Retopologizing MRI and Diffusion Tensor Tractography Datasets for Real-time Interactivity

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Retopologizing MRI and Diffusion Tensor Tractography Datasets for Real-time Interactivity

by

R. Scott Riddle

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Thesis Approval

Retopologizing MRI and Diffusion Tensor Tractography Datasets for Real-time Interactivity

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III
Abstract

Current technology allows MRI and other patient data to be translated into voxel-based 3D models for the purpose of visualization. However, these voxel models are extremely complex and are not suitable for rapid real-time manipulation. For true “on-the-fly” interactivity, polygon-based models must be hand-built using other methods and imported into a game engine. This project develops an algorithm to translate complex datasets into optimized models for real-time interactivity without sacrificing accuracy of the original imaging modality. A working prototype, ready for integration into game engines, has been built with brain tumor data exported from OSIRIX$^1$ and 3D Slicer$^2$ via Mudbox3, retopologized in 3D Coat$^4$ and re-imported to Maya$^5$. White matter tracts detected by Diffusion Tensor Tractography are exported as volume models using 3D Slicer. The model has been integrated into the Unreal Development Kit (UDK)$^6$ game engine to facilitate real-time interactivity across multiple platforms, including Mac, PC, Apple iOS, Google Android, Xbox 360, and SONY PlayStation. New techniques are being explored to automate and accelerate the process of retopologizing models.

2. 3D Slicer - A multi-platform, free and open source software package for visualization and medical image computing http://www.3dslicer.org
3. MudBox – Autodesk® Mudbox™ 3D digital sculpting and digital painting software http://usa.autodesk.com
4. 3D Coat – Retopologizing and 3D sculpting software http://3d-coat.com
5. MAYA - Autodesk® Maya® 3D animation software delivers an end-to-end creative workflow with compression tools for animation, modeling, simulation, visual effects, rendering, matchmoving, and compositing on a highly extensible production platform http://usa.autodesk.com
6. Unreal Engine 3 – a complete development framework for PCs, iOS, Xbox 360®, and PlayStation® 3, providing a vast array of core technologies, content creation tools and support infrastructure http://www.unrealengine.com/
Retopologizing MRI and Diffusion Tensor Tractography Datasets for Real-time Interactivity

Introduction

The use of three-dimensional imaging in neurosurgery began with the advent of MRI, Functional MRI (fMRI), Computed Tomography, and Diffusion Tensor Tractography (also called Diffusion Tensor Imaging or DTI), which visualizes the white matter tracts of the brain. While some of these imaging modalities have existed for years, their use in neurosurgery and operative planning is relatively new (Filler et al. 2010). The period 2005-2012 witnessed the emergence of operating suites such as the AMIGO (http://www.ncigt.org/pages/AMIGO) (Figure 1), which utilize several imaging modalities (including MRI and DTI) as integrated tools for pre-surgical planning and intra-operative guidance. As imaging modalities become more sophisticated, the role of the medical illustrator increases in importance. While interactivity between the surgeon, patient, and 3D imaging falls outside the traditional realm of medical illustration, today's illustrator strives to keep pace with continuous advances in the world of 3D imaging technology. Introducing the tools of our trade, such as MAYA (http://usa.autodesk.com/maya/), 3D Studio Max (http://usa.autodesk.com/3ds-max/), 3D Coat (http://3d-coat.com/) and Cinema 4D (http://www.maxon.net/) can help solve visualization challenges faced by surgeons and computer scientists. Creative thinking applied to user interface design, 3D modeling, and animation techniques employed by medical illustrators is needed to help shape the future of pre-surgical planning and intra-operative guidance. This emerging role for the medical illustrator has motivated our research into the utilization of existing software, and the design of new software, to supply interactivity and functionality of MRI and DTI data for pre-surgical planning and intra-operative usage. Integration of the roles of surgeon and medical illustrator can lead to techniques that correlate with improved patient outcomes.

3D Neuro Imaging, Pre-Surgical and Intra-Operative Planning

In order to improve patient outcomes, neurosurgeons must carefully plan incision sites, cranial window placement, and navigational routes to target structures. Pre-surgical imaging data can be segmented to create 3D models of anatomical and functional structures. Data from several imaging modalities (MRI, fMRI, DTI, CT, and Ultrasound) are combined in 3D scenes to help determine tissue characterization, localization and targeting, while utilizing real-time tracking based on surgical device placement.

