# SURFACE-BASED MODELING OF WHITE MATTER FASCICULI WITH ORIENTATION ENCODING

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## ABSTRACT

In this paper, we describe a novel technique for modeling sheet-like white matter (WM) fasciculi using *continuous medial representation (cm-rep)*. In the cm-rep framework, the skeleton of a fasciculus is described by a parametric surface patch. This modeling scheme is particularly appropriate for sheet-like structures, because the shapes of such objects can be effectively captured by their skeletons. We show that dimensionality reduction can be achieved without much loss of spatial specificity by projecting data along the "less interesting" thickness direction onto the skeletons. We demonstrate that local fiber orientation of the modeled fasciculi can be encoded in our framework and show how this information can be leveraged for deriving and analyzing brain connectivity patterns on the skeleton themselves.

***Index Terms*—** White Matter Modeling, Diffusion Tensor Images, Medial Modeling, Surface-based Modeling

## 1. INTRODUCTION

White matter (WM) fasciculi in human brain are thin, sheet-like or tube-like structures. The advent of Diffusion Tensor MRI (DT-MRI) [1] enables the identification of individual fasciculus using fiber tractography (See [2] for a review). A fasciculus derived from tractography is typically described by a dense set of space curves. The curve ensemble captures the spatial extent and shape of the fasciculus while each curve indicates the trajectory of the underlying fiber bundle in space. This representation provides a rich description of fasciculi. However, for the purpose of characterizing properties of fasciculi, it is often more desirable to use alternative models that are less complex but still able to capture the essential fasciculi features. A number of authors proposed to identify bundle of curves with similar shape and make inferences on the basis of bundle centerlines [3, 4]. This approach is well-suited for tubular fasciculi, but sheet-like structures like the corpus callosum (CC) have to be subdivided into several tubular bundles. Such structures can be more effectively described using skeletons that are 2-D manifolds because their skeletons reflect the shapes of the objects themselves. This fact is leveraged in the *tract-based spatial statistics* (TBSS) approach [5]. However, in that approach, skeletons are derived for the entire WM region and no distinction between fasciculi is made. This can lead to adjacent fasciculi that have different orientation being treated as a single structure. At such locations, there may be ambiguities in fiber orientations and the skeleton computed by TBSS may not correspond to the skeletons of the individual fasciculi.

In this paper, we describe a surface-based modeling technique for fasciculi that is inspired by both the TBSS and the centerline approaches. Similar to TBSS, we represent WM structures using their skeletons. However, unlike TBSS but similar to the centerline approach, we use skeletons to represent specific WM structures of interest, rather than all of WM. In order to distinguish between adjacent tracts, we derive individual fasciculi using fiber tractography. Instead of deriving the skeletons by skeletonization, parametric skeleton models with predefined topology appropriate for sheet-like structures are used and they are fitted to fasciculi in the standard deformable modeling framework. We describe how the dimensionality reduction can be achieved in the shape-based coordinate frame endowed by our parametric models. Finally, we show that the surface model encodes local orientation information that is similar to the centerline approach. To take advantage of the orientation encoding, a technique for deriving tracks indicative of underlying fiber connections directly on these surface models is developed. We demonstrate that the derived connection patterns are consistent with the curve representation of fasciculi and can be used to provide anatomically finer parcellation of the surface models.

## 2. METHODS

In this section, we first describe our surface-based geometric modeling of fasciculi, then elucidate the shape-based coordi-

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nate frame and the dimensionality reduction scheme enabled by the surface-based models. Finally, we describe the orientation encoding and its application to derive the connectivity information directly on the proposed models themselves.

### 2.1. Surface-Based Geometrical Modeling of Fasciculi

Given fasciculi derived from tractography, their corresponding binary segmentations are first generated by labeling voxels through which at least one fiber passes. Geometrical modeling of the fasciculi then involves fitting deformable medial models (cm-reps) to the binary segmentations. The cm-reps are models that describe the skeleton and the boundary of a geometrical object as parametric digital surfaces with predefined topology. Furthermore, the models describe the geometrical relationship between the skeleton and the boundary, such that deformations applied to the model's skeleton can be propagated to the model's boundary. In the current implementation, the skeleton surface is represented as a triangular mesh to allow maximum flexibility for modeling complex skeleton shapes. Each vertex in the mesh is a tuple $\{\mathbf{m}, R\}$, where $\mathbf{m} \in \mathbb{R}^3$ is the coordinate of the vertex and $R \in \mathbb{R}^+$ is the radius value, which describes the local thickness of the model. The boundary of the medial model is derived analyatically from the skeleton using *inverse skeletonization* [6]. The medial model is deformed to optimze some cost function by modifying the values of $\mathbf{m}$ and $R$ at each vertex in the mesh. Further details of the fitting algorithm can be found in [7].

