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Visualization of Probabilistic Fiber Tracts in Virtual Reality

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Abstract. Understanding the connectivity structure of the human brain is a fundamental prerequisite for the treatment of psychiatric or neurological diseases. Probabilistic tractography has become an established method to account for the inherent uncertainties of the actual course of fiber bundles in magnetic resonance imaging data. This paper presents a visualization system that addresses the assessment of fiber probabilities in relation to anatomical landmarks. We employ real-time transparent rendering strategy to display fiber tracts within their structural context in a virtual environment. Thereby, we not only emphasize spatial patterns but furthermore allow an interactive control over the amount of visible anatomical information.

Keywords. probabilistic tractography, virtual reality

Introduction

Neuroscientific research aims at understanding the structure-function relationship in the brain. Networks of communicating brain areas are required to fulfil motor, sensory as well as all mental and cognitive activities. The structural basis of such networks are nerve fibers connecting the participating brain areas. A profound knowledge about this connectivity structure is therefore necessary for understanding the computational activity of the brain. The mapping of nerve fibers and fiber bundles in the brain is also required to further understand psychiatric or neurological diseases.

Currently, diffusion tensor magnetic resonance imaging (DT-MRI) provides the most forward method for the assessment of white matter fiber tracts in the living human brain. Hereby, the course of the fibers is estimated by measuring water diffusion in the brain. Based on their Brownian motion, water molecules prefer to move along directions with lowest resistance which in the brain is provided along the myelin sheaths. By applying magnetic field gradients from different spatial directions, the uncertainty within the diffusion data can be estimated and used for consecutive analysis. From these DT-MRI

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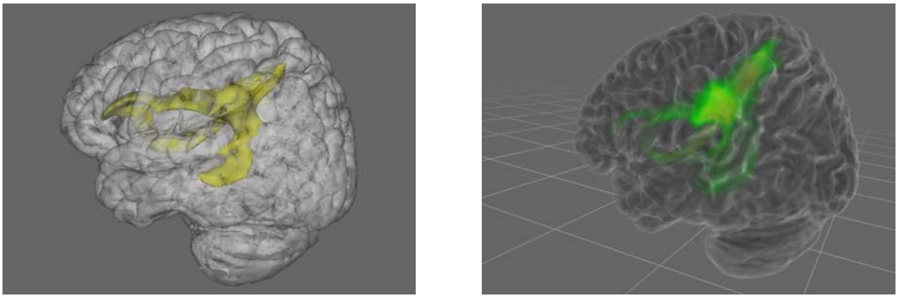

Figure 1. Solid surface representation of a fiber pathway, image created with FSL [4] (left). Our volumetric rendering shows the probability distribution within the fiber tract (right).

data an effective diffusion tensor can be estimated within each voxel. The quantities as mean diffusivity, principal diffusion direction and anisotropy of the diffusion ellipsoid can be computed from the elements of the diffusion tensor [1].

To reconstruct fiber pathways based on the diffusion data, two main methods are currently used: (1) deterministic tractography, and (2) probabilistic tractography. Deterministic tractography tries to find the path from a seed to a target voxel based on the main diffusion direction within each voxel on the way. Hereby, uncertainty within the course of the fiber pathway cannot reliably be accounted for. In contrast, probabilistic tractography explicitly accounts for the uncertainty of the actual fiber tracts. For each voxel, a local probability distribution of the diffusion direction is calculated. A probabilistic tractography algorithm then tries to find the most probable course of a fiber between a seed and a target voxel by deciding in each voxel which would be the most probable prosecution of the fiber, based on the local probability distribution and its prior course [2]. As a result of probabilistic tractography, no single fiber strand is provided, but a probability distribution of possible fiber pathways between seed and target voxels, ranging from voxels with a large number of passed traces to voxels with only a low number of passes.

