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Interactive Visualization of Neuroanatomical Data for a Hands-On Multimedia Exhibit

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Abstract

Magnetic resonance imaging is a technique which is routinely used by neuroradiologists. Within the last decade, several techniques have been developed to visualize those MR images so that medical experts, and thus the patients, can benefit from it. However, very little work has been done to use neuroanatomical MR data for educational purposes and to bring the general public into closer contact with the scientific knowledge.
In this paper, an interactive visualization of neuroanatomical data, which is controlled by a dedicated user input device, is presented for a novel neuroscience exhibit. State-of-the-art visualization methods are combined to facilitate easy perception of the complexity of the medical data. For that, fiber tubes and diffusion-weighted image overlays are integrated into a volume rendering of the brain. Ambient occlusion algorithms are utilized to calculate self-shadowing of the brain anatomy and the fiber tubes. Further, a physical model of the brain and a touch display are used as user input devices. The visibility of fiber bundles can be intuitively controlled by activating touch sensors, which have been inserted into the physical brain model at the corresponding functional areas.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications—J.5.2 [Computer Applications]: Life and Medical Sciences—Health

1. Introduction

In neuroscience, magnetic resonance imaging (MRI) is used to obtain images of internal structures in the brain. In order to reconstruct in-vivo images of neural tracts, diffusion tensor imaging (DTI) or high-angular resolution diffusion imaging (HARDI) is commonly utilized. Visualization methods for neuroanatomical data such as surface rendering or volume rendering can be used for different goals, e.g. for planning of neurosurgeries, for assessing the neurological status of a patient, for medical training, or for anatomical exploration. In this work, visualization as well as interaction methods are presented for a novel hands-on multimedia exhibit. To help professionals and non-specialists of all ages to get insights into neuroanatomical knowledge, the multimedia exhibit allows for personal interaction and exploration of the brain anatomy, its functional areas and their white matter fiber connections.

The presented methods allow for a high-quality visualization of the brain and its fiber tracts in real-time using image data which is typically used in clinical practice. The goal is to support the user in exploring the brain's anatomy and it's associated functionality. For that, intuitive exploration methods are integrated to enable an interactive insight into the brain and its fiber bundles connecting important functional areas. Additionally, a physical model of the brain is part of the exhibit in order to demonstrate the real size of the visualized brain. The brain model is a mouse- and keyboard-less interaction device to mentally correlate the real-size model with the visualization and also to allow hands-on exploration of the brain's anatomy and functionality. Questions that arise during the interaction should foment curiosity and a desire to inquire more about the topic.

Technical contributions of this work are:

- Real-time volume rendering of the brain combined with polygonal fiber tubes and diffusion-weighted image overlays to allow fast exploration. Ambient occlusion algorithms considering clip planes are included in order to calculate self-shadowing of the brain and the fiber bundles.
- Concept of a customized interaction device which establishes a connection between the physical and the virtual representation of the exhibits neuroanatomical data.

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2. Related Work

For planning of neurosurgical interventions, several works in the field of multimodal visualization have been proposed. Beyer et al. [BHWB07] present a high-quality multimodal volume rendering for preoperative planning of the surgical approach and for the visualization of deep-seated structures. Rieder et al. [RRRP08] focus on the visualization of the access path for neurosurgical tumor treatment. Jainek et al. [JBB*08] present an illustrative hybrid visualization tool, which allows neuroscientists to explore anatomical and functional brain data.

In order to enhance the perception of fiber tracts represented as lines, illumination of the fiber lines is used [MPSS05]. Also, illustrative methods are proposed [OVW10]. To further improve spatial and structural perception of line renderings, real-time ambient occlusion rendering of lines is introduced by Eichelbaum et al. [EHS12]. However, the primary disadvantage of fiber tracts represented as lines is the invariance of the fiber's width. To overcome this, Everts et al. [EBRI09] draw depth-dependent halos around lines to emphasize tight line bundles and Zhang et al. [ZDL03] propose streamtubes and stream-surfaces for the visualizing of diffusion tensor MR images. Stoll et al. [SGS05] extend the basic line primitives with additional visual attributes including color, line width, texture and orientation. To implement the visual attributes, they represented stylized line primitives as generalized cylinders. Merhof et al. [MSE*06] propose a hybrid visualization using triangle strips and point sprites which allows faster rendering of white matter tracts.

