Topology Correction for Brain Atlas Segmentation

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Abstract. Topological correctness of 3D human brain structures is an important prerequisite for brain atlas deformation and surface flattening. Our topology correction method uses an axis-aligned sweep through the volume to locate handles. Handles are detected by successively constructing and analyzing a directed graph. A multiple region-growing process is used which simultaneously acts on the foreground and background to isolate handles and tunnels. The sizes of handles and tunnels are measured, then handles are removed or tunnels filled based on their sizes.

1 Introduction

Representing the topologically correct shape of complex anatomical regions such as human brain structures is a challenging task, especially for regions in the cortex. Several methods for correcting the topology of the cortical surface have recently been developed. Dale et al. [1] flattened a cortex isosurface by ignoring small handles, identifying and fixing topology defects on the inflating cortical surface, thus leaving some large handles to be edited manually. More recently, Fischl et al. [2] inflated the cortex isosurface to a sphere and identified the overlapping triangles on the spherical surface which corresponded to the handles, and tessellated a new mesh as the topologically correct cortical surface. Shattuck and Leahy [3] and Xiao Han et al. [4] introduced graph-based methods for topology correction. Shattuck and Leahy examined the connectivity of 2D segmentations between adjoining slices to detect topological defects and minimally correct them by changing as few voxels as possible. One drawback of this approach is that the "cuts"which are necessary to correct the topological defects are necessarily oriented along the Cartesian axes. Building on their work, Xiao Han et al. developed an algorithm to remove all handles from a binary object under any connectivity. Successive morphological openings correct the segmentation at the smallest scale. This method works for small handles. Wood et al. [5] proposed a different approach. Handles in the tessellation are localized by simulating wavefront propagation on the tessellation and are detected where the wavefronts meet twice. The size of a handle is the shortest non-separating cut along such a cycle, which helps retain as much fine geometrical detail of the model as possible. One drawback of this method is that it requires the arbitrary vertex tessellation to be converted to a volumetric image in order to correct the defect.

Our method provides a fully automatic topology correction mechanism, thus avoiding tedious manual correction. What is new about our method is that it provides a very fast alternative approach which has several advantages over Shattuck and Leahy's model, including the fact that corrections are not oriented along cardinal axes. It can thus be done under any connectivity in 3D (6,18,26) without cutting the whole plane and changing as few voxels as possible.

2 Methods

Considering a digital object, computation of two numbers is enough to check whether modifying one voxel will affect the topology. These topological numbers, denoted T_n and $T_{\bar{n}}$, were introduced by Bertrand [6] as an elegant way to classify the topology type of a given voxel which is to be used by the algorithm. The object is henceforth termed X and its inverse object $\overline{X}$. A point $x \in X$ which can be added or removed without changing the topology of an object is characterized by $T_n(x, X) = T_{\bar{n}}(x, \overline{X}) = 1$. A point $x \in X$ is called a n-border point, if and only if at least one of its n-neighbors x', $x' \in \overline{X}$. The algorithm generates different connected components and assigns voxels with different labels for each component. Residual points characterize voxels belonging to a component that will change the topology of the object. If their component will not change the topology, they are termed body points.

A method is described whereby the topology of a volumetric binary image can be altered so that an isosurface algorithm can generate a surface with the topology of a sphere, i.e., a genus of zero. The genus of an object can be determined by its Euler characteristic, which can be computed using the Euler-Poincaré formula

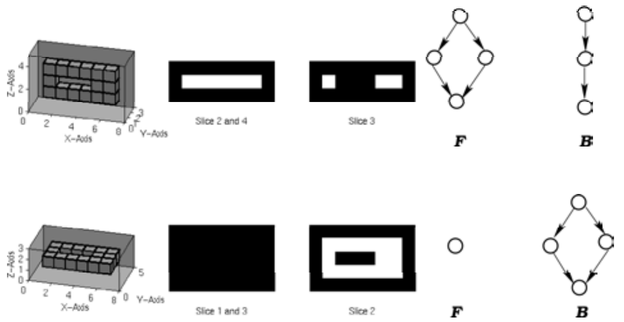
$$\chi = v - e + f = 2 - 2g \tag{1}$$

where v is the number of vertices, e the number of edges, f the number of faces, and g the genus. If $g = 0$, the object has the topology of a sphere. The Euler characteristic is a topological invariant of a generated isosurface. However, this calculation only provides a global criterion for topology correction, not information about the position and size of handles and tunnels. Hence, the size and location of both handles and tunnels need to be found.

To that end, we analyze the topology of the object while also analyzing its geometry. We create two directed graphs - one for foreground voxels and one for background voxels - which contain information about the volume. This allows us to determine if the foreground object is topologically equivalent to a sphere by counting the number of cycles in the graphs. The cycles also give information about the size and location of handles or tunnels.

A foreground connectivity graph $G = \{N, E\}$ is created which contains important information about the structure of the binary image foreground. The object is examined along a selected cardinal axis, identifying the connected components within each slice perpendicular to the axis, using 2D 4-connectivity if the foreground uses 6-connectivity in 3D, and 2D 8-connectivity if the foreground uses 18- or 26-connectivity in 3D. Each in-slice-connected component is called

Fig. 1. An $8 \times 3 \times 5$ binary volume with a torus, the corresponding slices and its connectivity graphs for foreground and background.



