State-of-the-Art Computer Graphics in Neurosurgical Planning and Risk Assessment

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Abstract

We present a novel software assistant that unlocks new potentials in neurosurgical planning and risk assessment. It allows surgeons to approach the task in an intuitive manner, by providing them with the possibility to simultaneously observe all relevant data of a case in synchronized 2D and 3D views. State-of-the-art technologies from the field of computer graphics are combined to allow simultaneous interactive rendering of anatomical and functional MR data in combination with manually segmented objects and slice-based overlays. This allows surgeons to perceive a clearer impression of the anatomical and functional structures affected by an intervention, and especially the way they are related to each other. Thus, it significantly facilitates the finding of an optimal intervention strategy.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Display algorithms I.3.5 [Computer Graphics]: Geometric algorithms, languages, and systems J.3 [Computer Applications]: Medical information systems

1. Introduction

Today, neurosurgical intervention planning benefits from the availability of a large variety of imaging modalities and analysis tools. Magnetic Resonance Imaging (MRI) allows e.g. the acquisition of high-resolution anatomical images of the human brain, the detection of lesions by differently contrasting individual tissue types in different MR sequences, the detection of cortical activation areas using functional MR imaging (fMRI), or the identification of major white matter tracts using diffusion tensor imaging (DTI). To support neurosurgeons in analyzing this data, a wealth of algorithms is published in the literature. These include automatic segmentation algorithms for the human brain (skull stripping), statistical methods for determination of cortical activation areas from fMRI data, reconstruction of major white matter tracts using fiber tracking algorithms on DTI data or semi-automated methods for segmentation of three dimensional lesion areas, to name but a few.

Despite the fact that most of these techniques have passed the stage of being pure objects of research, until now one has not succeeded in manifesting them in clinical routine usage. One important reason for this circumstance is the lack of an integrated solution that offers surgeons an access to all the relevant data of a case at the same time.

We describe a software assistant that aims at bridging this gap. It integrates tools for fMRI analysis, DTI-based fiber tracking, cerebral perfusion analysis, manual lesion segmentation and visualization of neurovascular structures into one workflow oriented application which allows both individual and simultaneous visualization of the results. Technically, this becomes possible by combining a hardware accelerated labeled volume rendering with conventional rendering techniques like textured triangle meshes. To avoid transparency artifacts — a common problem when combining and blending various nested objects in 3D — a depth peeling algorithm is used.

2. Methods

The system comprises a variety of software modules for viewing, processing and interacting with MR data. Tasks that have to be accomplished include inter-sequence image registration, calculation of activation maps from fMRI data, calculation of cerebral blood volume (CBV) and cerebral blood flow (CBF) from perfusion data, reconstruction of tensor fields for fiber tracking, estimation and visualization of security margins for dealing with data uncertainty, segmentation of lesions or other structures of interest, and many more. For a more general overview of the software, see [KHK*06].

In this article, we will focus on three of these components which highlight the importance of computer graphics in facilitating neurosurgical planning and risk assessment, as they actively support the surgeon in interacting with the large amount of data and perceiving and understanding the information carried.

2.1. Giga Voxel Renderer (GVR)

The high resolution anatomical images are rendered using our giga voxel renderer [LKP06], which is a slice-based direct volume renderer. It uses an octree-based approach to be able to render huge data sets and adapt the quality to the underlying system. It also makes use of an 8-Bit tagged volume which allows for different rendering styles per voxel. Thus, the brain mask from an automatic skull stripping step can be used to apply different look-up tables (LUT) to brain and non-brain areas of the data. Vessels, which are extracted from a contrast enhanced MR image, get their own tag, as well as other, manually segmented regions of interest. Besides using clip planes the GVR also supports a mask volume which allows to cut single quadrants or octants.

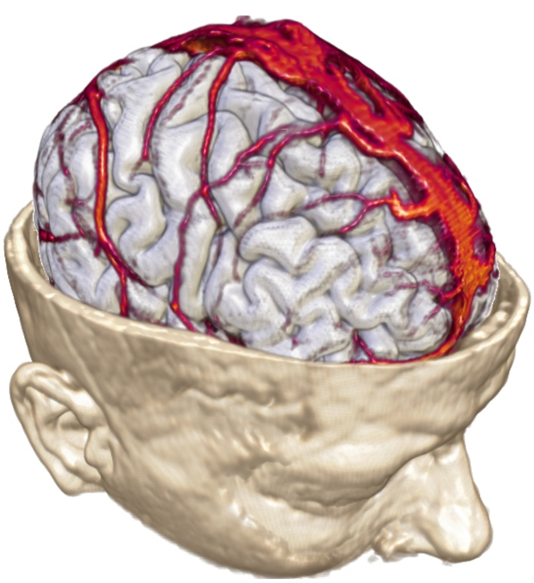

Figure 1: *Tagged volume rendering of anatomical data (resolution: 256*256*132 voxels): Skull, brain and vessels are marked with different tags for individual LUT usage.*

