FINITE ELEMENT DECOMPOSITION OF HUMAN NEOCORTEX

David A. Batte, Travis S. Chow, and Bruce H. McCormick

Scientific Visualization Laboratory
Department of Computer Science
Texas A&M University
College Station, TX 77843-3112

IMPORTANCE OF FINITE ELEMENT BRAIN

Modeling brain morphology at both cellular and tissue levels brings richness to our understanding of brain organization that both complements and transcends knowledge derived exclusively from neuron tracing and brain atlases.

The neocortex of the human brain has been geometrically modeled and visualized using finite element decomposition and grid generation techniques. The work reported here extends modeling techniques reported previously (CNS*96) [1] to the whole human neocortex. Approximately 2500 finite elements (FEs) of the scale and complexity shown in Figure 1 are used to model the right hemisphere of the human neocortex. The finite elements of the human cortical shell are established in a manner consistent with developmental neurobiology.

Each neuron in a neuron morphology data repository, whether a traced biological neuron or a synthetically generated neuron, can be assigned to the FE which contains its soma. The cerebral cortex, so modeled, can be viewed as a giant "chest of drawers" where a "drawer" (any selected FE or cluster of neighboring FEs) can be "opened" as a file and its population of neurons visualized as illustrated in Figure 2. These FEs therefore define a file structure isomorphic to the neocortex as modeled and visualized at both cellular and tissue levels.

Neuron morphology data repositories for the human neocortex are in an early state of development. In future work, adding stochastic L-system modeling of the neuron populations will lead to a normative morphological model of the human neocortex. In principle this normative model would generate neurons statistically indistinguishable in morphology from the neuron forests of an actual brain as viewed at the limit of optical resolution. The required storage space for the normative model is estimated as six megabytes of data.

Computational Neuroscience
edited by Bower, Plenum Press, New York, 1998

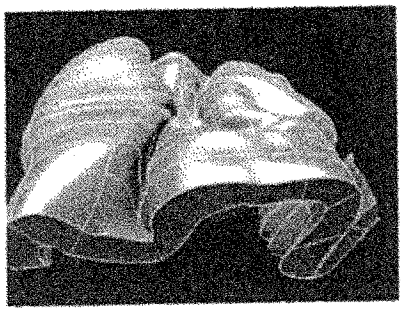

Figure 1. Finite element model for a piece of the neocortical shell.

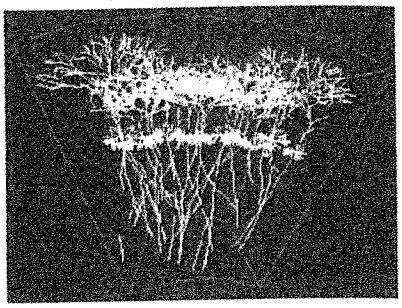

Figure 2. Finite element populated with synthetic neurons.

OBJECTIVES

The three objectives of the research are briefly described below.

Biologically Consistent Finite Element Decomposition of Human Cortical Shell

To establish finite elements in a manner consistent with developmental neurobiology, the elements are designed to follow the natural symmetries of the tissue. One coordinate axis is defined by the local orientation of its primary native neuron type (pyramidal cells). The other axes are chosen to simulate how a neuroanatomist would cut tissue locally to make successive sections look as similar as possible. Numerical grid generation algorithms establish a curvilinear coordinate system within each finite element and, hence, by extension throughout the entire solid model. This coordinate system provides a basis for orienting neurons and specifying physical barriers and chemical gradients within the tissue.

Mapping Neurons into Gridded Solid Model

Our second objective is to embed a population of neurons within the gridded solid model. Sparse populations of neurons can be drawn from databases of traced neurons, or generated stochastically using L-system modeling as described by McCormick and Mulchandani [2, 3, 4]. The grids provide a framework for positioning the neurons in the solid model of the reconstructed tissue and for specifying positional forces within the tissue. The embedded neurons are chosen to be statistically consistent with those found in the actual tissue.

Visualization of Neuron Populations within Gridded Solid Model

Our third objective is to visualize a population of neurons within the reconstructed tissue using computer graphics in conjunction with the grid generation and neuron mapping methods. An interactive approach, developed in [5], allows the user to freely explore the brain forest.

METHODOLOGY

Our methodology for the FE decomposition involves five steps, as shown in Figure 3, and the development of supplementary object-oriented software tools.