Note that the medial models used in this paper have skeletons consisting of a single surface patch. For most sheet-like fasciculi, this model appears sufficient, as our fitting results reported in Sec. 3 demonstrate.

### 2.2. Shape-Based Coordinate System

A key property of medial models is the ability to parametrize the entire interior of the model using a shape-based coordinate system. This is due to the fact that in medial geometry every point on the skeleton surface is associated with a sphere that is tangent to the boundary surface at a pair of points (which may coincide at edges of the skeleton). The line segments connecting the sphere's center to the points of tangency are called "spokes" and are orthogonal to the boundary. Furthermore, no two spokes intersect inside the model. This allows us to define a coordinate system for interior of the object based entirely on the shape of the object, where two of the coordinate values parametrize the skeleton surface and the third gives the position of a point on the spokes.

In the current context of modeling sheet-like fasciculi, this coordinate system affords us the ability to reduce the dimensionality of the problem by projecting data onto the skeleton along the arguably "less interesting" thickness dimension. From the point of view of statistical analysis, this may result in improved sensitivity without much loss in spatial specificity.

### 2.3. Orientation Encoding and Manifold Tracking

To encode orientation, i.e., to determine the direction of principal diffusion at a particular point on the manifold, we have two options. One is to choose the principal diffusion direction of the tensor sampled just at that location. The alternative is to take the principal diffusion direction of a mean tensor computed by averaging diffusion tensor data sampled along the spokes extending from that point on the skeleton. Currently, we chooses the former strategy for illustrative purposes. To demonstrate that the locally encoded orientation indeed captures the underlying fiber orientation and can be used to derive long-range cortical connectivities, we extend the concept of fiber tractography to the realm of tracking on the 2-D medial manifolds. Tracking on medial manifolds is akin to geodesic shooting except that here at each point the path taken is always parallel to the locally encoded direction of principal diffusion. Due to the noise in the data and/or residual fitting errors from modeling, the derived direction of principal diffusion might not be parallel to the triangular patch that the point belongs to. To correct for this type of errors, we project the direction of principal diffusion onto the plane of the triangular patch before proceeding with the following step.

## 3. RESULTS

Here we report the modeling of six major sheet-like fasciculus: corpus callosum (CC), cortico-spinal tract (CST), inferior fronto-occipital fasciculus (IFO), inferior longitudinal fasciculus (ILF), superior longitudinal fasciculus (SLF) and uncinate fasciculus (UNC). These fasciculi were extracted using fiber tractography from a symmetric WM template derived from diffusion tensor data of 31 developing children recruited for an ongoing clinical study. Since we used a symmetric template, fasciculi that exist on both hemispheres of the brain were tracked only from the left hemisphere. The details of the subject data, WM template construction and tractography-based fasciculi segmentation can be found in [7].

Fig. 1 illustrates the model-fitting process, using CC as an example. The initial fasciculus derived from tractography, the intermediate binary segmentation, and the resulting skeleton and boundary of the fitted model are shown. The resemblance in shape of the initial fasciculus and the fitted boundary model is apparent. The high fitting accuracy is confirmed quantitatively by the Dice overlap between the fitted boundary model and the binary segmentation, which are above $90\%$ for all six fasciculi and close to $95\%$ for five of them. Fig. 3 shows all six fasciculi, both their initial tractography results and final fitted skeleton surface models.

