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English summary

The key goal in scientific visualization is to transform numerical data into a visual form that enables us to reveal important information about the data. It is a tool that engages the human senses and an effective medium for communicating complex information. The engineering and scientific communities early employed applications of visualization. The computers were used as a tool to simulate physical processes such as fluid flows, ballistic trajectories and structural mechanics. As the size of the computer simulations increased, the large amount of data made it necessary to transform the numbers from calculations into images. The use of images to communicate information is especially effective as the human visual system is able to extract an enormous amount of information from a single image in very short time.

New challenges in scientific visualization emerge as advances in modern supercomputers make it possible to compute bigger simulations of physical phenomena with higher precision and increasing complexity. Contrary to the early computer simulations, current simulations often involve three spatial dimensions in addition to time (which together result in 4D data), producing terabytes of data containing complex dynamical and kinematical information. There are no indications that the trend of increasing complexity in computer simulations will cease. Increased ability to model more complex systems is an important progress, but the enormous size of present (and future) scientific data sets demands more efficient and advanced visualization tools in order to analyze and interpret the data.

VoluViz is a visualization tool developed at FFI which is capable of interactive visualization of large time-dependent volumetric data. It addresses many of the challenges for large-scale data analysis and supports a set of visualization tools to facilitate scientists in their work with huge data sets, including effective rendering techniques, easy navigation of the data (both in time and space) as well as advanced multi-field visualization techniques and feature enhancement techniques. The software takes advantage of commonly available modern graphics hardware and is designed with the goal of real-time investigation of the data. VoluViz has been used to investigate data from a number of applications: dispersion modeling (pollution, toxic gases), biomedical flow modeling (blood vessels, the human heart) and in industrial design optimization (aircrafts, missile seeker technology). Choosing the right visualization can turn gigabytes of numbers into easily comprehensible images and animations. If used properly, VoluViz can thus be an effective medium for communicating complex information and for presenting the result from scientific simulations in an intelligible and intuitive way, both to fellow scientists as well as a broader audience.

The report is divided into three main parts. The first part (sections 1-3) gives an overview of the rendering framework of VoluViz in addition to the description of some important volume visualization concepts. The second part (section 4) provides a more detailed description of the rendering algorithm used by VoluViz in addition to a presentation of the available tools with examples. The third part (sections 5-6) provides the user manual.

Sammendrag

Formålet med vitenskapelig visualisering er å forvandle numeriske data til en visuell form som gjør oss i stand til å vise viktig informasjon om dataene. Det er et verktøy som utnytter de menneskelige sansene og et effektivt medium for å kommunisere kompleks informasjon. Vitenskapelige miljøer tok tidlig i bruk dette verktøyet. Datamaskiner ble brukt til å simulere fysiske prosesser som strømninger, ballistiske baner og konstruksjonsmekanikk. Etter hvert ble datamengden så stor at det ble nødvendig å overføre beregningstallene til bilder. Bruk av bilder er spesielt effektivt ettersom det visuelle systemet hos mennesker er i stand til å trekke ut enorme mengder informasjon fra ett enkelt bilde i løpet av svært kort tid.

Nye utfordringer i vitenskapelig visualisering har oppstått parallelt med utviklingen av moderne superdatamaskiner. Dagens maskiner gjør det mulig å beregne større og større simuleringer av fysiske fenomener med høyere presisjon og med økende kompleksitet. I motsetning til tidligere, inneholder dagens simuleringer ofte tre romlige dimensjoner i tillegg til tid (som til sammen fører til 4D-data). Disse simuleringene kan produsere terabyte med kompleks datainformasjon. Det er ingen indikasjoner på at trenden med økende kompleksitet i datasimuleringer vil stoppe. Økt evne til å modellere komplekse systemer er et viktig framskritt, men samtidig fører størrelsen på dagens vitenskapelige datasett til et stadig større behov for mer effektive og avanserte visualiseringsverktøy.

Visualiseringsverktøyet VoluViz er utviklet ved FFI og i stand til interaktiv visualisering av store tidsavhengige volumetriske data. Det løser mange av de utfordringene som finnes for storskala dataanalyse og støtter et sett med visualiseringsverktøy for å hjelpe forskere i arbeidet med store datasett, inkludert avanserte flerfeltsvisualiseringsteknikker og enkel navigering av data (både i tid og rom). Programvaren utnytter moderne grafikkmaskinvareteknologi og er utformet med et mål om etterforskning av data i sanntid. VoluViz har blitt brukt til å undersøke data fra en rekke applikasjoner: spredningsmodellering (forurensning, giftige gasser), biomedisinsk strømningsmodellering (blodkar, menneskehjerte) og i industriell designoptimalisering (fly, missilsøkerteknologi). Å velge riktig visualisering kan forvandle gigabyte med tall til lett forståelige bilder og animasjoner. Brukt på riktig måte kan VoluViz være et effektivt medium for å kommunisere kompleks informasjon og et viktig verktøy for å presentere forskningsresultater på en forståelig og intuitiv måte, både til forskerkollegaer og et større publikum.

Rapporten er delt i tre hoveddeler. Den første delen (kapittel 1-3) gir en oversikt over rammeverket i VoluViz i tillegg til en beskrivelse av noen viktige begreper i volumvisualisering. Den andre delen (kapittel 4) gir en mer detaljert innføring i hvordan VoluViz visualiserer data, i tillegg til en beskrivelse av tilgjengelige verktøy med eksempler. Den tredje delen (kapittel 5-6) presenterer bruksanvisningen.

Contents

Preface

The development of VoluViz was started, in 2001, by Anders Helgeland who is the main architect behind the software. The software has been upgraded several times in the period from 2001 to 2014, partly with the help from some master and summer students associated with the Norwegian Defence Research Establishment (FFI). A special thanks goes to Trond Gaarder, Geir Kokkvoll Engdahl and Kim Kalland for their contributions. Thanks also goes to the students and scientists working at FFI, using VoluViz, for interesting and useful discussions on how to upgrade and to further improve the software. This also applies to all the people providing data sets used in this report.

What VoluViz is and isn't

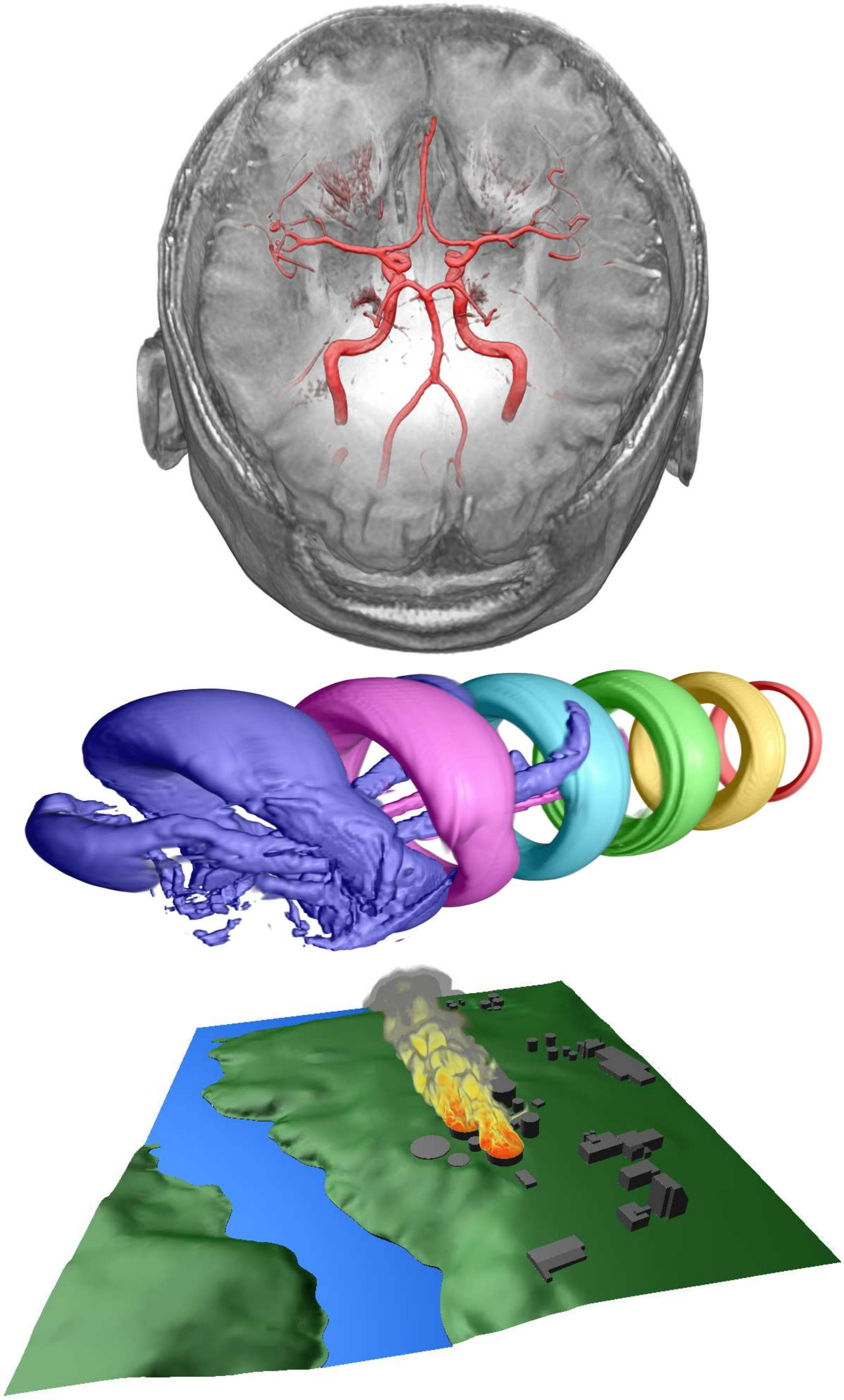
VoluViz was developed to overcome new challenges emerging in scientific visualization of large-scale data from numerical simulations. It is designed as a *Ferrari* to give interactive rendering of large time-dependent volumetric data. A high degree of interactivity is crucial to ensure an effective investigation of the data. If the visualization is carried out too slowly, we will forget what was displayed before the next image is rendered and then lose track of the information. As a result, all components of VoluViz (from color mapping to advanced multi-field rendering) is designed with the goal of immediate response when investigating data.

VoluViz is, however, not designed to replace other existing visualization software. It features tools and techniques that the other software lacks - in particular volume visualization techniques. We have not made efforts to re-implement the parts of other software that already works sufficiently for data visualization. VoluViz should therefore be used as one of many fine options for data investigation and data analysis. For data navigation and presentation of 3D (scalar, vector and tensor) field components, VoluViz comes with a particularly well developed tool box.

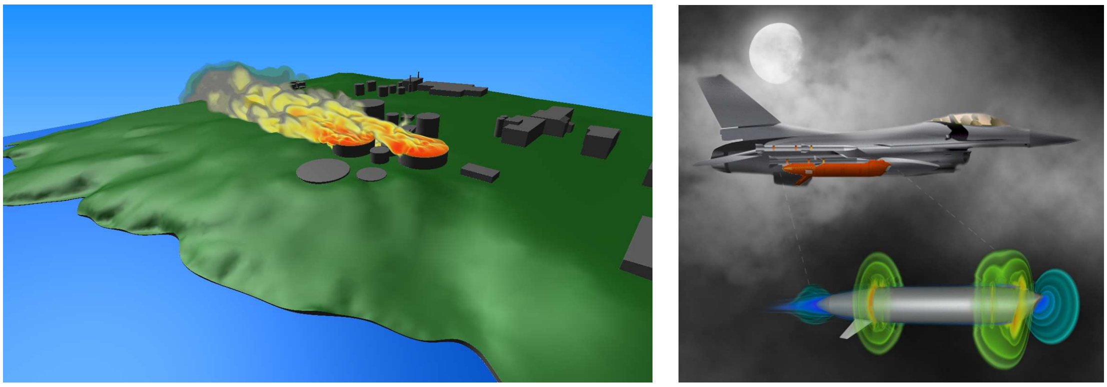
"Have fun :)"

A caution when analyzing data

It is important to remember that the quality of the physical interpretation made when using visualization tools, in general, are no better than the quality of the original data set.



