking technologies as well as our own research in knowledge-based image segmentation and 3D user interface design. Our priorities for system design have emphasized real-time performance, both in terms of rapid image acquisition and user interface interactivity. We have described a fast and accurate brain segmentation method that provides a basis for 3D visualization and surgical planning. The method permits 3D models of patient anatomy to be constructed within minutes of image acquisition, making 3D image acquisition and visualization clinically practical. These 3D models are beginning to provide simple simulations of what the surgeon may expect to see during the actual procedure (Figure 8).

In the last 10 months the system has been used to plan approximately 30 procedures. These procedures included depth electrode placements, pallidotomies, thalamotomies, and tumor biopsies. The use of this system has reduced overall planning time required from hours to tens of minutes. The 3D nature of the system has also enabled the surgeon to plan and execute procedures that would have otherwise been inaccessible from 2D oriented image data.

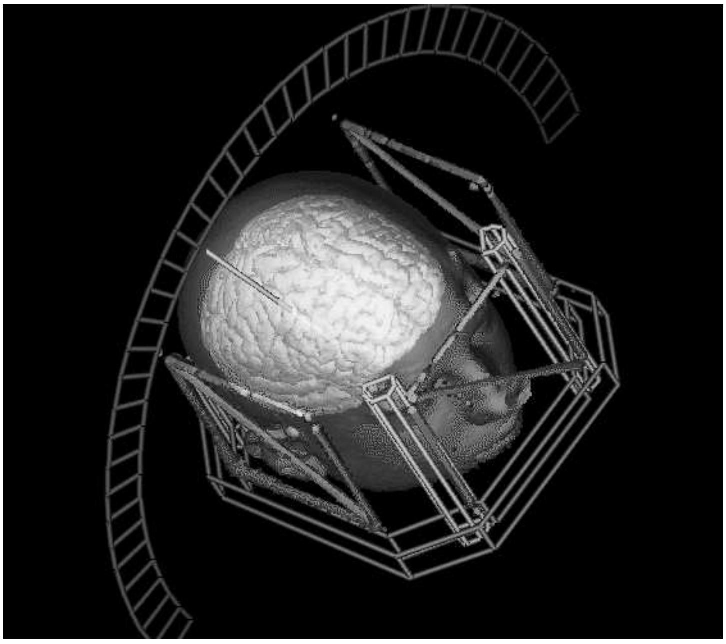

Figure 5 - A typical 3D view produced by the planning system. The brain and head surfaces are rendered with graphical representations of the stereotactic frame, positioning arc and proposed trajectory overlaid. The viewpoint and trajectory can be interactively manipulated by the user. Stereotactic coordinates are returned as the user selects surface points.

The trajectories created during a planning session are maintained on a list. Each trajectory can be accessed by name enabling quick review of the plan. The finalized trajectory list is printed on a form to be used by the surgeon during the procedure. The form records the target point, entry point, trajectory angles and trajectory length for each trajectory. The form, along with any pertinent images, is added to the patient’s chart as a permanent record of the surgical plan.

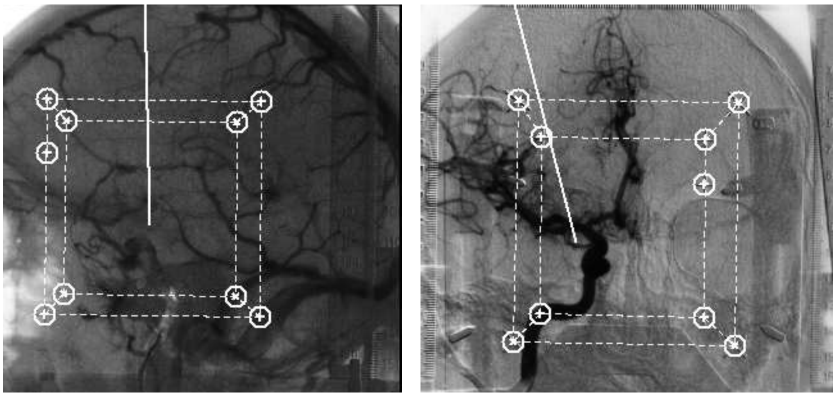

Figure 6 - Surgical trajectory superimposed on the angiographic views. The trajectory projection is updated interactively as the trajectory is manipulated by the surgeon.