Several algorithms have been published for surface rendering as stated in the survey of Méndez-Feliu and Sbert [MFS09]. In the context of volume rendering, Stewart et al. [Ste03] introduced vicinity shading as a variation of ambient occlusion. In order to reduce the time-consuming evaluation of the occlusion, optimizations have been proposed [HLY10]. In recent works, either directional [SPH*09] or multidirectional occlusion shading models [ŠPBV10] for direct volume rendering allow for interactive updating of transfer function and clip planes. The combination of surface and volumetric occlusion is introduced by Schott et al. [SMG*12]. They extend their previous work [SPH*09] to allow the rendering of geometric shapes in combination with a context providing 3D volume, considering mutual occlusion between structures represented by a volume or geometry.

3. Real-Time Visualization

The visualization developed for the multimedia-exhibit is a combined volume rendering with geometry and ambient occlusion (AO). The anatomical data set is obtained from a T_1-weighted MRI scan of a healthy volunteer. Since only the brain is of interest, the skull is removed using a semi-automatic skull stripping algorithm [HP00]. The fiber bundles connecting the functional areas in the brain are reconstructed from registered diffusion-weighted images using fourth-order spherical harmonics which are real and symmetric [ALS10, DAFD06] and global fiber tracking [KKH12]. Five volume rendering passes are developed with a shader framework [RPLH11] and are composed using frame buffer objects (FBO) in screen space via fragment shader operations (see Figure 1):

Color Pass The basic pass is a color rendering of the brain combined with reconstructed fiber tracts. Because internal structures are occluded by the brain, a clip plane can be specified to allow interactive volume exploration. To facilitate exploration of the whole diffusion in the white matter, a color map of the fiber orientation [DTP*91] is superimposed onto the clipped brain rendering. The geometry of the fiber tubes is represented by truncated cones [HPSP01] along the fiber tracts and is color-coded according to their primary orientation in 3D-space. The opaque shaded OpenGL geometry of the fiber tubes is correctly integrated into the volume rendering by back projecting the depth buffer of the geometry rendering and truncating the ray-caster rays accordingly.

Depth Pass For correct compositing in screen space, a depth rendering pass is also required. The depth of the brain is stored in the red color channel. The depth per pixel is used for calculation of the bilateral filtering in the brain AO pass. Furthermore, the clip plane boundary is rendered in the depth pass' blue color channel. Using the boundary, the color overlay is correctly mapped in the volume rendering.

Brain AO Pass For the AO calculation of the brain volume, first-hit ray-casting [HSS*05, KHF*06], i.e. ray-casting of iso-surfaces, is utilized. Using a threshold representing the grey matter boundary, this approximation enables fast reconstruction of the brain's surface. The AO is calculated by sparse-sampling the hemisphere using secondary rays. To reduce the visible artifacts, bilateral smoothing [PKTD08] is applied on the rendered image in screen space. For primary and secondary rays, clipping is considered by reduction of the samples' opacities to zero outside the clip plane, allowing full light contribution. Since the brain AO pass only contains the occlusion information with excluded fibers, it can be directly multiplied with the color pass.

Fiber AO Pass For rendering of self-shadowed fiber tubes, screen-space ambient occlusion [BSD08] (SSAO) is utilized. Because the fiber tracts are only visible if the clip plane of the volume rendering is enabled, they also have to occlude the clip boundary of the brain. For that, a plane geometry is added in the SSAO rendering at the position of the clip plane. The ambient occlusion rendering pass of the fiber tubes is multiplied with the color pass. Because a simple plane geometry is used instead of the correct brain boundary, the shadowing of the fibers onto the plane is also visible at the

