SIGRAD 2013, pp. 61-65
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Visual Planning and Verification of Deep Brain Stimulation Interventions

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Abstract

Deep Brain Stimulation is an alternative way for treating some motion disorders such as Parkinson's disease and essential tremor. In order to stimulate some brain centers during this intervention, high frequency electric fields are generated close by them. This involves permanently implanting a number of electrodes inside the brain. The final position of the electrodes is specified by the neurologist with the aid of fused data from CT and MR scans. In order to improve the therapeutic benefits of this treatment, the generated electric field must be studied. I developed a visualization and image analysis framework for visualize and insert the electrodes inside the brain. A mesh generator for the brain was added to the framework. The result model can be used by a PDE solver for interpreting the electric field distribution.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications—
I.4.6 [Image Processing and Computer Vision]: Segmentation—Edge and feature detection

1. Introduction

Deep Brain Stimulation (DBS) has resulted in a renaissance as an alternative way for treatment of Parkinson's Disease (PD) and essential tremor (ET). The ultimate goal of the Deep Stimulation research is to clearly demonstrate the stimulation process, understanding the reasons beyond several types of motion disorders and optimize the surgery. Eventually, this may lead to safer and faster surgery or even non-invasive electrical stimulation for the motion disorders. Benabid in [BA94] demonstrated the efficacy of SubThalamic Nucleus (STN) stimulation in parkinsonian patients treatment and it is safer than stimulation of Ventralis InterMedius. After one year of following up for twenty patients, Benabid showed that 60% improved in the Unified Parkinson Disease Rating Scale (UPDS) compared to stimulation of Ventralis InterMedius. In order to stimulate some regions in the brain, Deep Brain Stimulation techniques, employ the use of a high frequency electric field in the brain. The electric field is generated through chronic implanted electrodes close to the motion centers of the brain. The final position of the electrodes are depending on neurological and psychiatric disorder. Two important factors are affecting the success of the DBS treatment; the target localization and the stimulation parameters. The SubThalmic Nucleus stimulation is considered the most promising brain center treatment for most of the PD motion disorders. The STN is located in the midbrain and has an small almond shape. The position of STN is clearly identified in T2-weighted MRI and can not be easily identified in T1-weighted MRI. Nevertheless, T2-weighted MRI suffers from geometric in-homogeneity, that makes the localization of the STN in the image inaccurate. The relation between the STN position and the anterior and posterior commissure of the third ventricle in T1-weighted MRI can be found in [PG08].

Within this paper, I describe a multi-view visualization and image processing system, that can be used by the neurologist and physicist to design the leads and insert leads in the brain. The fused volumes help the physicist to visualize the final placement of the leads inside the brain and design a model to be used by a mesh generator. I describe in the following sections the image processing, the placement of electrodes, the data visualization and mesh generation for the designed case.

2. Related Work

In this section I review some related work used during designing the proposed system. A lot of work was done to plan the trajectory of the electrodes inside brain, multi-volume visualization and brain segmentation.

Gemmar et al, proposed a semi-automatic procedure to localize the STN and trajectory planning in the T1-weighted MRI [PG08]. The T1-weighted MRI was smoothed using non-linear anisotropic filtering kernel to preserve the edges. He used a region growing algorithm to segment the third ventricle. AC-PC locations are identified on midsagittal plane calculated from the segmented ventricle. A cost function evaluates the trajectory path from each entry point on the brain surface to the STN location. The best group of trajectories will be elected to be used by the surgeon. A framework introduced by Henri et al for brain segmentation using 3D mathematical morphology [HM], was used in this work.

The electrical field distribution in the region of contact with the electrodes are evaluated by the use of Finite Element Methods. In [AM08] and [FA11], the importance of the stimulation parameters and new target investigation were discussed. A mapping algorithm from the MRI to the 3D mesh were used to measure the electrical conductivity of the tissue in contact of the electrodes. A 3D modeling of the electrodes were used with the electrical conductivity properties, to visualize the electrical distribution around the targets. Delaunay tetrahedralization is a common way to produce 3D meshes from a cloud of points. A Refinement Delaunay tetrahedralization algorithms modify the meshes generated from Delaunay tetrahedralization to fit some criteria such as; mesh size and the mesh angle [Law77]. In [DBB09b] [DBB09a] labeled segmented data was used to produce 3D meshes. The mesh engine in their work is used in this paper to produce a mesh for the brain and the labeled electrodes.

