Localized Statistics for DW-MRI Fiber Bundle Segmentation

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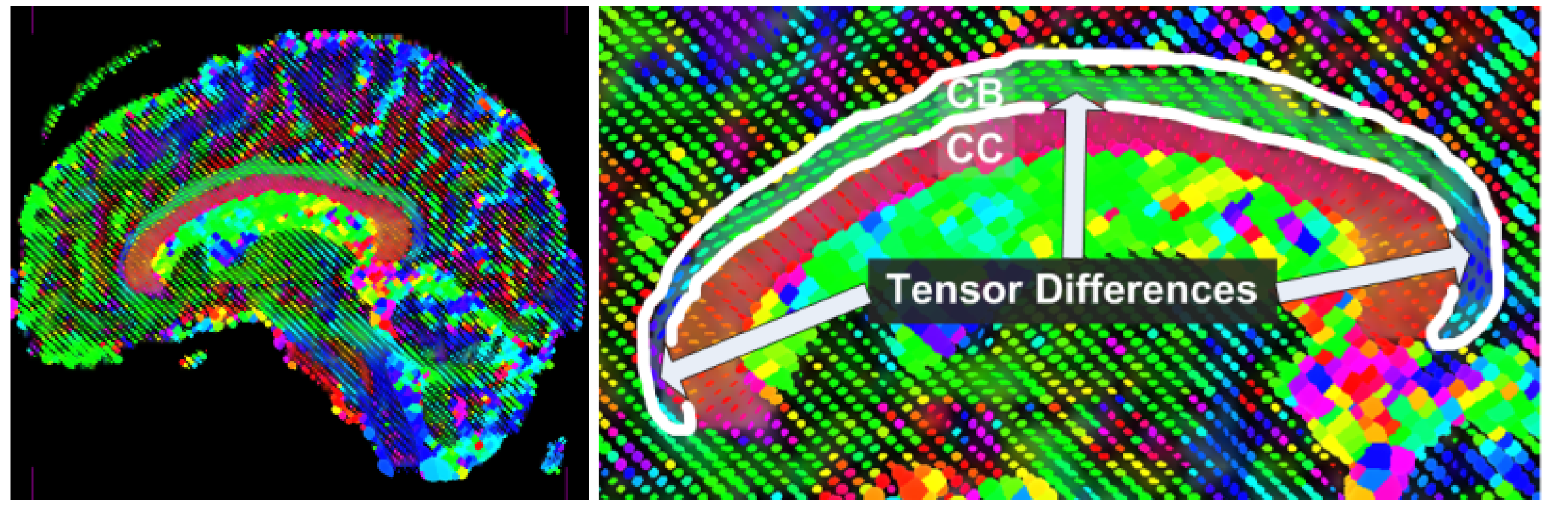
Abstract

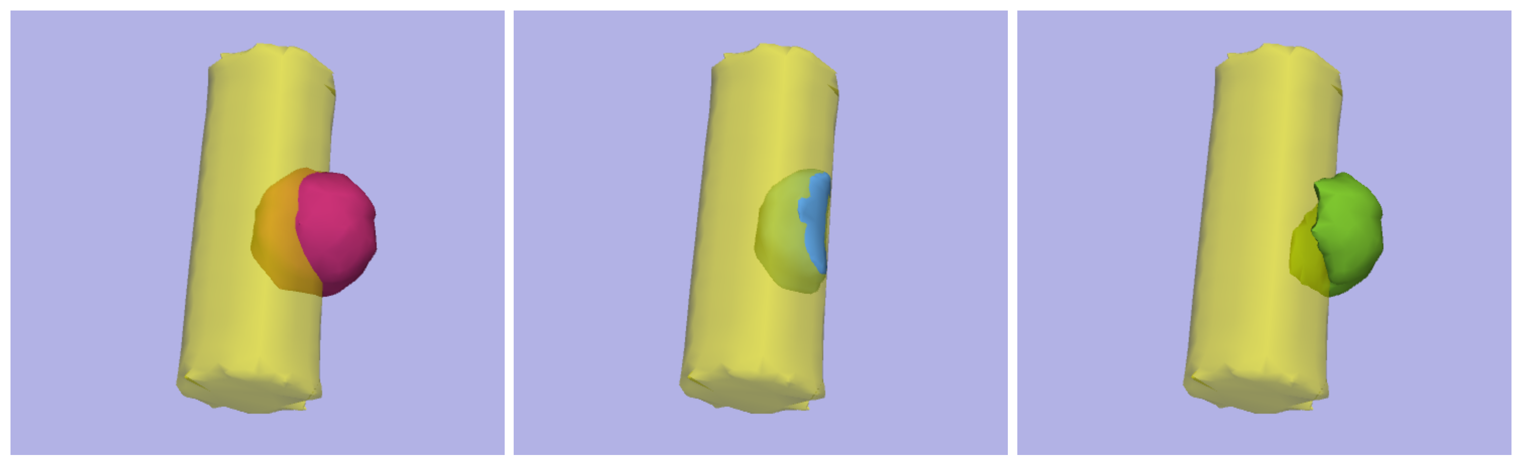
The key contribution of this work is the successful application of a statistical localization approach to the segmentation of neural fiber bundles in diffusion weighted magnetic resonance imagery (DW-MRI). We show that by extending active surface segmentation techniques to use locally sampled statistics, we can capture heterogeneous orientation information along the fiber bundles.