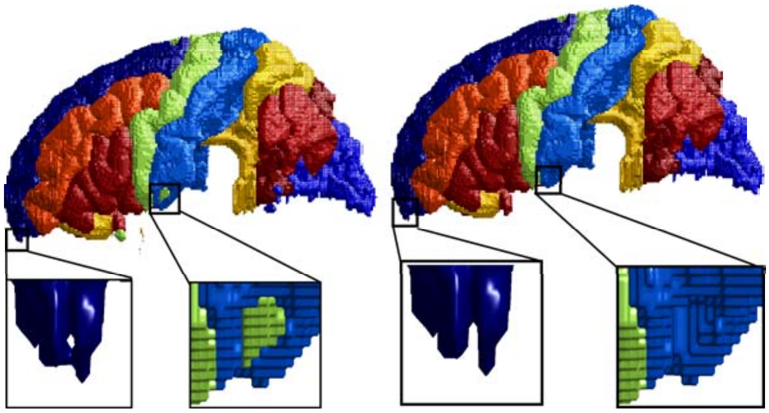
a node in the graph. Next, it is determined how each node is connected to the nodes in the next slice. Two nodes are defined as having a directed connection if they are n-connected. Each connection in the object is represented by an edge in the graph. Note that one node may be connected to two or more nodes, and that these nodes are connected to one node in the next slice (Fig. 1).

In the simplest case, one node will have multiple edges connecting it to one node in the next slice in the foreground. Such a representation is the simplest form of a topological handle existing in the object (Fig. 2). The background connectivity graph is created likewise using $\bar{n}$ connectivity (Fig. 1 and 2).

The basic idea of topology correction is dividing cycles into body and residue parts and discarding the smallest residue piece in each cycle in 3D. When these voxels are removed from the foreground, they are also removed from the object. This is called a handle cut. Conversely, when voxels are removed from the background, they are added to the object, and hence a tunnel is filled. When a cycle with two sides is detected, we choose the smaller one as the handle. Handles are good candidates for these residue parts. However, since the thinnest cut of a cycle may not fall within the handle, we introduce *residue part expansion* (RPE), which is intended to catch the thinnest cut by iteratively growing the handle. This is done as follows: We find the top and bottom connection sets $X_1 \subset X$ and $X_2 \subset X$ which are n-adjacent to the handle set S. The handle set S is grown by X_1 and X_2. Hence, the sets X_1 and X_2 are the border point sets

Fig. 2. A $5 \times 5 \times 4$ binary volume with a torus, the corresponding slices and its connectivity graphs for foreground and background.

Fig. 3. A sample surface rendering of the segmented volumes (10 different gyri) before and after topology correction.



of S. The growing procedure is done iteratively, e.g., if the number of n-adjoint points of X_1 is smaller than the number of points of X_1, X_1 is added to S and the n-adjoint points are labeled X_1, and so on. After RPE growing, each residual part S is an n-connected component n-adjacent to body part X, and a cut of it can reduce the genus by one. This is due to the fact that its growing by border points is equivalent to growing by adding simple points, and so the topology will be retained after growing.

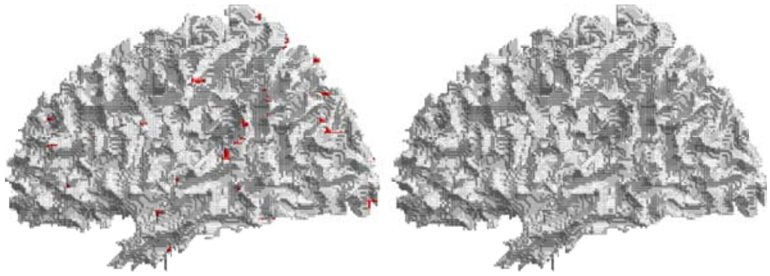
The main idea of cutting the residue part is to transfer as many points as possible from the residue back to the body without changing its topology. Specifically, sets X_1 and X_2 are the two cuts of the residue part after RPE, but they might not be the smallest ones. The body set is grown by successively detecting border points of X_1 or X_2 which lie within the residue, but only add those points (which are simple points) which come from the residue and do not adversely affect topology. Note that at each iteration, the largest set of simple points is added to the body, which ensures that the final residue points are not added back to the body and are positioned at the thinnest parts of the handles.

The nature of the changes described here depends on the axis along which the object is analyzed. In order to ensure that only the smallest changes are made to the object, corrections are applied iteratively along each axis. A threshold is used, and only corrections less than or equal to the threshold are done. This multi-axis approach dramatically reduces the number of voxels which are added to or removed from the object set.

3 Results

We applied the method to the labeled version of the ICBM Single subject MRI Anatomical Template (www.loni.ucla.edu/ICBM/ICBM_BrainTemplate.html). The high-resolution structural brain template is the average of 27 T1-weighted MRI acquisitions from a single subject (from the Montréal Neurological Institute

Fig. 4. WM/GM surface obtained before and after topology correction. Handles are highlighted in red.



database). The template is aligned within the stereotaxic space of the ICBM average template derived from Talairach and Tournoux [7]. The image size is $309 \times 362 \times 309$ voxels. Cortical gyri, subcortical structures and the cerebellum are assigned a unique label.

The tessellation of each topologically corrected segmentation has the topology of a sphere, i.e, it has an Euler characteristic of two, corresponding to a genus of zero. Figures. 3 and 4 show two sample rendering surfaces before and after topology correction. This algorithm changed between 0.0% and 1.23% of the voxels for each of the segmented brain volumes, with an average of 0.05%.

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