3. System Overview

The system proposed here, was designed to support the neurologist and physicist to design a case to be used for further studies of the electric field distribution around the localized target. In order to use the large amount of data produced from different modalities, image processing, segmentation and volume fusion are applied to give an insight of the data with less mental effort. The MR and CT images are used before and after the DBS intervention to examine the anatomical structure of the brain. The DBS procedure starts by the planning procedure, followed by surgical procedure and ending up with postoperative follow up [SH10]. During the preoperative procedure the head is scanned by CT and MR scanners. The *Stereotactic frame* are used during MR and CT scan to fix the position of the patient's head [GP01] and to guarantee accuracy and facilitate surgical planning. The trajectory plan of the leads and target localization, is main output from this phase. It requires a very accurate computing tool. The presented system was designed to use the trajectory plan data to place the leads inside the fused volumes from the MRI and CT. The stereotactic's landmarks appears in both scans serves as basis for rigid images registration and coordinate systems [DT08].

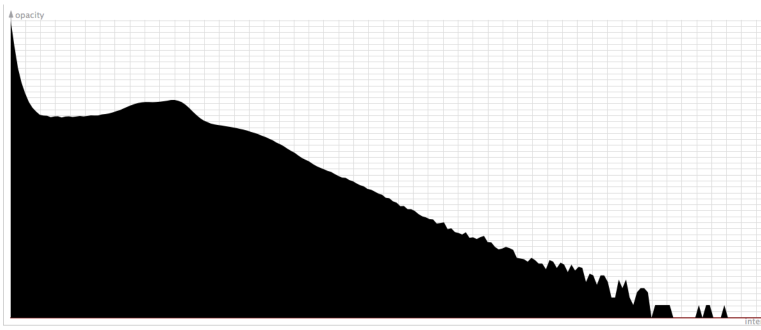


Figure 1: T1 MRI histogram

3.1. Brain Segmentation

The visualization process of the CT and the MRI includes fusing the two volumes in one model. MRI is supreme in soft tissue imaging. The aim of the analysis process in this section, is to segment out the brain from the skull and the skin in T1-weighted MRI. The resulted brain volume is visualized with the skull from the CT and is used for the mesh generation as I describe later in this paper.

I used a 3D mathematical morphology method to segment the brain from the skull in the MRI [HM]. This method uses prior anatomical structure information to be converted to morphological information. The brain can be defined as an elliptical shape that is surrounded by a dark circle (skull) and thin bright circle (skin). The developed algorithm can be divided in two stages. The first stage converts the gray valued volume to a binary volume by thresholding the images. The second stage applies, the 3D morphology operations and image filling to generate a brain mask. The distance function used for the erosion is a 3D version of chessboard.

A typical T1 weighted MRI histogram is shown in figure 1.

The first step is to threshold the image to eliminate as much as possible from the brain surroundings. The threshold values are crucial for the following steps to work perfectly. I proposed a histogram processing technique to generate the threshold values. The histogram of the MRI was first calculated and then smoothed by a Gaussian filter of standard deviation equal to 7 for removing local variations and window size of 5. The local minimums were computed. The lower minimum within every 10 pixels were picked. The previous process generates the lower and the higher threshold values. The lower value of threshold removes the CSF and the skull. The higher threshold value discards higher density materials (eyes, vessels and fat). The output from this step is a binary image representing the brain and the skin.

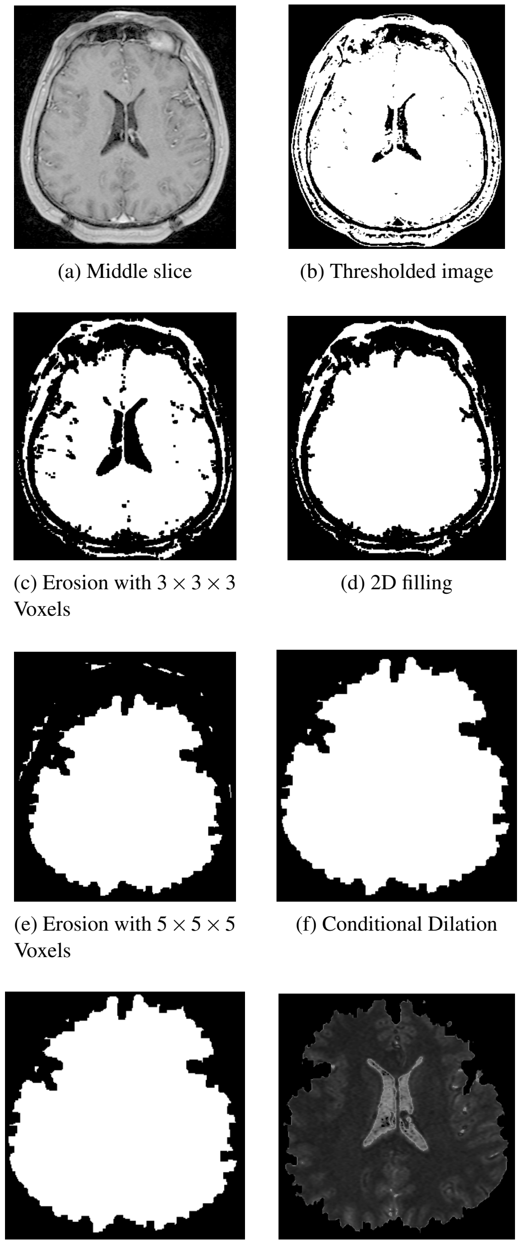
The resulted binary image is eroded by a cube of $3 \times 3 \times 3$ voxels, which is 2mm in every axial slice, to remove the narrow connections between the brain and the skin. A 2D filling algorithm is applied after this to every slice in the image to fill up the holes in the connected components. In order to suppress the big connections between the brain, the eyes and the ears, the resulted volume from the previous step is eroded by a cube of (5mm) $5 \times 5 \times 5$. The biggest connected component from this step is considered to be the brain. Due to the successive erosions in the previous steps, some of the parts of the brain are eliminated. By applying conditional dilation on the result from the first step and by using the marker from the previous step, the brain is reconstructed. Finally, a 2D filling algorithm is applied to every slice. The result is a brain mask that is replaced by gray value from the original volume. The result of every step is shown in the figure 2.

