Visibility Driven Focus+context Multimodal Volume visualization

by

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Thesis Certificate

This is to certify that the thesis titled **Visibility Driven Focus+context Multimodal Volume visualization** submitted to the International Institute of Information Technology, Bangalore, for the award of the degree of **Master of Technology** is a bona fide record of the research work done by **Srinivas R Vaidya (MT2010152)** under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. T K Srikanth

IIIT-Bangalore,

The 15th of June, 2015.

Abstract

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— MUN School of Graduate Studies

Acknowledgements

" I would like to express my appreciation to all those who helped me dur- ing the course of this thesis work. My deepest thanks to my advisor, Prof. T K Srikanth for his continuous encouragement and valuable suggestions. It was my pleasure to work under his guidance. I dedicate my work to my family and friends who have always been there to support and cheer me up throughout my ups and downs. "

— MUN School of Graduate Studies

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Chapter 1

Introduction

Visualization has become an indispensable tool in many areas of science and engineering. In particular, the advances in visualization made over the past twenty years have turned visualization from a presentation tool to a discovery tool.

Volume visualization is a technique which enables physicians and scientists to gain insight into complex volumetric structures. Currently, the trend towards information acquisition using data sets from multiple modalities is increasing in order to facilitate better medical diagnosis. As different modalities frequently carry complementary information, our goal is to combine their strengths and generate focus+context visualization.

1.1 Motivation

For volume models, the key advantage of using direct volume rendering is its potential to show the structure of the value distribution throughout the volume. The contribution of each volume sample to the final image is explicitly computed and included.

The key challenge of direct volume rendering is to convey that value distribution clearly and accurately. In particular, showing each volume sample with full opacity and clarity is impossible if volume samples in the rear of the volume are not to be completely obscured.

Despite the proliferation of volume rendering software, the design of effective transfer functions is still a challenge. The growing popularity of GPU-based volume renderers has advocated the use of a more exploratory approach, where users can arrive at good trans- fer functions via trial-and-error modification of opacity and color values. However, effective transfer functions are often the product of time-consuming tweaking of opacity parameters until meeting a desired quality metric, often subjective. One possible explanation for this ad hoc methodology is the lack of an objective measure to quantify the quality of transfer functions.

In interpreting volume data for surgical planning or medical diagnosis, the information which can be visualized from a single modality, example, Computed Tomography (CT), may be insufficient. A number of factors influence this, including limited resolution, sensitivity to tissue properties, noise, etc. For this reason, radiologists often make use of additional modalities that provide complementary or supplementary information. In this way, radiologists are able to extract more clearly the structures of interest and the spatial relationships among them. For example, CT provides the most detailed anatomical information from the human body, usually at high resolution. It helps depict high dense structures such as bone, as well as the shape of internal organs. On the other hand, the acquisition of metabolic activity must rely on a modality like Positron Emission Tomography (PET). In general, metabolic activity is important to detect cancer, since cancer tumors and other malignancies are usually located in regions with high rate of metabolic activity, such as regions with high blood flow. To obtain the best of the two modalities, recent visualization systems attempt at fusing both types of information in a single meaningful image.

The issue of visibility is not exclusive of medical data. Simulations of 3D phenomena often contain structures that evolve and are intertwined in 3D space with other less interesting structures. Therefore, visualization of internal flow becomes difficult.

With hardware acceleration, volume rendering has become very attractive to many applications. To be more widely adopated, however, its usability remains to be enhanced. In particular, the task of classifying volume data before rendering as well as the task of manipulating potentially a large number of rendering and viewing parameters to achieve desired visualization are often time-consuming and tedious. Recent research results show some good progress on visualizing individual volume data, but multimodal volume rendering presents additional challenges, from the problems of superimposing dual modality data and highlighting objects of interest, to the desire to suppress occluding materials while maintaining the context and to enhance structural and spatial clarity of the objects.