Also, additional data that is used as an overlay on both, the 2D and 3D views, is rendered as single slices using the GVR. This solves the problem of interpolation between datasets of different image- and voxelsizes, as well as a misalignment between volumes caused by acquisition parameters or inter-sequence image registration. This allows to correctly overlay any dataset onto a base-image, and even to combine e.g. fMRI activation maps with color coded diffusion maps from DTI data. For a correct transparency rendering of mesh models like security margins for fiber bundles or segmented tumors we use depth peeling [Eve02].

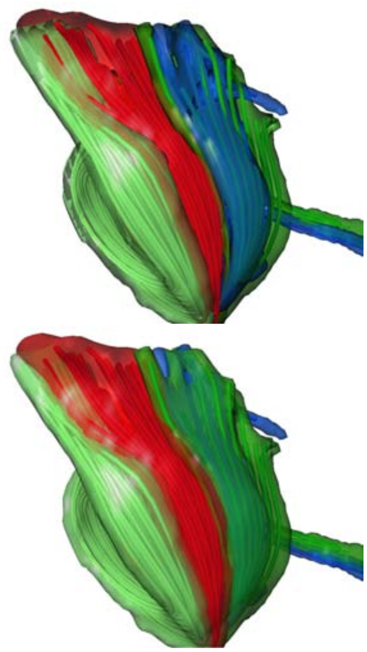

Figure 2: *Handling of multiple transparent layers (security margins of fiber bundles). Top: without depth peeling, bottom: with depth peeling.*

2.2. Surface Generation

In order to investigate certain structures further, it is necessary to segment them. This process should be as fast and precise as possible. Because most of the automatic segmentation algorithms demand either distinct image edges or topological knowledge about the structures to be segmented, we propose an interactive segmentation approach.

For our surface generation algorithm, we only need to draw a few arbitrarily oriented contours and the desired surface is computed by a smoothing 3D interpolation scheme on base of a variational implicit function [TO99]. This takes a subset of each contour's points and corresponding points to the interior of each contour. These points are charged against a thin-plate spline formulation to form a linear system of equations. Now, we yield a smoothed surface distance function that allows us to scan the surface by a recursive marching cubes algorithm. By using that, we are able to produce an anti-aliased mask image. The resulting mask can be visualized directly by using the GVR, or indirectly by converting it into a polygonal surface. Further analysis and statistics are possible by using the mask image on a more basic image processing level.

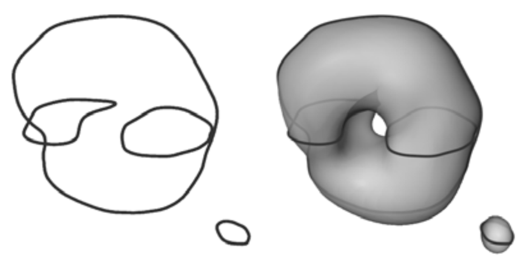

Figure 3: *Interpolation of surfaces from arbitrarily oriented contours.*

2.3. Spectral Fiber Clustering

Fiber tracking is a technique that allows to reconstruct white matter tracts in the human brain which are typically visualized in the shape of sets of fibers. Depending on various properties such as the size and the position of the white matter area used to initialize fiber tracking, a cluttered image may be generated from which it is difficult to get insight. Also, for quantification and comparison between individuals, it is necessary to identify fiber structures with anatomical meaning.

Therefore, we have developed a framework for clustering fiber tracts, where anatomically similar or related fibers are grouped together into bundles [KBL*07]. Since no user interaction is required, undesirable bias is not introduced. Being aware of the complex anatomical structure of white matter fiber tracts, we propose to use spectral clustering as it accounts for detecting non-convex clusters [PG01]. Compared to existing techniques, we have introduced valuable improvements on the computation of a similarity measure as well as on the computation of the number of clusters.