In Fig. 2, its left panel illustrates the result from tracking with the proposed technique on the fitted surface manifold of CC. To allow for a clearer visualization, we only initiated tracking from one in every four triangles on the surface patch. Its similarity to the original fasciculus derived from tractog-

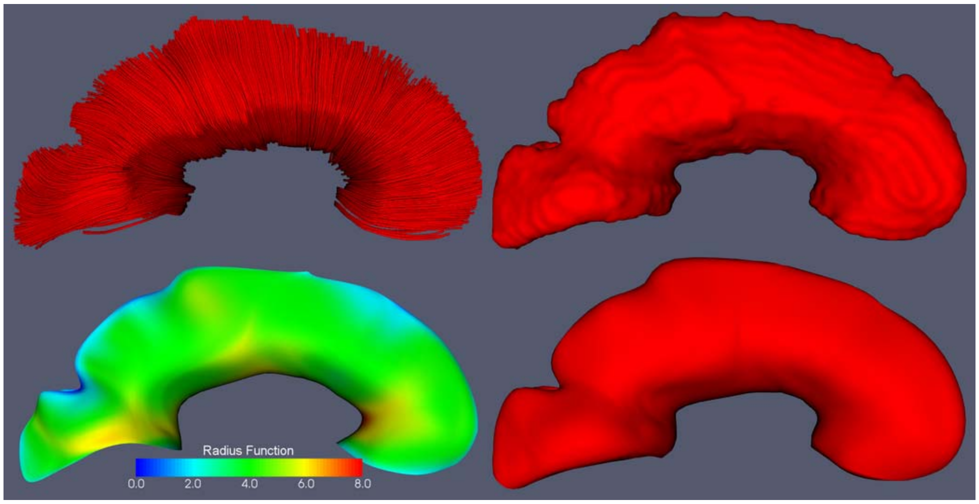


**Fig. 1**. An illustration of model-fitting using corpus callosum (CC). Top left: CC derived from fiber tractography. Top right: the corresponding binary segmenation of the CC. Bottom left: the skeleton surface of the cm-rep model fitted to the binary segmentation. The color map along the skeleton surface plots the radius scalar field $R$, i.e., the local thickness of the model. Bottom right: the boundary surface of the cm-rep model.

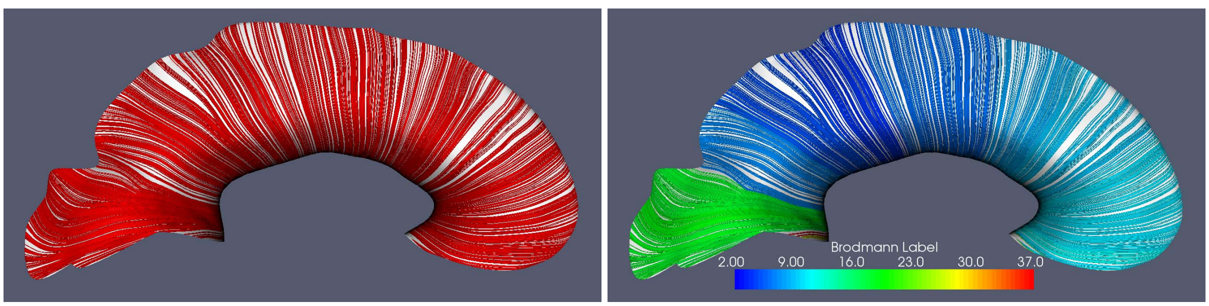


**Fig. 2**. Left: tracking on the skeleton surface of corpus callosum (CC). The tracks are in red and the skeleton is in white. Right: Labeling the skeleton surface of CC according to connectivity to individual Brodmann areas in cortex.

raphy is evident. Its right panel shows the result of labeling these tracts according to their connection to the Brodmann areas in cortex, demonstrating the ability to derive long-range connectivity with the surface model.

Finally Fig.4 shows the result of labeling all six fasciculi according to their connections to the Brodmann areas. Only a single label is necessary for CC and CST, because for commissural fasciculi individual connection to the cortex is primarily to homologous areas and for projection fasciculi only one end of the pathway connect to the cortex. For association fasciculi, which are the other four selected structures, each end of their pathways generally connects to different cortical area. Hence, two labels are necessary for each track to be labeled. To help visualizing the labeling results, the labels corresponding to connections to anterior/superior part of the cortex are shown in the left panel while the labels corresponding to connections to posterior/inferior part of the cortetx are shown in the right panel.