1.2 Background/Related Work

1.3 Objective

1.4 Non Photorealistic Rendering

The emergence of non-photorealistic rendering (NPR) over the greater part of a decade has created an intriguing new field espousing expression, abstraction and stylisation in preference to the traditional computer graphics concerns for photorealism. By lifting the burden of realism, NPR is capable of engaging with users, providing compelling and unique experiences through devices such as abstraction and stylisation. Non-photorealistic rendering can be used to illustrate subtle spatial relationships that might not be visible with more realistic rendering techniques.

Volume rendering has remained a prevalent tool in medical and scientific visualisation for over a decade. The ability to visualise complex real-world phenomena has found its way into practical applications including CT and MRI scans of the brain and imaging flow in fluid dynamics. The integration of volume rendering with non-photorealistic rendering(NPR) is an intuitive and natural progression given the communicative and expressive capabilities of NPR.

Volume Non-photorealistic rendering acheives two complimentary goals, the communication of information using images and rendering images in interesting and novel visual styles which are free of the traditional computer graphics constraint of producing images which are life-like. Hence, Volume non photorealistic rendering techniques can be used to create visualizations of volume data that are more effective at convey-ing the structure within the volume.

[1] Volume Illustration: Non-Photorealistic Rendering of Volume Models [2] State of the Art Non-Photorealistic Rendering (NPR) Techniques

1.5 Focus and Context for Volume Visualization

In the case of volume data (3D datasets), direct volume rendering [4] is one of the most used approaches for visualization. Medical applications are amongst the most popular ones, data acquired from a scanner (computerized tomography, magnetic resonance, etc) is fed to a volume rendering system, allowing physicians and radiologists to see internal structures and organs with much greater detail than with conventional methods.

However, in some cases there is too much data to be displayed at once on a computer display (or the displays resolution may be insufficient for practical use). A simple and widely used solution is to apply a magnification factor to get closer to a specific region. But by doing so, it is equally easy to get lost in the dataset. This is generally called loss of context, because we are no longer able to visualize the entire dataset. When we zoom in, we are focusing on a certain feature that is of interest. In the field of Visualization this problem is called focus+context [22] and a number of successful solutions have emerged. The challenge is to find a way of looking at a high level of detail at this area of focus, without losing the overall context.

[22] Robert Spence. Information Visualization. ACM Press, 1st edition, 2001. [4] Robert A. Drebin, Loren Carpenter, and Pat Hanrahan. Volume rendering. In Proceedings of the 15th annual conference on Computer graphics and interactive

techniques, pages 6574. ACM Press, 1988.

1.6 Organization of thesis

Thesis is be divided into two parts. First part deals with visibility histogram, which represents the visibility of the sample values from a given viewport. These visibility histogram provides a feedback mechanism for designing transfer function. Visibility histograms are view and opacity dependent. This method becomes an important aid for volume exploration. Therefore, first part of thesis we deal with defining visibility driven transfer functions.

Second part of deals with challenges posed by multimodal visualization to generate informative pictures from complementary data(we used CT and PET). The visibility information is used to fuse multimodal datasets for generating focus+context visualization. Using visibility calculations, tradeoff between visibility and spatial clarity is handled.

1.7 Chapters

The thesis should contain an abstract, acknowledgments, chapters, and bibliography. Appendices are optional. The chapters should include an introducted, related work (or literature survey), background, hypothesis, implementation, results, and conclusions.

chapter 1: Introduction chapter 2: Background/Literature survey chapter 3: Direct Volume rendering using raycasting chapter 4: Visibility Histograms chapter 5:

Visibility guided multimodal volume visualization chapter 6: Prerequisite Installations chapter 7: Implementation chapter 8: Results & Future Work

Chapter 2

Direct Volume rendering using raycasting

The term volume rendering is used to describe techniques which allow the visualization of three-dimensional data. It is a technique for visualizing sampled functions of three spatial dimensions by computing 2-D projections of a colored semi-transparent volume. In scientific visualization and computer graphics, volume rendering is a set of techniques used to display a 2D projection of a 3D discretely sampled data set, typically a 3D scalar field.