Our clustering algorithm works as follows: First, an affinity matrix representing the similarity of fibers is computed from which afterwards the fibers are grouped into clusters. Due to the large number of 3D points constituting each fiber, existing methods map the high dimensional fiber data to a low dimensional feature space, so that valuable distance information may be neglected. To overcome this problem, we gather more accurate spatial information by our fiber grid. The bounding box around the fiber set is divided into 3D cells of equal size. Then, conceptually, for each pair of fibers

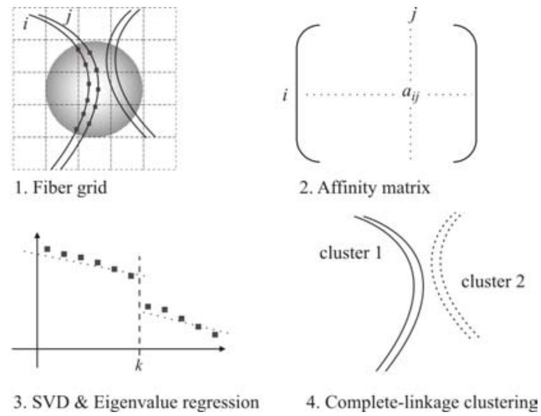

Figure 4: *Schematic overview of the data processing pipeline for spectral fiber clustering.*

the number of cells shared by both fibers is determined. The more such cells exist, the higher is the corresponding value in the affinity matrix. The idea of spectral clustering is fairly simple. A matrix composed of the eigenvectors of the affinity matrix is clustered using a standard clustering algorithm like complete-linkage. The number of clusters can be computed automatically by our eigenvalue regression based on the idea that clusters in a graph correspond to large eigenvalues of the affinity matrix.

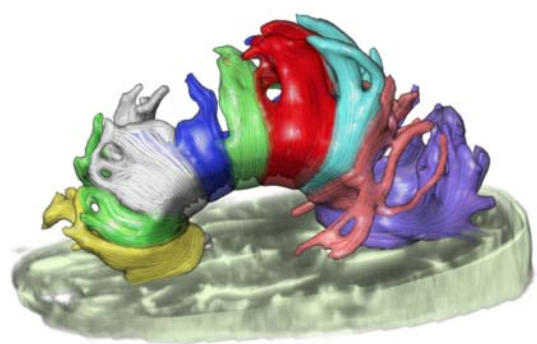

Figure 5: *Clustering results of the reconstructed corpus calossum.*

For visualizing the fiber tracts, we use polygon-based streamtubes colored corresponding to the cluster indices. We apply alpha blending so that further properties of the fibers such as fractional anisotropy can additionally be displayed. However, if color is used to encode spatial and non-spatial information, the visualization of spatial relations and the perceptive separation of adjacent fiber bundles becomes demanding, especially in the case of multi-parameter visualizations. Therefore, we utilize and extend on non-photorealistic rendering techniques [SS02] to emphasize spatial depth and topology with only limited use of color. A new GPU-based hatching algorithm as well as distance encoded stroke shadows improve the perception of spatial relations, such as curvature [RHD*06]. Both algorithms rely on the extraction of depth differences in multi-renditions of the fibers to particularly enhance the perception of spatial depth. Only important surface features are accentuated thereby minimizing the occlusion of properties illustrated by color coding. Color may now be used as a distinct visual attribute for the visualization of non-spatial properties.

3. Results

Our goal in developing the presented software assistant was to create a tool that offers a maximum of possible support in neurosurgical intervention planning and risk assessment. By integrating tools for fMRI-, perfusion- and DTI-analysis together with automatic skull stripping, vessel extraction and manual segmentation of lesions or risk structures, neurosurgeons receive a tool which allows to make planning decisions based on a maximum of available information and therefore reduces the risk of running into unexpected situations during an intervention.

The technical basis of this is build upon state-of-the-art computer graphics. Our system achieves interactive framerates using consumer PC hardware. The attached video demonstrates the techniques described in this paper. It was shot using a prototype of our software, which is currently in the final beta stage and expected to be released later on this year. Until now, we received overwhelming reactions from neurosurgeons who certified the high clinical value of the software.

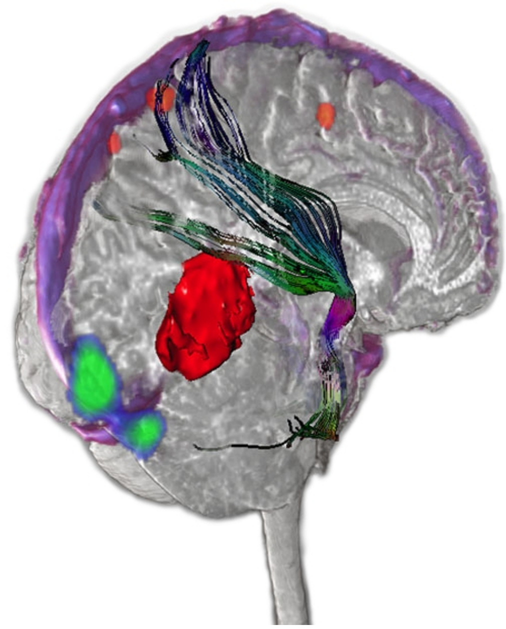

Figure 6: *Putting it all together: Skull stripped anatomical image combined with reconstructed pyramidal tracts, activation maps of the visual motor, a manually segmented tumor and the neurovascular system.*

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