

Medical Applications of Multi-field Volume Rendering and VR Techniques

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Abstract

This paper reports on a new approach for visualizing multi-field MRI or CT datasets in an immersive environment with medical applications. Multi-field datasets combine multiple scanning modalities into a single 3D, multi-valued, dataset. In our approach, they are classified and rendered using real-time hardware accelerated volume rendering, and displayed in a hybrid work environment, consisting of a dual power wall and a desktop PC. For practical reasons in this environment, the design and use of the transfer functions is subdivided into two steps, classification and exploration. The classification step is done at the desktop, taking advantage of the 2D mouse as a high accuracy input device. The exploration process takes place on the powerwall. We present our new approach, describe the underlying implementation issues, report on our experiences with different immersive environments, and suggest ways it can be used for collaborative medical diagnosis and treatment planning.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Multimedia Information Systems]: Artificial, Augmented, and Virtual Realities; I.4.10 [Image Representation]: Multidimensional; I.4.10 [Image Representation]: Volumetric; J.3 [Life and Medical Sciences]: Medical Information Systems.

1. Introduction

Direct volume rendering is an important and flexible technique for visualizing 3D volumetric data. This technique has been used with great success in medical imaging applications, especially diagnosis [NT01, TKHS03, HWC*03] and treatment planning [LFP*90]. The success of this technique and its resulting popularity can be attributed to several factors. First, volume rendering does not require an intermediate representation of the data for image generation, permitting interactive feature extraction with immediate feedback. Second, because the optical model used for volume rendering allows features to be rendered with any degree of transparency, it can naturally provide context without obscuring features of interest by simultaneously rendering semi-transparent physical or anatomical landmarks. Finally, the use of a transfer function, converting data into renderable optical properties, allows one to classify and visualize features that may not be captured using other traditional techniques such as iso-surface extraction. In particular, multi-

dimensional transfer functions allow features to be classified based on a unique combination of data values, which helps to disambiguate distinct features that may share data values with other, unimportant, features.

Immersive visualization using stereoscopic displays with head and hand tracking can enhance visualization and data analysis by providing the user with a truly three dimensional view of the dataset. This is especially applicable to direct volume rendering since multiple overlapping semi-transparent features may lead to perceptual ambiguities in shape and depth. An immersive environment addresses these problems in several ways. Stereopsis and motion parallax help the user resolve spatial feature placement using natural and precognitive abilities of the human visual system. The coupling of head and hand tracking with direct manipulation of the visualization allows the user to gain knowledge of the relative placement and scale of features within the dataset. These techniques are important for medical imaging, diagnosis, and treatment plan-

ning [Sht92, SR97, RC94, GELP*96] as high resolution 3D scans become increasingly more prevalent.

The goal of this work is to design a system for volume rendering in virtual reality that allows the user to freely explore data without being burdened by the traditional ergonomic problems of VR or the difficulties of manipulating a high dimensional transfer function. Such an environment is particularly applicable for collaborative work where domain experts interact with each other and with visualization experts. One such application is diagnosis of tumors through the use of multiple imaging datasets. The immersive environment with its high spatial acuity allows for collaborative surgical planning among multiple domain experts.

However, the manipulation of a desktop interface for multi-dimensional transfer functions is cumbersome in an immersive environment. To address this, we divide the specification of multi-dimensional transfer functions into two independent tasks, which we term classification and exploration, and describe their unique interface characteristics.

In the next section, Section 2, we describe our physical VR environment and identify several key design choices. In Section 3 we describe a novel interface for manipulating high dimensional transfer functions in VR. In Section 4 we describe implementation details of our interface and the hardware that it involves. Section 5 compares our suggested immersive environment to the CAVE, and shows how it can be used in a clinical environment. Finally, we conclude with results and future work.

2. A Collaborative Immersive Environment

Our immersive volume visualization system was developed based on three primary design criteria. First, successful visualizations are typically accomplished via collaboration between one or more domain and visualization experts. Visualization systems can be complicated and require extensive knowledge of both the hardware and software that comprise them. This is especially true for immersive environments and modern hardware assisted volume rendering techniques. Software and hardware resources must be carefully managed in order to maintain a high level of interactivity. Second, user interfaces must be carefully designed to meet the needs of the user. This issue is particularly relevant when we consider the difficult task of transfer function design. Finally, ergonomic factors are an important issue for immersive environments. Since the primary mode of user interaction is through head and hand tracked input, the user is typically encouraged to stand and move about the environment using hand gestures to manipulate the visualization. This is in dramatic contrast to desktop configurations where the user views the visualization in a comfortable sitting position and interacts with it via minimal hand motions using a 2D mouse. Fatigue from standing and pointing (gesturing) for long periods can discourage the user from spending the time to thoroughly investigate, and thus gain maximal benefit from, the visualization session.

