Generation of High-Quality Tetrahedral Head Mesh Models from MRI Scans

Phong A. Tran
Department of Chemical Engineering
Northeastern University
Boston, USA
tran.anh@husky.neu.edu

Qianqian Fang
Department of Bioengineering
Northeastern University
Boston, USA
q.fang@neu.edu

Abstract— **Generating accurate tetrahedral mesh models for the human brain is a critical step for a wide range of applications, yet the availability of a robust, accurate and computationally efficient meshing algorithm is still lacking. In this work, we present a meshing pipeline that combines various open-source meshing utilities as well as customized MATLAB scripts to generate anatomically accurate and high-quality head mesh models with a typical processing time of less than 1 min. The methodology presented has the advantage to not only be able to combine multiple neuroimaging tools including the often-used SPM, FSL, FreeSurfer and BrainSuite, but also to allow different combination of tissues depending on the availability of the segmentations. The surface-based approach allows great control over the size and quality of the tetrahedral elements. While the focus of the work was on the human brain, segmented datasets of an ovine brain and a baboon brain are also shown to be compatible with the workflow.**

Keywords— brain segmentation, tetrahedral mesh, finite element analysis, head model

I. Introduction

The importance of high-quality mesh models has taken a key role in medical image analyses. While the voxelated representation of medical datasets has been the most common form of data storage and access, it suffers from the terraced boundaries that prevent it from representing smooth and curved tissue boundaries; also the uniform grid structure lead to large storage sizes when representing fine structures. To remediate to these issues, many numerical methods are based on tetrahedral mesh models to gain computational and memory efficiency. Aside from 3D rendering, tetrahedral meshes are used in functional near-infrared spectroscopy (fNIRS) [1] to recover the hemodynamics required to estimate brain activity, electroencephalography (EEG) [2] uses measured electrical potential on the scalp surface and the conductive properties of a head mesh model to similarly estimate brain activity, transcranial magnetic stimulation (TMS) [3] and transcranial direct current stimulation (tDCS) [4] can evaluate brain damages or measuring its effects on major brain disorders using patient-specific head models. Additionally, brain tissue deformations can be simulated for neurosurgeons to assist brain operations [5].

Deriving high-quality head mesh models for the human brain is a major challenge. Voxel-conforming meshing tools such as Cleaver can achieve good surface accuracy, but at the cost of high element density near the boundaries. The Delaunay-based 3D meshing algorithm used in CGAL [6] is robust, fast and parallelizable, but can present rough boundaries. BioMesh3D, an open-source meshing tool, gives high-quality elements, but is extremely slow. Commercial meshing tools such as ScanIP still requires a few hours. Our proposed meshing pipeline is designed to be fast, robust, easy-to-use, flexible and criterion-based to generate high-quality tetrahedral meshes for complex brain anatomies.

II. Methodology

Segmentation volumes are generated using common neuroanatomical analysis tools such as SPM, FSL and FreeSurfer, and are then pre-processed to ensure a layered tissue model - containing white matter (WM), gray matter (GW), cerebrospinal fluid (CSF), skull and scalp, ranked in the inner to outer layer order. This is achieved through a combination of maximum and minimum filters to ensure that any adjacent inner and outer layers are always separated by a small gap. Triangular surface meshes for each tissue layer are extracted using the CGAL Surface Mesh Generation library [7]. These surfaces are smoothed and repaired using the iso2mesh [8]. A modified Cork 3D Boolean library [9] is used to perform surface Boolean operations and merge all layers into a combined surface mesh. When the cortical surface is available, MeshFix [10] is used to decouple the surface mesh layers. Once the surface meshes are resolved in a valid configuration and free of intersecting elements, TetGen [11] is used to generate the final tetrahedral mesh with a set of given quality criterions including radius-edge ratio, minimum dihedral angle, sizing field and mesh density. The generated tetrahedral mesh is then mapped to the segmentation volumes to ensure proper tissue labeling for subsequent analysis.

III. Results

The proposed meshing pipeline is applied to the three presented examples below. In Fig. 1, a five-tissues segmentation of a 40-44 years-old atlas from the NeuroDevelopmental Imaging Database [12] is made using the standard SPM probabilistic segmentation. The surface extraction, tetrahedral mesh generation and labeling steps took ~44.14 sec on an i7-6600K processor. The grayscale extraction is performed with a maximum radius of the Delaunay sphere values of 2 mm for the pial and white matter surfaces, 3 mm for the CSF layer, and 3.5 mm for the other tissue layers for a

1x1x1 mm^3 segmented volume resolution. The maximum element volume size was defined as 40 mm^3; the minimum radius-to-edge ratio was set to 1.414, and mesh sizing field of 4. The final generated mesh contained 487,209 tetrahedral elements and 82,015 nodes.

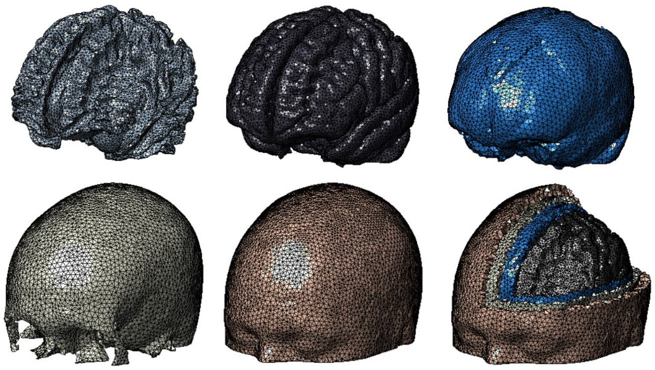

Figure 1. Tetrahedral mesh for WM, GM, CSF, bone, scalp and combined tissues (from left to right and top to bottom) generated from an SPM segmentation of a brain atlas for the 40-44 years-old group.