Motivation

Neural fiber bundles can curve significantly causing the orientation of tensors along the bundle to vary along its length. Consider the differences in orientation in the Cingulum Bundle.



Considering statistics in local regions simplifies this problem.



(a) Local Region (b) Local Interior (c) Local Exterior

In these regions, statistics of the fiber bundle and the surrounding structures are easily separable. A segmentation can be driven by simple statistics such as the localized tensor mean.

Algorithm Summary

- Compute normalized tensors so each has unit magnitude
- Compute a single medial anchor tract using a tractography technique by Melonakos *et. al.*
- Create an initial surface by dilating the medial tract
- Deform the initial surface iteratively to obtain the segmentation

Localizing Tensor Statistics

To compute localized statistics, we use three functions. First, local regions along the edge of the surface are selected with a ball function

$$\mathcal{B}(x,y) = \begin{cases} 1 & \|x-y\| < r \\ 0 & \text{otherwise.} \end{cases}$$

Second, the smoothed Heavyside function

$$\mathcal{H}\phi(x) = \begin{cases} 1 & \phi(x) < -\epsilon \\ 0 & \phi(x) > \epsilon \\ \frac{1}{2}\{1 + \frac{\phi}{\epsilon} + \frac{1}{\pi}\sin(\frac{\pi\phi(x)}{\epsilon})\} & \text{otherwise} \end{cases}$$

selects the interior of the surface. Third, its derivative $\delta\phi(x)$ selects the interface. These are combined using log-Euclidean tensor arithmetic to define local interior means, $u(x)$ and local exterior means, $v(x)$

$$u(x) = \exp\left(\frac{\int_{\Omega_y} \mathcal{B}(x,y)\, \mathcal{H}\phi(y)\, \log(\mathbf{T}(y))\, dy}{\int_{\Omega_y} \mathcal{B}(x,y)\, \mathcal{H}\phi(y) dy}\right)$$

$$v(x) = \exp\left(\frac{\int_{\Omega_y} \mathcal{B}(x,y)\, (1-\mathcal{H}\phi(y))\, \log(\mathbf{T}(y))\, dy}{\int_{\Omega_y} \mathcal{B}(x,y)\, (1-\mathcal{H}\phi(y)) dy}\right)$$

To evaluate the distances between log-Euclidean tensors and means computed in the exponential space, we define

$$d_{LE}[\mathbf{T}_1, \mathbf{T}_2] = \|\log(\mathbf{T}_1) - \log(\mathbf{T}_2)\|^2$$

Separating Local Means with Active Surfaces

To perform the segmentation, we begin by constructing an energy based on the localized interior and exterior means.

$$E(\phi) = \int_{\Omega_x} \delta\phi(x) \int_{\Omega_y} \mathcal{B}(x,y)\, F(\mathbf{T}(y), \phi(y))\, dy\, dx + \lambda \int_{\Omega_x} \delta\phi(x) \|\nabla\phi(x)\| dx$$