Top: Advanced *focus+context* visualization with the purpose of revealing and emphasizing major arteries, known as the *Circle of Willis*, inside an MRI data set of a human brain (see figure 4.9).
Middle: Advanced temporal-spatial visualization of a breakdown of a single vortex ring by projecting data from six different time steps into the same scene (see figure 4.14).
Bottom: Visualization of a surface model of an industrial environment together with consentration data (of pollution) released from the industrial plant (see figure 6.11).



(a) (b)

Figure 1.1 (a) Concentration of pollution released from an industrial plant [11]. (b) Visualization of the velocity field around a carrier pod for F-16 [12]. Both visualizations were made using VoluViz.

1 Introduction

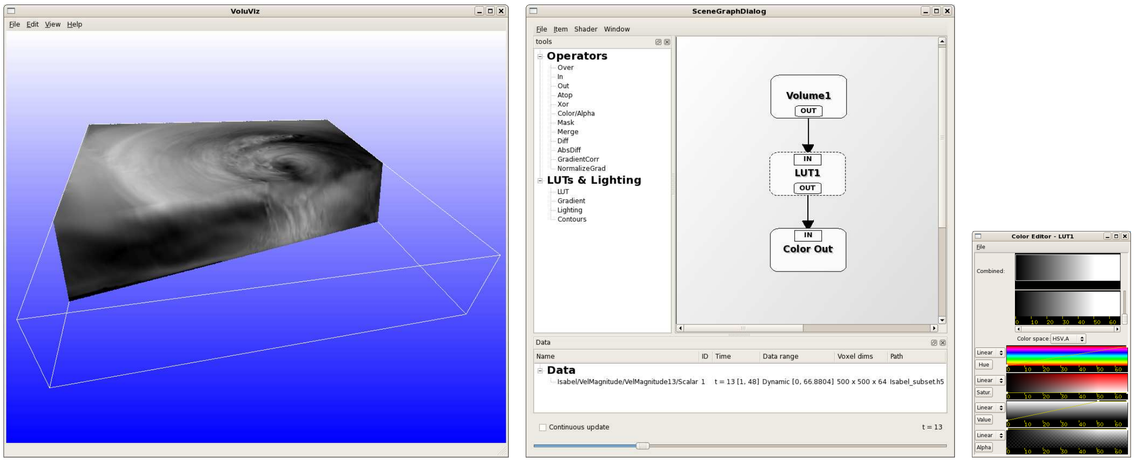
VoluViz is a volume rendering application designed for viewing time-dependent and time-independent (static) volumetric data. Such data is the output of a number of applications such as in dispersion modeling (e.g. smoke, pollution), biomedical flow modeling (e.g. blood vessels, drug delivery systems) and in industrial design optimization (e.g aircrafts, engines), see figure 1.1.

VoluViz was developed to overcome new challenges emerging in scientific visualization of large three-dimensional (and time-dependent) data. Large tree-dimensional data sets is challenging to visualize effectively mainly due to two reasons. Firstly, while one- and two-dimensional data sets are rather straightforward to visualize, volumetric data sets cannot be projected to a 2D screen without losing information. For instance, important information embedded in the data might get lost if it is hidden behind other parts of the data or if the “wrong” parts of the domain are selected for display. Good tools for exploring and navigating volumetric data sets, to help scientists and engineers to convey only the important and interesting parts of the data, are therefore needed to ensure an effective visualization. Secondly, these tools need to be interactive. A high degree of interactivity is important when investigating data due to the short-term memory of the human brain. If the visualization is carried out too slowly, we will forget what was displayed before the next image is rendered and then lose track of the information.

VoluViz takes advantage of commonly available modern graphics hardware and advanced visualization techniques to implement a wide variety of visualization modes. It features tools to facilitate scientists in their work with huge data sets including effective rendering techniques, easy navigation of the data (both in time and space) as well as advanced multi-field visualization techniques and feature enhancement techniques. The software is implemented in C++ [38], Qt [2], OpenGL [35] and OpenGL Shading Language (GLSL) [32]. The development of VoluViz was initially started in 2001 by Anders Helgeland and has been upgraded several times in the period from 2001 to 2014.

It is an ongoing project, and VoluViz is still being extended to include new features to support scientists working at the Norwegian Defence Research Establishment with data analysis and data presentations. Choosing the right visualization can turn gigabytes of numbers into easily comprehendable images and animations. If used properly, VoluViz can thus be an effective medium for communicating complex information and for presenting the result from scientific simulations, both to co-workers as well as a broader audience, in an understandable and intuitive way.

The document works both as a user guide and a detailed theoretical description of some of the visualization techniques used by VoluViz. The report is divided into tree main parts. The first part (sections 2 and 3) provides an overview of the rendering framework of VoluViz in addition to the description of some concepts important in volume visualization. The second part (section 4) gives a more detailed description of the rendering algorithm used by VoluViz in addition to a presentation of the available tools with examples. The third part (sections 5-6) provides the user manual. The three different parts are, to some extent, independent of each other. This means that a reader could start reading the user manual first and then move on to the other parts to learn more about details of the software and the visualization techniques.



(a) (b) (c)

Figure 2.1 (a) Render window. (b) Volume Scene Graph window. (c) A transfer function editor.

2 VoluViz3.0 Framework Overview

VoluViz is a volume visualization application capable of fast visualization of 3D data defined on a regular structured grid. As most of the rendering code is executed on the GPU (graphics processing unit), it manages interactive analysis of quite large data. It reads files in the HDF5 [1] format and includes a browser for easy navigation of HDF5 files. In addition, VoluViz has the following key features:

- Fully interactive color table editor for specifying transfer functions
- Support for interactive visualization of time-varying fields
- Support for interactive multi-field visualization with custom GLSL shaders
- Interactive clip plane and picking of subset utilities for easy navigation of the data

The framework basically consists of volume data, operators to manipulate the data, a volume scene graph, and a renderer. Figure 2.1 shows a very simple setup where a single dataset (the velocity magnitude of a hurricane simulation [28]) is visualized using volume rendering. In this setup, the volume data is first mapped to a color and transparency value before it is rendered in the main VoluViz render window (figure 2.1(a)). The scene graph window can be seen in figure 2.1(b). Here, different types of visualizations can be constructed by connecting the volume data to different types of operators. In the current visualization, a single operator is used, namely a lookup table (LUT), which maps every data value inside the data domain into to a color and transparency value by using a color table editor. The lookup table (also known as a transfer function) used for constructing the current scene can be seen in figure 2.1(c). In this case, it maps all data to grayscale values giving maximum and minimum data values the colors white and black, respectively.

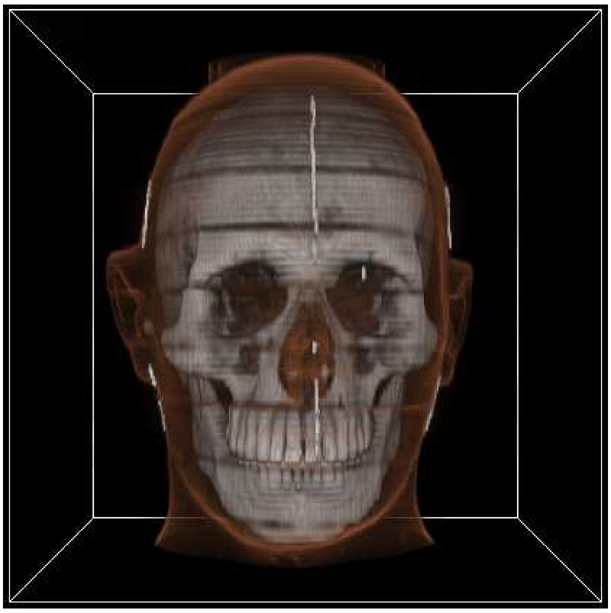


Figure 3.1 The skull of a head is emphasized by assigning low opacity to the soft tissues.

3 Introduction to Volume Rendering

Volume rendering is the process used to create images from volumetric data. Large data sets obtained from instruments (such as medical scanners) or numerical simulations have led to an increasing demand for more efficient visualization techniques. As a result, several volume rendering techniques have emerged. As VoluViz uses a technique known as direct volume rendering as its main rendering algorithm, this section will cover a few concepts that are important in volume visualization. Understanding these concepts will make it easier for scientists to benefit from using VoluViz as an interactive tool for data navigation and data analysis. A more detailed and complete description of volume visualization can be found, for instance, in [15, 42, 14].

3.1 Transparency, Opacity and Alpha Values

An important concept in visualization of volumetric data is transparency or opacity. Although many visualization techniques involve rendering of opaque objects, there are applications that can benefit from the ability to render semitransparent objects and even objects that emit light. The internal data from an MRI scan can for instance be shown by making the skin semitransparent, see figure 3.1.

Opacity and transparency are complements in the sense that high opacity implies low transparency, and are often referred to as *alpha* in computer graphics. The opacity or alpha value, A, is a normalized quantity in the range $[0, 1]$. If an object has maximum opacity ($A = 1$), it is opaque and the objects and light behind are shielded and invisible. If $A < 1$, the object is transparent and makes objects behind visible. An alpha value of zero ($A = 0$) represents a completely transparent object. The relation between opacity and transparency, T, is given by $A = 1 - T$.

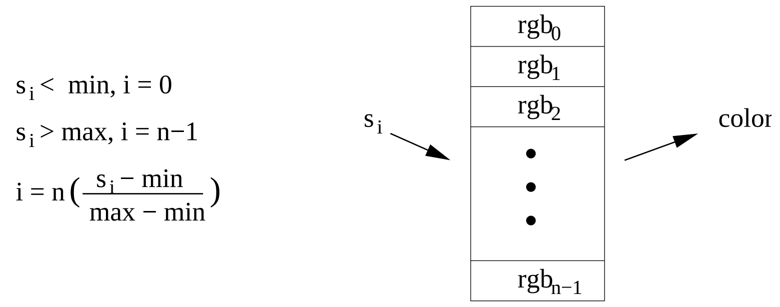


Figure 3.2 Mapping scalars to colors via a lookup table.

3.2 Color Mapping

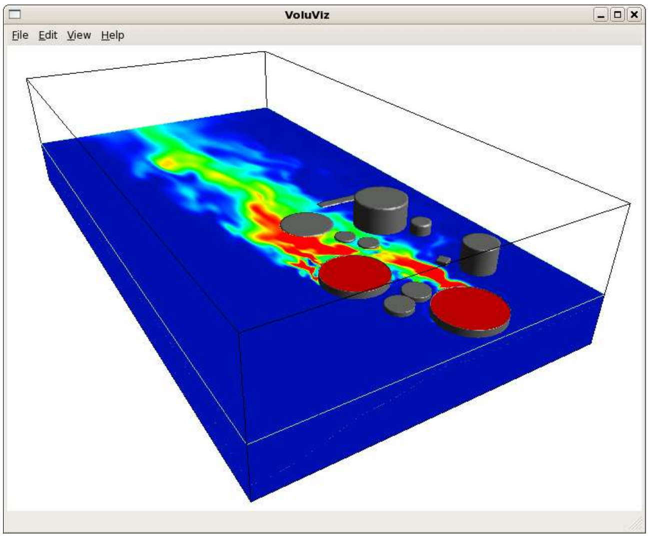
Color mapping is a common scalar visualization technique that maps scalar data into color values to be rendered. In color mapping, the scalar values are divided into n equal intervals and serve as indices into a lookup table. The table holds an array of colors and is associated with a minimum and maximum scalar data range $(\min, \max)$ into which the scalar values are mapped. Scalar values with either lower or greater value than the chosen data range is clamped to the minimum and maximum color value, respectively. The rest of the scalar values, s_i, are given colors associated with the index, i, in the lookup table, see figure 3.2.

The lookup table holds an array of colors that can be represented for example by the *RGBA* (red, green, blue, alpha) or the *HSVA* (hue, saturation, value, alpha) color system. The RGBA system describes colors based on their red, green, blue and alpha intensities and is used in the raster graphics system. The HSVA system, which is by scientists found to give good control over colors in scientific visualizations, represents colors based on hue, saturation, value and alpha. In this system, the hue component refers to the wavelength which enables us to distinguish one color from another. The value V which also is known as the intensity component, represents how much light is in the color and saturation indicates how much of the hue is mixed into the color.