Our system is designed to accommodate multiple users either sitting or standing using two large stereoscopic displays and a traditional desktop display. Figure 1 illustrates the configuration. Two side by side vertical displays (A and B) are each configured using two projectors with complementary polarization filters for passive stereo. A traditional desktop display (C) is located in front of one of the large vertical displays. The left display (A) is setup to provide head tracked 3D stereoscopic imagery. The right display (B) can be configured as an extension of the left display making the 3D environment larger, or as a separate 3D display providing different views of the data and interaction tools. It can also be configured as a 2D display replicating the desktop's output for an audience. The entire workspace has 3D position and orientation tracking.

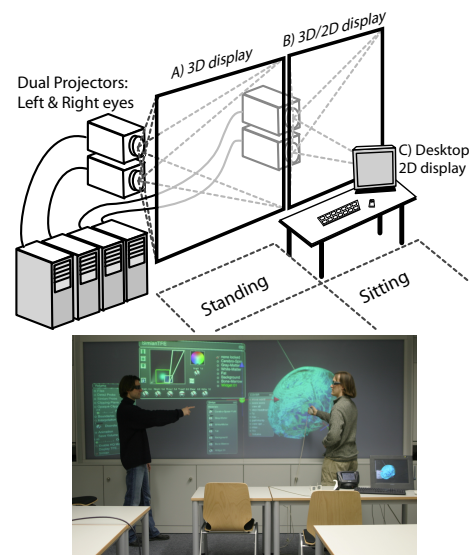


Figure 1: Immersive volume rendering workspace. The top illustration shows the workspace configuration. The bottom image shows standing interaction using the immersive 3D display.

This workspace allows users to interact with the visualization using the most appropriate modality. In a typical session, a visualization expert drives the visualization and provides assistance using the 2D display. The domain expert is allowed to freely explore and interact with the visualization on any of the three displays. We found that interacting with the virtual environment while sitting not only reduced fatigue but also improved the accuracy of interactions with immersive tools and visualization. The preferred posture using the 3D mouse had one's elbow resting firmly on the table providing additional stability for fine movements.

3. Immersive Volume Rendering

The use of multi-dimensional transfer functions for volume rendering applications has been shown to dramati-

cally improve one's ability to classify features of interest in volume data [KKHar]. The visualization of nearly all datasets can benefit from multi-dimensional transfer functions, even scalar datasets. Unfortunately, manipulating high-dimensional transfer functions is difficult and has a steep learning curve. In our experiments, we found that this difficulty is further compounded in an immersive environment due to low accuracy in one's ability to select relatively small control points and make fine movements with 3D input devices. Although recent studies demonstrate that improved accuracy for some interactions can be accomplished by mapping small movements to wrist rotations [SWWL01], we have found the design of good transfer functions in an immersive environment to be a tedious and time consuming task.

Our solution to this problem stems from the observation that the role of transfer function design for volume rendering is essentially two independent tasks, classification and optical property specification. The classification step involves identifying the regions of the data domain, or feature space, that correspond to unique materials or material boundaries. Once these regions have been determined, all that remains for the user to do is assign color and opacity, making the classified materials corresponding to features of interest visible and unimportant materials transparent. With this in mind, our system is designed with two distinct interfaces for transfer function design.

3.1. Classification

The classification interface, seen in Figure I A (see color section for Roman numbered figures), is designed primarily for the visualization expert. It is most similar to that proposed in [KKHar], with the addition of an interface for assigning a name to each classified feature. Initially, classification is carried out as a preprocessing step prior to the visualization session using a 2D desktop configuration. The visualization expert attempts to classify any and all relevant features using a variety of tools such as dual-domain interaction and joint histogram analysis. Once features have been classified and named, the visualization expert can specify the initial optical properties and save the classification specification for later use.

A classification interface, seen in Figure I B, has also been developed for use in the immersive 3D display. The intent of this interface is to allow the user immediate access to classification parameters for refinement during the visualization session. As noted earlier, direct manipulation of classification elements may not be appropriate when using 3D input devices. To address this, we also provide the user with a set of rotary knobs for manipulating each degree of freedom linearly and independently. An example of the immersive classification tool can be seen in Figure I B.