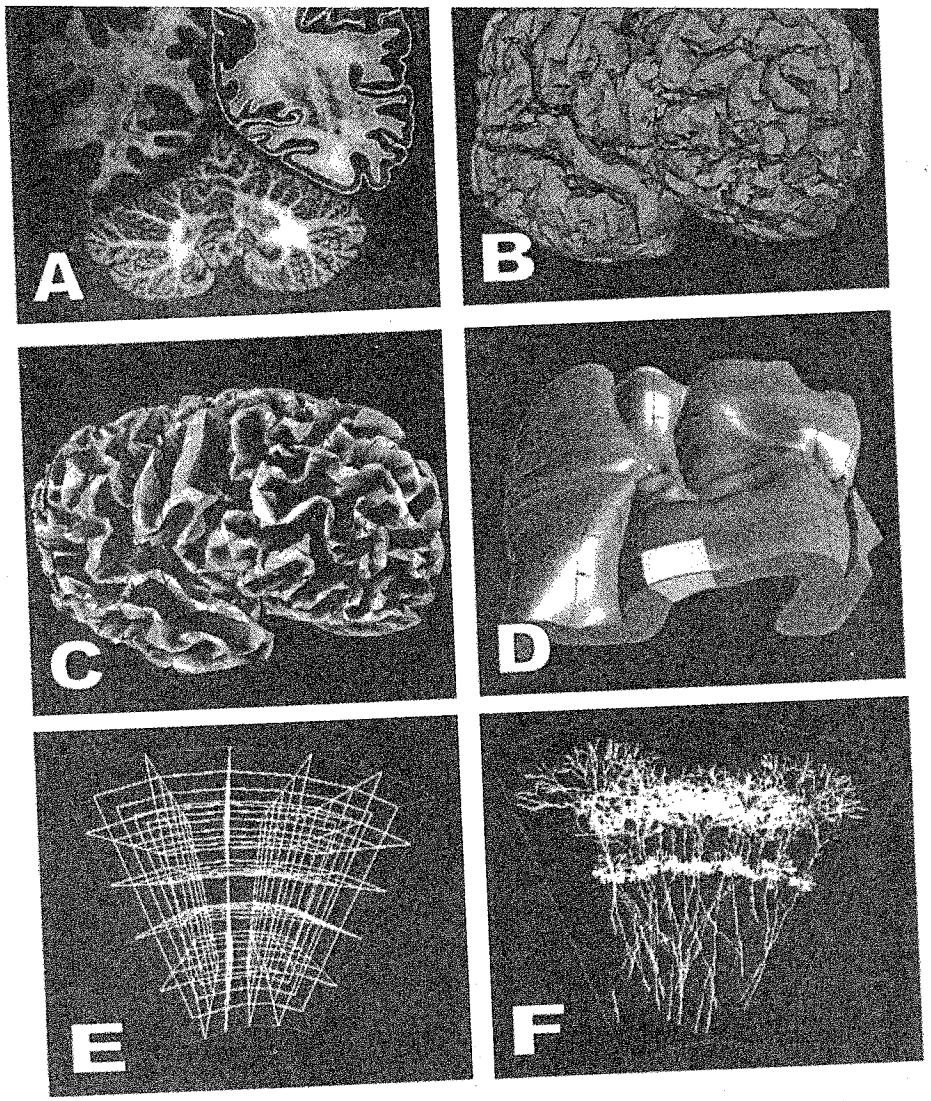

Figure 3. The five steps of our methodology. **A, B**: 3D reconstruction of the manually traced contours of the human neocortex yields a solid model. **C**: Feature extraction extricates the prominent *sulci* and *gyri* from the reconstructed solid model. **D**: Finite element decomposition of the model provides "drawers" for neuron populations. **E**: Curvilinear 3D grids are generated for the finite element "drawers." **F**: Neuron populations are implanted into the gridded finite elements.

3D Reconstruction of Neocortex

Serial reconstruction of cross-sectional slices of a *post mortem* human brain generates a solid model of the neocortex with minimal loss in morphological detail. The dataset for the reconstruction consists of 217 x 512 x 512 images of a 76-year-old normal female human cadaver brain cryosectioned through the horizontal plane [6]. Contours of the

neocortex were manually traced using a third party application (*Elastic Reality* from Avid Technologies, Inc.). Tissue segmentation was performed manually with the subsequent evaluation by a neuroanatomist (Dr. Ian Russell). Because of the precision and consistency of the cryosectioning technique, the spatial alignment of the consecutive images along the cutting axis automatically insures the registration of the contours between adjacent sections. Then, a Delaunay-based surface reconstruction algorithm generates triangulated surfaces for both the exterior and interior side of the neocortical tissue [7]. Thus, the inner and outer surfaces jointly define the volume of the neocortex, producing a *boundary representation* (B-Rep) solid model.