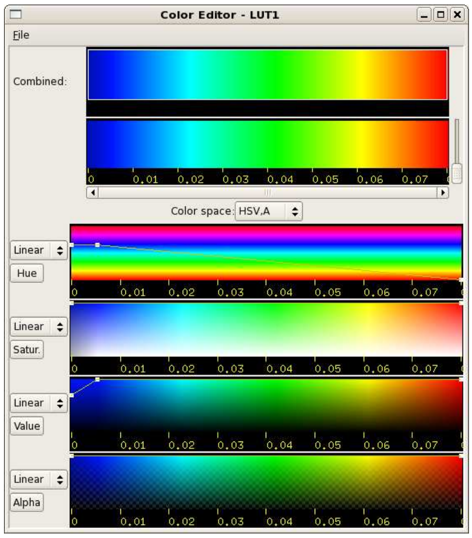
Use of colors is important in visualization and should be used to emphasize various features of the data set. However, making an appropriate color table that communicates relevant information is a rather challenging task. “Wrong use” of colors may exaggerate unimportant details. Some pieces of advice in making appropriate color tables are given in [37, 4]. In volume visualization, lookup tables are often referred to as *transfer functions*. Figure 3.3 illustrates the use of transfer functions on data from a simulation of aerosol dispersion in an industrial environment [11].

3.3 Texture Mapping

In computer graphics, geometric objects are represented by polygonal primitives (consisting of vertices and cells). In order to render a complex scene, millions of vertices have to be used to capture the details. A technique that adds detail to a scene without requiring explicit modeling of the detail with polygons, is *texture mapping*. Texture mapping maps or pastes an image (a texture) to the surface of an object in the scene. The image is called a *texture map* and its individual elements are called *texels*. Texture maps can be one-, two- and three-dimensional. A texture may contain from



(a)



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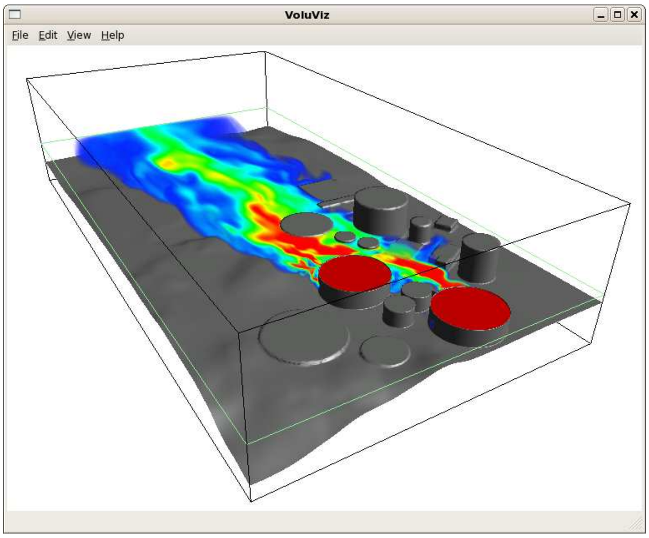

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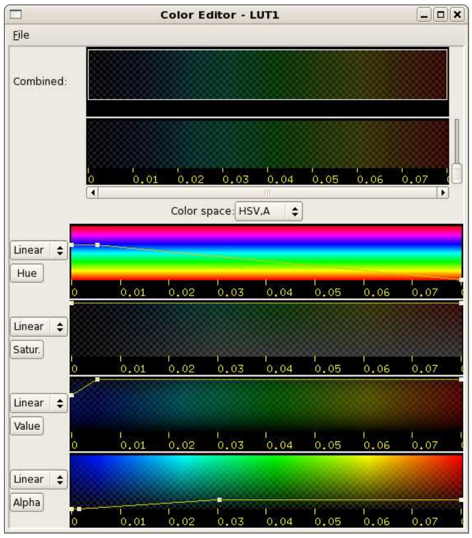


(d)

Figure 3.3 Visualization of concentration of pollution released from an industrial plant using the HSVA color system for the color mapping. The consentration data are first mapped to a voxel set with 8-bit precision (in the range $[0, 255]$*), and serve as indices into a lookup table giving each value a separate color and opacity value. Figures (a) and (c) show two scenes rendered using the transfer functions displayed in (b) and (d), respectively. In both transfer function editors, the consentration data are mapped to identical colors using identical mappings for the HSV components. The only difference between the two scenes is in the mapping to the opacity values also known as the alpha (A) component. While one of the scenes is rendered with maximum opacity (A=1) for all data points, the other scene (c) is rendered using much lower opacities resulting in a very different representation of the data. Here, all data points containing the lowest amount of consentration are made completely invisible (by setting alpha to zero for all these values). In addition, the rest of the data are rendered in a semi-transparent fashion using low opacity values. A clip plane is used in both scenes, removing all data between the clip plane and the view.*

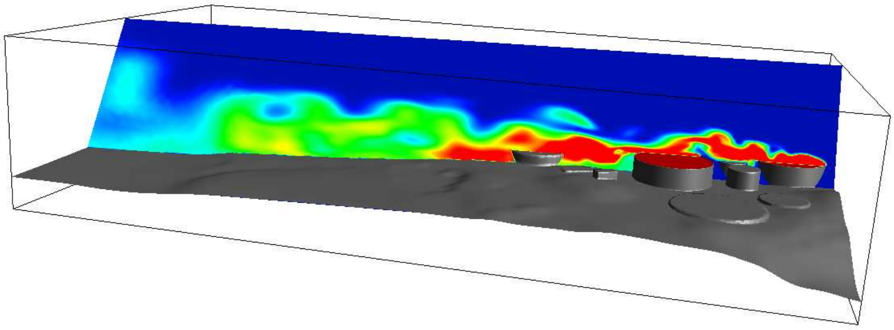


Figure 3.4 Texture mapping example in 3D. Here, a single planar surface has been cut through the volume. Local texture coordinates are then sampled along the surface which gives the mapping to the 3D texture storing the volumetric data. The data is then mapped to colors and opacities and finally pasted as an image on top of the surface.

one to four components. A texture with one component contains only the intensity value, and is often referred to as an *intensity map* or a *luminance texture*. Two component textures contain information about the intensity value and the alpha value. Three component textures contain RGB values and a texture with four components contains RGBA values. To determine how to map the texture onto the polygons, each vertex has an associated *texture coordinate*. The texture coordinate maps the vertex into the texture map. The texture map in 1D, 2D and 3D can be defined at the coordinates (u), (u, v) and (u, v, w), respectively, where u, v, w are in the range $[0, 1]$.

Texture mapping is a hardware dependent feature and is designed to display complex scenes at real time rates. While 2D textures is most common in computer gaming, both 1D and 3D textures are widely used in scientific visualization, especially in volume rendering. One-dimensional textures can for instance be used to store transfer functions (see section 3.2). As an example, the transfer functions displayed in figure 3.3 are implemented using one-dimensional textures to store the data mapping to the color and opacity components used in the visualization. Three-dimensional textures can, for instance, be used to store volumetric scalar data fields. In volume rendering, the scalar values are often normalized and represented as a regular structured data set with 8-bit (or 16-bit) precision. These values can be used as indices into a lookup table. In that case, texel values in the volume texture are mapped to color (and opacity) values to be rendered. If the transfer functions are implemented in texture hardware, this allows an instant update of the color and opacity in the scene after altering the lookup table. If the transfer functions are not supported in hardware, the 3D textures have to be regenerated every time the lookup table changes. Figure 3.4 illustrates the use of texture mapping, where concentration data (of pollution) from an industrial plant is mapped to colors and then pasted as an image onto a single surface intersecting the data domain.

3.4 Direct Volume Rendering

Direct volume rendering is a group of rendering methods that generates images of volumetric data sets without explicitly extracting geometric surfaces from the data. In direct volume rendering, voxels are used as building blocks to represent the entire volume. Typically, each voxel is associated with a single data point which is mapped to optical properties such as color and opacity (see figure 3.5(b)). As opposed to the indirect techniques, such as isosurface extraction [24, 27, 34], the direct methods immediately display the voxel data. These methods try to give a visual impression of the complete 3D data set using light transport models which describes the propagation of light in materials. During rendering, the optical properties are accumulated along each viewing ray to form an image of the data (see figure 3.5(a)). An overview of different optical models ranging from very simple to very complex models that account for absorption, emission as well as scattering effects can be found in the work by Max [26]. The most widely used method for volume rendering is the one limited to absorption and emission effects only. This *emission-absorption* [26] model can be expressed by the differential equation

$$\frac{dI_\lambda}{ds} = g_\lambda(s) - \tau(s) I_\lambda(s), \tag{3.1}$$

where $I_\lambda(s) = I_\lambda(\mathbf{x}(s))$ is the intensity of radiation with wavelength λ at the position s along the ray $\mathbf{x}(s)$. The function $g_\lambda(s) = C_\lambda(s)\tau(s)$ is called the *source term* and describes the emissive characteristics throughout the volume. Here, $C_\lambda(s)$ is the emissive color contribution at a point $\mathbf{x}(s)$ in the volume. The function $\tau(s)$ is called the *extinction function* and gives the amount of radiation that is absorbed. Solving equation (3.1) by integrating from $s = 0$ at the edge of the volume to the endpoint $s = D$ leads to the *volume rendering integral* (VRI)

$$I_\lambda(D) = I_\lambda(0) e^{-\int_0^D \tau(t)dt} + \int_0^D C_\lambda(s)\tau(s) e^{-\int_s^D \tau(t)dt} ds. \tag{3.2}$$

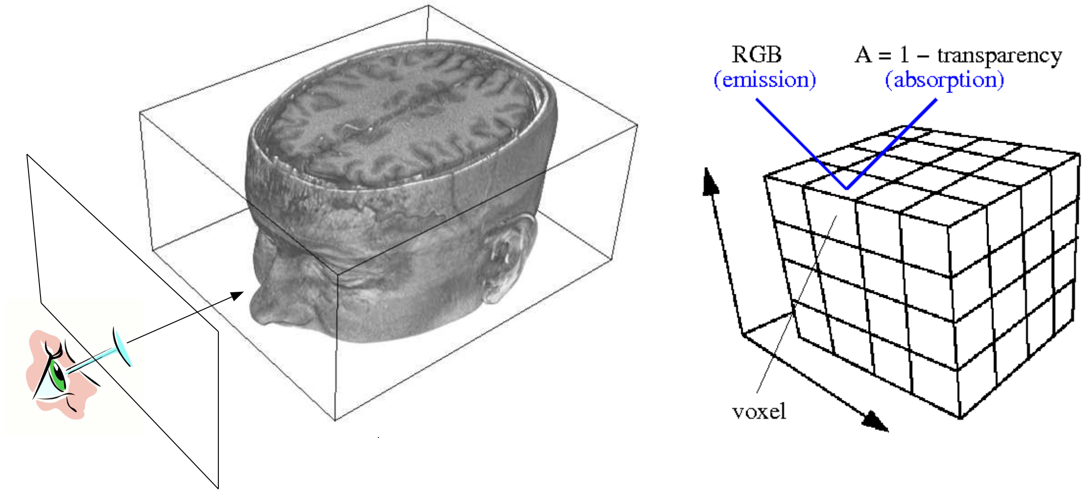
The term $I_\lambda(0)$ gives the light coming from the background at the position $s = 0$ and $I_\lambda(D)$ is the total intensity of radiation leaving the volume at $s = D$ and finally reaching the eye. The first term represents the light from the background multiplied by the volume's transparency between $s = 0$ and $s = D$. The second term represents the integral contribution of the source term at each position s, multiplied by the volume's transparency along the remaining distance to the eye. Using this definition of the transparency, $T(s_1, s_2) = e^{-\int_{s_1}^{s_2} \tau(t)dt}$, we obtain a slightly different version of the volume rendering integral

$$I_\lambda(D) = I_\lambda(0) T(0, D) + \int_0^D C_\lambda(s)\tau(s) T(s, D) ds.$$

By approximating the VRI (3.2) with a Riemann sum and using a second order Taylor series to approximate the exponential, we get the discrete volume rendering integral (DVRI)

$$\begin{aligned} I_\lambda(D) &= \sum_{i=0}^{L/\Delta s - 1} C_\lambda(i\Delta s) A(i\Delta s) \prod_{j=i+1}^{L/\Delta s - 1} (1 - A(j\Delta s)), \\ \text{with} \quad & g_\lambda(0) = C_\lambda(0) A(0) = I_\lambda(0). \end{aligned} \tag{3.3}$$

Here, $A(i\Delta s) = (1 - T(i\Delta s)) \approx (1 - (1 - \tau(i\Delta s)\Delta s)) = \tau(i\Delta s)\Delta s$ is the opacity. When looking at equation (3.3), the reason for preferring this particular discretization of the VRI becomes



(a) (b)

Figure 3.5 (a) In Ray Casting, the final image is obtained by sending rays from the screen into the scene. The final color at each pixel is obtained by evaluating a rendering integral along samples containing optical properties (color and opacity) along each ray. (b) Data to be rendered are typically represented as a voxel set. Each voxel is associated with a single data point which is mapped to a color and opacity value giving the local emissive and absorption properties which can be used directly in the emission-absorption *[26] model.*

apparent. It is equal to the recursive evaluation of the *over* operator [30]. Not only is this a useful theoretical tool for describing the science behind direct volume rendering, but it also enables the use of existing general compositing (software and hardware) algorithms to render volumes.