5. USER INTERFACE

Neurosurgery occurs in three dimensions and deals with complex three-dimensional structures. The neurosurgeon must be able to visualize these structures and understand how a proposed surgical intervention will impact different regions of the brain. Manipulating 3D models with input devices such as mice has proven ineffective. The selection of a viewpoint and a trajectory can require the user to define as many as 12 degrees of freedom simultaneously. To facilitate this task, our planning system incorporates a 3D interface based on the surgeon’s everyday skills for manipulating real-world tools with two hands.

We use a commercially available six-degree-of-freedom tracking system called the FASTRAK, manufactured by

These estimates are refined automatically by searching for neighboring bright corners in the image volume. These eight points are mapped by the transform into their known positions in the Leksell coordinate system. The 3D transformation allows for stereotactic localization to be achieved on any oblique slice through the volume as well as on any object surfaces defined by segmentation procedures.

Following computation of the affine transformation between the image co-ordinates and Leksell space surgical co-ordinates, the location of the fiducial marks can be rendered into the 3D volume image as shown in Figure (3). The modeled marks should exactly overlay the actual fiducial locations, providing visual verification to the physician that the registration has been accomplished correctly.

4.2 Trajectory Selection

A surgical trajectory is specified by the selection of two 3D points within the stereotactic coordinate system. The first point is the actual target to be reached within the brain. A second point is used to define a path to the target. This second point is often the entry point which is used to specify the burr hole placement.

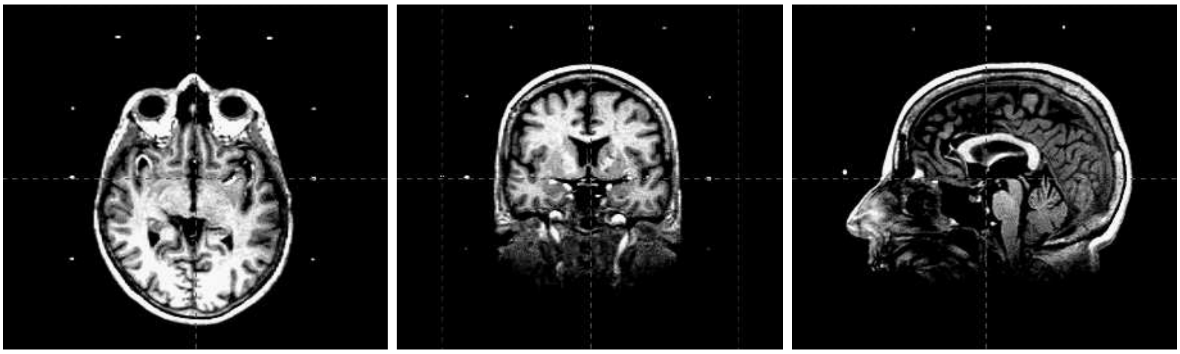

Figure 4 - Targets are selected on orthogonal views through the MR volume. The target cursor is linked between each view so that the three views update as the cursor is moved. Stereotactic coordinates are reported continuously during target selection.

The target point is selected interactively by using an orthographic display tool as shown in Figure (4). Three orthogonal slices through the image volume are displayed showing axial, coronal and sagittal reformats. Each of these slices passes through the currently indicated target point. The current target can be moved in any of the slices while the other two update interactively to reflect the new target position. The stereotactic coordinate of the target is also displayed and updated continuously.

Once a target is selected, a second point must be specified to define a trajectory. This point may also be selected with the orthographic tool, or it may be selected directly from the 3D rendered view. The trajectory can be interactively manipulated by selecting surface points in the 3D view with the mouse. The ability to select skin surface points in the 3D view provides an effective means of positioning burr holes. The fully specified trajectory is displayed as a 3D overlay graphic in the 3D view as well as a projection on the projection angiographic views as shown in Figures (5) and (6). The interactive nature of the trajectory manipulation allows rapid evaluation of potential trajectories regarding their spatial relationships to surrounding vasculature as shown in 2D and 3D angiography views.