Feature Extraction from Boundary Representation Model

The identification of *gyri* and *sulci* on the neocortex corresponds to the extraction of extremal points, defined loosely as the local minima and maxima of a surface, and other shape metrics, such as curvedness and shape index, from the B-Rep model. The extrication of these topological features rely on the determination of principal curvature values, defined loosely as the curvature of a point on a surface, for each vertex on the exterior and interior triangulated surfaces obtained from the previous step. Approximation techniques estimate the principal curvatures; then, various shape metrics are computed directly from these values, and extremal points are determined by solving a set of "extremality" equations [8].

Finite Element Decomposition

Extremal points and shape metrics extracted from the B-Rep model determine the constraints guiding the mesh generation. The decomposition takes a coarse-to-fine approach. First, the convoluted tissue is broken down into more manageable pieces, which roughly corresponds to the major *gyri* defined in anatomical atlases [9]. Second, 2D meshes, congruous with the ridge and valley lines, are determined for the inner and outer surfaces for each piece. Third, a graph correspondence algorithm associates complementary extremal points between the inner and outer mesh. In the absence of pyramidal cell axis data, coarse 3D grid generation is used to compute the hexahedral finite elements [10].

Grid Generation for Finite Element Model

Numerical grid generation methods establish a curvilinear coordinate system for the solid model. Batte [5] has applied 3D ITTM grid generators and several 3D variational grid generators [11] to parametric solid models of neocortical tissue segments. We apply these generators to the finite elements obtained in the finite element decomposition above.

First, we construct local 3D boundary-conforming grids within each finite element. Algorithms that iteratively optimize boundary and inter-element geometric continuity are available to generate unfolded, continuous grids for each finite element (as opposed to the convolutions of the entire neocortex). We have explored both geometric and variational grid generation methods to fill the solid model with locally-defined coordinate systems.

A global coordinate system minimizing discontinuities between grids of adjacent finite elements greatly facilitates neuron implantation. The continuity reduces irregularities and mitigates population shifts at finite element boundaries. We have investigated reparametrization techniques and related strategies for solving the continuity constraints to unify the disjoint grids into a continuous 3D grid for the entire solid model.

Neuron Implantation within Finite Elements

Computer graphics in conjunction with neuron mapping methods provides the facilities to visualize a neuron population within the gridded solid model. Sparse

stochastically using L-system modeling as described by [2].

The finite element model provides a spatial indexing scheme for a neuron morphology data repository. First, neurons are assigned to the finite element containing their somas. This spatial decomposition gives the initial categorization criterion for the data repository. Subsequently, various relational ordering can be defined by creating different index-trees to the finite elements. One such relational ordering is a hierarchical breakdown through multiple levels of neocortical regions, represented as a group of finite elements, to the level of individual finite elements.

RESULTS

The resulting finite elements in B-Spline tensor product representation [12] follow the natural symmetries of the tissue as shown in Figures 4 and 5.

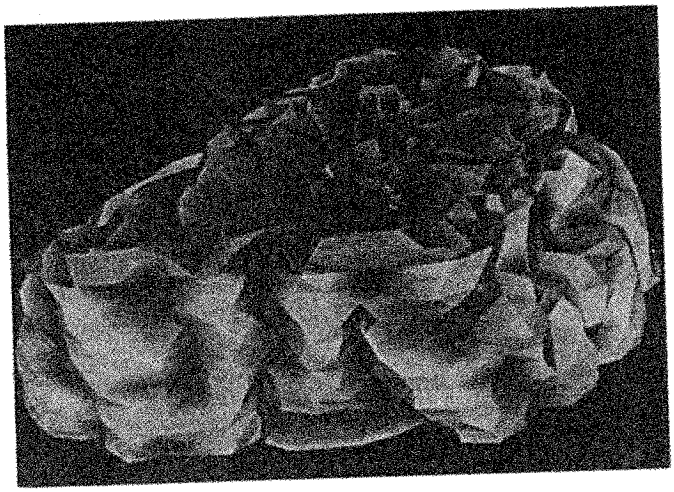

Figure 4. Band of reconstructed neocortex in triangulated mesh representation (shown in reduced resolution).