In order to produce images of the volume data, an algorithm must be used to evaluate the volume rendering integral (equation (3.3)). The conceptually most simple algorithm is *ray casting* [9, 22], since it immediately follows from the discussion above. The basic idea of ray casting is to determine the value of each pixel in the image by sending a ray through the pixel into the scene. Typically, when rendering volumetric data, the rays are parallel to each other and perpendicular to the view plane, see figure 3.5. The DVRI (equation (3.3)) is then evaluated for each ray by sampling the volume at a series of sample points a distance Δs apart.

Other direct volume rendering techniques are splatting [44], shear-warp [21], and texture-based direct volume rendering [7, 8], which is the algorithm VoluViz is based upon.

3.5 Texture-Based Direct Volume Rendering

Hardware assisted volume rendering using 3D textures can provide interactive visualizations of 3D scalar fields [7, 8], The basic idea of the 3D texture mapping approach is to use the scalar field as a 3D texture. If the texture memory is large enough, the entire volume is downloaded into the texture memory once as a preprocess. To render the voxel set, a set of equally spaced planes (slices) parallel to the image plane are clipped against the volume. The hardware is then exploited

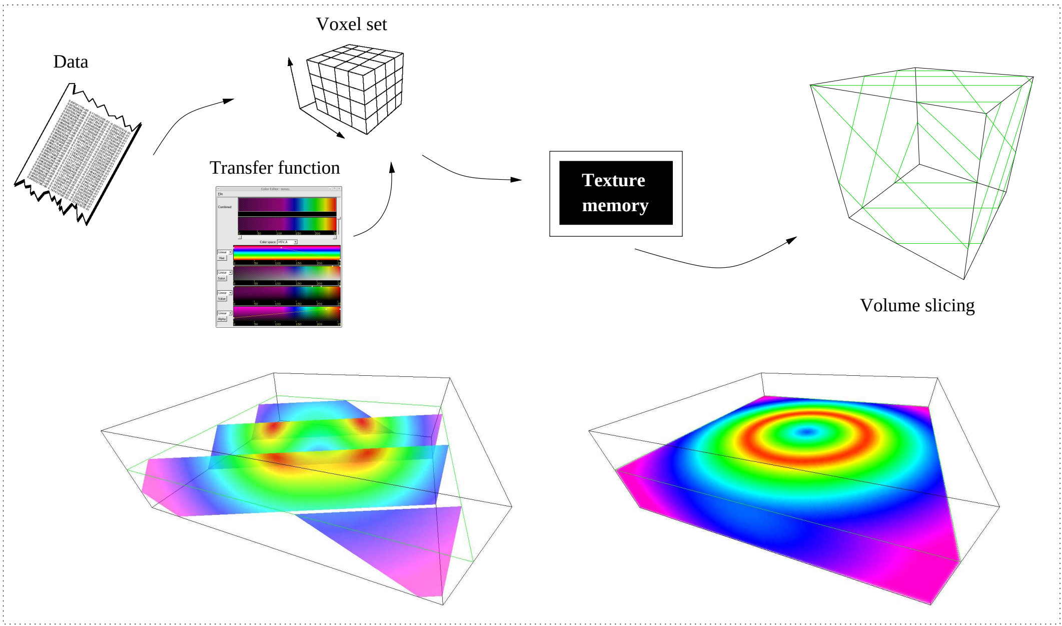


Figure 3.6 Direct volume rendering by texture slicing. First, data volumes and color tables are uploaded to texture memory on the graphics card as a preprocess. Then, a set of view aligned slices are clipped against the volume and blended in a back-to-front order. The bottom left image shows the result from applying volume slicing on a data set using four slices only. In the bottom right image, a considerably larger amount of planes are used to render the same data set. This gives a much more continuous visualization of the data.

to interpolate 3D texture coordinates at the polygon vertices and to reconstruct the texture samples by trilinearly interpolating within the volume. If a transfer function is used, the interpolated data values are passed through a lookup table that maps the values into color and opacity values. This way, graphics hardware allows fast response when modifying color and opacity. Finally, the volume is displayed by blending the texture polygons back-to-front onto the viewing plane using the *over* operator [30] (which is equivalent to solving equation (3.3)). This technique is called *texture slicing* or *volume slicing*. Texture slicing is capable of producing images of high quality at interactive rates. Figure 3.6 shows an illustration of the steps involved when rendering volumes using texture-based direct volume rendering.

Although 3D texture mapping is a powerful method, it strongly depends on the capabilities of the underlying hardware. When the size of the volume data sets exceeds the amount of available texture memory, the data can be split into subvolumes (or bricks) that are small enough to fit into memory. Each brick is then rendered separately, but since the bricks have to be reloaded for every frame, the rendering performance decreases considerably.

4 The VoluViz Rendering framework

4.1 Introduction

Even though most computer simulations involve the solution of a multiple set of related data fields, much of the current data analysis focus on studying the data in a single-field variable manner only. While single-variable visualizations can satisfy the needs of the user in many applications, it is clear that in some areas, such as in fluid mechanics research, it would be extremely useful to be able to effectively visualize multiple fields simultaneously and the relation between them. However, due to perceptual issues, such as clutter and occlusion, it can be very challenging to produce an effective visualization of multiple volumetrical fields.

To facilitate a more effective visualization of multiple data fields, VoluViz is designed using a flexible multi-field visualization framework that is capable of combining a multiple set of data fields (both temporal and spatial) into a single field, for rendering. This is achieved through a set of operators. The final output is selected through a powerful and flexible graphical user interface which makes it very easy to change between different types of visualizations. The user interface allows the generation of visualization scenes through drag and drop events, connecting the operators into a volume scene graph. To enable interactive analysis, each visualization scene, which is the outcome of a tree graph, is converted to a mathematical expression and corresponding GPU (graphics processing unit) shader code to be run on the graphics card.

Interesting features in the data can be emphasized by manipulating transfer functions (to control color and transparency of the data) in addition to applying feature enhancement techniques to enhance depth, boundaries, edges, and detail. The latter techniques can be used to give the user a better appreciation of the three-dimensional structures in the data.

4.2 Flexible Direct Volume Rendering

Our rendering framework is based on texture-based direct volume rendering [7, 8] which is explained, in detail, in section 3.5. Here, a set of view aligned slices are clipped against the volume and blended in a back-to-front order. The hardware is then exploited to interpolate 3D texture coordinates at the polygon vertices and to reconstruct the texture samples by trilinearly interpolating within the volume. Typically, for single-field data volume rendering, data values are sampled at each sample position on the view-aligned slice planes. The data values are then mapped to a color and transparency value and then used directly in the (discrete) volume rendering integral

$$\mathbf{I}_{\text{eye}} = \sum_{i=0}^{L/\Delta s-1} \mathbf{C}(i\Delta s) A(i\Delta s) \prod_{j=i+1}^{L/\Delta s-1} (1 - A(j\Delta s)). \tag{4.1}$$

This particular integral is derived from the *emission-absorption* [26] model where $\mathbf{C}(i\Delta s)$ and $A(i\Delta s)$ are the emissive color and opacity contribution at given sample points in the volume and Δs is the sampling distance between the individual slice planes.

VoluViz however, takes advantage of the flexibility of modern graphics hardware to implement a much more flexible variant of volume rendering. On modern graphics hardware, a separate program,

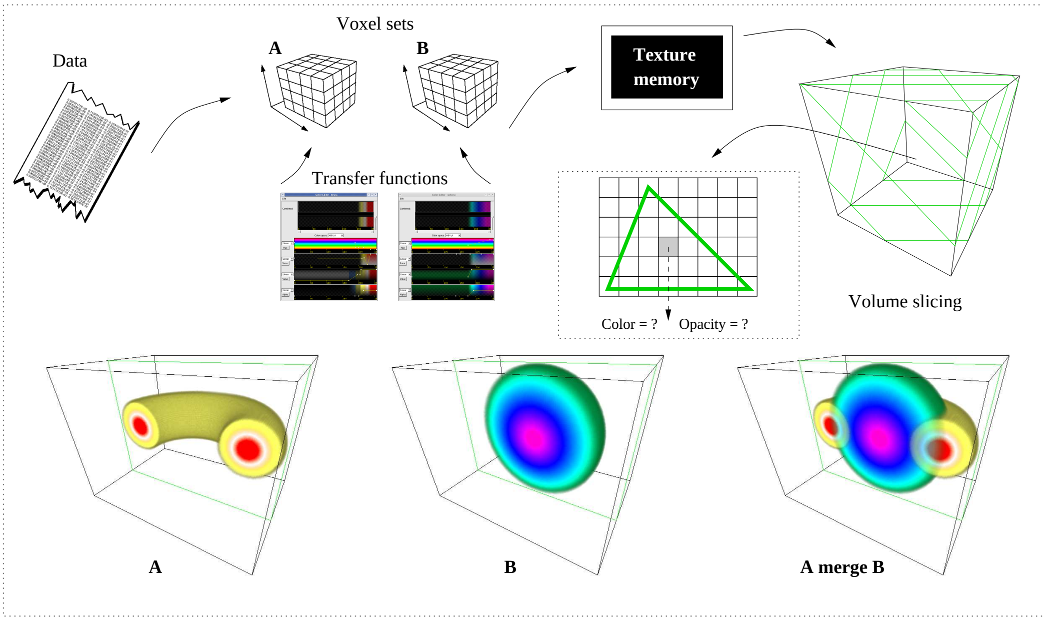


Figure 4.1 Flexible volume rendering pipeline used by VoluViz. By writing separate GPU programs called shaders, allows the user to control what is sent as local color and opacity values when evaluating the volume rendering integral (eq. 4.1). Hence, it is possible implementing compositing operators, such as the merge operator, for local blending of multiple data sets.

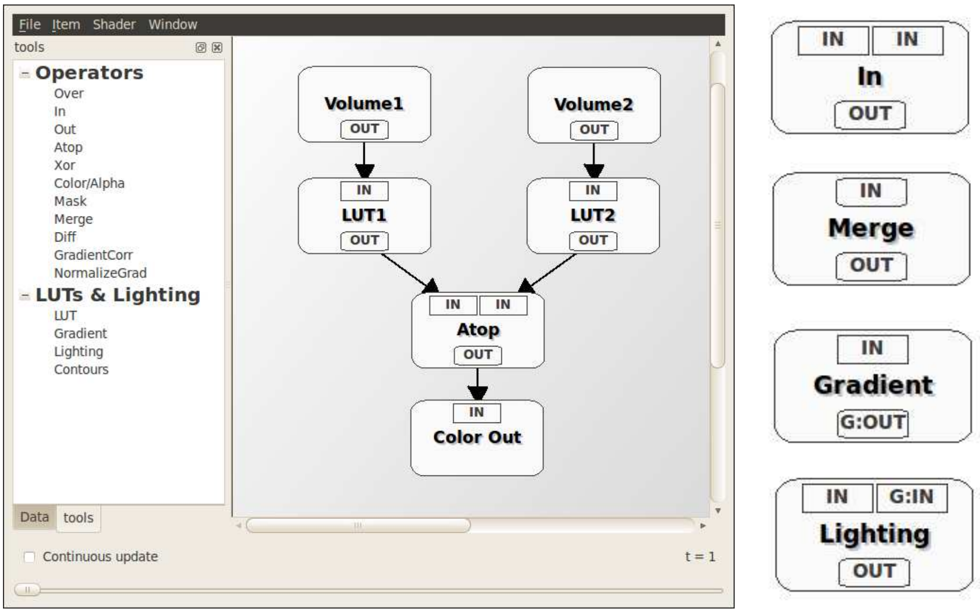
referred to as a fragment program, or a fragment shader, can be called for each time a single volume sample is processed in the above volume integral. This means that we can override what is sent as color and opacity contributions, and write our own shaders. This enables a flexible way of implementing a number of more sophisticated volume rendering techniques such as volume shading, non-photorealistic volume rendering techniques as well as multi-field volume rendering.