The availability of accurate brain surface information allows trajectories to be positioned using cortical surface landmarks. Minimally invasive routes through sulci are readily evaluated with 3D views of the brain surface. The path of a trajectory through the brain can also be visualized by “flying” the orthographic tool down the trajectory. If the combination of orthogonal and 3D views in insufficient to fully visualize a particular structure or trajectory, an oblique reformatted image can be computed. Pallidotomy or hippocampal targets can best be evaluated by creating oblique planes which optimally bisect these structures.

The tissue-selective masking operations effectively removes other enhancing structures which would normally obscure the cortical surface veins. Venography produced in this way has proven extremely valuable in planning surgical trajectories because the 3D nature of the image allows projections from arbitrary viewpoints to be generated. Superior-inferior surgical trajectories are difficult to evaluate with conventional projection angiography because of the loss of depth information. The 3D MR venography is a valuable adjunct to projection angiography in many situations where these trajectories are desirable.

4. SURGICAL TRAJECTORY PLANNING

Our system is currently centered around the Leksell stereotactic system. Fiducial systems for MR, CT and projection angiography allow all the image modalities to be registered into the same Leksell stereotactic coordinate system. Once registration is complete, target points and trajectories can be selected, manipulated and evaluated using all the imagery in an integrated fashion.

4.1 Stereo Registration

CT scans and subtraction angiography images are currently registered using 2D algorithms and standard Leksell localizers. Angiographic images are generally produced using right and left internal carotid contrast injections in a bi-plane angiographic suite. Late phase images are obtained to delineate the venous structures. Photographic subtraction of the cut film images are then digitized using a high resolution film scanner.

The stereotactic localizer box, with four opaque markers on each face, is attached to the frame and remains visible even in the subtracted images. The projection of the markers onto the films is analyzed using a method adapted from Siddon.[8] Our physicians prefer to specify target and entry points of the surgical trajectory from MR images, and then evaluate the projection of the path on the registered angio subtractions.

Axial and coronal MR images may be registered using well known three fiducial techniques similar to those used in CT scanning. We have developed a new, more accurate technique that takes advantage of the three dimensional nature of the MR volume and performs a 3D registration.

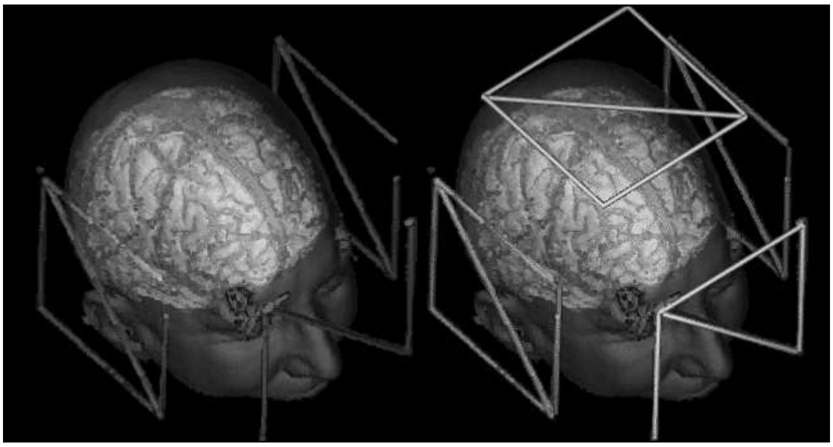

Figure 3 - Before and after 3D Leksell fiducial registration. A graphical representation of the fiducials is overlaid on the image for visual confirmation of the registration.

A 3D transformation between the MR image volumes and the Leksell coordinate system is established by localizing the vertices of the left and right side fiducial boxes as they appear in the 3D rendered image. The initial points indicated by the user are projected along a line orthogonal to the screen and into the image volume until an intersection with the segmented fiducial marker is reached. Since the Z depth is known, we can recover the screen co-ordinates of the individual vertices.

