

Visualizing Diffusion-Weighted MRI Data Using Collaborative Virtual Environment and Grid Technologies

A.Steed, D.Alexander, P.Cook, C.Parker
Department of Computer Science, University College London
{A.Steed|D.Alexander|P.Cook|C.Parker}@cs.ucl.ac.uk

Abstract

We describe a collaborative virtual environment system for visualization of diffusion magnetic resonance imaging scans. The system represents the 3D data by arrays of polyhedra, coloured by the degree of anisotropy and directed by the principal component of the diffusion tensor. Users can then collaboratively explore the data and interactively spawn tractography processes that compute tracks that depict white matter fibre pathways through the brain. These tracks are computed on a Grid service currently supporting 72 nodes on a Beowulf cluster.

1. Introduction

The ability to visualize the results of 3D medical image volumes of the human brain enhances the understanding of anatomy and can be key to the diagnosis of pathologies and pre-surgical planning. The development of effective visualization tools is difficult, even for standard imaging modalities, such as MR and PET. However, the introduction of new modalities, such as diffusion, perfusion, functional and permeability imaging, in which considerably more information is gathered, has made the task even more difficult. In diffusion imaging, for example, the measurements in each voxel provide a three-dimensional function that describes the local dispersion of water molecules. This dispersion reflects the local connectivity of tissue, rather than the physical structure of the brain [8].

We have developed a Grid-based visualization of diffusion-tensor MRI (DT_MRI) data using an immersive presentation system. DT-MRI is a popular form of diffusion MR imaging [8]. Figure 1 shows a sample view of our system.

The system allows a surgeon to plan operations with enhanced understanding of what will be required. The application demonstrates the following facilities:

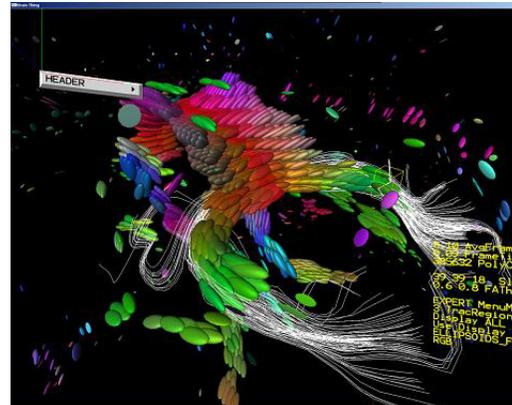


Figure 1. View from the visualization system. 3D ellipsoids represent the diffusion tensor and tractography is depicted by bundles of white lines.

- Visualization of complex functional MR brain image data using 2D and 3D representations on a state-of-the-art immersive presentation system.
- Dynamic alteration of the visualization of the diffusion MRI data at run-time by altering thresholds and primitives for tensor representation, 2D slices and tractography.
- Parallel implementation of tractography on a cluster of Grid nodes.
- Remote collaboration between the surgeons, clinicians, anatomists and imaging experts during diagnosis and pre-surgical planning.

In the following sections, we will outline the visualization system, the rendering facilities and the collaboration facilities.

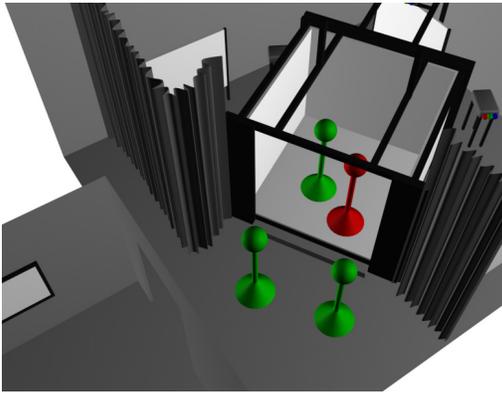


Figure 2. View of a CAD model of UCL's Trimension ReaCTor. It comprises 3 stereo back-projected 3x2.8m walls a 3x3m stereo front projected floor. Head and hand tracking are provided by an Intersene IS-900 tracker. Graphics are provided by an SGI Onyx2 with four InfiniteReality2 pipes.