A sketch of the flexible volume rendering pipeline can be seen in figure 4.1. As opposed to traditional volume rendering, which only handles a single data set, VoluViz can visualize data from a multiple set of data fields simultaneously. This means that we can upload multiple data sets and their associated transfer function into texture memory on the graphics card and then control the local output by our fragment program. This is illustrated in the bottom right image of figure 4.1, where the two data sets *A* and *B* are merged locally into the same scene using a merge operator.

4.3 Framework Overview

To benefit from the flexible volume rendering pipeline, a powerful and intuitive framework is needed that allows the user to quickly change between different data sets and types of visualization techniques.

The framework basically consists of data objects, volume objects, a volume scene graph, and a renderer. First, the selected data fields are stored as data objects together with information such as



(a) (b)

Figure 4.2 (a) Volume shader scene graph. (b) Four different shader items and their connection areas. Single field areas are drawn as straight rectangles while multiple field areas are drawn as rounded rectangles.

data range and time information. Then, volume objects are created from the data sets and put in the volume scene graph. Each volume object is defined by a uniform 3D scalar field and stored as a separate 3D texture on the graphics card. In this process, the original data values are normalized and stored according to the internal texture format specified by the user. The framework supports 8-bit, 16-bit as well as 32-bit (floating point) precision.

A visualization scene graph is then created by connecting the volume objects to supported operators through a flexible graphical user interface (GUI). The scene graph is then automatically converted to a shader program which is used in the volume rendering pipeline.

4.4 Volume Shader Scene Graph

The scene graph consists of a set of nodes, called *shader items* or *scene graph items*, with input areas on the top and output areas on the bottom (see figure 4.2). The shader items are connected by connecting the input and output areas through drag and drop events.

To increase the user friendliness, the color and opacity (represented by the red, green, blue, and alpha, (r,g,b,a), components), which are the output of most of the shader items, are hidden from the user. This simplifies the GUI and makes it easier to switch between different visualization scenes. For single-value operators[1] such as the *diff* operator, which can be used to calculate the local difference between two selected data sets, the input values are transferred through the alpha

[1]While many of the shader items have the four (r,g,b,a) components as inputs, single-value operators only need a single component as input which is sent through to the shader item as the alpha component.

component. For consistency, the resulting output value is copied to all the (r,g,b,a) components. The same applies for the volume node which copies the sampled (scalar) data volume values, after texture lookup, in a similar way. The connection (input and output) areas of the shader items are currently of the two types *RGBA* and *Gradient*. They can either be defined as a single-field or a multi-field connection area. While single-field areas only support a single connection to any other shader item, multi-field areas can be connected to a multiple set of nodes. Single-field areas are drawn as straight rectangles whereas multi-field areas are drawn as rounded rectangles (see figure 4.2(b)).

The shader scene graph consist of a number of various shader items and is continuously extended to include new operators. Currently, the following shader items are supported:

- *Volume:* Returns data values from the associated data set after a 3D texture lookup.
- *LUT:* Performs a 1D transfer function lookup. A lookup table (LUT) can be used at any level in the scene graph. More details on transfer functions can be found in section 3.2 which covers color mapping. A graphical user interface of the transfer function editor is obtained by double-clicking on the shader item. More details on how to use the transfer function editor can be found in section 5.4.4.
- *Color Out:* This is the root node of the shader graph. It contains the final $(\mathbf{C}, A) = (RGB, A)$ values that are used in the volume rendering integral (eq. 4.1).
- *Compositing Operators:* The scene graph supports all the compositing operators defined by Porter and Duff [30] and the merge operator defined by Helgeland et. al. [17].
- *Color/Alpha:* Combines two fields by taking the RGB values from the first field and the opacity value from the second field.
- *Mask:* This operator combines two fields by multiplying the alpha value of the first chosen field with the alpha value of the second field, while taking the RGB value from the first field.
- *Diff:* Computes the difference between two fields.
- *AbsDiff:* Computes the absolute difference between two fields.
- *Gradient:* Computes the gradient using a second-order central difference scheme. The evaluated gradient is based on the total expression that is sent as input to the gradient operator.
- *NormalizeGrad:* Can be used to visualize the gradient field. It normalizes the local gradient and sends the vector component values through the RGB values. The alpha value is set to 1.
- *GradientCorr:* Evaluates the gradient similarity measure [33] of two selected fields.
- *Lighting:* Computes the Blinn-Phong [6] volume shading model.
- *Contours:* Computes contours from the the input field. This operator can be used to create silhouettes.

4.5 Shader Code Generation

Our shader composer evaluates the volume shader expression through a recursive traversal of the shader tree graph starting from the *Color Out* root node. First, all the volumes and LUTs are located. Once found, the corresponding data objects are located and converted to 3D and 1D textures, respectively. A shader program is then generated by replacing all of the shader nodes with corresponding GLSL shader language code. A new shader program is created every time the user makes changes to the scene graph. For instance, the shader graph depicted in figure 4.2(a) is converted to the following shader code.

```
/* Shader generated by VoluViz */

uniform sampler3D Volume1;
uniform sampler3D Volume2;
uniform sampler1D LUT1;
uniform sampler1D LUT2;
varying vec3 TexCoord0;

void main()
{
/* Res1 = Volume1 */
vec4 Res1 = texture3D(Volume1,TexCoord0.xyz).rgbr;

/* Res2 = LUT1(Res1) */
vec4 Res2;
Res2.rgb = texture1D(LUT1,Res1.r).rgb;
Res2.a = texture1D(LUT1,Res1.a).a;

/* Res3 = Volume2 */
vec4 Res3 = texture3D(Volume2,TexCoord0.xyz).rgbr;

/* Res4 = LUT2(Res3) */
vec4 Res4;
Res4.rgb = texture1D(LUT2,Res3.r).rgb;
Res4.a = texture1D(LUT2,Res3.a).a;

/* Res5 = Atop(Res2,Res4) */
vec4 Res5;
Res5.rgb = Res2.a * Res2.rgb + (1 - Res2.a) * Res4.rgb;
Res5.a = Res4.a;

gl_FragColor = Res5;
}
```

The most complex shader item is the gradient operator. Since the gradient can be evaluated at any level in the scene graph this implies that the entire expression prior to the gradient node has to be evaluated at six different sample positions (assuming a second order finite difference scheme is used). The beauty of the system is that any new field can be computed in the scene graph, mapped to a color and alpha value through a separate texture lookup, and then rendered correctly with a gradient based light model or a non-photorealistic rendering technique.

Figure 4.3 shows an example where data from a hurricane simulation [28] is rendered using a bit more advanced scene graph construction including the computation of gradients and the use of a gradient based light model.

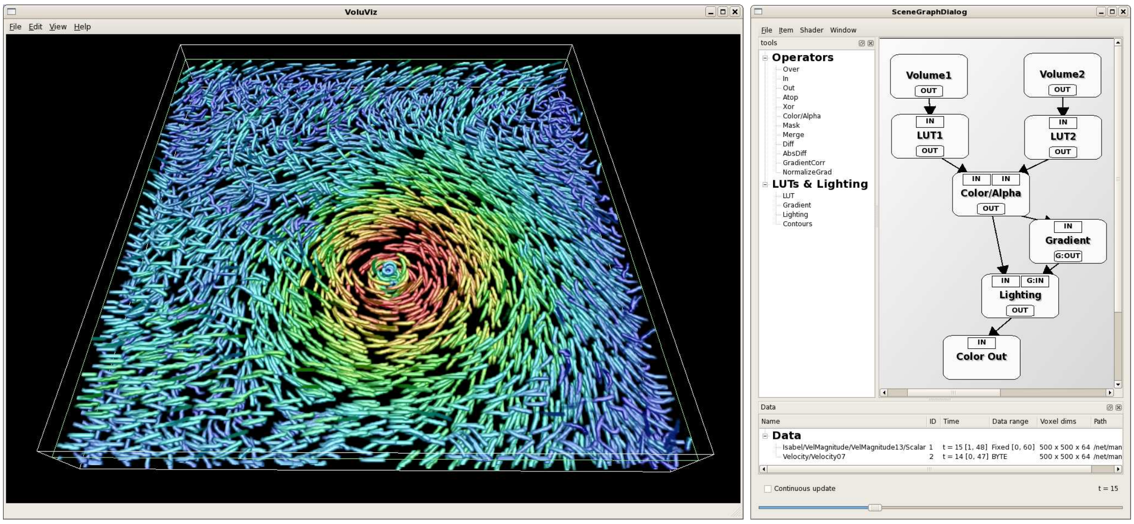


*Figure 4.3 Visualization of volumetric streamlines giving the local wind direction of the hurricane data. The streamlines (*volume2*) are color encoded by the velocity magnitude (*volume1*) using the* Color/Alpha *operator and rendered using a gradient-based light model.*

4.6 VoluViz Operators

4.6.1 Compositing Operators

One method for combining multiple data sets into a single field is by using the compositing operators presented by Porter and Duff [30]. Here, a composited color and opacity value of the two volumes A and B is obtained by the formulas

$$A = a_A F_A + a_B F_B, \tag{4.2}$$

$$C = \frac{c_A a_A F_A + c_B a_B F_B}{A}, \tag{4.3}$$

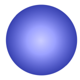
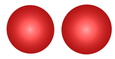
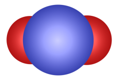
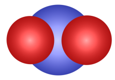
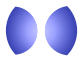
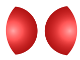
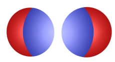
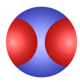
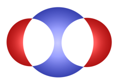
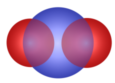
where c_i and a_i are the color and opacity values associated with the contributing volumes and F_i is a weight function. The following combination of weight functions defines the operators given in table 4.1. These operators are very useful for showing correlation between multiple data fields, such as finding overlapping regions of selected data sets. Different operators correspond to different visible regions using union and intersection operations on the opacity values.

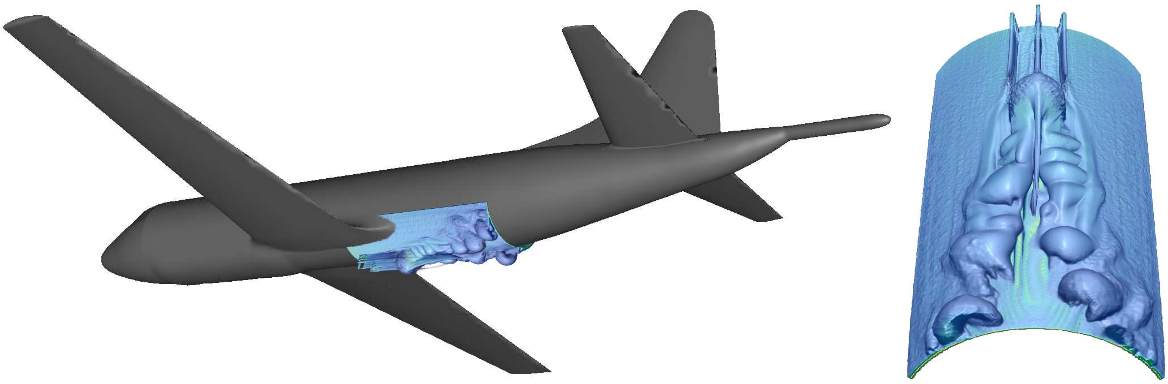
As an additional compositing operator we have also implemented the *merge* operator presented by Helgeland et. al. [17]. For some applications, the merge operator is preferable compared to, for instance, the over operator since this expression holds no precedence in any area covered by multiple data fields (see table 4.1). It also handles arbitrary number of input fields as opposed to the binary operators presented by Porter and Duff. The merge operator is given by the formulas

$$A = 1 - \prod_{i=1}^{n}(1 - a_i) \tag{4.4}$$

$$C = (\sum_{i=1}^{n} c_i a_i) / \sum_{i=1}^{n} a_i. \tag{4.5}$$

Table 4.1 Compositing operators. The alpha (or opacity) values are set to be completely opaque ($a_i = 1$) for both the visible (blue and red) regions defined by the data sets A and B in all the examples.