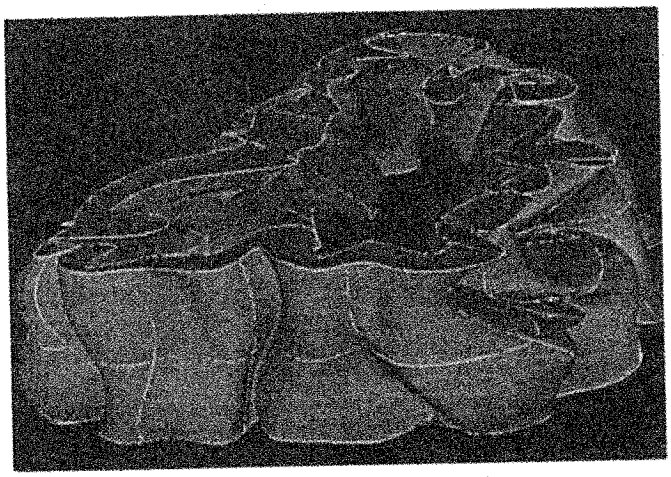

Figure 5. Finite element decomposition in B-Spline tensor product representation of above neocortical band.

One of the curvilinear coordinate axis, obtained by interpolating the cortical surface normals between corresponding extremal lines on the exterior and interior surfaces, approximates the local orientation of the pyramidal cell axes. The finite element boundaries geodesic to the exterior and interior surfaces correspond to the ridge and valley lines along gyral and sulcal folds.

SIGNIFICANCE

The methodology described above:

1. Constructs a parametric solid model of the human neocortex that captures the morphology hidden within its deep convolutions.
2. Builds a finite element mesh for the human neocortex.
3. Provides a global framework and coordinate system for a 3D atlas of the human brain and for a normative neocortical model.
4. Shows the viability of mapping neuron populations within a 3D graphical model as a means for structural and functional analyses.
5. Prototypes a hierarchical spatial data management system for neuron data sets.

The supplementary software tools are planned to allow the visualization and modeling of the neocortex through an exploratory environment accessible over the Internet.

ACKNOWLEDGMENTS

This work was supported by Texas Advanced Technology Program grant 999903-124 (McCormick) from the Texas Higher Education Coordinating Board.

REFERENCES

1. D. A. Batte and B. H. McCormick, Grid generation for brain visualization at the cellular and tissue level, in: *Computational Neuroscience: Trends in Research, 1997*, J. Bower (ed), Plenum Press, New York (1997).
2. B. McCormick and K. Mulchandani, L-system modeling of neurons, *Proc. Visualization in Biomedical Computing*, SPIE, 2359 (1994).
3. K. Mulchandani. *Morphological Modeling of Neurons*, Master's Thesis, Department of Computer Science, Texas A&M University, College Station, TX (1995).
4. K. Mulchandani and B. McCormick, A framework for modeling neuron morphology, in: *Computational Neuroscience: Research Trends for 1995*, J. Bower (ed), Academic Press, San Diego (1996).
5. D. A. Batte. *Finite Element Decomposition and Grid Generation for Brain Modeling and Visualization*, Master's Thesis, Department of Computer Science, Texas A&M University, College Station, TX (1997).
6. A. Toga, K. Ambach, and S. Schluender, High-resolution anatomy from in situ human brain, *NeuroImage*, 4 (1994).
7. B. Geiger, Three dimensional modeling of human organs and its application to diagnosis and surgical planning, *INRIA Rapports de Recherche–Sophia Antipolis*, 2105 (1993).
8. J. Thirion and S. Benayoun, Image surface extremal points, new feature points for image registration, *INRIA Rapports de Recherche–Sophia Antipolis* , 2003 (1993).
9. H. Duvernoy. *The Human Brain: Surface, Three-Dimensional Sectional Anatomy and MRI*, Spring-Verlag, Wien, New York (1991).
10. T. Chow. *Finite Element Decomposition of the Human Neocortex*, Master's Thesis, Department of Computer Science, Texas A&M University, College Station, TX (January 1998).
11. P. Knupp and S. Steinberg. *Fundamentals of Grid Generation*, CRC Press, Boca Raton (1994).
12. P. Dierckx. *Curve and Surface Fitting with Splines*, Oxford University Press (1995).