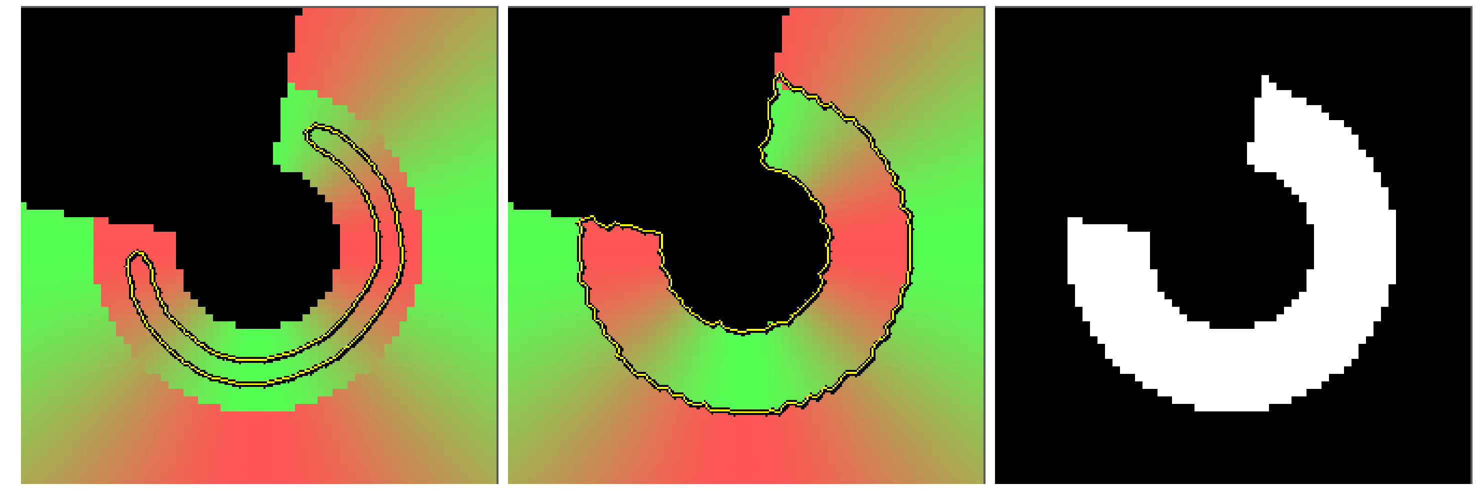
$$F(\mathbf{T}, \phi) = \mathcal{H}\phi(y)\, d_{LE}[\mathbf{T}(y), u(x)] + (1-\mathcal{H}\phi(y))\, d_{LE}[\mathbf{T}(y), v(x)]$$

Next, we minimize this energy by iteratively evolving an active surface segmentation in 3D. Using localized statistics allows the surface to adapt to the changing orientations along the fiber bundles.

Active surfaces also make use of intrinsic smoothness properties to prevent leaks and keep the segmentation reasonable.