Frameless and frame-based stereotaxy are navigational technologies that allow neurosurgeons to accurately determine their location and direction during surgery. Frame-based systems employ a rigid frame connected to the skull as a point of reference before and during surgery (Gerber et al 2001). Frameless stereotaxy does not require a
fixed frame and relies instead on the use of fiducials (nearby anatomic structures) as placement markers. These methods of intra-operative navigation permit continuous updating of 3D images based on the surgeon’s position during the operation. Probes such as ILDs (Interactive Localizing Devices) and unlinked surgical probes like the ISG Viewing Wand System (ISG Technologies, Mississauga, ON, Canada) are utilized in combination with 3D imaging to enhance intra-operative navigation and improve patient outcomes (Atlas 2008, Schiffbaur 1999). Other examples of intra-operative guidance technologies include sonic triangulation, infrared light-emitting diode (LED) triangulation, machine vision-passive video, magnetic field deflection, and inertial guidance systems. Recent data underscore the advantages of intra-operative accuracy, as measured by perioperative morbidity and long-term patient outcomes, but so far is limited to cerebral glioma surgeries (Schulz et al 2012).

Cranial stereotactic systems that rely solely on pre-operative imaging data are subject to inaccuracy introduced by resection of pathology and movement of the brain during surgery (“brain shift”). Although these systems allow precise navigation initially during a procedure, brain shift resulting from surgical intervention can lead to progressive degradation in accuracy, with the greatest inaccuracy occurring when deep structures are manipulated (Nabavi et al 2001, Mislow et al 2009). No matter how good the pre-operative imaging, it is of little use once the structures of the brain begin to change shape and position during surgery. This underscores the importance of continuously updated “on-the-fly” intra-operative imaging. Newer systems employ continuously updated intra-operative imaging to compensate for this phenomenon.

The use of 3D imaging in neurosurgical planning has existed since MRI was first developed in 1972, and has stimulated ardent efforts to integrate all imaging modalities available (MRI, 1974; CT, 1979; DTI, 1996) to aid in surgical planning (Filler et al 2010). Founded in 1990, the Surgical Planning Laboratory at Brigham & Women’s Hospital (BWH) in Boston has been a leader in intra-operative imaging. A cooperative effort between Neurosurgery, Radiology, Otorhinolaryngology, and other departments, the Surgical Planning Laboratory has created an open-configuration MRI scanner that allows concurrent intra-operative guidance (Mislow et al 2009). First completed in 1994, their system has since evolved into the 0.5 tesla iMRI Advanced Multimodality Image Guided Operative Suite (AMIGO; Figure 1). Various pre-operative scans (T1- and T2-weighted MRI, MR angiography, and functional MRI) are combined and automatically aligned with the operating field of the interventional MR system (Atlas 2008). The Surgical Planning Laboratory at BWH has since added software such as 3D Slicer (http://www.slicer.org/) (Figure 2) to create volumetric imaging of the brain’s white matter tracts, as determined by Diffusion Tensor Imaging (DTI). 3D Slicer’s volumetric imaging is part of the software system developed to determine acceptable resection margins, while maintaining brain function and dealing with imaging complications associated with surgically induced deformations, i.e., brain shift.
Algorithm to Construct Brain and Tumor Models

The goal of the current research is to identify a methodology that enables patient-specific MRI and DTI data to interact in real time across multiple computer platforms (PC’s, tablets, hand-held devices, etc.) for pre-surgical planning and intra-operative guidance. The methodology uses open-source and commercial software that is readily available to the 3D animator/illustrator to generate clean “quadratically usable meshes” from patient specific data sets. While CT, fMRI and other imaging modalities are used in intra-operative and pre-surgical planning strategies, this research focuses only on the use of MRI and DTI. This is only an initial “test of concept” and further research is needed before it can be applied to actual surgery.

For optimum performance, 3D models must utilize “clean geometry”, a term used by 3D modelers and animators to describe a quadratic mesh that is free of extra vertices, triangular faces, and other defects. A clean mesh must also take into account “edge flow,” or the way in which edges are deformed during animation and manipulation of the model. Since medical imaging data often consists of highly complex triangular meshes with many artifacts and defects, an important part of this algorithm is to convert this data to a more efficient, usable form. A clean mesh is essential for subsequent import into a game engine for real-time interactivity.

The first portion of this work focused on obtaining data sets for patient specific MRI information that included brain, brain tumor, and relevant anatomical orientation models. Specific Regions of Interest (ROI’s; e.g. brain, tumor, ventricles) were exported as non-quadratic surface meshes for retopologizing, i.e., converting from triangular to
quadratic meshes. MRI data was obtained from the BRAINIX and CEREBRIX open source datasets provided by OSIRIX (http://www.osirix-viewer.com/datasets/). These data sets were opened in OSIRIX to create a surface mesh from a 3D volume created by “stacks” of MRI slices at 1mm intervals. These files were opened in 2D viewer, then into 3D volume rendering within OSIRIX (Figure 3). A 3D preset of red on white was chosen to provide as much contrast between structures that required exporting.

