Tractography in the CST using an Intrinsic Unscented Kalman Filter

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1 Introduction

In this short paper, we describe the tractography method based on the intrinsic unscented Kalman filter (IUKF) [1]. This method is a generalization of unscented Kalman filter (UKF) and involves the use of intrinsic geometry of the space of symmetric positive definite matrices denoted henceforth by $P_n$. In this filter, operations that are intrinsic to $P_n$ are employed and thus no explicit constraints are needed to guarantee the positive definiteness of the estimated diffusion tensors unlike in [2]. This method is applied to the given human brain data to perform tractography and recover the CST.

2 Method

Our tractography pipeline consists of three steps, namely, (1) preprocessing, (2) fiber tracking and (3) fiber reduction. In the following, we describe each step in details.

2.1 Preprocessing

In the preprocessing step, each volume corresponding to a given magnetic gradient direction from the DW MRI dataset is denoised using the unbiased non-local means algorithm for Rician noise [3]. Since our tracking method is based directly on the MR Signals, no multi-fiber reconstruction over the whole image lattice is needed as a preprocessing step. However, the DTI reconstruction method [4] is employed at the seed points as the initialization for the IUKF.

2.2 Fiber Tracking

In this fiber tracking stage, we made use of the IUKF [1] combined with a streamline algorithm, which is initialized from a seed point. Here the tractography is performed in the whole brain, therefore, the seeds are placed in every voxel inside the brain. At iteration step $k$ for a single fiber, the reconstruction is performed by the IUKF using a bi-tensor model, and the direction $\mathbf{d}_k$ is computed as the major eigen vector of one of the tensors that is closer to the direction from

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the last step. The streamline algorithm then updates the position by computing $x_{k+1} = x_k + \Delta t d_k$, where $\Delta t$ is the step size. The tracking stops if one of the following cases happens: the angle between $d_k$ and the fiber direction is large (exceeds an angle threshold $\Theta_m$), the signal strength at the current voxel is less than a threshold $S_0$, the length of the fiber exceeds a given threshold $L_f$ (in order to discard too large fibers), or it is at the boundary of the dataset. The parameters values used in our experiments are summarized in Table 1.

The Intrinsic Unscented Kalman Filter for Diffusion Tensors

In this section, we briefly present the intrinsic unscented Kalman filter to track diffusion tensors. It is well known that diffusion tensors lie in the space $P_n$ and we refer the reader to [5, 6] for an introduction to the mathematical properties of $P_n$. The IUKF has three main components, namely, an observation model, the state transition model and the filter. The IUKF is similar to the standard UKF [7] with the key difference being, some of the vector operations, e.g. the update of the posterior are replaced by the general linear (GL) group operation on $P_n$. Here we will limit our explanation to the observation and state transition model. We may refer the reader to [1] for more details.

The observation model is based on the bi-tensor diffusion model.

$$S_k^{(n)} = S_0 (e^{-b_n g_n^T D_k^{(1)} g_n} + e^{-b_n g_n^T D_k^{(2)} g_n})$$  \(1\)

where $g_n$ denotes the direction of $n$-th magnetic gradient, $b_n$ is the corresponding $b$-value, and $S_k^{(n)}$ is the MR signal encountered at the $k$-th iteration along the $n$-th magnetic gradient field direction. The covariance matrix of the observation noise for all the magnetic gradients is a diagonal matrix denoted by $R$.

For the state transition model on $P_n$, we propose the general linear (GL) group operation/action and the LogNormal distribution [8]. For the bi-tensor (sum of two Gaussians) model, the state transition model at step $k$ is given by,

$$D_{k+1}^{(1)} = Exp_{F D_{k}^{(1)} F} (v_{k}^{(1)})$$

$$D_{k+1}^{(2)} = Exp_{F D_{k}^{(2)} F} (v_{k}^{(2)})$$  \(2\)

where, $D_k^{(1)}$, $D_k^{(2)}$ are the two tensor states at step $k$, $F$ is the state transition GL-based operation, $v_k^{(1)}$ and $v_k^{(2)}$ are the Gaussian distributed state transition noise for $D_k^{(1)}$ and $D_k^{(2)}$ in the tangent space $T_{D_k^{(1)}} P_3$ and $T_{D_k^{(2)}} P_3$ respectively. Here we assume that the two state transition noise models are independent from each other and the previous states. The covariance matrices of the state transitions are $Q^{(1)}$ and $Q^{(2)}$ respectively. $Exp$ is the matrix exponential. The square root in Eq. 2 is defined as $P^{1/2} := g$, such that $gg^T = P$, and $g$ is symmetric.