A typical 3D data set is a group of 2D slice images acquired by a CT, MRI, or MicroCT scanner. Usually these are acquired in a regular pattern and usually have a regular number of image pixels in a regular pattern. This is an example of a regular volumetric grid, with each volume element, or voxel represented by a single value that is obtained by sampling the immediate area surrounding the voxel.

2.1 Introduction

Volume rendering involves the following steps: the forming of an RGBA volume from the data, reconstruction of a continuous function from this discrete data set, and projecting it onto the 2D viewing plane (the output image) from the desired point of view. An RGBA volume is a 3D four-vector data set, where the first three components are the familiar R, G, and B color components and the last component, A, represents opacity. An opacity value of 0 means totally transparent and a value of 1 means totally opaque. Behind the RGBA volume an opaque background is placed.

The mapping of the data to opacity values acts as a classification of the data one is interested in. Isosurfaces can be shown by mapping the corresponding data values to almost opaque values and the rest to transparent values. The appearance of surfaces can be improved by using shading techniques to form the RGB mapping. However, opacity can be used to see the interior of the data volume too. These interiors appear as clouds with varying density and color. A big advantage of volume rendering is that this interior information is not thrown away, so that it enables one to look at the 3D data set as a whole.

2.2 Definitions

2.2.1 Voxel

A voxel represents a single sample, or data point, on a regularly spaced, three-dimensional grid. It is the basic element of the volume. This data point can consist of a single piece of data, such as an opacity, or multiple pieces of data, such as a color in addition to opacity. A voxel represents only a single point on this grid, not a volume; the space between each voxel is not represented in a voxel-based dataset.

2.2.2 Direct Volume rendering

A direct volume rendering is that visualizations can be created without creating intermediate geometric structure, such as polygons comprising an isosurface, but simply by a direct mapping from volume data points to composited image elements. Together with traditional computer graphics elements such as camera, lighting, and shading, the central ingredient in that direct map- ping is the assignment of optical properties (opacity, color, etc.) to the values comprising the volume dataset [1].

[1] Transfer Functions in Direct Volume Rendering: Design, Interface, Interaction Gordon Kindlmann Scientific Computing and Imaging Institute School of Computing University of Utah, SIGGRAPH 2002 notes.

2.2.3 Ray Casting

Ray casting is a method in which for every pixel in the image, a ray is cast through the volume. The ray intersects a line of voxels. While passing, the color of the pixel is accumulated according the voxels color and transperacy.

Complexity = O(Depth * ImageSize)

2.2.4 Transfer functions

Transfer function make volume data visible by mapping data values to optical properties, usually done by mapping data values to color and opacity.[2]

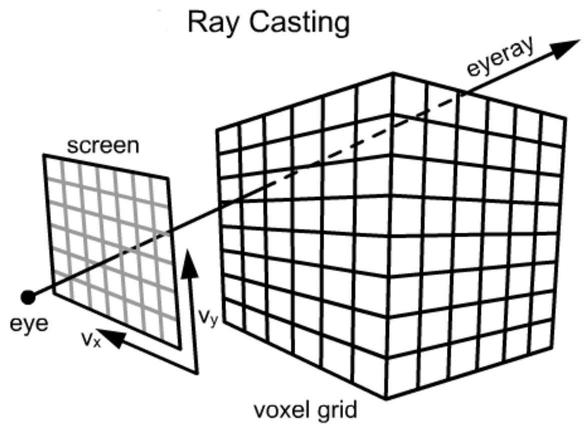

Figure 2.1: Direct Volume rendering using Raycasting.

[2] Barthold Lichtenbelt, Randy Crane, and Shaz Naqvi. Introduction to Volume Rendering, chapter 4. Prentice-Hall, New Jersey, 1998.

2.3 Volume Ray Casting

Raycasting is a technique to visualize volume data at interactive frame rates. For every pixel of the image plane a ray is traced through the scene starting from the viewer. The ray equation is given by a starting point and a direction. If the ray hits the volume the color of the pixel is calculated by sampling the data values of the ray at a finite number of positions in the volume. On each sample the transfer function is applied and composited with accumulated values of the ray.