The visualization of the probability in three dimensions (3D) is an essential step for the registration of the most likely course of a fiber bundle. Furthermore, anatomical information is required to reveal the fiber in its structural context. In this paper we extent the ideas from [3] and address both the visualization of probabilistic fiber tracts with a special focus on how to provide the required degree of anatomical context. We embed our visualization system in a virtual environment which not only improves depth perception due to stereoscopic projections but enables the use of direct interaction techniques such that the user becomes an integral part of the visualization pipeline. We use direct volume rendering for structural as well as fiber information in order to provide semi-transparent renderings in real-time. The amount of visible anatomical context can be controlled by a so-called magic lens interaction metaphor which we will refer to as *virtual flashlight*.

The remainder of this paper is structured as follows. After briefly reviewing previous work in Section 1, we will describe our visualization and interaction approach in Section 2. We present the results in Section 3 and conclude our work in Section 4.

1. Related Work

Deterministic streamline tractography emphasizes the course of the neuronal fibers using the principal eigenvector of the diffusion tensor [5]. To visualize the 3D large scale structure, Kindlmann [6] applied direct volume rendering strategies to the anisotropy values to map from the diffusion tensor data to color and opacity. Other common visualizations often make use of glyph-based techniques that represent a single tensor as a geometric primitive or via streamline advection among the principal eigenvector of the local tensor. Chen at al. [7] for example, merge ellipsoids to show the connectivity information in the underlying anatomy while characterizing the local tensor in detail. Sherbondy et al. [8] implemented interaction techniques to place and manipulate regions to selectively display deterministic fiber tracts that pass through specific anatomical areas. However, due to the relatively low resolution of DTI data as compared to the diameter of an axon, only the main fiber direction within each voxel is accounted for.

Therefore, a main methodological issue are crossing fibers. Qazi et al. [9] successfully trace through regions of crossing fibers deterministically by extracting two tensors at any arbitrary position. Nevertheless, streamline methods only represent a single fiber path between two points without indication of correctness. Current probabilistic tractography algorithms [2] model different courses of fibers within each voxel using priors about the previous course of the estimated fiber tract and anatomical plausibility assumptions [10], thereby addressing the issue of crossing fibers adequately.

Conveying uncertainty in the rendering is an inherent requirement for neuroscientists to evaluate probabilistic tractographies. The high interest in uncertainty and fiber crossing is shown in the recent work of Descoteaux et al.[11]. Deterministic and probabilistic tractography are compared with respect to crossing and splitting fiber bundles. In most current visualizations uncertainty is only represented on two-dimensional (2D) slices. 3D representations of probabilistic fiber tracts are often generated by extracting opaque isosurfaces for certain probability ranges (see Figure 1 left).

In addition to visualization, the exploration of data also requires interactive manipulation. Therefore, we introduce the so-called magic lens interaction metaphor. It was first discussed by Bier et. al [12] as a 2D see-through user interface that changes the representation of content in a special window. A popular example is for instance a magnifying glass. In [13], Viega et. al extend the concept of magic lenses to virtual environments. They present the implementation of volumetric lenses that uses hardware clipping of geometric primitives to reveal the inner structure of objects. Whereas in [14] a magic box is used to present a higher-resolution of a flow visualization in order to focus attention on these regions and investigate them in more detail.

2. Method

A major issue of current 3D visualization techniques in common DTI analysis tools is that no indication of uncertainty in the fiber tracts is contained in the final renderings. For instance in Figure 1 (left), the rendering of tracts is achieved by extracting an isosurface from the fiber tract but with no further clues to anatomical details or probability distribution within the fiber tract. However, anatomical context information is crucial for the registration of the most likely course of a fiber pathway in relation to structural landmarks.

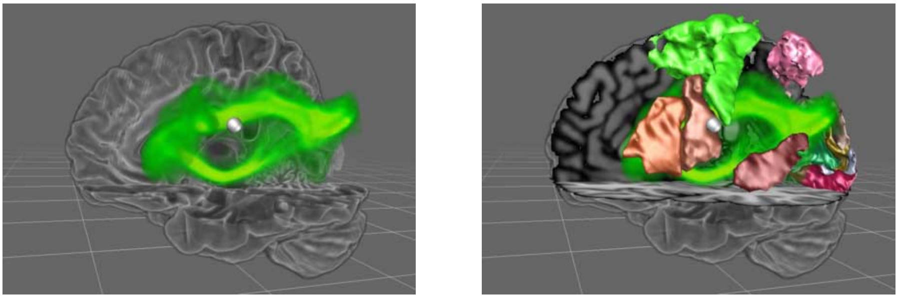

Figure 2. Three-dimensional brain with fiber bundle (left). Brain areas provide additional anatomical context (right).