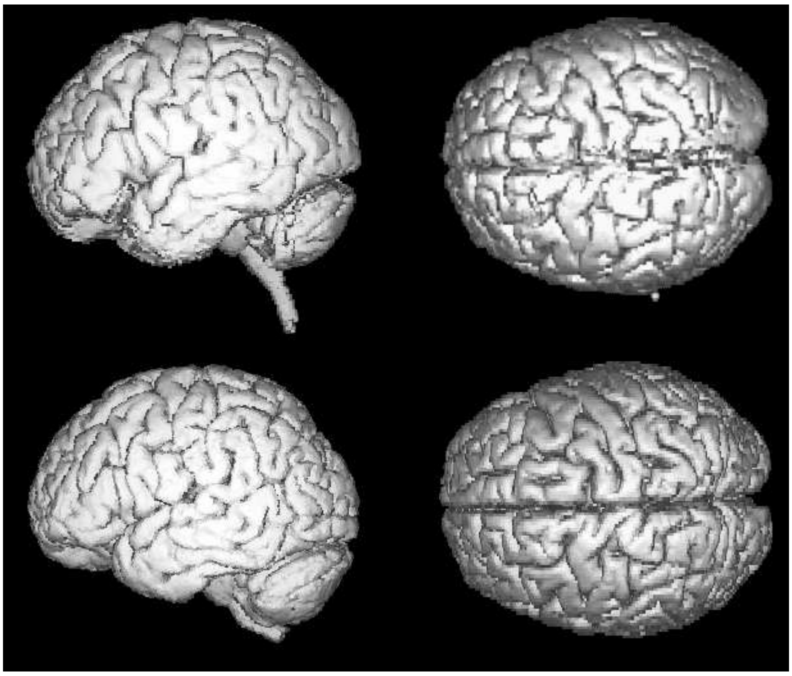

Figure 1 - Comparison of automated segmentation with actual brain dissection. The top row shows reconstructions of the segmented brain in situ. The bottom row shows the equivalent reconstructions of the imaged dissected brain

The segmentation process currently requires less than five minutes on our current platform and works well within the clinical time constraints imposed on our system. We have validated the visualization and volumetric results of the segmentation with a number of cadaver experiments. An example is shown in Figure (1) which compares the segmented image with the image of the manual dissection.

3.2 Subtraction Venography

Once the brain has been segmented, the surface boundaries are used in a secondary step to identify cortical surface veins in a gadolinium contrast enhanced image. A simple subtraction is performed between the post-contrast and pre-contrast MR images after correcting for overall intensity differences. The resulting image is masked using an eroded version of the brain surface found in the segmentation step. A typical result is shown in Figure (2).

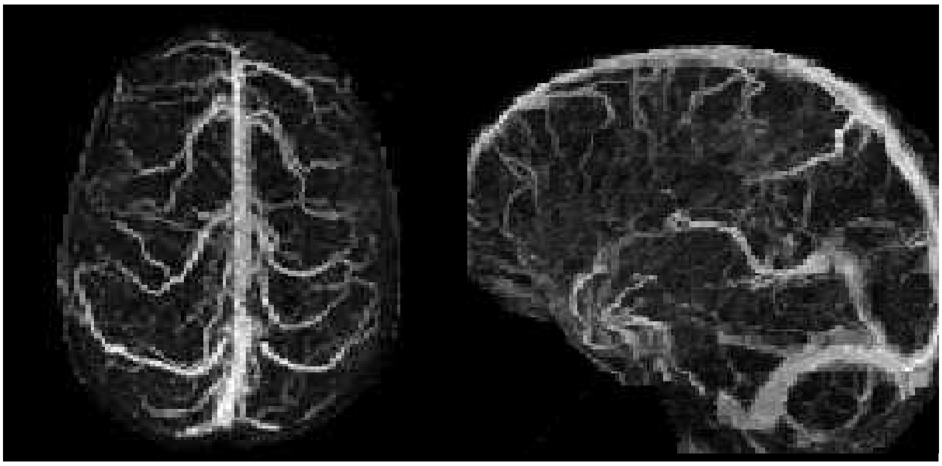

Figure 2 - Superior and lateral maximum intensity projections (MIP) of the MR subtraction venogram after masking with a tissue-selective mask. The mask is derived from the brain segmentation result.