3.2. Optical Properties

During the visualization session, the saved classification is loaded with the dataset and the domain expert is presented

with the initial optical properties specified in the classification step. Rather than being presented with the complicated classification interface, the user is provided with a simplified *material mixer*, seen in Figure I C, which allows one to adjust the optical properties associated with each classified feature. Each classified feature is identified by name. The feature's opacity is specified by rotating a knob widget, its color is set using a standard color picker tool.

The main advantage of this interface is that the user is not burdened, or worse distracted, by the complicated and abstract nature of the high dimensional feature space in which materials are classified. Rather, users are provided with the relevant degrees of freedom, namely; what feature is being manipulated, how opaque it is, and its color.

3.3. Collaboration

While it is expected that the visualization expert carry out the classification step, it must often be done with the guidance of the domain expert. It is frequently the case that feature classification must be refined during the visualization session. The visualization expert can choose to manipulate the transfer function using either the 2D desktop interface or assist the domain expert in the immersive environment.

4. Implementation

4.1. Hardware

Our hybrid work environment consists of two rear projected passive stereo displays, and a table in front of them. A video switching unit is used to select which PC's output is used for each projector and desktop display. Our software also works in CAVE-like environments [CNSD93] like the four screen CUBE at HLRS. Both environments are driven by COTS PCs with NV25 based NVidia graphics cards.

4.2. Software

Our immersive volume rendering application is built on top of several existing visualization and scientific computing frameworks, namely OpenGL, OpenGL Performer, COVER, COVISE, Simian, and using Linux as the operating system. Figure 2 illustrates conceptually how these software components interact.

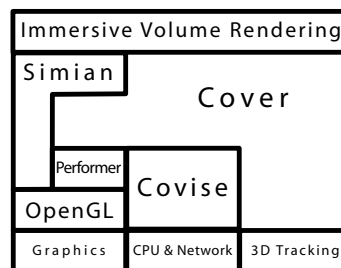


Figure 2: Software framework for immersive volume rendering.

Simian [KKH01] is a volume rendering tool designed to

support multi-field volume rendering. It has been developed at the University of Utah. The entire tool is used for classification at the desktop, and its rendering code is extracted for use in the virtual environments, which run with COVISE. The original Simian software lacked the capability of passing the transfer function widgets on to other programs. We added the option to write the widget parameters to a file.

COVISE is a visualization and scientific computing framework developed at the University of Stuttgart [RLR96]. Its virtual reality renderer COVER [RFL*98] is a standalone, OpenGL Performer based program that supports arbitrary virtual environments and input devices. The user interface software used in the virtual environments is based on the volume rendering application presented in [SWWL01] and [WSWL02]. Performer supports parallel application, culling, and draw processes on multiprocessor machines. For the integration of Simian, the user interface and rendering routines had to be separated and integrated into the application and draw processes, respectively.

4.2.1. Material Mixer

The material mixer (see Figure I C) is made up entirely of standard COVER menu items, in this case labels for material names and rotary knobs for the opacity. The value range of the knobs is from “fully transparent” to “fully opaque”.

4.2.2. VR Classification Interface

The classification interface (see Figure I B) consists of several groups of elements. The main rectangular region shows the histogram. Here the transfer function widgets are located, similar to the Simian transfer function editor [KKH01]. They can be moved by pointing and clicking at them with the 3D wand. Widgets are created and deleted with the green icons at the left of the window. The “Hist” button toggles the display of the histogram. The color disk and the “Bright” knob define the color of the active widget. The rotary knobs at the bottom of the window change a widget’s geometry and opacity. All the widgets are listed at the right edge of the window.

5. Results

5.1. Immersive Comparison

As previously stated, we have implemented this system for both a CAVE immersive environment and a power wall immersive environment. A comparison of the two immersive environments for collaborative exploration tasks involving medical diagnosis and surgical planning (described in the next sub-sections) was useful. While the CAVE environment is an attractive option for many immersive visualization and graphics applications, we found it difficult to meet our system design goals in this workspace. The CAVE is designed to function primarily as a single user environment. Because of limited space and the use of all four displays as a single integrated view of the visualization, close collaboration between the domain and visualization experts is difficult. We

cannot place a desk or use chairs inside this environment since it would interfere with the immersion gestalt, further limit the available space, and potentially damage the delicate projection surfaces. We considered having the visualization expert assist in this environment using a laptop PC with wireless networking. Although this allowed the visualization expert to participate in the session from within the environment, its use was quite limited. Since the laptop’s user has to carry the unit, it is difficult to make fine adjustments in the classification interface, and the user quickly becomes fatigued. Thus, the power wall environment was better suited to our applications.