1.1. Related Work

Visualization of volume data is one area where virtual environments have long been used. Zhang et al. describe a similar immersive visualization of DT-MRI scan [10]. Their system is single user and they visualize a static subset of pre-computed stream-tubes representing white-matter fibres. Our system is both collaborative, allows interactive calculation of similar stream tubes in regions of interest and provides a flexible representation of the diffusion tensor. Zhukov and Barr have recently demonstrated a process for tracing neural pathways in diffusion tensor MRI data [11]. They improved the tractography results by the use of a regularisation filter. This approach has been attempted before, for example [1][9]. Such filtering would make an obvious extension to the functionality of our GRID tractography server.

Many data types have been visualized in the immersive situation. Leigh et al. describe a range of examples and introduce associated toolsets such as CAVERNsoft [6]. There is quite a gulf between the current sets of high-end immersive visualization toolkits such as CAVERNsoft, more general collaborative virtual environment systems which provide higher-level user-centered functionality such as DIVE [4], and the current generation of Grid-based real-time tools epitomized by the AccessGrid (www.access-grid.org) which provides multi-media but no shared space. Although some efforts have been made to integrate such tools in more general ways [7], there are still no general tools that allow the flexibility for

visualization authors to integrate their particular models into a shared space.

2. System Overview

MRI scans are obtained and then pre-processed to remove noise and artifacts and compute the diffusion tensor in each voxel. The data comprises a 128x128x42 voxel space with each voxel representing 1.7x1.7x2.5mm. This voxel data is stored as a Visualization Toolkit (VTK) file (<http://public.kitware.com/VTK/>) for preliminary checking of conformance to required format. This voxel data is loaded by our visualization clients. Two classes of client are supported. The first client is a desktop client, is written using GLUT (www.opengl.org/developers/documentation/glut.html). The use of GLUT ensures portability to most operating systems. The second client is written on top of the CAVELIB library (www.vrco.com) and supports a wide variety of immersive platforms. At UCL we have a Trimension ReaCTor facility that is similar to a CAVE^{TM1} [3], see Figure 2. Both clients use custom renderers and both use our own 3D widget library (see Section 3).

The visualization clients can be connected together using a custom collaborative virtual environment toolkit. This supports the real-time facilities of avatar representation, shared menus and widgets (see Section 4).

Once running the visualization can be augmented with dynamically computed tractography results. Requests to analyze particular regions are forwarded asynchronously to a Grid server. This server also loads the MRI database and dispatches the analysis to various computational nodes (see Section 5). Figure 3 gives an overview of this process.

3. Visualization Components

The visualization comprises three main parts: textured cut-planes showing the raw data set; arrays of polyhedra, coloured by the degree of diffusion anisotropy and directed by the principal component of the diffusion tensor; and 3D tracks extracted by tracking white-matter fibre pathways through the voxel space (see Figure 4). 3D tracks are generated by calculating integral curves through the principal eigenvector field of the diffusion tensor.

3.1. 2D Cut Planes

The most common way of visualizing MRI data is by making cuts through the data set parallel to the axial, coronal, or sagittal planes. Any scalar value associated with water mobility could be displayed but due to texture memory restriction we currently allow just anisotropy and the root-mean squared particle displacement (trace) [5].

¹ CAVE is a registered trademark of the University of Illinois' Board of Trustees.