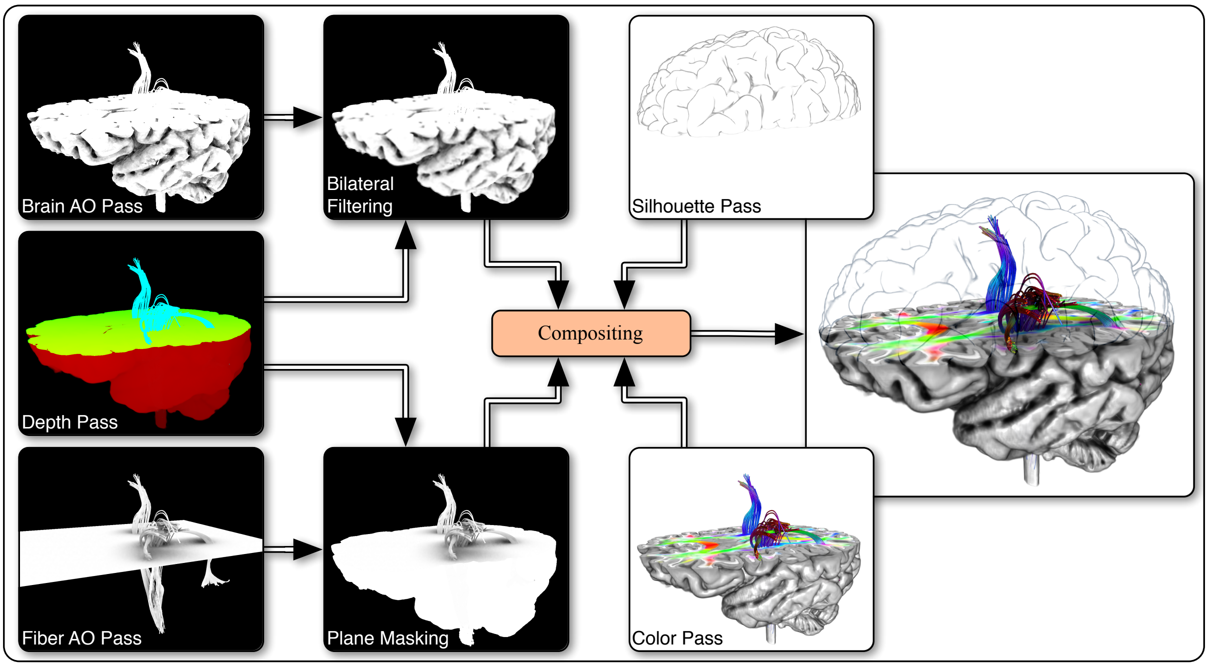

Figure 1: *Illustration of the screen-space compositing. Five rendering passes are composed to the final color image.*

brain's surface. To multiply the occlusion only at the fibers itself and the clipped brain, the fiber AO rendering pass is masked with the clip plane boundary of the brain.

Silhouette Pass Because contextual information is lost in the volume if the brain is hidden by the clip plane, silhouettes of the brain's surface are drawn. For that, the current clip plane is inverted, i.e., the part to be clipped is visible and vice versa. The silhouettes of the brain's gyri and sulci are visible by utilization of boundary enhancement [RE01] and subsequent thresholding the rendering output. Finally, the silhouette rendering pass is composed with the color pass

4. User Interaction and Experience

The interaction concept of the exhibit combines both the physical model of the brain and its virtual counterpart on the touchscreen, with different interaction possibilities being accessible through each of them. The ambition behind this is to establish a direct coupling between both elements and thereby motivate the user to explore all features and possibilities of the exhibit by himself. For the most part, these interactions do not overlap between both devices, which effectively requires the user to make use of both elements in order to fully access all information. This follows the concept of a bottom-up activity [Nor05]: draw attraction through physical model and illumination, invoke the unusual interaction by touch sensors and support reflection of the abstract visualization of brain and fiber tracts.

4.1. The Physical Brain Model

The physical model of the brain is mounted on a turntable and provides several illuminated touch sensors. In contrast to common input devices such as mouse and keyboard, the brain itself is utilized as a gateway to the visualizations of the inside of the brain. Also, the brain model is a more robust input device than mouse, keyboard or other controllers such as the Wii remote. Due to numerous visitors in popular-science exhibitions, physical robustness of the input devices is of high interest.

The turntable itself has a sensor to report its current position to the PC, which allows synchronizing the camera of the 3D scene to automatically reflect the current position of the physical model. This technically simple method helps the user to intuitively grasp the connection between the model and the touchscreen. By merely playing around with the physical brain, he immediately experiences the connection between the model and the touchscreen.