5.2. A Multi-spectral MRI Case Study: Preliminary Results

We are currently investigating the use of our immersive volume rendering system for medical diagnosis and surgical planning in a collaboration with the Olgahospital in Stuttgart. The Olgahospital is a childrens’ hospital where a number of patients are treated for seizures caused by cortical neurons. In patients with intractable epilepsy, the detection of lesions in areas of interest can help to decide whether surgery to remove the lesions has a chance to stop the seizures without creating significant damage. The detection of these lesions is typically done using MRI. Unfortunately the lesions are often difficult to identify in these scans because they are characterized by subtle differences in contrast, thickness, and sharpness of the border between white and gray matter. Today, these lesions are diagnosed using several high resolution and high contrast MRI sequences that are visually inspected using software designed to deal with the acquired data on a slice by slice basis.

The focus of this study is two fold. First, we intend to demonstrate the effectiveness of multi-modal MRI data classification using multi-dimensional transfer functions. Our hope is that the tissue characteristics captured by different MRI scanning sequences can be combined to better identify tissue types and lesions. Second, we intend to identify the ways in which our immersive visualization system can assist in diagnosis and treatment planning. By providing a collaborative environment that allows multiple physicians and visualization experts to gain spatial awareness of the anatomical features, surgery can be planned as a collaborative process.

5.2.1. Registration

Figure II shows an example of three MRI scan modalities used in traditional diagnosis and this study. The bottom right image is a multi-modal visualization, created by assigning each modality to a color channel. In many cases, these scans are acquired at different resolutions and times. Thus, an initial co-registration pre-processing step is required. There are several approaches for intermodal data registration ranging from completely manual to fully automatic. There are two widely available and free registration tools *Automatic Image Registration* (AIR) [AIR] and *Statistical Parametric Mapping* (SPM) [SPM]. A comparison of these packages can be

found in [KAPF97]. Although these tools are automatic, we discovered that substantial manual registration was required, and that AIR performed best when the datasets were registered to within 2 voxels and 3 degrees of rotation along any axis.

5.2.2. Classification

Once the registration parameters have been determined, the scans are resampled and combined into a single multi-valued dataset. In addition to the scan intensities, we add multi-gradient magnitude measure, which is discussed in [Sap97, KKHar]. Classification is performed manually, guided primarily by joint histogram analysis. Figure 3 shows an example of joint histograms of co-registered proton density (PD) and T2 MRI scans. Figure 3 A, left, shows how considering the unique combinations of datavalues in these scans, using a joint histogram, can help identify features more clearly than the 1D histograms of each dataset, seen at the left and top. Figure 3 B, right, shows how the exclusion of high multi-gradient magnitudes can further disambiguate homogeneous materials, i.e., B shows a joint histogram of values representing relatively homogeneous materials. The labeled materials are: *a* cerebro-spinal fluid, *b* gray matter, *c* white matter, *d* fat, *e* background, *f* bone marrow. Conversely, a joint histogram of values with high multi-gradient magnitude allows us to identify boundaries between materials or material mixtures.

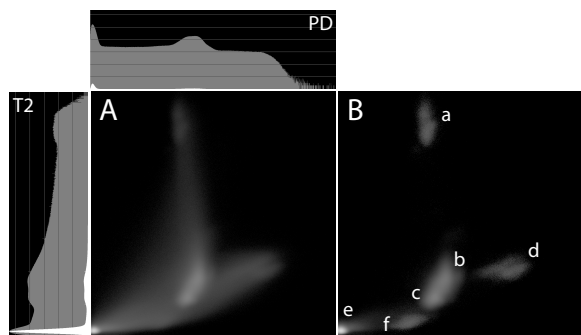


Figure 3: Example joint-histogram of T2 and Proton Density (PD) MRI scans. A shows the log-scale joint histogram with the corresponding scalar histograms for each scan seen at the left and top. B shows a joint histogram created by excluding values with high multi-gradient magnitudes. The labeled materials are: *a* cerebro-spinal fluid, *b* gray matter, *c* white matter, *d* fat, *e* background, *f* bone marrow.

The desktop classification interface, described in Section 3.1, allows the visualization expert to use the mouse and place classification widgets at all locations in the 2D histogram where materials have been identified.

For the dataset used in Figure 3 B the classification process is trivial for materials *a*, *d*, *e*, and *f*, but it requires careful refinement and some experience to correctly distinguish materials *b* and *c* (gray and white matter). The transfer function

widgets can optionally be assigned names for the materials they represent.

Note that in the classification step the domain expert does not need to be present. This is important because the domain expert, typically a radiologist or physician, should not have to spend time dealing with technical details that do not require his expertise.