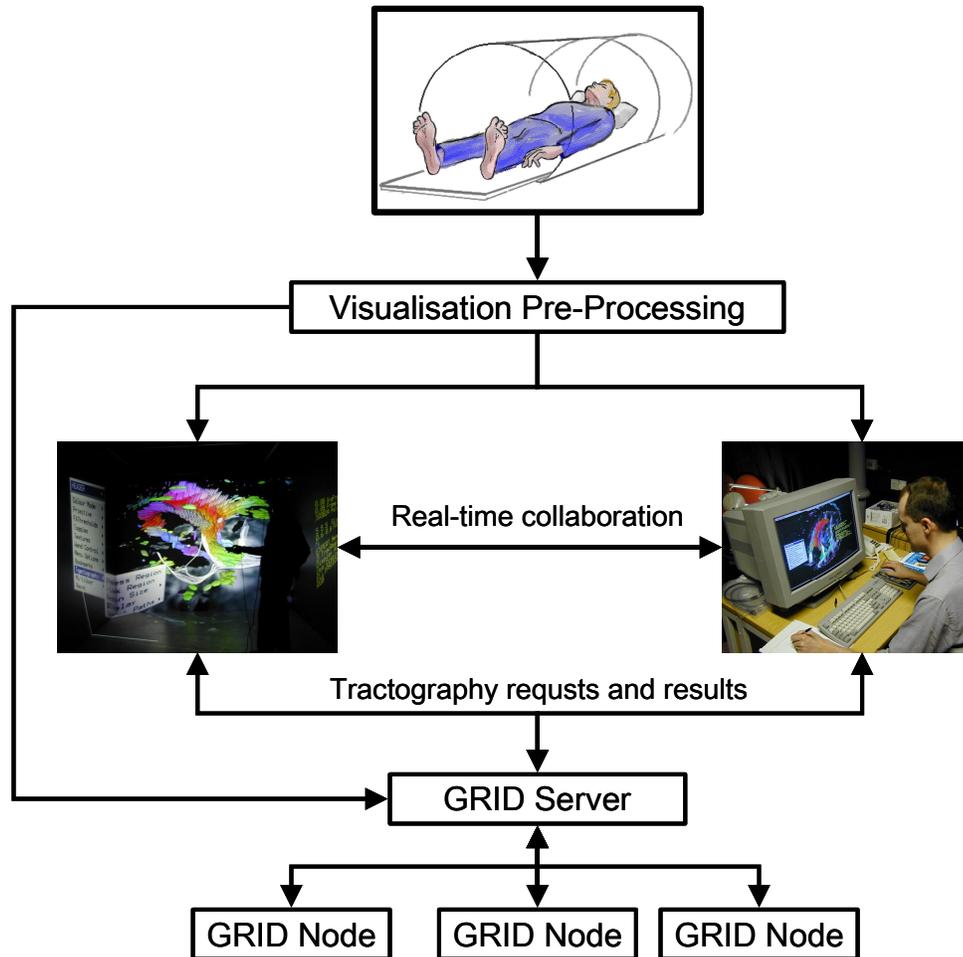


Figure 3. Overview of system components

We display three orthogonal sections and allow the user to scroll the cuts plane through the volume to focus on particular regions of interest.

3.2. 3D Tensor Display

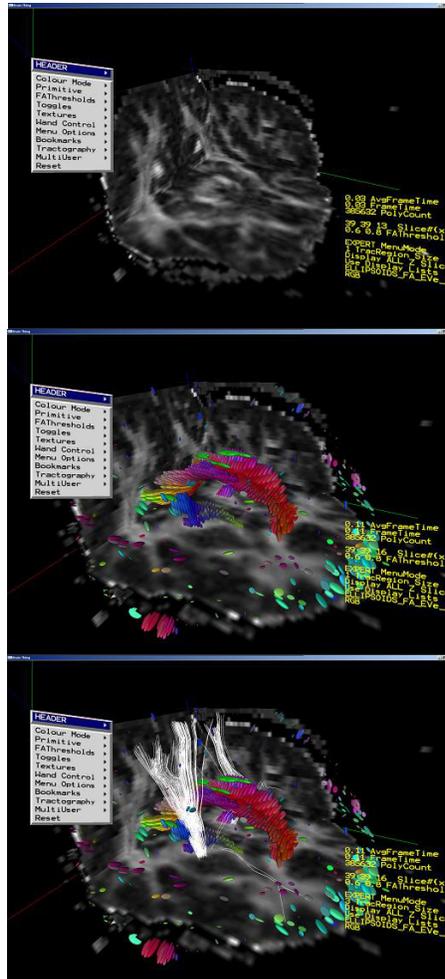
Scalar data does not convey the full complexity of the diffusion properties captured in the MRI data. We allow visualization of the full diffusion tensor through oriented polyhedra that are oriented along the principal direction of the diffusion tensor. The principal direction is also coded by colour so that a quick overview can be gained of the homogeneity in direction of a sub-space. Scaling of the polyhedra display relative magnitudes in direction orthogonal to the principal direction. These polyhedra thus indicate the direction of white-matter fibre pathways.

3.3. Tracks

We can further elucidate fibre structure by tracking white-matter fibres by following the principal directions of diffusion through the voxel data [2]. These are displayed using line sets. Tracks are computed using either matrix or eigenvector interpolation of the data set. Tracks are computed on a Grid service (see Section 5).