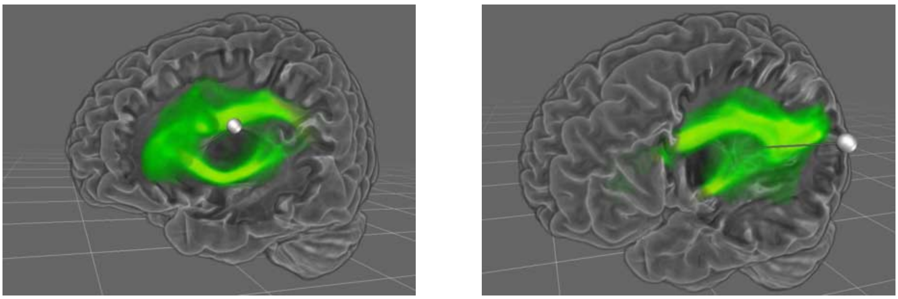

Figure 3. A user defined clipping region relates the fiber pathway with structural information.

2.1. Requirements

To overcome such shortcomings, we formulate four conceptual requirements of our visualization system based on an interdisciplinary discussion with DTI domain experts as follows: (1) The visualization should emphasize spatial patterns and present the three-dimensional physical structure in an intuitive fashion. (2) The final rendering should convey the uncertainty within each fiber tract. (3) The location of fiber tracts within the human brain should easily be deduced by the anatomical context. (4) None of the above requirements must interfere with the interactivity of the visualization system.

2.2. Visualization Technique

We employ a direct volume rendering as the underlying rendering technique for our visualization system. However, our visualization system requires the display of multiple and transparent volumetric (voxel-based) information simultaneously. Here, state-of-the-art techniques for direct volume rendering are no longer sufficient for an interactive visualization in a virtual environment. The main reason for this is that the process of rendering transparent objects, which usually relies on either depth sorting or ray casting, is a complex process in general and becomes even more demanding the more objects are involved.

However, we can exploit the fact, that most medical datasets are already registered in a common reference space. Therefore, we adapt classical slice-based volume rendering to efficiently handle multiple co-registered data sets as follows: First, we interleave the data

Figure 4. Users in an immersive CAVE virtual environment (left). A spatial input device allows interaction directly in 3D (right).

sets into one vector-valued data field. The proxy geometry (texture slices) is setup such that it represents the shared reference space and is rendered only once which alleviates the problems of depth-sorting multiple proxy geometries. Then, a special shader program handles each integration step of the individual data sets, separately. In a subsequent step the temporary integration values are interpolated according to user setting (e.g. maximum intensity or weighted sum). Hence, fiber probability and structural information can be classified according to separate transfer functions but form a consistent and correctly depth-sorted transparent image (cf. Figure 1 right).

2.3. Anatomical Context

The anatomical context is provided by including a standardized reference brain (Figure 1). As illustrated in Figure 2, the opaque rendering of cross sections of the brain resembles the 2D slices the domain expert are familiar with from common DTI tools and provides an unbiased view on the original data. The rendering of functional or cortical defined brain areas is used to give additional clues to the anatomical connection of fiber tracts. Additionally, the reference brain is volume rendered semi-transparently with user-defined clipping regions in order to reduce visual cluttering. The clipping regions can either be simple axis-aligned planes or can directly be controlled by the user via a virtual clipping cone (virtual flashlight) as depicted in Figure 3.

2.4. Emphasizing Spatial Patterns

We use the virtual reality toolkit ViSTA [15] as basis for our implementation. This allows the deployment of our visualization system on common desktop computers as well as on immersive virtual environments (cf. Figure 4 left). Depending on the available hardware infrastructure, this also allows the combination of 3D rendering with user-centered projection (head-tracking) which increases the overall depth perception, significantly.