**Figure 2.** Screen capture of image from 3DSlicer – Top: DTI data displayed as linear paths. Bottom: delineating the ventricle as a Region of Interest.
Figure 3. Screen capture of images from OSIRIX - Brain and tumor displayed as volumes.

Figure 4. Screen capture of image from OSIRIX - Brain surface model.
A series of manipulations within OSIRIX were applied, including Color Lookup Table (CLUT) and contrast adjustments to define the volume data as precisely as possible. The brain volume data was viewed as a surface mesh by choosing 3D surface rendering and exported from Osirix as an .obj file using the Export 3D-SR command (Figure 4). The same method was used to export tumor volumes. An MRI dataset was opened in 2D viewer within OSIRIX. The tumor volume was located and isolated as a Region of Interest (ROI). Excess volume data was discarded by deleting information before transferring to 3D surface render.

The brain orientation model and tumor volume surface meshes were then opened in Mud-Box and converted from .obj to .fbx file format. There is no specific advantage to the .fbx format. This was done simply to prevent frequent crashing of the 3D software. The large size of the files in this state, software interpolation of these meshes during interaction, and hardware limitations may explain the high incidence of software crashes experienced.

Each .fbx file was then opened in MAYA as a non-quadratic surface mesh. The mesh is created from a point cloud, which is temporarily interpolated into a triangular mesh of limited application for interactive modeling. The brain surface mesh was “cleaned up” in MAYA after importation, deleting any irrelevant information carried over from OSIRIX (Figure 5). The same process was followed for the tumor volume data.

The brain and tumor volume triangular meshes were saved from MAYA in .obj and .fbx formats and imported into 3D Coat for retopologizing as clean, quadratic meshes (Figure 6). They were imported into 3D Coat via the AUTOPO function and automatic retopologization was applied. Auto-retopologization (AUTOPO) is a function of the software that interpolates what the software “thinks” the retopologized model should look like while converting the initial triangular mesh into a cleaner quadratic model. The retopologized models were exported and re-opened into the same scene file within MAYA, and, saved as a maya.ascii file.

The AUTOPO import method was somewhat less accurate and had poorer edge flow properties than a model retopologized “by hand” within 3D Coat. However, AUTOPO was chosen because it more closely approaches the sort of “instantaneous retopologization” that will be necessary to generate models on-the-fly during surgery. With improvements in auto-retopologization software, it will be possible to generate interactive models that respond to changes in the operative field during surgery (i.e., brain shift).
Figure 5. Screen capture of image from MAYA - “Cleaned up” brain model.

Figure 6. Screen capture of image from 3D Coat - Brain model during retopologizing.
**Algorithm to Construct Tractography Data**

Diffusion Tensor Tractography (also called Diffusion Tensor Imaging or DTI) is a method of imaging white matter tracts in the brain. Water molecules diffuse through the cytoplasm of axons and, therefore, flow along the pattern of white matter fibers. Diffusion-weighted MRI follows the flow of these molecules and allows clear mapping of white matter tracts as elliptical tubes (Masutani et al 2003) (Figure 7). The importance of DTI in brain surgery has been recognized since its invention in 1996. In that time it has proven invaluable in functional neuro-navigation – utilizing DTI information to delineate white matter tracts from surrounding tissue. DTI data is rigidly registered to 3D datasets of anatomical and pathological structures. From this combination, a preoperative plan is developed that maximizes tumor resection while preserving the tracts. During surgery, intra-operative MRI and DTI data are combined to help compensate for the effects of brain shift (Nimsky, et al 2001; Mislow et al 2009).

3D Slicer (http://www.slicer.org/) was used to obtain Diffusion Tensor Tractography (DTI) data from a patient-specific data set. This software, developed with the help of Dr. Golby and the team at Brigham & Women’s Hospital, reads DICOM files, but is designed specifically for use with DTI data.

Navigation and use of this software is complex, and the process for generating DTI information is beyond the scope of this paper. Briefly, the DTI information was determined by opening a set of DICOM images within 3D Slicer, selecting a ROI and...
applying a fiducial to a region within a specific portion of the brain. Fiducials are used in many imaging modalities as a point of reference for comparing images. In this case, a volume model of the brain ventricles was used as a reference point in determining DTI within the 3D Slicer software. The 3D volume of this anatomical landmark in relation to the DTI data was useful in determining volume relationships in space between the ventricles and white matter tracts (Figure 8).

The DTI model was then exported from 3D Slicer as a .vtk file and imported into MAYA using the ImportVTK plug-in (http://importvtk.sourceforge.net). The DTI data appears as a series of linear paths corresponding to white matter tracts (Figure 9). In MAYA, the paths can be rendered as a surface mesh using the loft function within the polygons menu. These independent lofts are combined using polygon modeling functions in MAYA, producing a clean quadratic mesh with no need for retopologization.