Operations	F_A	F_A	Result
A	1	0	
B	0	1	
A over B	1	$1 - a_A$	
B over A	$1 - a_B$	1	
A in B	a_B	0	
B in A	0	a_A	
A out B	$1 - a_B$	0	
B out A	0	$1 - a_A$	
A atop B	a_B	$1 - a_A$	
B atop A	$1 - a_B$	a_A	
A xor B	$1 - a_B$	$1 - a_A$	
A merge B	eq. (4.4),(4.5)	eq. (4.4),(4.5)	



(a) (b)

Figure 4.4 (a) Visualization of vortices generated in the wake of a radome mounted on the P3-C aircraft. (b) A zoomed in rendering of the vortices.

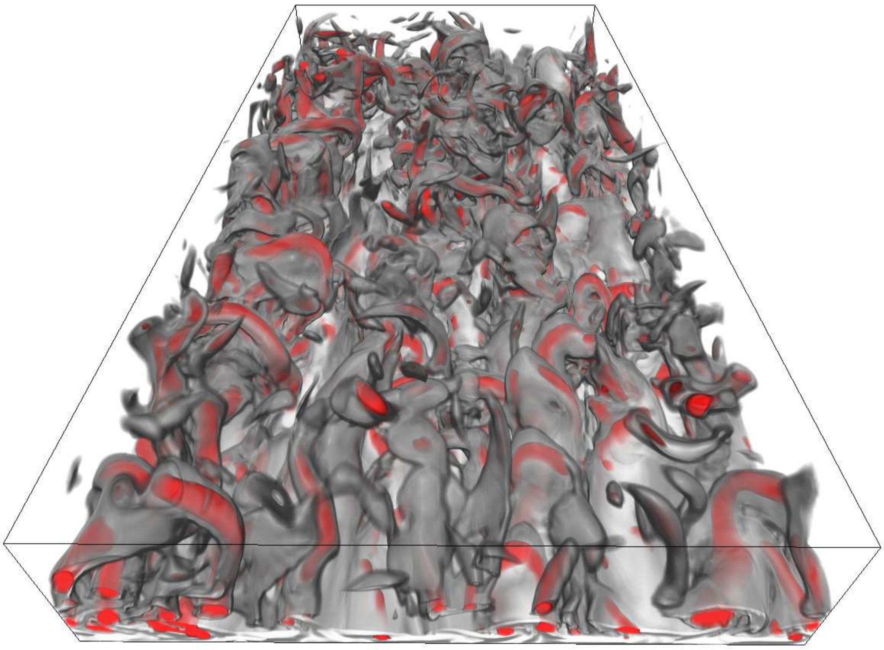
Figure 4.5 gives an example where we demonstrate the usefulness of the compositing operators by showing relationships between three different vortex identification measures used on a channel flow simulation data set [13]. In fluid dynamics research, the study of vortices is important for understanding the underlying physics; vortices are often viewed as "the sinews and muscles of turbulence" [20]. In engineering applications, vortices can either be desirable or undesirable and attempts to promote or to prevent the occurrence of vortices are used for optimizing and modifying design. Figure 4.4 shows an example of undesirable vortex formations created in the wake of a radome mounted on the P-3C aircraft [5]. The turbulent wake impacts the aft part of the aircraft and may trigger vibrations in the aircraft.

Many vortex-detection methods have been proposed in the literature. Among the most popular and successful identifiers are the three criteria

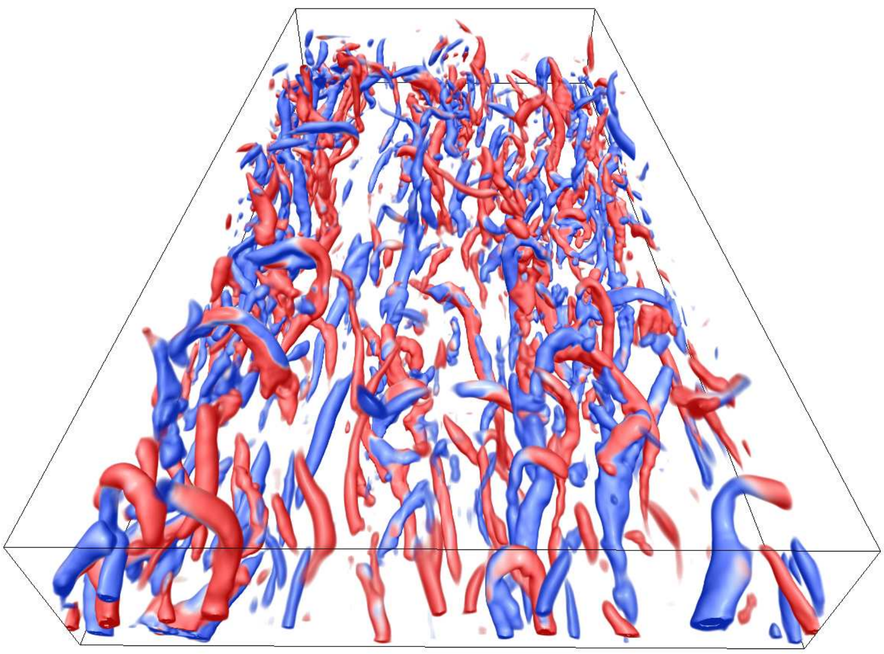
- *helicity* ($\mathbf{v} \cdot \boldsymbol{\omega}$),
- *enstrophy* ($\|\boldsymbol{\omega}\|^2$), and
- λ_2 [19],

where $\mathbf{v}$ and $\boldsymbol{\omega}$ are the velocity and vorticity vectors, respectively.

In Figure 4.5(a), the relation between the λ_2 and the enstrophy field is revealed using the *atop* operator. The operation (λ_2 **atop** enstrophy) gives a rendering where the visible region (given by the opacity) is defined by the enstrophy field while the color is determined by both fields but with an emphasis on the λ_2 field. Setting the alpha values of the λ_2 structures equal to one results in a rendering where regions occupied by the intersection of the two fields are colored by the λ_2 field while the remaining region of the enstrophy structures is colored by the enstrophy field. Hence, we are able to see the spatial relation between the two fields. Regions of high vorticity magnitude result both in vortex cores and vorticity sheets. By using the atop operator we are thus able to distinguish between the vortex cores (red) from the vorticity sheets (gray/white) as can be seen in figure 4.5(a).



(a) λ_2 **atop** enstrophy



(b) Helicity **in** λ_2

*Figure 4.5 Visualization of relationships between three different vortex identification measures using compositing operators. (a) The operation λ_2 **atop** enstrophy is used to distinguish the vortex cores (red) from the vorticity sheets (gray/white). (b) Individual vortices defined by the λ_2 criterion are colored by the helicity using the* in *operator. Red and blue colored vortices indicate clockwise and counter clockwise rotation, respectively.*

Figure 4.5(b) gives another example where the *in* operator is used to convey information about the spatial correlation between helicity and vortices defined by the λ_2 criterion. Here, the visible region is defined by the λ_2 field while the color is determined by the helicity field. There is a strong correlation between helicity and coherent structures in a turbulent flow field, and this quantity has previously been used to extract vortex core lines [23]. The assumption is that that near vortex core regions, the angle between $\mathbf{v}$ and $\boldsymbol{\omega}$ is small, which means that local extreme values of helicity can be used as indicators of vortex cores. The sign of the helicity value indicates the direction of the rotation (or swirl) with respect to the streamwise velocity component. Positive values give clockwise rotation while negative values give counter clockwise rotation. In figure 4.5(b) individual vortices defined by the λ_2 criterion are colored by the helicity. Red and blue vortices indicate clockwise and counter clockwise rotation, respectively.

4.6.2 Feature Enhancement Operators

Even though the *emission-absorption* model [26] and the resulting volume rendering integral (equation (4.1)) does not take external light sources into account, shading of volumes can still be achieved. Volume shading can increase realism and understanding of volume data. Most volume shading is computed using the Phong [29] or Blinn-Phong [6] illumination models. The resulting color is a function of the gradient, light, and view direction, as well as the ambient, diffuse, and specular shading parameters.

Traditional local illumination models is based upon a normal vector which describes the orientation of a surface patch. In volume rendering no explicit surfaces exist. So instead, the model is adapted assuming light is reflected at isosurfaces inside the volume data. For a given point $\mathbf{p}$ an isosurface is given as:

$$I(\mathbf{p}) = \{\mathbf{x} | f(x) = f(p)\}$$

with normal, $\mathbf{n}$, defined as

$$\mathbf{n}(\mathbf{p}) = \frac{\nabla f(\mathbf{p})}{\|\nabla f(\mathbf{p})\|}, \quad \nabla f(\mathbf{x}) = \left(\frac{\partial f(\mathbf{x})}{\partial x}, \frac{\partial f(\mathbf{x})}{\partial y}, \frac{\partial f(\mathbf{x})}{\partial z}\right).$$

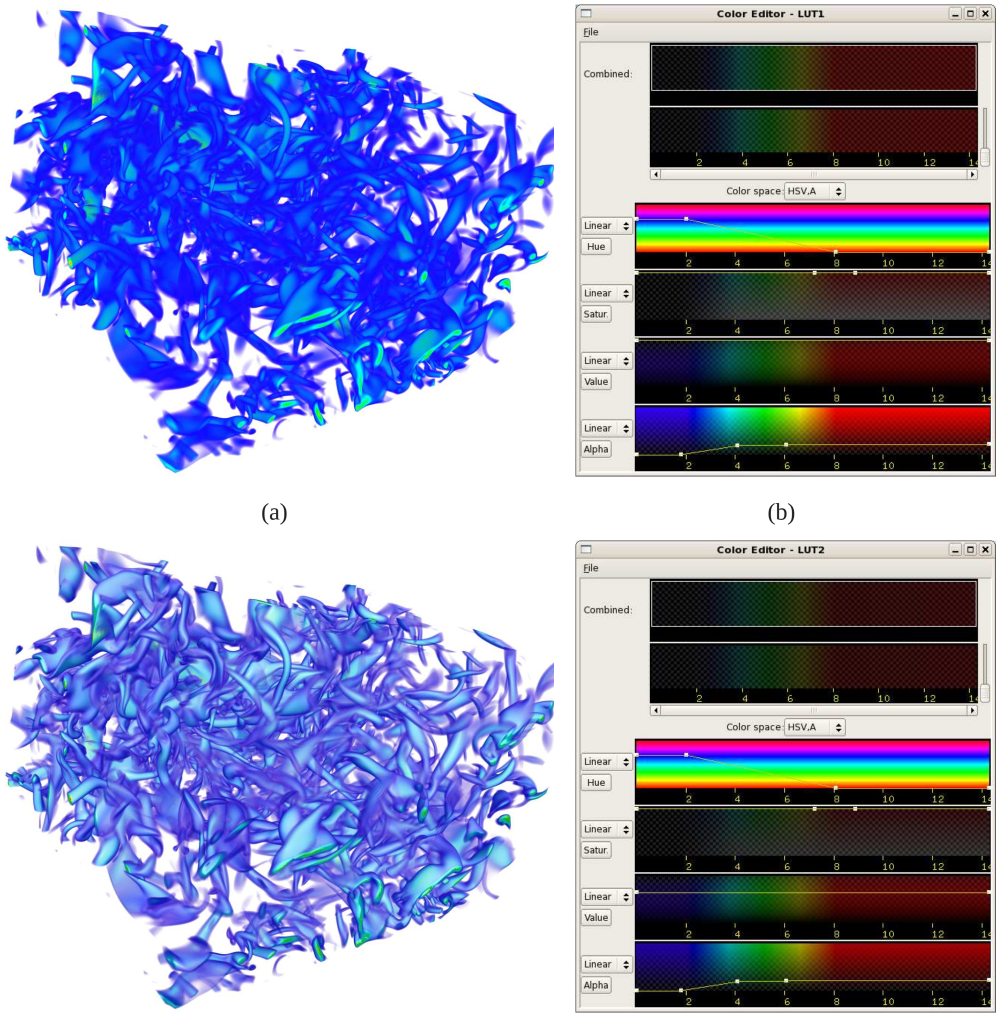
A local illumination model can thus be incorporated into the emission-absorption model by using the gradient, $\nabla f(\mathbf{p})$, as the normal vector. The volume shading is typically added to the emissive color contribution in the emission-absorption model resulting in an alternative color contribution, $\boldsymbol{C}_{\text{volume}}$, substituting the pure emissive term in the volume rendering integral (eq. 4.1) by

$$\boldsymbol{C}_{\text{volume}} = \boldsymbol{C}_{\text{emission}} + \mathbf{C}_{\text{illumination}}, \quad (\mathbf{C}_{\text{illumination}} = \mathbf{I}_{\text{Phong}} | \mathbf{I}_{\text{BlinnPhong}}). \tag{4.6}$$

The Blinn-Phong model can, for instance, be expressed as

$$\begin{aligned} \mathbf{I}_{\text{BlinnPhong}} &= \mathbf{I}_{\text{ambient}} + \mathbf{I}_{\text{diffuse}} + \mathbf{I}_{\text{specular}}, \\ &= k_a + k_d(\mathbf{l} \cdot \mathbf{n}) + k_s(\mathbf{h} \cdot \mathbf{n})^s, \end{aligned} \tag{4.7}$$

where $\mathbf{l}$ is the light direction vector, $\mathbf{h}$ is the half vector which is halfway between the viewing vector and the light direction, s is the specular power and k_a, k_d and k_s are the ambient, diffuse and specular coefficients.