4. Interaction and Collaboration

The 3D polyhedra and track visualizations convey very rich data, and the visualization can be visually overwhelming if every detail is turned on. A menu system allows the user to rapidly alter the following properties of the visualization:



2D texture cut planes show scalar properties of the MRI scan. Here we see anisotropy

Volumetric arrays of ellipsoids are also used to visualize the full diffusion tensor data. They are coloured according to the principal direction of the diffusion tensor, which points in the direction of connecting white-matter fibres in the brain.

White-matter fibre pathways are tracked through the volume, and displayed in 3D for the end user (these tracks are shown as white lines in the picture above). The computationally expensive algorithms needed to track the pathways are performed in parallel using GRID technology.

Figure 4. Main Components of the Visualization

- Enable/disable and reposition individual cut planes
- Trace or anisotropy textures
- Alter polyhedral representation of the diffusion tensor from line (principal direction only) through quads to volumetric primitives (cuboids or ellipsoids).
- Colouring scheme for polyhedra
- Upper and lower bounds on trace threshold for reduction of displayed polyhedra
- Polyhedra constrained to a single plane or full-volume

As can be seen in the Figure 4, the menu system is provided in a near-body space on the left. Configuration and performance statistics are displayed on the right-hand side.

Users point at the volume with a hand held device when immersed. Users can alter their viewpoint either by flying around in a body-centred coordinate system, or can pick up and rotate the volume in an object-centred

metaphor. In order to interact with the tractography server, the users need to position and scale starting volumes in order to provide seeds for tracks. Users simply point at the brain to select a volume. Whilst pointing, the selection boxes snap to the nearest suitable site within the volume, using the polyhedra as snapping points. This process cuts down the number of possible selection points and is less complicated for the user than direct selection of an arbitrary volume of space using a method such as 3D box dragging.

The system supports collaborative working in either passive or active modes. A client can slave their display to another and have their workspace interactively update as the master node changes. This can be useful for simple remote display situations, though our experience is that users viewing a 3D visualization in passive mode can get disoriented quickly and thus the user operating the master node needs to be very careful about explaining what they are doing and the need to move reasonably slowly. In active mode, users get individual control over their

viewpoint. Users are represented by simple avatars. Selection rays are conveyed so that users can point and gesture. We have found that users quite quickly start to use the ability to switch between passive and active modes, to jump to or fetch their colleague to see a particular facility. Audio conferencing is normally provided by the Robust Audio Toolkit (RAT) and the Video Conferencing Tool (VIC) has been used to convey background awareness of activity at remote sites (both tools are available at www-mice.cs.ucl.ac.uk/multimedia/software/). These tools are the foundation of the AccessGrid software (www.accessgrid.org).

In the current implementation all 2D and 3D rendering properties of the visualization are synchronised. This need not be the case if, say, differences in rendering speed became an issue. We wish to maintain a high frame-rate for the immersed user (20Hz or over), and fortunately at this time a high-end desktop provides close to this performance (10Hz or more). To ensure high performance we have avoided scene graph based application programming interfaces or generic visualization toolkits such as VTK, and have used immediate modes approaches. Even so, very wide threshold ranges provide too many polygons to draw at a comfortable rate. This is compensated somewhat by reducing the complexity of the diffusion tensor representation to 1D or 2D, or by choosing less complex polyhedra. In the current system we do not apply scalability algorithm adaptively, but it is easy to reach a menu option to reduce the diffusion tensor representation to a single plane, which gives users control back.

5. Grid Tractography Server

White-matter fibre pathways are tracked through the volume, by using the principal directions of the diffusion tensor. These are then displayed in 3D as line sets. The tractography can work in two modes: single source volume or source and target volume. The interactive testing of connectivity between two volumes is novel for such a system. The users set one or two volumes interactively, and these are then dispatched to a Grid server that can calculate the fibres. The source volume is used to seed tracks, and then individual tracks can be calculated in parallel. A typical source selection region might result in 3-4000 tracks, which would take 5 seconds to calculate on a single processor. The source and destination calculation typically uses a much denser seed grid and takes an order of magnitude longer.

Currently we have implemented the tractography service on 72 nodes of a 256 node Beowulf cluster in our department. On this server, reasonable tractography requests can be displayed in near real-time. Note that clients individually connect to the tractography server. We used the MPICH implementation of the Message

Passing Interface (MPI) developed at Argonne National Lab (www-unix.mcs.anl.gov/mpi/mpich/). The Grid version of this toolkit (MPICH-G2) allows us to plug into Globus services.