2.3.1 Basic Algorithm

In its basic form, the volume ray casting algorithm comprises of a ray of being cast through the volume, for each pixel of the final image. Generally, the volume is enclosed within a bounding primitive, a simple geometric object usually a cuboid that is used to intersect the ray of sight and the volume. Along the part of the ray of sight that lies within the volume, equidistant sampling points or samples are selected. In general, the volume is not aligned with the ray of sight, and sampling points will usually be located in between voxels. Because of that, it is necessary to interpolate the values of the samples from its surrounding voxels, this is called sampling. After all sampling points have been fetched, they are composited along the ray of sight, resulting in the final colour value for the pixel that is currently being processed, this is called compositing, explained in detail at later section.

Raycasting is performed on the GPU. We use two float-textures, where the color value encodes the entry and respectively the exit points. For that we need to pass Entry and Exit params to the relevant fragment program. To generate these textures we render a cube with an edge length of 1 (from (0,0,0) to (1,1,1)) and set the vertex color to the coordinates. OpenGL will interpolate the color values between the vertices automatically. For the entry points texture we enable back face culling and respectively front face culling for the exit points texture.

Image Entry and Exit Params.

Pseudocode:

Lookup volume entry position

Lookup volume exit position

Compute ray of sight direction

While in volume

Lookup data value at ray position

Apply transfer function to data value

Accumulate color and opacity

Advance along ray

2.3.2 Sampling

Along the part of the ray of sight that lies within the volume, equidistant sampling points or samples are selected. In general, the volume is not aligned with the ray of sight, and sampling points will usually be located in between voxels. Because of that, it is necessary to interpolate the values of the samples from its surrounding voxels. (commonly using trilinear interpolation).

2.3.3 Compositing

The discrete version of the volume rendering equation replaces the continuous integral with a Riemann sum.

Discrete Volume Rendering Equations:

$$C = \sum_{i-1}^{n} C_i \prod_{j=1}^{i-1} (1 - A_j) \quad \ldots\ldots \ (2.1)$$

$$A = 1 - \prod_{j=1}^{n} (1 - A_j) \quad \ldots\ldots \ (2.2)$$

Here, Opacity A_i approximates the absorption and opacity-weighted color C_i approximates the emission and the absorption along the ray segment between samples i and i+1.

This formula is efficiently evaluated by sorting the samples along the viewing ray and computing the accumulated color C and opacity A iteratively. The colour of

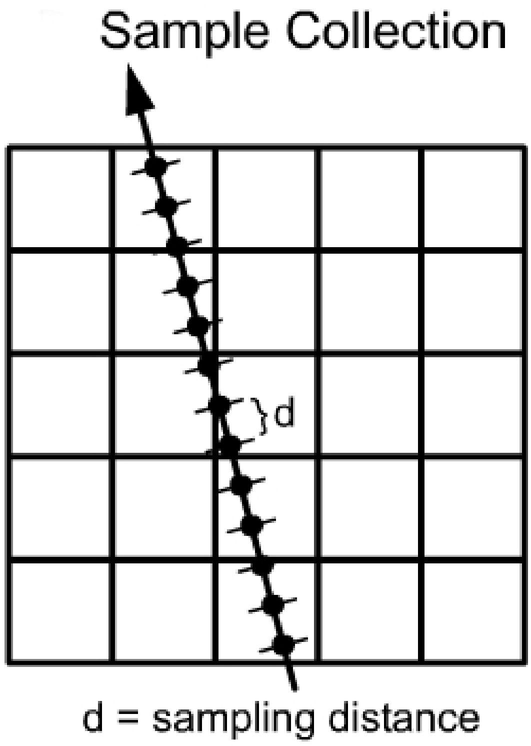

Figure 2.2: Direct Volume rendering using Raycasting.

each sample is determined by classification and shading, and when the transparency is determined by classification, the next step is to evaluate the volume rendering equation. This evaluation is performed by a process called compositing. Two techniques for compositing ray shot into the volume to generate final pixel are front-to-back and back-to-front compositing.