The resulted volume has a 90 degrees corners and straight edges, that is resulted from the erosion and dilation of a cube shape structured element. Nevertheless, the produced edges are not affecting the accuracy of the calculation of the electric field. According to my knowledge, until now electric field calculation in the brain is using Dirichlet boundary condition and the edges of the brain are far away from the leads [ea]. The produced volume corners will be further smoothed during the mesh generation making the electric field calculation using Neumann boundary condition even possible. The insertion of the leads are not depending on the produced edges, because the insertion was planned by another sophisticated tools.

3.2. Multi-Volume Visualization and Lead Insertion

Medical image modalities blossomed during the 20th century, Computed Tomography and Magnetic Resonance Imaging marked a major steps in operation planning. The data acquired from CT and MRI are fused to reveal the interesting parts during insertion of the leads in the brain. During insertion of the leads and the electric field studying, MR data is the most interesting data. The volumes are rendered on the screen to discard the external shell of the brain from the CT volumes around the leads as shown in figure 3. The CT volume and MR volume are assumed to be registered. For volume rendering, I used the ray casting technique presented in [KW03]. I modified the previous work by applying conditional ray casting. The CT voxels are discarded when the MR voxels are not zero. I employed this to prevent the blending of gray value of the CT voxels when MR voxels are presented. The geometric information of both volumes are used by ray casting algorithm for early termination [Sch05]. I added to the previous rendered volumes, an axial and a sagittal view for the MRI and the inserted leads. The leads outside the slice position are clipped out.

The planning of the lead's and electrode positions usually is done by some sophisticated tools. The geometry of the leads are used to place the leads inside the image space. Vertex buffers are created for the surface representation of the leads. The leads surface patches are divided into three patches that represents the top of the lead (half sphere), the