Experiment I: Synthetic Example

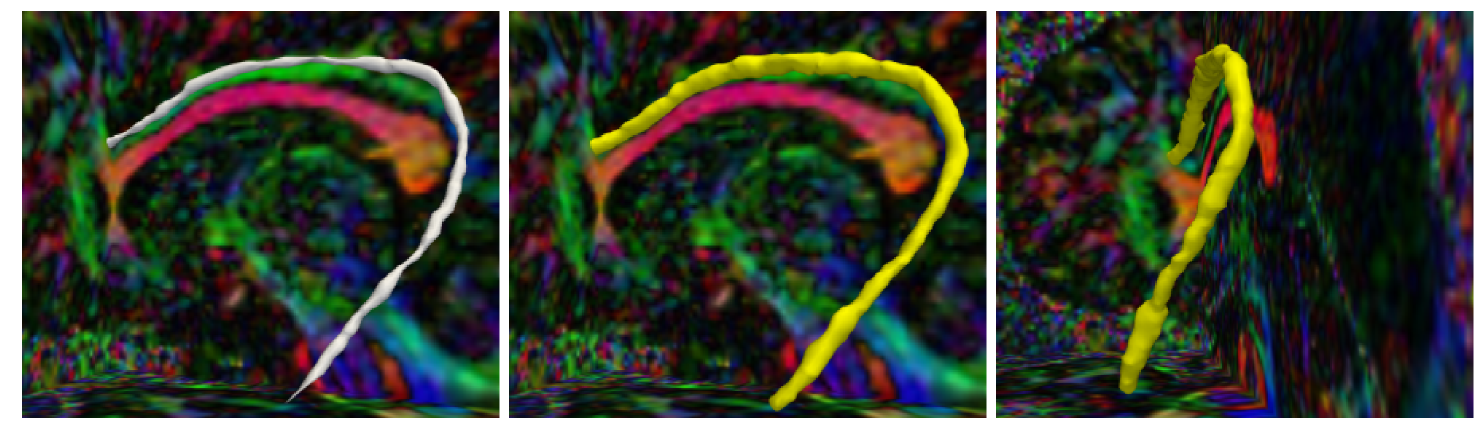
- Validation on data with known truth values
- Curved structure (similar to fiber bundles)
- Structure and background share global statistics
- Correct segmentation is achieved.



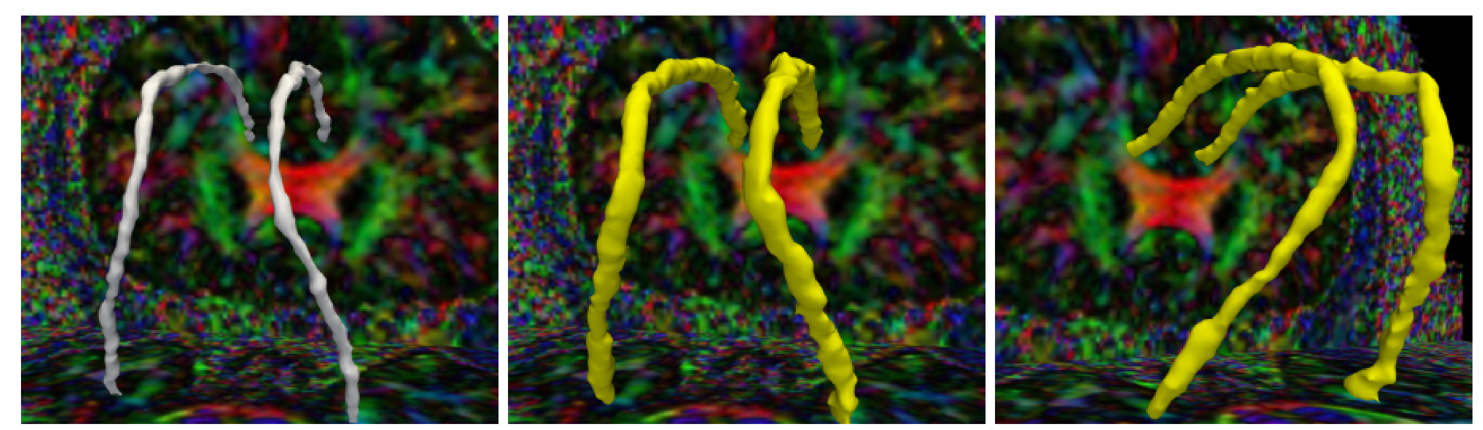
(a) Initialization on Synthetic (b) Final Result on Synthetic (c) Final Result on Synthetic

Experiment II: Cingulum Bundle

- Cingulum Bundle (CB) curves along the length
- Forms "ring-like belt" along corpus callosum
- Useful for diagnosis of depression and schizophrenia
- Parameters: $r = 7$mm based on anatomical knowledge



(a) Initialization of Left CB (b) Final Result of Left CB (View 1) (c) Final Result of Left CB (View 2)



(d) Initialization of both CBs (e) Final Result of both CBs (View 1) (f) Final Result of both CBs (View 2)

We plan to extend this work by applying the technique to more fiber bundles and using more sophisticated tensor statistics.