(a) (b) (c) (d)

Figure 4.6 (a) Traditional direct volume rendering without any feature enhancements with associated transfer function (b). (c) Gradient-based volume shading (Blinn-Phong model) with associated transfer function.

Figure 4.6 demonstrates the effect of applying gradient-based volume illumination to a selection of vortices from a simulation of stratified turbulent shear layer [43]. The figure shows the rendering result both with and without a local illumination model, in addition to the transfer function used for the two cases.

It is important to note that the transfer function gives the mapping to the emissive term in equation (4.6) only and that the contribution from the illumination model is added to the emissive term to produce the final local color. As a result, more "white" light is added to the scene when applying volume illumination compared to traditional volume rendering (when using the same transfer function for the emissive color). When designing transfer functions well suited for volume illumination, a piece of advice is thus to use lower values for the *Value* component in the HSV color system (see section 3.2) than what would be ideal for traditional volume rendering without a local illumi-

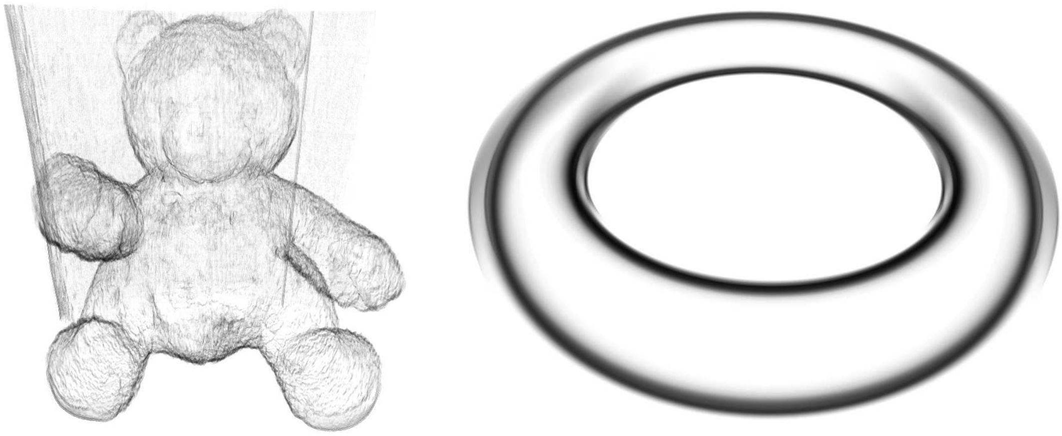


Figure 4.7 Visualization of contours in a volumetric teddy bear and torus data set.

nation model. This is illustrated in figure 4.6. Here, a constant *Value*, $V = 0.65$, is used for the transfer function associated with the local illumination model, whereas $V = 1$ is used for the pure emission-absorption model.

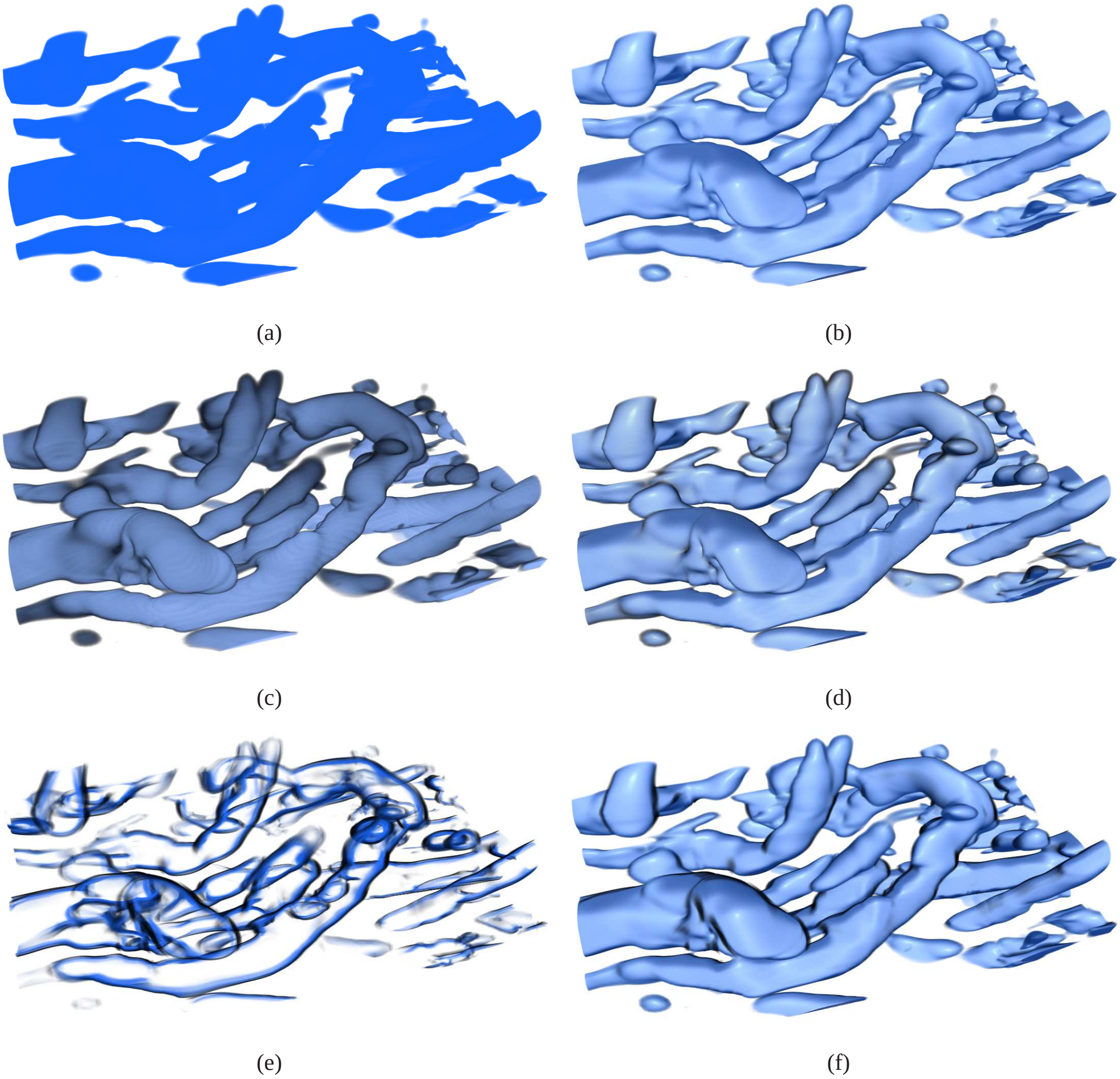
Another way of enhancing volume data features is by using Non-Photorealistic Volume Rendering (NPVR) techniques. The overall goal of NPVR is to go beyond the means of photorealistic volume rendering and produce images that emphasize important features in the data, such as edges, boundaries, depth, and detail, to provide the user with a better appreciation of the three-dimensional structures in the data. NPVR techniques are able to produce artistic and illustrative effects, such as feature halos, tone shading, depth enhancements, boundary enhancements, fading, silhouettes, sketch lines, stipple patterns, and pen-ink drawings [18, 40, 31, 36, 25, 16]. For volumetric data, silhouettes or contours can, for instance, be obtained by computing a contour intensity field, I_{contours}, evaluated by the following equation

$$I_{\text{contours}} = g(\|\nabla f\|)(1 - \|(\mathbf{v} \cdot \mathbf{n}\|)^n. \tag{4.8}$$

In our implementation of the *contours* operator, the derived intensity field, I_{contours} defines the opacity while the colors is sent as input parameters to the operator. Figure 4.7 shows an example where equation (4.8) has been used to create volumetric contours of two data sets using $g(\|\nabla f\|) = \|\nabla f\|$ and $n = 8$.

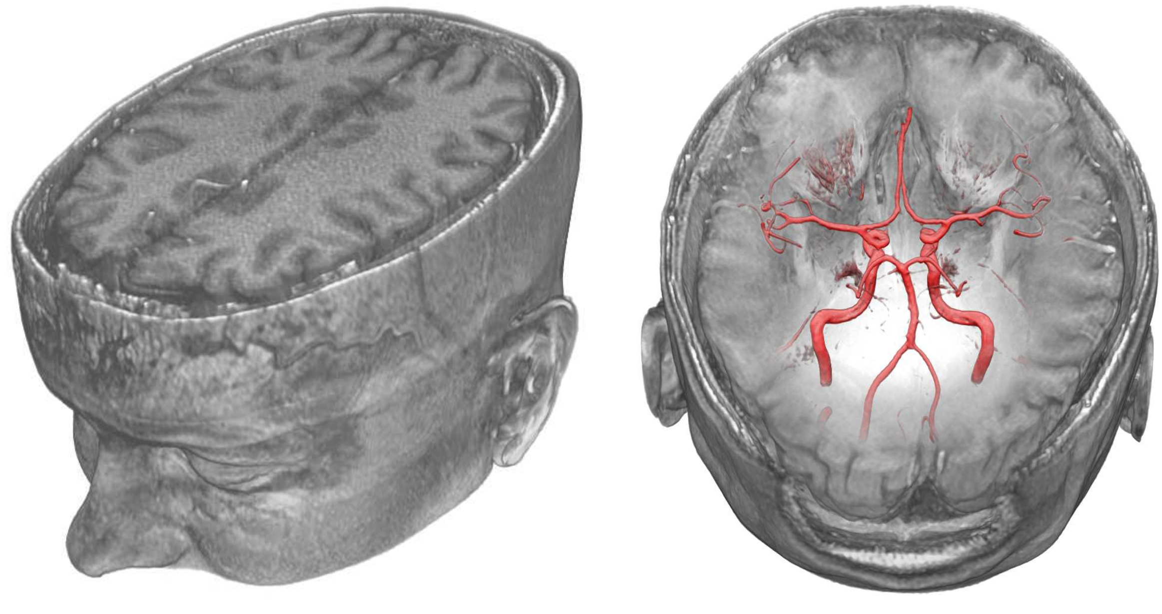
Figure 4.8 illustrates different feature enhancement techniques used on a selection of vortices from a channel flow [13]. The images clearly reveal how volume shading and non-photorealistic rendering techniques can add detail, enhance spatial structures and give the necessary 3D appearance of the volume data.

The above example also demonstrates the flexibility of the presented visualization framework. As volume shading and NPVR techniques, in addition to compositing operators and transfer functions, can be assigned individually to all of the volume data objects, this provides a detailed control of the final rendering appearance, enabling a numerous variety of visualizations such as the ones depicted



(a) (b) (c) (d) (e) (f)

Figure 4.8 *Feature enhancement techniques used on a selection of vortices. (a) direct use of the volume integral given in equation (4.1) without any feature enhancements. (b) Gradient-based volume shading (Blinn-Phong model). (c) Feature enhancement using limb darkening [16]. (d) Volume shading in combination with limb darkening. (e) Silhouette rendering using the gradient-based contour operator. (f) Volume shading in combination with silhouettes.*



(a) (b)

Figure 4.9 (a) Regular volume rendering of an MRI data set [41] of a human brain. (b) Volume rendering (of the same data) in combination with compositing operators and feature enhancement techniques used with the purpose to reveal (and emphasize) arteries in the human brain.

in figure 4.9. Here, a single MRI data set of a human head [41] is visualized with different rendering techniques resulting in two quite different visualizations. One of the visualizations is rendered with regular volume rendering (figure 4.9(a)) while the other one is visualized using a combination of compositing and feature enhancement operators (fig 4.9(b)). The latter visualization is generated with the purpose of emphasizing the major bloodvessels inside the human brain revealing a ring of arteries located at the base of the brain known as the *Circle of Willis*.