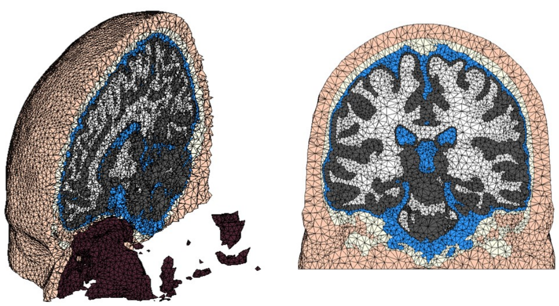

Figure 2. Tetrahedral mesh generated from the segmented Colin27 volume. The air pockets are represented in brown.

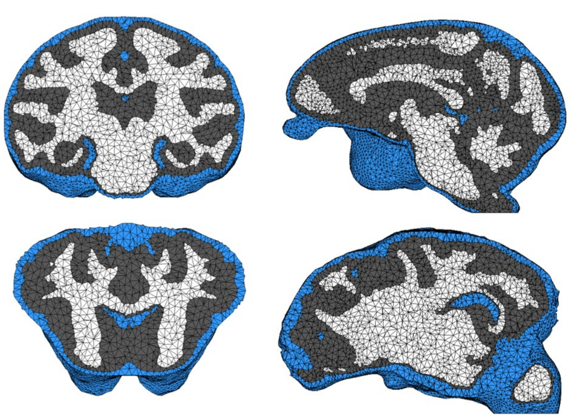

Figure 3. Tetrahedral meshes generated from the “Haiko 89” baboon dataset (top row) and “Ovine Brain Atlas” (bottom row).

The grayscale extraction for the Colin27 [13] in Fig. 2 had values of 1.75 mm for the pial and white matter surfaces, 2.5 mm for the CSF layer, 3 mm for the bone layer, and 3.5 mm for the scalp layer from 0.5x0.5x0.5 mm^3 resolution already segmented volumes of the Colin27. The final tetrahedral mesh was composed of 1,076,118 tetrahedral elements and 177,211 nodes.

To show the flexibility of the proposed workflow, we also use it to process non-human brain scans. In Fig. 3, the mesh for the “Haiko 89” baboon brain [14] contains 331,405 elements and 58,546 nodes. The mesh created from the ovine brain scan from the McConnell Brain Imaging Center [15] contains 363,557 tetrahedral elements and 64,701 nodes.

IV. Conclusion

An efficient meshing pipeline is proposed and tested for generating high-quality and anatomically accurate tetrahedral meshes from segmented brain data. This workflow is flexible to the segmentation input type, shows applicability to other types of mammal brains, and has desirable properties in terms of element quality, mesh density and mesh generation speed.

Acknowledgment

The authors wish to thank the funding supports from the NIH R01GM114365 and R01CA0204443 grants, as well as Dr. Hang Si for the advice on the use of TetGen.

References

[1] Strangman, Gary, David A. Boas, and Jeffrey P. Sutton. "Non-invasive neuroimaging using near-infrared light." Biological psychiatry 52.7 (2002): 679-693.

[2] Ramon, Ceon, Paul H. Schimpf, and Jens Haueisen. "Influence of head models on EEG simulations and inverse source localizations." BioMedical Engineering Online 5.1 (2006): 1.

[3] Yang, King H., et al. "Modeling of the brain for injury prevention." Neural tissue biomechanics. Springer Berlin Heidelberg, 2011. 69-120.

[4] Rampersad, Sumientra M., et al. "Simulating transcranial direct current stimulation with a detailed anisotropic human head model." IEEE Transactions on Neural Systems and Rehabilitation Engineering 22.3 (2014): 441-452.

[5] Warfield, Simon K., et al. "Real-time registration of volumetric brain MRI by biomechanical simulation of deformation during image guided neurosurgery." Computing and Visualization in Science 5.1 (2002): 3-11.

[6] Pons, J-P., et al. "High-quality consistent meshing of multi-label datasets."*Biennial International Conference on Information Processing in Medical Imaging*. Springer Berlin Heidelberg, 2007.

[7] Jean-Daniel Boissonnat and Steve Oudot. Provably good sampling and meshing of surfaces. Graphical Models, 67:405–451, 2005.

[8] Fang, Qianqian, and David A. Boas. "Tetrahedral mesh generation from volumetric binary and grayscale images." *2009 IEEE International Symposium on Biomedical Imaging: From Nano to Macro*..

[9] Bernstein, G.. Cork Boolean library. https://github.com/gilbo/ cork; 2008–2015.

[10] Attene, Marco. "A lightweight approach to repairing digitized polygon meshes." *The visual computer* 26.11 (2010): 1393-1406.

[11] Si, Hang. "TetGen, a Delaunay-based quality tetrahedral mesh generator."*ACM Transactions on Mathematical Software (TOMS)* 41.2 (2015): 11.

[12] Fillmore, Paul T., Michelle C. Phillips-Meek, and John E. Richards. "Age-specific MRI brain and head templates for healthy adults from 20 through 89 years of age." *Frontiers in aging neuroscience* 7 (2015): 44.

[13] Holmes, Colin J., et al. "Enhancement of MR images using registration for signal averaging." Journal of computer assisted tomography 22.2 (1998): 324-333.

[14] Love, S.A., Marie, D., Roth, et al.. The average baboon brain: MRI templates and tissue probability maps from 89 individuals. NeuroImage. doi:10.1016/j.neuroimage.2016.03.018

[15] Nitzsche B, Frey S, Collins LD, et al. A stereotaxic, population-averaged T1w ovine brain atlas including cerebral morphology and tissue volumes. Front. Neuroanat. 9:69. doi: 10.3389/fnana.2015.00069