In addition to stereoscopic vision, direct interaction where the user takes an active role is an integral part of every interactive virtual reality system. We have incorporated a direct interaction metaphor into our visualization system, the *virtual flashlight*. Similar to the beam of a flashlight, the user can directly control the amount of visible anatomical structure by a 3D interaction device (cf. Figure 4 right). Interesting parts of the probabilistic fiber tracts can be revealed and referenced with the anatomical landmarks with reduced occlusion or visual clutter. This allows a more accurate inspection of the anatomic structure in the direct vicinity of fiber pathways. The concept is illustrated by the image series in Figure 5.

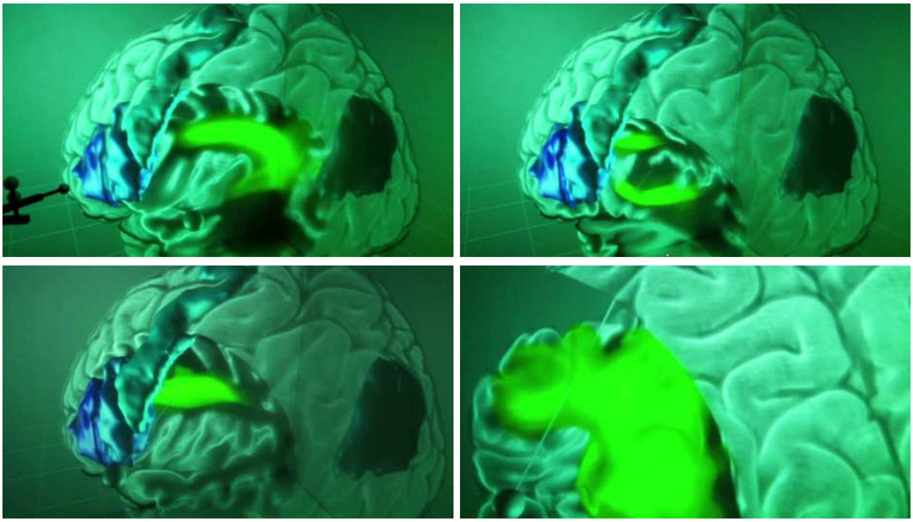

Figure 5. The user can control the clipping region with a virtual flashlight in the CAVE virtual environment.

3. Results

The data used for all visualizations were obtained in the Institute of Neuroscience and Medicine of the Research Centre Jülich and the C. and O. Vogt Institute for Brain Research of the Heinrich-Heine-University Düsseldorf. The brain areas shown here were depicted from the Jülich-Düsseldorf cytoarchitectonic atlas [16]. All data were displayed on the standard reference brain of the Montreal Neurological Institute (MNI) as internationally used as common reference space (voxel resolution: 1mm^3).

Domain experts state that by combining anatomical information from the reference brain with overlaying fiber tracking results, the visualization gives first hints to the anatomical context of the fiber tracts. Former visualization software most widely used in DTI tractography research only reconstructed fiber tracts in 3D as solid paths without any information about the uncertainty. Therefore, the coding of different probability values with different colors and transparencies allows a 3D impression of the fiber tract while still revealing its main direction and the uncertainty around it. Furthermore, the new visualization method allows interactive manipulation of the magnitude of anatomical information displayed which was hardly possible in former software packages.

4. Conclusion

Our work addresses the visualization of probabilistic fiber tracts in the human brain. Here, the comprehension of the course of the fiber in relation to its confidence is one of the most crucial steps. The interactive 3D visualization of probabilistic fiber tracts referenced with their anatomical landmarks allows the domain scientists to directly interpret their results in 3D. Hereby, reducing the additional mental workload previously required from judging 2D slices or missing uncertainty information in non-interactive 3D plots.

We have embedded our visualization in a virtual reality application which increases the depth perception of structural patterns and enables direct interaction metaphors due to tracking of 3D input devices. Furthermore, the degree of anatomical information necessary in order to establish a relationship between nerve fibers and structural landmarks can be controlled by the virtual flashlight metaphor. Here, the user is provided with a fine-grain control which parts of the structural information is cut away while the fiber tracts remain visible in the cone of the virtual flashlight.