6. Summary and Conclusions

We have described a collaborative system for interactive 3D visualization. The novel features of this visualization are in the representation of diffusion tensor and the implementation of tractography on a Grid server.

Many users have experienced our system and feedback has been positive. We have had access to a number of interesting data sets with pathologies that have proven much easier to discern with 3D than they were in 2D. Besides remote collaboration between UCL's ReaCTor and desktops or laptops, we have demonstrated collaboration between our ReaCTor and a similar ReaCTor at the University of Reading. These collaborations hint at potential future contexts of use, with visualizations and annotations being driven or prepared at high-end facilities and replayed or viewed remotely from desktop machines. Going forward, research and development need to focus on integrating the currently disparate tools found in GRID toolkits, CVE toolkits and high-end visualization toolkits.

Acknowledgements

We would like to thank David Swapp for help with ReaCTor facilities. We would also like to thank colleagues from Computer Science and Neurology at UCL who have made many suggestions that have improved the usability and utility of the demonstration. This work was funded by UK e-science programme as an early demonstrator. The project is a collaboration between the EQUATOR Interdisciplinary Research Collaboration (www.equator.ac.uk) and the MIAS Interdisciplinary Research Collaboration. Both IRCs are funded by the UK EPSRC.

References

- [1] O.Coulon, D.C. Alexander, and S.R.Arridge., "Tensor Field Regularisation for DT-MR Images", *Proceedings of British Conference on Medical Image Understanding and Analysis*, Birmingham, United-Kingdom, 2001.
- [2] T.E. Conturo, N.F. Lori, T.S. Cull, E. Akbudak, A.Z Snyder, J.S. Shimony, R.C. McKinstry, H. Burton and M.E. Raichle, "Tracking neuronal fiber pathways in the living human brain", *Proceedings of the National Academy of Sciences*, 96, 10422-10427, Aug. 31, 1999.
- [3] C. Cruz-Neira, D. J. Sandin, T. A. DeFanti, R. V. Kenyon, and J. C. Hart, "The Cave - Audio Visual Experience Automatic Virtual Environment", *Communications of the ACM* 35(6): 64-72, 1992

- [4] E. Frécon, G. Smith, A. Steed, M. Stenius, and O. Ståhl, "An Overview of the COVEN Platform", *Presence: Teleoperators and Virtual Environments*, 10(1), February 2001, MIT Press.
- [5] G. Kindlmann, D. Weinstein, D. Hart, *Strategies for Direct Volume Rendering of Diffusion Tensor Fields*, IEEE Transactions on Visualization and Computer Graphics, 6(2):124-138, April-June 2000.
- [6] J. Leigh, A. Johnson, M. Brown, D. Sandin and T. DeFanti, "Visualization in Teleimmersive Environments", *IEEE Computer*, December, 1999, pp. 66-73.
- [7] J. Leigh, G. Dawe, Talandis, J., E. He, S. Venkataraman, J. Ge, D. Sandin and T. A. DeFanti, "AGAVE : Access Grid Augmented Virtual Environment", *Proceedings AccessGrid Retreat*, Argonne, Illinois, Jan, 2001.
- [8] C. Pierpaoli, P. Jezzard, P. J. Basser, A. Barnett and G. Di Chiro, "Diffusion tensor MR imaging of the human brain", *Radiology*, 201(3), pp637-648, 1996
- [9] C. Poupon, C. A. Clark, V. Frouin, J. Régis, I. Bloch, D. LeBihan, and J.-F. Mangin, "Regularization of diffusion-based direction maps for the tracking of brain white matter fascicles", *NeuroImage*, 12(2):184--195, 2000.
- [10] S. Zhang, C. Demiralp, D.F.Keefe, M. J. da Silva, D. H. Laidlaw, B. D. Greenberg, P.J. Basser, E.A. Chiocca, C. Pierpaoli and T.S. Deisboeck, "An Immersive Virtual Environment for DT-MRI Volume Visualization Applications: A Case Study", *Proceedings IEEE Visualization 2001*, San Diego, October 2001
- [11] L. Zhukov and A. H. Barr, "Oriented Tensor Reconstruction: Tracing Neural Pathways from Diffusion Tensor MRI", *Proceedings of IEEE Visualization 2002*, October 2002.