## 4. CONCLUSIONS AND DISCUSSIONS

In this paper, we described a novel surface-based modeling scheme for sheet-like WM fasciculi. Compared to previous works, the strength of the proposed scheme includes both the support for dimensionality reduction and the preservation of orientation information of the underlying fasciculi. We proposed a technique for deriving long-range connectivity from the locally-encoded orientation information directly in the surface-based modeling framework and demonstrated for the cortical connectivity-based parcellation of the fasciculi in the surface-based modeling framework. Our future work will focus on deriving integrated measures of fasciculus integrity in the proposed modeling framework.

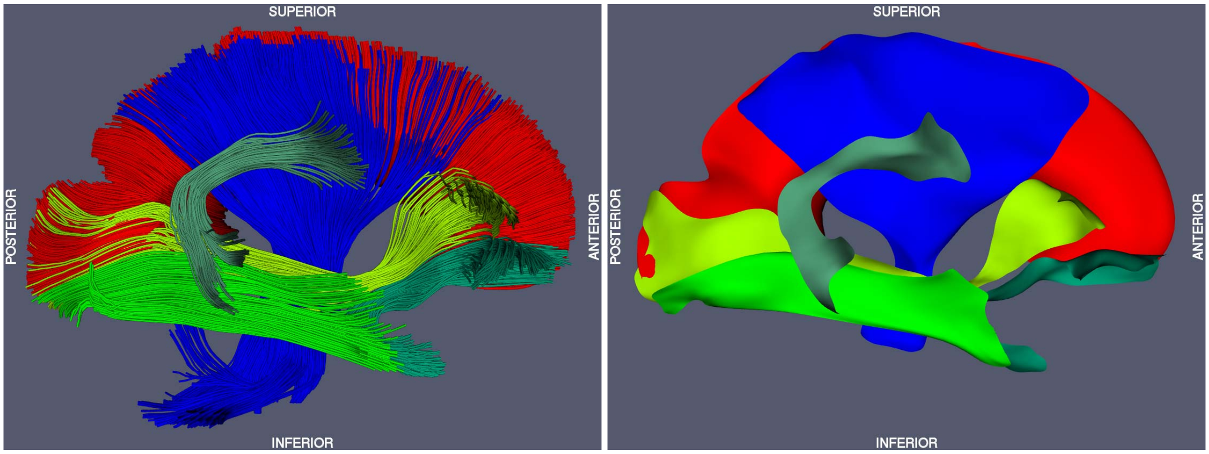


**Fig. 3**. Left: fiber tracking results for the six selected fasciculi. Right: skeleton surfaces of the cm-rep models fitted to the six selected fasciculi.

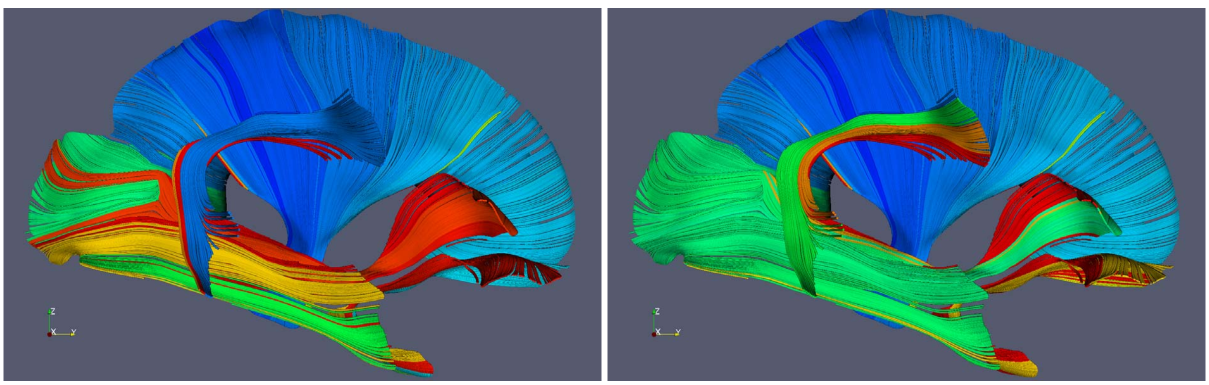

**Fig. 4**. Labeling the tracks derived on the skeleton surfaces of the six selected fasciculi. For the commissural (corpus callosum) and the projection (cortico-spinal tract) fasciculi, the left and right panels show the identical images. For the other four association fasciculi, the left panel shows the anterior/superior cortical connections while the right panel shows the posterior/inferior cortical connections.

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