5.2.3. Exploration

A complete classification is often composed of a dozen or more individual classified features, which can make the classification interface complicated and difficult to manipulate. This emphasizes the need for the simplified material mixer interface. Our initial results suggest that our classification/exploration approach is appropriate for this type of medical data and the immersive visualization can assist in understanding the spatial relationships among important 3D structures.

During exploration, the domain expert uses the material mixer and the color picker to change the parameters of the previously defined materials. Depending on how well the visualization expert was able to set the transfer function, this will be all the domain expert needs to work with. In ambiguous cases, e.g., the differentiation of gray and white matter in Figure 3 B, the complex transfer function editor in the virtual environment allows the domain expert to further refine the transfer function parameters, which he might be able to do better than the visualization expert, given his greater domain knowledge.

In contrast to the classification step, the focus of the exploration is not on the definition of the transfer functions, but rather on finding spatial features in the dataset that may lead to the diagnosis of a patient's illness. For this purpose, the user can rotate the dataset, zoom in on arbitrary regions, use clipping planes, or look at the dataset from different angles just by moving the head. All of this having real-time visual feedback, including any changes of the transfer functions, provides doctors a novel method to work with their MRI and CT datasets.

6. Conclusion

This paper presents a new immersive visualization workspace layout that emphasizes tight collaboration between domain and visualization experts. We achieve this by providing a workspace that combines traditional desktop and immersive modes of interaction, emphasizing comfort and ergonomics.

We describe a novel interface for volume rendering multi-field volume datasets in immersive environments. For application areas like medical data, in which the datasets consist of a combination of several distinct materials, we advocate a two step approach to transfer function design, classification and optical property specification, which can significantly increase the usability of the system for doctors.

The combination of the proposed workspace and user interface designs has demonstrated usefulness in applications

like the analysis of both scalar and multi-field volume data from MRI or CT scanners. Because transfer function design is divided into a classification, which benefits from the features of the desktop PC, and an exploration phase, which takes advantage of the virtual environment, the ability to rapidly switch between the tasks and platforms allows users to more efficiently achieve their visualization goals.

7. Future Work

We intend to continue our multi-spectral MRI collaboration. The preliminary results suggest several ways our system could be improved. The co-registration step is tedious and time consuming in our current visualization pipeline. This is due to the fact that datasets must be relatively well coregistered before automatic methods succeed. As such, we are developing interactive and immersive tools to assist with the initial registration step. While manual histogram analysis aids in material classification, automating this step using statistical methods and segmentation would improve the quality of classification. Suggested exploration and interaction tool improvements include interactive local histogram analysis that allows the user to investigate values in a subset of the data, and an interactive manual segmentation tool that allows the user to mark or mask off localized features of interest so they can be visualized in isolation.

One frustrating aspect of our classification interface, for both the desktop and immersive versions, is that we can only visualize the feature space as 2D projections. We are investigating an immersive interface that permits classification in 3D, that is, the system allows users to refine the classification using three axes of the transfer function at once, rather than just two.

8. Acknowledgments

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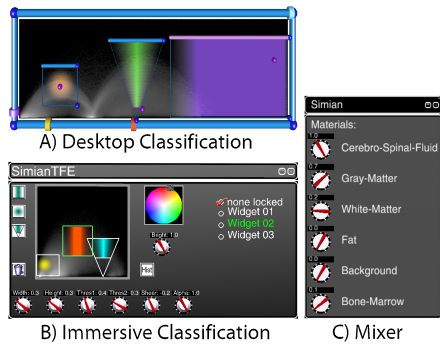


Figure I: Dual transfer function specification interfaces. The left images (A and B) show the classification interfaces. A is the interface used for classification on the desktop, B is the extended interface for classification in an immersive environment. C shows the material mixer.

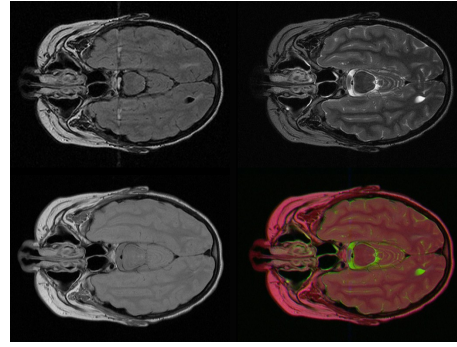


Figure II: Scans with different modalities. Top left: Fluid Attenuation Inversion Recovery (FLAIR), top right: T2, bottom left: PD. At the bottom right is a multi-modal visualization, created by assigning each modality to a color channel.