(a) Middle slice

(b) Thresholded image

(c) Erosion with $3 \times 3 \times 3$ Voxels

(d) 2D filling

(e) Erosion with $5 \times 5 \times 5$ Voxels

(f) Conditional Dilation

(g) 2D filling in every direction

(h) Gray value assign

Figure 2: Brain segmentation steps

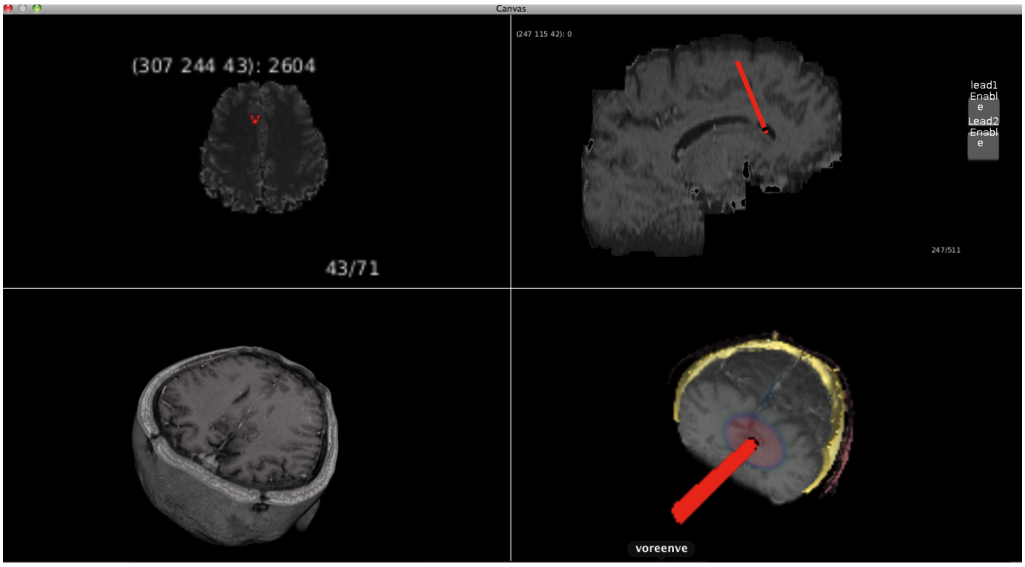


Figure 3: The top left view is axial view. The top right view is sagittal view. The bottom left view is MRI. The bottom right is reconstructed volume with a lead

electrodes (cylinders) and the body of the leads (cylinders). Color attributes are used to visually distinguish between the lead and the electrodes. The leads are rendered in a different path and the depth information is used to blend the colors in the final scene from the volume and the geometry. In this work, I used the lead specification from the Medtronic model 3387 manual [MTS].

3.3. Brain Meshing

The meshing processing is the process of converting a 3D domain of points into a set of tetrahedra. The most popular algorithms of mesh generation can be divided into three classes; Delaunay triangulation, advancing front methods and grid based methods [Owe98]. The studying of mesh generation algorithms is out of scope of this work. Nevertheless, the step of generation of the mesh is required to validate the work presented here. I used the three dimensional constrained Delaunay refinement algorithm described in [She98]. Mesh generation algorithms based on Delaunay refinement starts by Delaunay triangulation followed insertion of vertices in the mesh until certain mesh criteria specified meet. In this work I specified the facet size to be 0.1, the facet angle to be 30 and the ratio between the tetrahedrons circumradius and the length of the shortest edge to be 2 as mesh refinement criteria. Shewchuk [She98] called the input for the algorithm a *piecewise linear complex* (PLC). PLC defines the a set of vertices, segments (which are a contiguous edges presented in the final mesh) and facets which will be triangulated in the final mesh. *CGAL* [cga] provided an 3D mesh Delaunay mesh generator based on the previous described work.

In order to identify the facets for the mesh engine, the voxels of zero value are not considered for the triangulation. The voxels occupied by the leads were set to different values. The leads can be modeled by a quadric equations of cylinders and sphere to represent the lead ad lead's tip. I used these quadric equations that represents the leads, to specify the voxels that are inside the leads. I also used the binary mask representing the segmented brain, that was generated from the segmentation algorithm discussed earlier, to avoid treating the CSF inside the ventricles as holes. The facets and segments of an isosurface representing the input domain are used with the labeled voxels as inputs for the mesh generation engine. The resulting mesh of the segmented brain with one lead inserted is shown in figure 4.

4. Conclusion and Future Work

In this paper I presented a framework for multi-volume visualization and image processing, that can be used for visualizing the lead insertion in the brain. The inserted electrodes inside the brain are meshed to be used for further studies of the electric field. The segmentation process of the brain gives better interactivity on the result of the multi-volume visualization by controlling the transfer functions of every volume separately and removes the complication of ray cast algorithms to separate between bony structures and soft tissues. The main of idea of integrating the segmentation algorithm in this framework is because of its importance in the meshing step. The electric characteristic, that physicist wants to study exists in the brain soft tissues that is provided by MRI.

In the future, I would like to evaluate the presented system by a physicist or neurologist. I also hope to build and

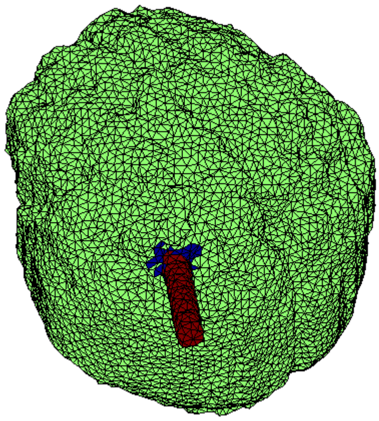


Figure 4: Mesh generation of the brain and one lead

enhance the image analysis system to fully segment out the brain organs. This will make the visualization task for the brain organs clearer and more accurate for the electric field calculation. Also I hope to use DTI for adding organ's conductivity values to generated mesh. I would like to include visualization techniques for the electric field distribution and to find an intuitive way for the adding electric field values in the MRI of the brain.

ACKNOWLEDGEMENTS

The work presented in this paper was conducted during my master thesis of computational science at Uppsala University. I would like to thank the Center of image analysis at Uppsala university, Sweden for their help and comments. The presented work is realized using Voreen framework (www.voreen.org).

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