2.3.3.1 Back-to-front Compositiong Equations

In this technique, samples are sorted in back-to-front order, and the accumulated color and opacity are computed iteratively. A single step of the compositing process is known as the Over Operator.

$\hat{C}_i = C_i + (1 - A_i)\,\hat{C}_{i+1}$ ...... (2.2)

$\hat{A}_i = A_i + (1 - A_i)\,\hat{A}_{i+1}$ ...... (2.3)

where, C_i and A_i are color and opacity obtained from fragment shading stage for the ray i, along the viewing ray, and $\hat{C}_i$ is the accumulated color from the back of the volume.

2.3.3.2 Front-to-Back Compositiong Equations

In this technique, samples are sorted in front-to-Back order. Front to back compositing is equivalent to back to front, but it has an added advantage. Since the composition is done towards the back and the current transparency is known at all times, the compositing can be stopped early when the translucency is full(nothing behind that point is going to affect the final image). This is one of the more powerful optimizations that can be done for several rendering techniques.

The front to back equation is:

$$\hat{C}_i \;=\; (1 \;-\; \hat{A}_{i-1}\;)\; C_i \;+\; \hat{C}_{i-1} \text{ ...... } (2.4)$$

$$\hat{A}_i \;=\; (1 \;-\; \hat{A}_{i-1}\;)\; A_i \;+\; \hat{A}_{i-1} \text{ ...... } (2.5)$$

where $\hat{C}_i and \hat{A}_i$ are the accumulated color and opacity from the front of the volume.

Chapter 3

Visibility Driven Transfer function

3.1 Motivation

Medical imaging has given radiologists an ability that photography was not able to provide, it lets them see inside the human body. With the advent of 3D visualization systems, these images can be put together into crisp and impressive renderings of the human body from a variety of perspectives that were only dreamt of before, revolutionizing clinical practice.

Light transport models soon emerged to allow light interactions that, although not realistic in the physical sense, proved to be more effective for understanding the complex relationships among the anatomical structures. For instance, bone could be made semi-transparent to provide visibility of brain tissue. Skin could be removed altogether from an image to show only muscle or internal organs. However, soon it became evident that simply rendering these images in their raw form was no longer effective and the clear visualization of internal structures remains elusive.

The depiction of internal parts in the context of the enclosing space is a difficult problem that has occupied the mind of artists, illustrators and visualization practitioners. Despite the advances made in computer graphics for simulating the light transport in semi-transparent media, the problem of visualizing internal objects is no longer a rendering problem, but that of classification. Medical imaging technology obtains representations of anatomical structures via indirect ways, such as the response of tissue to X-rays or the alignment of electrons in a magnetic field. Therefore, the absence of semantic information prevents visualization practitioners from clearly marking up the regions that must be visualized. Without access to those regions, exploration becomes tedious and time-consuming. The predominant approach has been the use of transfer functions, or opacity mappings, which assign transparency properties to different intervals in the data. This method, however, does not guarantee visibility that internal structures or structures of interest in the volume. There is need to incorporate a measure for visibility. In this chapter, visualization techniques to obtain clear views of internal features in 3D volume data is discussed along with visibility metric.

3.2 Related Work

With the fast growth in computational power of graphics hardware, only until recently it has been possible to manipulate 3D volume data in fashions that were only possible for surface meshes and CAD models, where semantic information is often explicit and readily available. When volume data are understood as explorable objects, we can disassemble it into parts that can be decomposed in numerous ways. One of the foremost ideas that were explored in this direction where cutaways, where certain parts can be removed to uncover hidden parts of the 3D volume. [14] Exploded views extend this idea to reveal the relationships among the internal parts of a complex volume [1].

Another strategy is to assign material properties to different regions or layers of a volume and simulate the physical response to the deformation and cutting of such regions [5,6,10].