In addition, the illuminated sensors on the brain surface are used to activate or deactivate rendering of the fiber bundles. They are introduced into the model which can be reached from all directions in order to allow intuitive user interaction. The sensors represent functional areas with which the corresponding fiber tracts are connected. Touching one sensor enables or disables the display of the corresponding fiber tracts. During the modeling process of the brain print, fiber bundles connected with the following nine functional areas have been selected:

- Speech comprehension and production (two sensors)
- Left and right visual field (one sensor each)
- Left and right side of the face (one sensor each)
- Left and right hand (one sensor each)
- Left and right hip as well leg (one sensor each)

4.2. Touch Display

The touch display is framed by a tilted steel box in order to guarantee robustness and touch interaction of users of all body sizes. It serves primarily to control several options of the visualization itself and shows the graphical user interface (GUI) of the exhibit software. The GUI includes the brain visualization and a text field which gives brief description of the brain's functionality and anatomy. Also, the body region which is controlled by the activated sensors (functional area) is highlighted in an illustrative human body. Background information concerning the different functional entities is toggled on the touchscreen when activating a sensor on the brain. A large slider widget allows the user to move a clip-plane through the dataset using a single-touch gesture. Buttons allow for setting the orientation of the clip plane to the three main directions and toggling the DTI color-overlay. As such, it complements the physical brain, by offering a look inside and revealing the structures located under the surface. Additionally, the rendering can be rotated in arbitrary directions using a touch gesture.

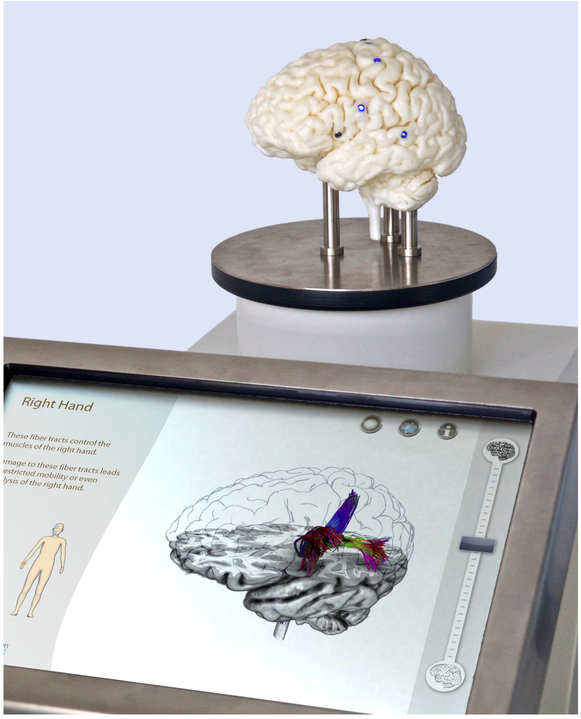

Figure 2: *Photograph of the final exhibit. The touch screen in the foreground displays the GUI with the proposed brain rendering. The physical brain model with illuminated touch sensors is attached on the turntable.*

5. Results

The presented visualization and interaction concept relates to prior knowledge (the users recognizes the shape of the brain) and showcases the topic through self-directed exploration of the neuroanatomical data, particularly the connections between the brain's fiber tracts with specific functional areas. Emotionalization is achieved through the overall aesthetic of the visualization, the physical model with blue sensors, and the design of the enclosure.

The hands-on multimedia-exhibit is constructed as a single wood furniture with mounted display and physical brain model (see Figure 2), which are connected to a hidden computer placed into the furniture. It has been successfully presented on the MS Wissenschaft exhibition ship. The converted inland vessel was underway for four and a half months during the "Year of Health Research" in 2011. The vessel traveled 3640 kilometers in Germany and Austria and docked in 35 different cities. About 72.000 visitors – thereof 420 school classes – have extensively examined the presented exhibit. After informal discussions with the exhibition volunteers, they stated that the interaction could be easily explained to visitors. Nevertheless, most visitors were attracted by the presented visualization and tried to interact with it by themselves. Commonly, they rapidly figured out how to explore the neuroanatomy using turntable and touch sensors of the brain as well as the touch display. After successful exhibition during the "Year of Health Research", the multimedia exhibit was invited to be presented during the Girls'Day 2012 into the German Federal Chancellery in Berlin.

6. Conclusions

In this work, a high-quality volume rendering combined with visualization of fiber tubes is presented as part of a novel hands-on multimedia exhibit. Fast ambient occlusions methods are utilized to emphasize the spatial relations of the anatomy within real-time frame rates. To allow mouse- and keyboard-less user interaction, touch sensors are integrated in a physical model of the brain, which is mounted on a turntable, and a touch display is used for interactive visualization. From a user point of view, the physical brain model also represents a well-known body part which can be explored with hands-on and thus arouses interest in the topic. Among other locations, the multimedia exhibit has been successfully presented at the MS Wissenschaft exhibition ship. Concluding, users of all ages were delighted by the presented combination of visualization and interaction.

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