Sulci Segmentation Using Geometric Active Contours

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Sulci are groove-like regions lying in the depth of the cerebral cortex between gyri, which together, form a folded appearance in human and mammalian brains. Sulci play an important role in the structural analysis of the brain, morphometry (i.e., the measurement of brain structures), anatomical labeling and landmark-based registration. Moreover, Sulcal morphology changes is related to cortical thickness which its measurement could provide useful information for studying variety of psychiatric disorders. Manually extracting sulci requires complying with complex protocols, which make the procedure both tedious and erroneous. To be able to compute different characteristics of the cortex, a number of 3D analyses have been developed using dynamic programming, watershed technique and Parametric representation. We have developed a method, employing geometric active contours. The initial curve evolved according to the external force, derived from geometry of the surface as well as the internal curvature flow, which is the conformal curve shortening flow on the surface. The curvature flow is responsible for the inward motion of the curve towards sulci regions and the evolving curve tend to lie along a high mean curvature groove. The Level set technique which can handle merging and splitting of curves naturally was used for the curve evolution implementation. Geometric variables needed in the implementation of curve evolution equation were computed based on the level-set function utilizing numerical methods.

Keywords: cortex 3D mesh, sulci extraction, active contour model, level set

100-word abstract

Sulci are groove-like regions lying in the depth of the cerebral cortex between gyri, which together, form a folded appearance in human and mammalian brains. Sulci play an important role in the structural analysis of the brain, morphometry, anatomical labeling and landmark-based registration. Manually extracting sulci requires complying with complex protocols, which make the procedure both tedious and erroneous. To address this problem, we have developed a method, employing geometric active contours, which evolve towards the sulci. Sulci boundaries were obtained by minimizing a energy functional such that minimum was attained at the boundary of the sulci.

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ABSTRACT

Sulci are groove-like regions lying in the depth of the cerebral cortex between gyri, which together, form a folded appearance in human and mammalian brains. Sulci play an important role in the structural analysis of the brain, morphometry (i.e., the measurement of brain structures), anatomical labeling and landmark-based registration.\textsuperscript{1} Moreover, sulcal morphological changes are related to cortical thickness, whose measurement may provide useful information for studying variety of psychiatric disorders. Manually extracting sulci requires complying with complex protocols, which make the procedure both tedious and error prone.\textsuperscript{2} In this paper, we describe a method, employing geometric active contours, which automatically extract the sulci. Sulcal boundaries are obtained by minimizing a certain energy functional whose minimum is attained at the boundary of the given sulci.

Keywords: cortex 3D mesh, sulci extraction, active contour model, level set

1. DESCRIPTION OF PURPOSE

Analysis of the cortical surface is important for clinical monitoring and statistical analysis of the brain.\textsuperscript{3–5} To be able to compute different characteristics of the cortex, a number of 3D analyses have been developed using dynamic programming,\textsuperscript{6} watershed techniques\textsuperscript{7,8} and parametric representations.\textsuperscript{9}

In this work, we propose a geometric curve evolution approach for detecting and extracting sulci from MRI data. The evolution equation is derived via the minimization of a certain energy function defined on the extracted cortical surface. More specifically, the energy functional is defined in such a manner that the evolving contours will be attracted to regions of high mean curvature. The level set technique (which can handle merging and splitting of curves) was employed for the implementation of the curve evolution.\textsuperscript{10} The key idea is that the user defined initial curve evolves according to the external force, derived from geometry of the surface as well as the internal curvature flow, which is the conformal curve shortening flow on the surface. The curvature flow is responsible for the inward motion of the curve towards sulcal regions and the evolving curve tends to lie along a high mean curvature groove.

Unlike other works\textsuperscript{4,6,8,11,12} that have focused solely on the curve representation of the sulci, our work can detect regions surrounding them as well. The proposed method is applied to the cortical surface mesh rather than on the image data directly.