In the future, we intend for the system to act as a DICOM 3.0 client which will allow it to interact with the Radiology PACS system over its private FDDI network. This will eventually free our planning system from all data transfer, storage and archiving responsibilities.

2.2 Data Storage

We have implemented a database server that communicates with its clients over Internet stream sockets. This strategy provides for a reliable and persistent two way communication link between one or more planning processes and the database server/loader process. Authorized clients may query the database for patient lists and image study information. The database provides pointers into a distributed file system that holds the actual image data in a format native to the original source. The server translates the images from their native format into a simple internal format while preserving all the important image header information. This translation simplifies the client side interface and makes file format support changes transparent to the application.

The database also registers “resources” so that associations between image studies and derivative data items may be recorded. Segmented volume data, regions of interest, volume calculations, surgical trajectories and other image related data can be stored and recalled from the database on a per-user basis. With the addition of appropriate data locking mechanisms, this design provides the possibility for multiple, physically separate planning sessions to collaborate using the same image and resource data objects.

3. DATA PROCESSING

The primary image processing step currently used in our system is the semi-automatic segmentation of the brain from 3D MRI studies. This is a particularly difficult problem when confronted with the lack of contrast between the brain and its adjacent structures as they appear in these images. We typically deal with 3D MR data sets acquired with the 3D MP-RAGE pulse sequence[1] on a 1.5 T Siemens Magnetom. This sequence employs a 180 degree inversion pulse to produce a strongly T1-weighted image with an inversion time of 500 ms. The 3D images are acquired with a 256x256x128 matrix with a typical voxel size of 1.0x1.0x1.5 mm. In order to effectively visualize the brain surface in these image volumes, the brain volume must be identified and separated from its surrounding structures. The segmentation technique we use is described in the following section.

3.1 Image Segmentation

The segmentation of the brain from 3D MRI is accomplished by an active surface template method[6]. A surface model of the brain is stored in the piece-wise linearly scaled coordinate frame defined by Talairach and Tournoux[3]. This system attempts to normalize all brains into a consistent coordinate system based on the localization of specific anatomical landmarks. Once a given image volume is aligned with the Talairach coordinate system, the surface model is mapped into the image volume and used to initialize a deformable surface model based on the mathematics of deformable models[4]. The hemispheres, cerebellum and brainstem are modeled by separate, but mutually constrained surfaces. This allows high curvature folds to form along the boundaries of the subsurfaces while enforcing smoothness and continuity everywhere else. An energy functional derived from a vector distance transform[2] pushes the deformable surface model from its initial conditions into close alignment with the individual brain surface. When convergence is achieved, the final surface configuration is used to assign tissue class identifiers to each voxel.

The system consists of several principal software components, including:

- A simple, distributed database for medical images, segmented data, regions of interest and other resources related to the planning system. The database server will be DICOM compliant in the near future and will generate queries against the recently installed Radiology PACS system.
- An intelligent image loader. The loader recognizes a number of common image file formats, including GIF, TIFF, PPM and Sun Rasterfiles. It also can load ACR/NEMA v2.0 data files, including most vendor's private blocks, and also recognizes some purely proprietary formats such as those for GE 9800 and Picker CT scanners, Lumisys film digitizer files, etc.
- Support for Asynchronous Transfer Mode (ATM) links in the local area and wide area environments over 100 Mbit/sec multi-mode fiber connections. Many current imaging devices do not have ATM capability, so planning workstations and file servers are also connected through nominal 10 Mbit/sec Ethernet connections.
- Complete stereotactic registration software for the Leksell system, including MR, CT and projection angiographic localizers.
- Software for semi-automatic 3D MRI image segmentation. This module uses a knowledge-based approach to classify each voxel in the volume into one or more tissue classes.
- A planner module that permits surgical trajectory selection from any stereotactically registered modality.

The principal planning computers are essentially commercial high performance UNIX workstations connected via a private ATM network using multi-mode fiber. To permit planning in real-time, these machines must be robust. A typical configuration:

- Processor: Hewlett-Packard HP9000/735.
- 2 Gbytes of fast-wide SCSI disk with NFS access to a 20Gbyte file server.
- At least 196 Mbytes of memory.
- 48 CRXZ dual 24bit frame buffers
- ATM and Ethernet network interfaces.
- Custom user interface devices.