In this work, the covariance matrix of the observation noise is set to be a scaled identity matrix $R = r I$, and so is the covariance matrix of the state transition model set to $Q_1 = q_1 I$, $Q_2 = q_2 I$. The initialization of the IUKF is also important. Here at each seed point, a diffusion tensor reconstruction
method [4] is employed to initialize $D_0^{(1)}$ and $D_0^{(2)}$. The state transition matrix $F$ is set to the identity. All the parameters settings are depicted in table 1.

2.3 Fiber Reduction

The last step is to remove the unwanted fibers. In this post-processing step, we need to discard the fibers that do not belong to the corticospinal tract. Here the fiber reduction consists of three criteria, which are described in below.

Firstly, each fiber should pass through both of the two ROIs, one at the top of the brain, and the other in the brainstem, as shown in the upper left figure in Fig. 1. In this way, the fiber length criteria is implicitly applied such that only long fibers starting from brainstem and ending in the cortex are retained. The ROI in the experiments is manually set using ITK-SNAP [9].

Secondly, based on the structure of corticospinal tracts, the resulting fibers have to be sufficiently vertical. Therefore, we also used an angle threshold criteria to remove unwanted fibers. In this way, each fiber that has an angle less than a threshold ($\Theta_c$) to the X-Y plane, is discarded. The value of $\Theta_c$ in our experiment is depicted in the table 1.

In the tracking stage, the left and right corticospinal tracts are tracked jointly. To split them, the mid sagittal plane is manually selected, and the fibers with larger portion in the right of the plane are treated as right corticospinal tracts and vice versa. At the end, any fiber that passes the mid sagittal plane is discarded.

Lastly, retained fibers are all long enough to connect the brainstem to the cortex, and also are vertical enough to be included in corticospinal tract.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$\Delta L$ (mm)</th>
<th>$\Theta_M$</th>
<th>$q_1$</th>
<th>$q_2$</th>
<th>$r$</th>
<th>$\Theta_c$</th>
<th>$S_0$</th>
<th>$L_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient 1</td>
<td>0.5</td>
<td>60°</td>
<td>0.1</td>
<td>0.1</td>
<td>0.03</td>
<td>10°</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Patient 2</td>
<td>0.5</td>
<td>60°</td>
<td>0.1</td>
<td>0.1</td>
<td>0.03</td>
<td>5°</td>
<td>500</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 1. Parameters values

3 Experimental Results

The fiber tracking results from the first patient are depicted in Fig. 1, where we observe that the shape of the fiber bundle looks satisfactory, since the estimated CST fibers connect the brainstem to the cortex as expected. Also, from the figure on the top right we can see that the fiber bundle on the right side is pushed by the tumor as expected. The fiber bundle is displayed using MedINRIA [10].

4 Conclusion

We performed the tractography by using the IUKF technique. The performance of our method is visually satisfactory, since the structure of the resulting fiber
Fig. 1. Fiber reconstruction results for the first patient. (a) the ROIs used as the fiber reduction (region) criteria. (b) overlays the fibers with two $S_0$ image slices in the coronal and axial views, to depict the relative position w.r.t the tumor (the red region in the right). (c) shows the shape of the fiber bundle in 3-D space. (d), (e) and (f) represent the fibers from right, posterior and superior views, respectively.
bundle is very close to the expected corticospinal tracts, and as expected is deformed by the presence of the tumor for the patient data. However, since IUKF is a streamline based method, and like all streamline methods it can not handle the fanning issue very well. So in this work, we placed the seed points in the whole brain, and then used the ROIs in the cortex and brainstem to reduce the unwanted fibers. In this way, satisfactory results are obtained even when the ROI is not an accurate segmentation from the dataset.

References