References

[1] P. J. Basser, J. Mattiello, and D. Lebihan, "MR diffusion tensor spectroscopy and imaging," *Biophysical Journal*, vol. 66, pp. 259–267, 1994.

[2] T. Behrens, H. Johansen-Berg, M. Woolrich, S. Smith, C. Wheeler-Kingshott, P. Boulby, G. Barker, E. Sillery, K. Sheehan, O. Ciccarelli, A. Thompson, J. Brady, and P. Matthews, "Non-invasive mapping of connections between human thalamus and cortex using diffusion imaging," *Nature Neuroscience*, vol. 6, no. 7, pp. 750–757, 2003. [Online]. Available: http://dx.doi.org/10.1038/nn1075

[3] A. von Kapri, T. Rick, S. Caspers, S. B. Eickhoff, K. Zilles, and T. Kuhlen, "Evaluating a visualization of uncertainty in probabilistic tractography," K. H. Wong and M. I. Miga, Eds., vol. 7625, no. 1. SPIE, 2010, p. 762534.

[4] "FSL 4.1," August 2008. [Online]. Available: http://www.fmrib.ox.ac.uk/fsl/

[5] G. Kindlmann, "Visualization and analysis of diffusion tensor fields," Ph.D. dissertation, School of Computing, University of Utah, 2004.

[6] G. Kindlmann, D. Weinstein, and D. Hart, "Strategies for direct volume rendering of diffusion tensor fields," *IEEE Transactions on Visualization and Computer Graphics*, vol. 6, no. 2, pp. 124–138, 2000.

[7] W. Chen, S. Zhang, S. Correia, and D. F. Tate, "Visualizing diffusion tensor imaging data with merging ellipsoids," *IEEE Pacific Visualization Symposium*, vol. 0, pp. 145–151, 2009.

[8] A. Sherbondy, D. Akers, R. Mackenzie, R. Dougherty, and B. Wandell, "Exploring connectivity of the brain's white matter with dynamic queries," *IEEE Transactions on Visualization and Computer Graphics*, vol. 11, no. 4, pp. 419–430, 2005.

[9] A. Qazi, G. Kindlmann, L. O'Donnell, S. Peled, A. Radmanesh, S. Whalen, A. Golby, and C.-F. Westin, "Two-tensor streamline tractography through white matter intra-voxel fiber crossings: Assessed by fMRI," in *IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops.*, 2008, pp. 1–8.

[10] T. Behrens, H. Johansen-Berg, S. Jbabdi, M. Rushworth, and M. Woolrich, "Probabilistic diffusion tractography with multiple fibre orientations: What can we gain?" *NeuroImage*, vol. 34, no. 1, pp. 144–155, 2007. [Online]. Available: http://dx.doi.org/10.1016/j.neuroimage.2006.09.018

[11] M. Descoteaux, R. Deriche, T. Knosche, and A. Anwander, "Deterministic and probabilistic tractography based on complex fibre orientation distributions," *IEEE Transactions on Medical Imaging*, vol. 28, no. 2, pp. 269–286, 2009.

[12] E. Bier, M. Stone, and K. Pier, "Enhanced illustration using magic lens filters," *IEEE Computer Graphics and Applications*, vol. 17, no. 6, pp. 62–70, 1997.

[13] J. Viega, M. J. Conway, G. Williams, and R. Pausch, "3d magic lenses," in *UIST '96: Proceedings of the 9th annual ACM symposium on User interface software and technology*. New York, NY, USA: ACM, 1996, pp. 51–58.

[14] A. Fuhrmann and E. Gröller, "Real-time techniques for 3d flow visualization," in *VIS '98: Proceedings of the conference on Visualization '98*. Los Alamitos, CA, USA: IEEE Computer Society Press, 1998, pp. 305–312.

[15] I. Assenmacher and T. Kuhlen, "The ViSTA Virtual Reality Toolkit," The SEARIS Workshop on IEEE VR 2008, Reno, 2008.

[16] K. Zilles and K. Amunts, "Receptor mapping: architecture of the human cerebral cortex," *Current Opinion in Neurology*, vol. 22, no. 4, pp. 331–339, 2009.