QUASI-ISOMETRIC FLATTENING OF LARGE-SCALE CORTICAL SURFACES *

Mukund Balasubramanian1, Jonathan R. Polimeni2, and Eric L. Schwartz1,2,3

1Department of Cognitive and Neural Systems, Boston University, Boston, MA 02215, USA
2Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, USA
3Department of Anatomy and Neurobiology, Boston University School of Medicine, Boston, MA 02118, USA

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Abstract

Objective

For quantitative analysis in high-resolution imaging studies of neo-cortex derived from either MRI or tissue section data, surface-based representations, including flattened configurations, have come into wide use. This is especially important for receptorotopically organized cortex, since sensory maps are two-dimensional in nature but are embedded in three dimensions as a highly convoluted surface. Both visualization and data analysis are difficult without access to accurate flattened representations of these structures. Early quasi-isometric flattening algorithms [1] were based on computing a geodesic distance matrix, followed by a least-squares optimal non-linear mapping into two dimensions. Variants of this algorithm are currently in wide use, but algorithms based directly on geodesic distance matrix computation have been considered too expensive for use on large scale MRI data sets. Here, we show that recent work on improving the efficiency of these algorithms has made them feasible for use on large data sets, producing mesh-independent, optimally quasi-isometric solutions without requiring relaxation cuts—properties which are not available on other contemporary flattening methods.

Methods

First, we present a method for computing minimal geodesics and shortest paths on a triangular mesh, which rapidly computes exact distances on meshes with thousands of triangles. Then, two algorithms for flattening triangular meshes are presented. The first optimally preserves the lengths of minimal geodesics. However, it is not computationally practical for meshes with more than several thousand triangles. To flatten large-scale meshes, a second algorithm is presented that operates at multiple scales while respecting the geodesic distances at coarser scales. This algorithm operates at all scales, using the first algorithm at the coarsest scale and iteratively refining the flattening at finer scales. Together, these algorithms significantly improve the speed and accuracy of quasi-isometric flattening methods.

Results and Discussion

Demonstrations of the flattening algorithm applied to simple artificial surfaces are given. We then present flattenings of the full surface reconstructions of human occipital cortex and provide a per-vertex error analysis. Examples are provided of flattenings computed by preferentially weighting subregions of interest to yield lower flattening error in these areas. Finally, applications of this method to flattening surface reconstructions of serial tissue section data collected from macaque visual cortex will be presented.

Conclusions

For applications in which a metrically accurate, mesh-independent, unique solution is required, the least-squares optimal quasi-isometric flattening algorithm, based on the computation of a geodesic distance matrix representing the metric structure of the cortical surface, provides a method that efficiently computes accurate flattenings of large-scale meshes without requiring relaxation cuts.

1Contact info: Mukund Balasubramanian, Computer Vision and Computational Neuroscience Lab, 677 Beacon St., Boston, MA, 02215. URL: http://eslab.bu.edu, Email: mukundb@nmr.mgh.harvard.edu
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**Figure 1**: Demonstration of the quasi-isometric flattening algorithm on a reconstruction of human occipital cortex extracted from structural MRI data of a full cortical hemisphere. (A) The surface reconstruction of the white matter surface of a full human cerebral hemisphere, with sulci shown in *dark gray* and the gyrii in *light gray*. The color overlay represents the per-vertex error produced by the quasi-isometric flattening in pseudo-color on a logarithmic scale. The average RMS error over the flattened surface is 21.642%, whereas the maximum error is 91.58% and the minimum error is 1.7519%. The occipital patch consists of 46909 vertices and 93303 faces, and its surface area is 31383 mm$^2$. The lateral (left), posterior (middle), and medial (right) views of the white matter surface are provided. (B) The per-vertex error map is shown on an inflated representation of the full hemisphere in the three views above to aid visualization of the error in the sulcal depths. (C) The result of the quasi-isometric flattening the occipital patch of the white matter surface shown in (B). The *white star* marks the occipital pole on both the posterior aspect of the inflated surface and the flattened representation of the occipital patch. The pseudo-color scale of the flattening error is provided on the right.