Although the deformation unrealistically simulates an elastic material for the piggy bank, the metaphor is effective for depicting the internal structures. More realistic effects are obtained by simulating the response of tissue, such as skin, to incisions and retractions, as used in real surgical procedures. Figure 3 shows the result of peeling the skin, and muscle layers of a foot CT scan to reveal the internal vessels (left) or bone (right).

Rigid and deformable cuts, although effective for visualizing the internal structures, work under the premise that the internal and external layers are clearly separated. In a more general sense, this separation is not easy to come by, and, in most cases, there is a degree of uncertainty. For this reason, the effective visualization of internal structure must rely on robust classification.

The main challenge when attempting to see the internal features remains that of classification. An effective visualization must first decide what is it that we must preserve and what regions are unimportant. Traditional classification systems, found in off-the-shelf visualization systems, only consider a single dimension for classification, without regards of the spatial characteristics or the semantics of the data. However, volume data seldom contain any semantics about the captured structures. Acquisition technology outputs a series of images with intensity values, while simulations of 3D phenomena sample a continuous scalar or vector field in a grid.

In an attempt to extract semantic information, one may analyze the spatial properties of the data, such as the location of boundaries [9], regions of high curvature [7], shape [12] or size[6]. In most of these cases, these properties are just approximations of the local distribution of data in a small neighborhood. Size, for example, can be measured as the extents of regions of a certain homogeneity. Regions of a certain material, such as brain, that occupy a large volume, have different properties than those regions, such as skull and skin, that are relatively thin.

These observations have enabled us to construct classification based on size, and assign opacity based on the relative thickness of features. A particular example is the visualization of brain MRI, where the data is comprised of a series of thin layers (i.e, skin, skull and tissue) surrounding a large region, the brain, of a certain material. Exploiting these properties lets us minimize the effects of occluding tissue, such as skin, to reveal the brain tissue clearly, as shown in Figure 4.

Other approaches do not operate on the data itself but on the rendering process. For example, importance-driven techniques [13] and ghosted views [2,8] assign different opacities in a viewpoint dependent manner, so that the user constantly gets an uninterrupted view of internal structures. A different approach, opacity peeling, automatically finds the layers that compose an image from a given point of view [11].

3.3 Notion of Visibility metric

One of the limitations of contemporary visualization systems is the inability to quantify how visible a feature of interest is. To be more effective, along with traditional transfer function design, must incorporate a measure of visibility.

Visibility Metric attemps to measure the impact of individual samples on the image generated by a volumetric object. It is measured as the contribution of a structure of interest to the final image. Here, visibility can be used to quantify the quality of transfer function and ease their design towards more meaningful and efficient visualization. Transfer function generated with this approach are called as visibility driven transer functions.

This process measures visibility of all structures in a volume to arrive at a good transfer function. In general, a visibility-driven transfer function is constructed in such a way that we guarantee the visibility of all structures of interest and at the same time maximizes the visibility of structure of interest, in particular, of those features lying at the interior of a data set.

3.4 Visibility Histogram

The contribution of a sample in the volume to final image is refered to as visibility of that sample.

$\alpha(s) \ = \ 1 \ - \ e^{\int_s^D \tau(t)dt}$ .....(3.1)

where $\tau(t)$ is the attenuation coefficient of a sample, usually represented as an opacity transfer function $\mathcal{O}$ which is defined by user. Visibility also depends viewpoint as accumulated opacity in front of the sample may differ at different viewpoints.

A visibility histogram is a graphical representation of distribution of visibility function in relation to the domain values of the volume. Samples are weighted by visibility and added into bins that partition the range of values in the scalar field.