**Real-Time Interactivity**

Retopologized models of the brain and tumor volume (from Osirix/Mudbox/3D Coat) along with DTI and brain ventricle models (from 3D Slicer) were combined into a single scene within MAYA (Figure 10 and Figure 11). The models were then integrated into the game engine Unreal Development Kit (UDK) (www.unrealengine.com/udk) for real-time interactivity. The retopologized MAYA models of the brain ventricle and volume surface meshes, as well as the DTI surface model and tumor volume surface mesh were exported from MAYA as .obj files, and imported as assets into UDK. Using the 3D Slicer color palette as a guide, the models were colorized to differentiate anatomic structures. The assets were combined within UDK and placed within a default game engine environment (Figure 12). Collisions or actions were not applied to parts or sub-parts of the prototype. Once integration of the prototype into the interactive environment was completed, “proof of concept” was verified.

It was hoped that UDK could provide the sort of “instantaneous retopologization” that is needed for intra-operative guidance. While satisfactory results have not been achieved at the time of this writing, UDK has a function that enables certain aspects of a 3D model to change morphology in “real-time” in response to user actions within the game engine. In a video game, for example, this might include the explosion of an object in response to a collision. The pieces of the “new” environment created by the explosion (programmed similarly to particle effects within MAYA) are automatically retopologized to produce new interactive objects and collision codes. These objects are automatically interactive within the new environment, making it possible to create instantaneous “real-time” interaction to newly introduced 3D models. This concept can be applied to intra-operative navigation, where MRI and DTI data are continuously updated. Software development emphasizing this real-time auto-retopologization – and its integration into a surgical environment – becomes a very real possibility.
Figure 8. Screen capture of image from 3DSlicer - Brain ventricle and tumor data (cystic and non-cystic) visualized as a 3D volume.

Figure 9. Screen capture of image from 3DSlicer - DTI data depicted as 3D tubules.
Future Directions

This project has identified a workflow to obtain highly accurate 3D models from diagnostic imaging studies, retopologize the models to generate “clean” geometry, and import the models into a game engine for real-time manipulation. At present, this workflow is labor intensive and requires cobbled together a variety of different software programs to perform each function (Osirix, Slicer, 3D Coat, Mudbox, Maya, UDK). Although this process may be useful for pre-surgical planning, it is far too complex and time-consuming to have practical applications for intra-operative guidance. Nevertheless, it demonstrates that patient data can be modified and displayed in a game engine for real-time interactivity.

For intra-operative guidance, new software would have to be developed that integrates and streamlines the functionality of all the software mentioned above. Such software would have to:

1. Import patient data from imaging studies such as MRI and DTI.
2. Generate 3D surface meshes or volume models from the imaging data (similar to Osirix or 3D Slicer).
3. Instantaneously retopologize the meshes to generate lighter, cleaner models suitable for import into a game engine environment.
4. Display the models in a game engine environment for real-time manipulation.
5. Automate the entire process for greater speed.
6. Be able to update the models “on the fly” as new imaging data is obtained. This step is critical if the software is to be used for intra-operative guidance in addition to pre-surgical planning. Continuous updates are necessary to show how tissues respond to surgery (e.g., the “brain shift” that occurs during resection of a tumor). Once software is developed in this manner, it could be applied to pre-surgical planning and intra-operative guidance in neurosurgery and other fields. Based on discussions with the Surgical Planning Laboratory at Brigham & Women’s Hospital, this seems the most viable application of the ideas presented here.

The 3D datasets generated “on the fly” during surgery could be archived, just as abdominal surgeons keep a videotaped record of their laparoscopic procedures. Studying these 3D datasets in relation to long-term patient outcomes could help identify a set of “best practices” for the surgical approach, tumor resection, and other surgical decisions. This approach, therefore, could improve outcomes for individual patients and contribute to future advances in surgical technique.

The workflow created from this research can be applied to any medical field that utilizes diagnostic imaging data to obtain better patient outcomes. It is worth noting that this is part of a paradigm shift in the role of the biomedical communicator. Generating 3D models, manipulating those models, and designing the game engine user interface are part of the emerging role of the biomedical communicator.
**Figure 10.** Screen capture of image from MAYA - Brain ventricle, tumor and Diffusion Tensor Tractography (DTI) data – Prototype model.
Figure 11. Screen capture of image from MAYA - Brain ventricle, tumor and Diffusion Tensor Tractography (DTI) data – Prototype model.

Figure 12. Screen capture of image from UnReal Development Kit (UDK) - brain ventricle, tumor and DTI data.
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