

Analysis-ready meshes of neuronal forests

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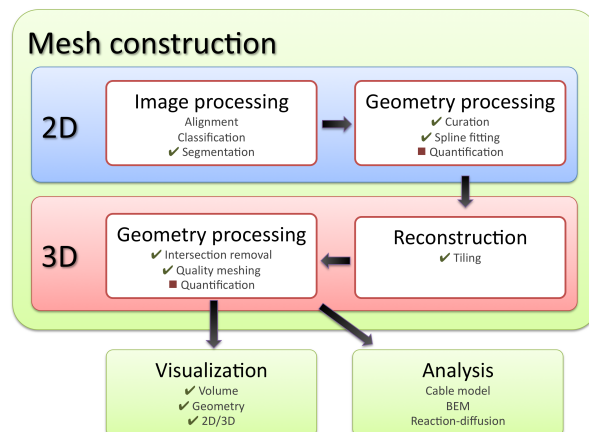
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Construction of spatially realistic models of neuronal processes, glia, and intracellular organelles is an essential step toward meaningful electro-physiological and reaction-diffusion simulations. Many techniques have been developed to replicate the intricate branching of the dendritic arbor of single neuronal processes, but few methods are able to capture the native structures of multiple cells in close proximity, i.e. the 3D structure of neuropil, or a “forest” of structures. In this abstract, we propose criteria for analysis-readiness of a mesh and present a pipeline of methods along with a suite of computational tools to reconstruct, from a stack of serial section transmission electron microscopy (ssTEM) images, surface and volumetric mesh forests that meet these criteria.

Our ongoing work aims to produce meshes that are appropriate for both visualization and analysis, and to provide an interactive environment for both. This opens up exciting possibilities. For example, while traditional simulations of electrical signals in the brain approximate neuronal geometry with cylindrical chunks, accurate surface triangulations enable 3D boundary element method (BEM) simulations that are reliant on geometric accuracy and topological correctness. Accurate volumetric models enable 3D finite element method (FEM) simulations. If these models are built using user-validated cross-sectional traces, surface meshes can have sub-voxel accuracy.

Our reconstruction pipeline is summarized in figure 1.

We present VolumeRover [1], a software package that contains reconstruction, visualization, and analysis algorithms suitable for neuronal data (see figure 6). We aim to provide software that (1) builds analysis-ready surface models of neuronal data, (2) visualizes the data in 2D/3D and with both volume and geometry renderers, and (3) provides tools for analysis. VolumeRover pulls together published, high-quality algorithms for all three of these tasks into a single user interface. A unified data management and visualization core enables transparent transitions between stages of the pipeline.

Our criteria for models that are suitable for analysis are derived from requirements in visualization, cable model, boundary element

Figure 1: A high-level look at our pipeline of algorithms that convert EM images to spatially realistic models of neuronal processes. There are four main phases. The first two deal with 2D processing. The third bridges the gap from 2D to 3D. The last processes the 3D data to render simulation quality models. Tasks shown with a check mark are currently available in VolumeRover. Tasks shown with a box are in progress. Remaining tasks are implemented in third-party software packages.

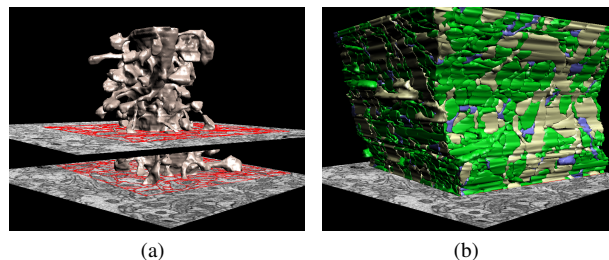


Figure 2: Overview of our reconstruction pipeline. (a) Components are singly reconstructed from the contours. Contours are shown in red on the image slices. (b) Components are added to the full reconstruction forming a tightly packed block of geometries.

(BEM), finite element (FEM) and WEB-spline analysis. These criteria include

1. water-tight
2. consistently oriented surface normals
3. non-intersecting
4. no mesh irregularities
5. manifold edges and vertices
6. low aspect ratio triangles
7. topologically correct

Our surface mesh reconstruction pipeline reconstructs tightly-packed surface mesh forests of neuropil from stacks of 2D contours (figure 2). It 1) reconstructs single components, 2) resolves intersections between components due to tortuosity and anisotropy (figure 3), and 3) improves surface triangulations (figures 4 and 5). Runtime performance is reported in table 1.

Once surface meshes are obtained, they can be visualized with VolumeRover (figure 6). VolumeRover also includes tools to 1) generate skeletonizations for cable model synthesis 7 and 2) tetra-heralize for finite element analysis.

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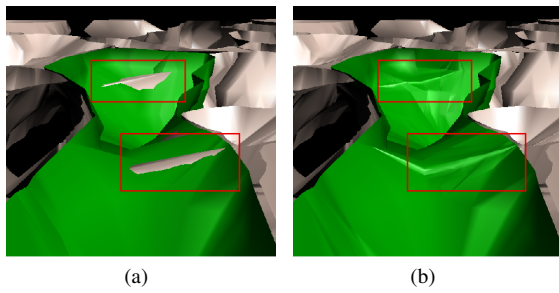


Figure 3: 3D intersection removal. (a) Two intersections between the green component and other components. Surface intersections such as these are prevalent in highly tortuous data. (b) The geometries with intersections removed.