VH(x) = $\mathcal{O}(x) \int_{s\epsilon\omega} \delta(s,x)(1 - \alpha(s))ds$ .....(3.2) where, $\delta(s,x)$ is a function.

$$\delta(s,x) = \begin{cases} 1 & V(s) = x \\ 0 & Otherwise \quad .....(3.2) \end{cases}$$

In this thesis, front-to-back compositing is used, as discussed in section 2.4.3. Accumulated opacity is computed as,

AccumulatedOpacity[i] = AccumulatedOpacity[i-1] + (1 - AccumulatedOpacity) Opacity(x)

Hence, for all sample values x in the volume. VH[x] = VH[x] + (1 - AccumulatedOpacity) Opacity(x)

Visibility histogram helps find string occusion patterns on the data, as shown in the figure 3.1.

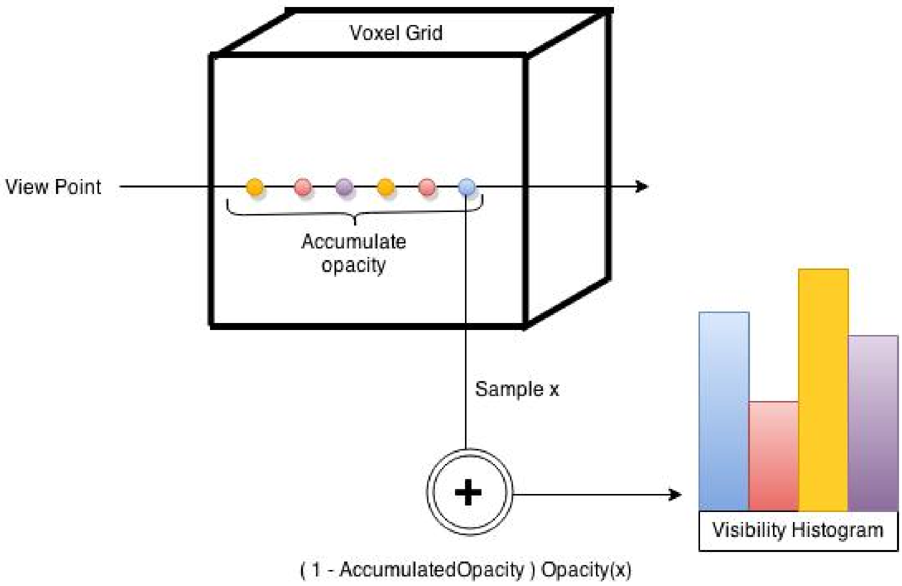

Figure 3.1: Direct Volume rendering using Raycasting.

Figure 3.2: Direct Volume rendering using Raycasting.

Chapter 4

Visibility guided multimodal volume visualization

4.1

Chapter 5

Handling Citations

BibTEX can be used to handle all your bibliographic needs. Simply add references to the file `ref.bib` and BibTEX will take care of the rest. An example of a BibTEX book, conference paper and journal article are given in the sample `ref.bib` file. Many online journals have links to BibTEX citations that you can download and incorporate into the `ref.bib` file. *Do not change the name of the file* `ref.bib`.

The order of the fields is unimportant. BibTEX will display them in the correct order when constructing your bibliography. Also note that you can specify information about a reference that may not even be included in the actual bibliography. For example, the ISBN field is not required by the bibliography, but you can, if you want, put the ISBN to the BibTEX entry.

We can cite a journal article [3] and a conference paper [2] in the same way as a book citation. More information can be found in [1].

Chapter 6

Conclusions

That's all folks!

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[1] L. Lamport. *LaTeX: A Document Preparation System*. Addison-Wesley Publishing Company, second edition, 1994.

[2] F. LastName, F. I. LastName, and F. LastName Jr. Conference paper MUN title. In *Proceedings of the Conference of Sample Conferences*, pages 100–110, Apr. 1996.

[3] F. name Last-name and S. Guy. Journal article SWGC title. *Journal of Sample Journals*, 1(12):1000–1024, 2002.

Appendix A

Appendix: How to Add an Appendix

This is Appendix A.

You can have additional appendices too, (*e.g.*, `apdxb.tex`, `apdxc.tex`, *etc.*). These files need to be included in `thesis.tex`.

If you don't need any appendices, delete the appendix related lines from `thesis.tex`.

Appendix B

Appendix: How to Add Another One

This is Appendix B.