2. METHOD

In this section, we sketch the mathematical details. Let $\Gamma \subset \mathbb{R}^3$ be a smooth surface, and let $\gamma : [0, T) \times \mathbb{R} \to \Gamma$ be an evolving family of curves. At a given moment in time we define the cost of the curve to be

$$
C[\gamma(t, \cdot)] = \int \gamma e^{-\lambda H(\gamma(t, z)) \| \gamma_z(t, z) \|} \, dz
$$

where $H : \Gamma \to \mathbb{R}$ is the outward mean curvature function on the surface. Note that sulci are regions where $H \gg 0$, gyri are regions where $H \ll 0$. Accordingly, curves with small cost will tend to be located in the sulci.

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The cost of a curve as defined here is invariant under reparametrization. We will from here on always assume that $\gamma$ is a normal parametrization, i.e. we assume that
$$\gamma_z \perp \gamma_t \text{ holds for all } z \text{ and } t.$$  
(2)
Then we can define the normal velocity of the curve by
$$\gamma_t = vN$$
where $N$ is the unit vector which is tangent to the surface $\Gamma$ but perpendicular to $\gamma$.

The first variation of the cost function is
$$\frac{d}{dt} C[\gamma(t, \cdot)] = - \int_{\gamma} e^{-\lambda H(\gamma(t, s))} \{ \kappa + \lambda N \cdot \nabla H \} v \, ds$$
(3)
in which $\kappa$ is the geodesic curvature of the curve $\gamma$, and $s$ is the Euclidean arclength on $\gamma$. Thus, a steepest descent flow will be obtained by choosing
$$v = \beta \{ \kappa + \lambda N \cdot \nabla H \}$$
(4)
for some positive function $\beta$.

The mean curvature normal operator $K^{13}$ was utilized to estimate the mean curvature $H$:
$$K(x_i) = \frac{1}{2A_{\text{Mixed}}} \sum_{j \in N_1(i)} (\cot \alpha_{ij} + \cot \beta_{ij})(x_i - x_j)$$
(5)
where on the triangulated mesh, $\alpha_{ij}$ and $\beta_{ij}$ are the two angles opposite to the edge in the two triangles sharing the edge $(x_i, x_j)$. $N_1(i)$ is the set of 1-ring neighbor vertices of vertex $i$ and $A_{\text{Mixed}}$ is a surface area.

The level set method proposed by Osher and Sethian\textsuperscript{10,14,15} for the numerical implementation of curve evolution flows, was utilized for the evolution equation defined above. Geometric variables can be expressed based on the level-set function. The necessary gradient operators were computed by adopting the discretization framework on surfaces.\textsuperscript{16}

3. EXPERIMENTS AND RESULTS

We used the open source softwares 3D Slicer\textsuperscript{17} and FreeSurfer\textsuperscript{18} for generating the input data. These software packages are ideal for processing and analyzing brain MRI data.

The overall framework was implemented in C++. VTK\textsuperscript{19} was used for visualization task. Matlab also was used for implementing and testing of some basic tasks.

Figure 1 shows the approximation of the mean curvature on a data set with 290134 faces and 14069 vertices. Figure 2 shows the exponential feature function (stopping criterion). Comparing figures 3 and 4, one can notice that, regions with higher mean curvature correspond to regions with lower feature function.

Figures 3 and 4 show the initial and evolved contour after 1000 iterations. Another example is shown in Figure 5.

4. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

In this work, we devised a cost functional based on geometric properties of the sulci. The derived curve evolution equation was applied to evolve initial contours towards the sulci. The curve evolution equation was implemented via the level set method. All the necessary geometric variables for the level set scheme were computed based on previously specified numerical methods. Once the initial curve was chosen around the desired features, the geometric flow automatically captured the sulci.

Future work will center around improving the implementation (here we used narrow banding), e.g., for using sparse field methods. We will also explore certain temporal smoothing operators to get a Sobolev type flow to derive the contour more quickly to the desired minimum.

The work has not been submitted for publication or presentation elsewhere.
Figure 1. Mean Curvature Estimation

(a) Mean Curvature
(b) Enlarged

Figure 2. Feature function

(a) Feature function
(b) Enlarged

Figure 3. Initial contour

(a) Initial contour
(b) Enlarged

Figure 4. Evolved Contour

(a) Evolved contour
(b) Evolved Contour (enlarged)
REFERENCES