Planning computers are located in the Neurosurgical Visualization Lab (NVL), in a Neuroradiology reading area, and in the principle neurosurgical operating room suite. An 100Mbit/sec multi-mode fiber connection also links the NVL to the operating room suite via ATM switches. Simultaneous data, JPEG-compressed video and high quality stereo audio can be transmitted.

2. DATA ACQUISITION

2.1 Data Transfer

Acquiring the original source images from the digital imaging modalities in clinically useful times remains a challenge. Many MR and CT scanners still in active and useful service are based on computers that are not well suited to networking. Vendor software has traditionally used proprietary file formats, undocumented file compression techniques, and little ability to co-exist in mixed vendor environments. More recent acquisitions are usually based on commercially available processors, and can often be networked more easily - although transfers are likely to be limited to Ethernet speeds.

In our facility, the principal MR scanner used for surgical planning is running third party TCP/IP software running over an Ethernet transport layer. The imaging required for typical surgical planning may easily exceed 20 Mbytes, and transferring these data sets to our planning workstations over a heavily loaded hospital 10BaseT network can be a major problem.

Currently, the source images are stored on a workstation that functions as a file server, with several Gbytes of fast SCSI storage and an attached 20Gbyte optical jukebox. This storage is adequate for clinical operations but requires frequent migration of image files to backup 4mm DAT tapedrives when the surgical case load is high.

Proc. SPIE Medical Imaging '95: Image Display, SPIE Vol. 2431, pp. 110-118.

A Three-Dimensional Stereotactic Neurosurgical Planner/Simulator

J.W. Snell, T.R. Jackson, W.T. Katz, K. Hinckley, J.C. Goble and N.F. Kassell

Department of Neurological Surgery, University of Virginia, Charlottesville, VA 22908, U.S.A.

ABSTRACT

Abstract - We have designed and implemented a computer-based system for three-dimensional stereotactic planning of minimally invasive neurosurgical procedures. The system integrates rapid acquisition of digital medical images, segmentation, multi-modality registration, and three-dimensional planning capabilities. Emphasis on real-time planning is central to our system: imaging, pre-processing and planning are performed on the morning of surgery in clinically useful times. We have tested the system on procedures such as needle biopsies, depth electrode placements, pallidotomies, thalamotomies and craniectomies for arteriovenous malformations, aneurysms and tumors. We describe in this paper the core algorithms of our system, and discuss issues related to implementation, validation and user acceptance.

1. INTRODUCTION

The recent and widespread availability of 3D medical imagery, together with rapid advances in computer and communications technologies, has shifted the role of modern medical imaging in patient care. Once purely diagnostic tools, magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET) and others are playing an increasing role in planning and execution of therapeutic interventions. While 3D imagery is routinely available in clinically acceptable times, it is only with the emergence of capable software tools that the 3D nature of this data has become accessible. We have developed a system for the planning of stereotactic neurosurgical procedures in a consistent and integrated 3D context.

With careful design, the range of available image data may be made simultaneously available in an intuitive and timely way. Our system allows all operations and measurements to be conducted within a consistent stereotactic coordinate system. Transformations between image volumes and the stereotactic coordinate system are provided by a 3D fiducial registration technique. The 3D nature of this registration provides increased accuracy and allows for real-time computation of arbitrary, coregistered 2D reformatted images. An automated 3D brain segmentation algorithm based on active surfaces rapidly provides accurate brain surface data for visualization of important landmarks including brain surface vasculature. Target points can be interactively selected on surfaces in a 3D display or in any of the 2D reformatted views. An available 6D prop-based interface allows the neurosurgeon to manipulate 3D image objects with hand held props, making complex visualization tasks intuitive. Most importantly, by emphasizing the real clinical constraints on time, our system can function within the neurosurgeon's clinical routine.

1.1 System Overview

A principal goal of our system is to act as a framework for a continuing program of research in techniques for pre-surgical planning, intra-operative navigation, image measurement and analysis and physician-computer interface design. Written entirely in *C++*, the system is inherently modular and can easily be configured for specific research and clinical support projects.