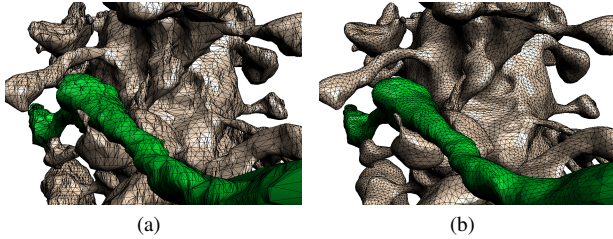


Figure 4: Mesh improvement. (a) The original triangulation. (b) The reconstruction after decimation and smoothing.

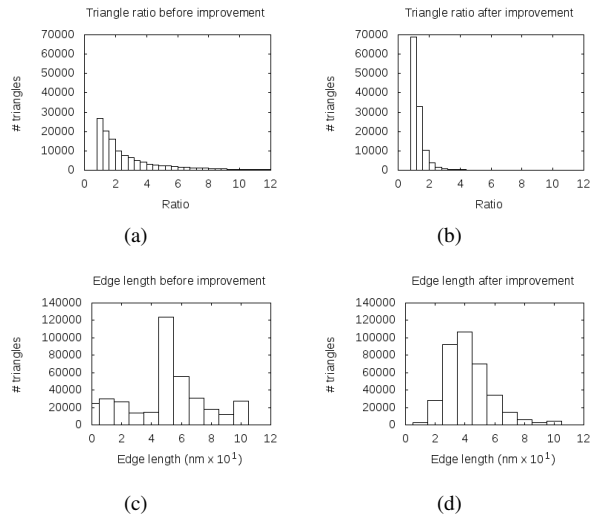


Figure 5: Triangle quality histograms. (a) and (b) show triangle ratio statistics, with the ratio of an equilateral triangle equal to 1. A histogram of ratios before and after improvement are shown. (c) and (d) show statistics on lengths of triangle edges.

dataset	slices	reconstruction time (s)	num triangles
CA1 (axons)	116-117	78.6	50308
CA1 (axon a001)	61-160	12.2	7199
CA3 (2 dendrites)	149-150	99.1	7607

Table 1: Table of tiling timing and triangle statistics. Tests were performed on a Linux Kubuntu workstation with an Intel Xeon quad core CPU at 3.20 GHz with 4 GB memory. The CA1 dataset (figure 2) was taken from the hippocampal region of the brain and has 452 axons. The CA3 dataset is unreleased.

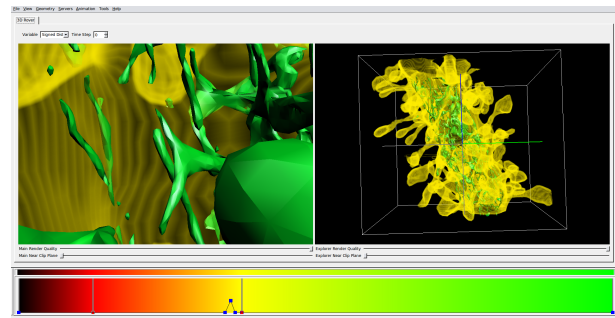


Figure 6: Main window of VolumeRover which includes a main view (left), thumbnail view (right) and transfer function tool (bottom). An apical dendrite is shown with some transparency revealing reconstructions of endoplasmic reticulum (ER) inside. The dendrite is volume rendered and the ER uses standard geometry rendering. Hierarchical data storage and rendering enables rendering the volume-rendered dendrite at two scales simultaneously.

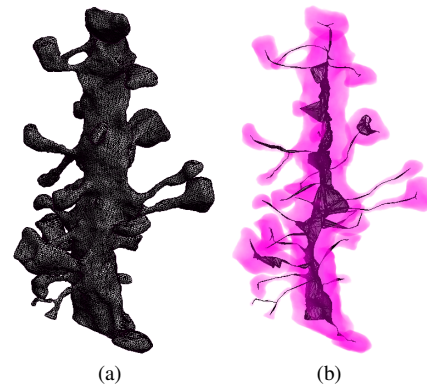


Figure 7: Skeletonization. (a) The dendrite surface mesh. (b) A skeletonization of the dendrite.

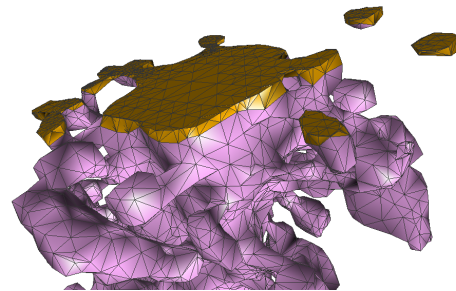


Figure 8: Tetrahedralization of a dendrite surface mesh. The yellow tetrahedra represent the boundary of a cut plane through the mesh. The surface mesh created by VolumeRover's contour tiler was converted into a volume using a signed distance function and then tetrahedralized using our adaptive meshing algorithm.

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- [1] CVC. Volume Rover. http://cvcweb.ices.utexas.edu/cvcwp/?page_id=100.