Figure 4.10 shows another example where non-photorealistic rendering techniques have been used to visualize data from a hurricane simulation [28]. Here, areas with the greatest wind speed have been rendered in grey colors using volume shading (revealing the 3D structure of the hurricane) while areas with the lowest wind speed have been rendered in white to red colors using volumetric contouring (revealing the eye of the hurricane).

In both the two latter examples (figure 4.9 and figure 4.10) variations of a branch of techniques known as *focus+context* visualization has been used. In focus+context visualizations, some objects or parts of the data are shown in detail, while other objects or parts act as a context. While the data ”in focus” often are displayed rather opaque (to emphasize these regions), the rest of the data can be shown rather transparent.

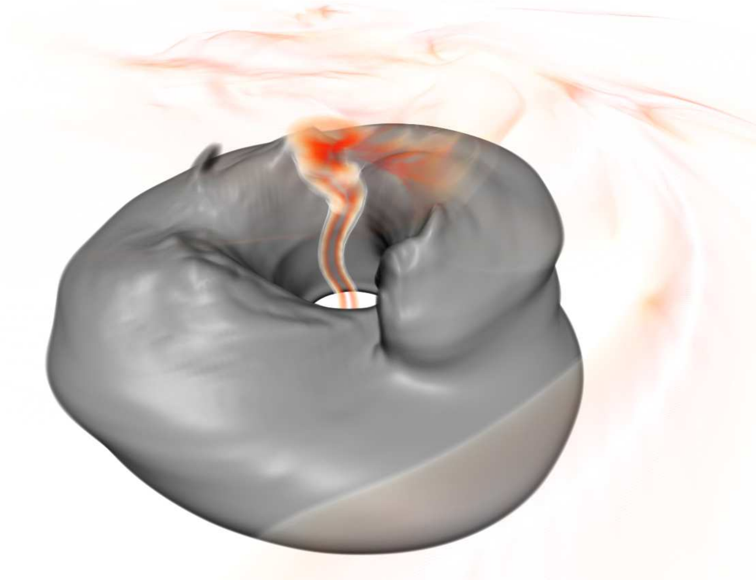


Figure 4.10 Hurricane data visualized using two different rendering techniques. Areas with the greatest wind speed are rendered densely, in gray, (with high opacity) using volume shading to enhance the 3D structure of the hurricane. Areas with the lowest wind speed are visualized in a more semitransparent way (using lower opacities) in combination with silhouette rendering, in white to red colors, to reveal the eye of the hurricane.

4.6.3 Numerical Operators

In addition to the compositing and feature enhancement operators, numerical operators acting directly on the volume data can also be incorporated in the proposed visualization framework. Two operators that we have found particularly useful are the operators *Diff* and *AbsDiff* given as

$$\text{Diff}(A,B) = A - B, \quad \text{Diff} \in [-1,1],$$

$$\text{AbsDiff}(A,B) = \|A - B\|, \quad \text{AbsDiff} \in [0,1].$$

These can be used to estimate the local difference between two data fields. The difference operators can be used for a variety of applications. It can for instance be used for debugging of numerical code, but also for finding the effect of adjustments made to a simulation. These can range from minor adjustments such as the change of simulation parameters to larger adjustments including the change of boundary conditions and choice of model, to major adjustments such as adding or removing terms in the mathematical equation describing the problem. In addition, it can be used to visualize the change occurring between different time steps of a simulation such as calculating time derivatives. Time derivatives can be obtained by calculating finite differences, which can be computed using the diff operator on two copies of a chosen data field with a time difference equal to one. Then, a first order backward or forward difference can be obtained depending on the setup.

Figure 4.11 gives an example where the *AbsDiff* operator has been used to examine the convergence of statistical steady turbulence in a chamber simulation [11]. The visualization shows regions where

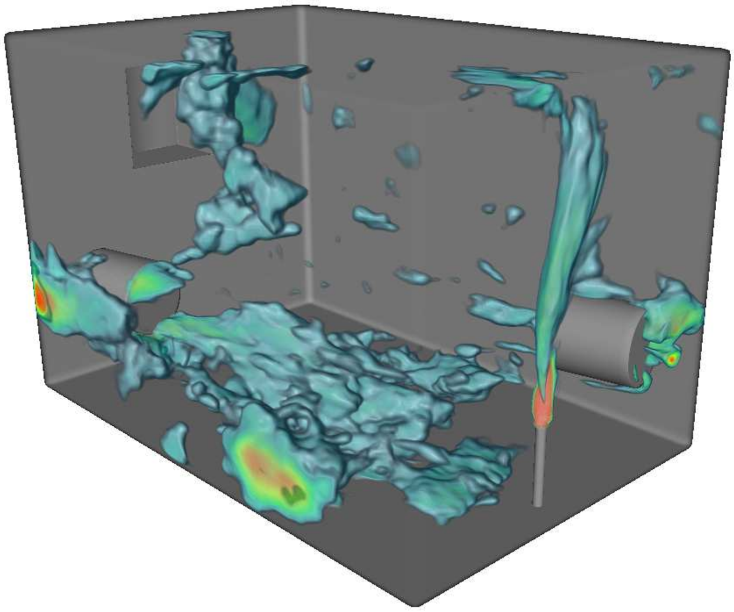


Figure 4.11 Visualization of statistically non-converged regions of a turbulent chamber flow simulation.

the statistics of the flow has not yet reached a fully converged state. This is done by computing the root-mean-square (RMS) of the velocity for two different time steps for a given time interval. For statistically converged regions the RMS value should not change, which means that we can visualize numerically non-converged regions inside the computational box by applying the diff operator on the two RMS fields and then render all areas that are not close to zero. Figure 4.11 shows the result after a transfer function lookup table (LUT) has been connected to the output from the diff operator in addition to a gradient-based volume shader operator.

Figure 4.12 provides another example where where the *diff* operator is used to compare two channel flow simulations [13] using different boundary conditions. While the first data set is obtained using no-slip boundary conditions, the second channel flow simulation is generated by first splitting the channel in the middle and then using a slip boundary condition at one of the surfaces. Data derived from the second simulation is then compared to data from half of the channel from the first simulation. The data is compared by visualizing regions of difference only. Similar to the previous example (see figure 4.11), regions of difference are enhanced using gradient based volume shading. Volume shading has, in both cases, been used in combination with *limb darkening* [16] to highlight the boundaries of the visualized regions.

4.7 4D Data Analysis

4.7.1 Animation

Once the desired data is selected and an appropriate visualization scene is created, our visualization framework handles two types of navigations through the time-varying data set. The data set can be explored by either dragging a time slider or by using the animation utility. The time slider is

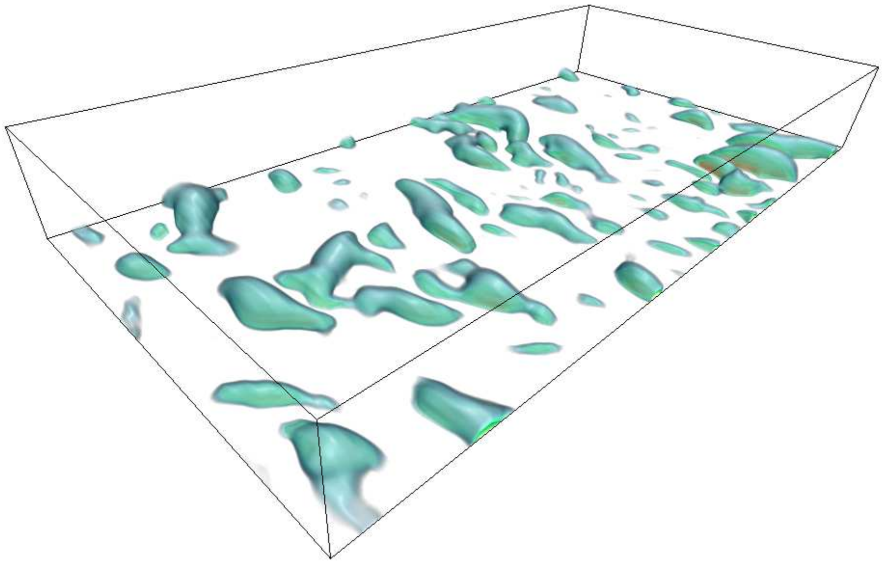


Figure 4.12 Comparison of two channel flow simulations with different boundary conditions by visualizing the local difference between the two solutions.

very useful for investigating the data at different time steps. Once a new time step is selected, the visualization scene graph is automatically updated accordingly. The time slider feature also simplifies the process of finding transfer functions that are well-suited for the whole time-series. Finding good transfer functions is often a tedious process that sometimes involves clipping of data value ranges. To facilitate this process we have implemented a histogram renderer that also updates according to the time slider. The user can select between continuous update or updates that occur only when the time slider is released.

The animation utility, on the other hand, allows a pre-defined and a more controlled animation of the time-dependent data. Here, the user can select the time interval, the order of the data sets to be loaded, the step size, as well as pre-generated user interactions such as rotation and zooming.

4.7.2 Time-Varying Multi-Field Volume Visualization

The most common method to investigate the time-dependent behavior of a data set is through animation. Even though animations can be sufficient, for a number of applications, it can be difficult to analyze spatio-temporal relationships using this technique. This is due to the loss of positional information when moving between individual time steps. To facilitate a more complete spatio-temporal investigation of the multi-variate and time-varying data, VoluViz is designed using a novel 4D data analysis framework. Instead of just relying on animation utilities, VoluViz also support the projection of a multiple set of data fields (both temporal and spatial) in the same scene. This extended 4D analysis functionality is incorporated into the already presented shader scene graph (section 4.4) in the following way. Multiple copies of selected data fields from the time-varying data sets can be generated by the user. Each of these n copies have assigned a local time difference which is added

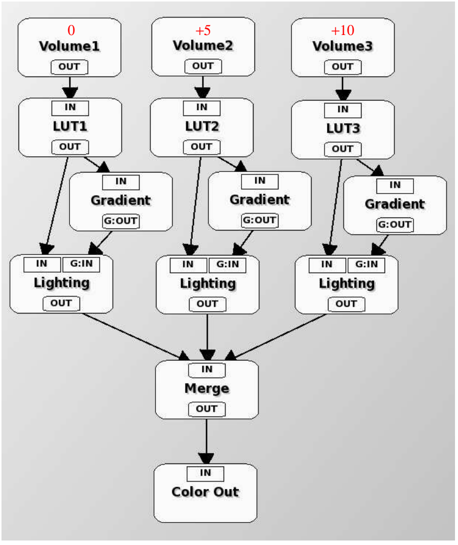


Figure 4.13 An example of a volume scene graph used to visualize data from three different time steps in the same scene.

to the global time to produce the local time of each copy

$$(\text{time})_i = \text{global time} + (\text{time difference})_i, \quad i = 1...n. \tag{4.9}$$

When data copies are used to generate volume objects in the volume scene graph, the local time of each volume is used when accessing the data. Hence, the volume scene graph can consist of multiple data fields from different time steps. This allows the computation of time-varying quantities such as time derivatives (provided that the time difference is sufficiently small) and high-dimensional projection volumes. When the global time is changed, all of the data volumes in the scene graph are adjusted accordingly. For example, if the scene graph is constructed to visualize the spatio-temporal relationship of a time-evolving volume structure by visualizing the structure at three different time steps ($t_1 = 0, t_2 = 5, t_3 = 10$) for $t = 0$ together in the same scene, an animation of the scene will preserve the time difference between the volumes for all scenes (as long as the local time steps are inside the global time interval). Hence, we get a 4D visualization which both exhibit time-evolution as well as the depiction of spatio-temporal relationships at each time step of the animation. Figure 4.13 gives an example of how such a scene graph can be constructed.

Figure 4.14 gives an example where the 4D data analysis framework of VoluViz has been used to depict the spatio-temporal evolution of the breakdown of a single vortex ring. Here, the vortex structure is rendered in the same scene (using the *merge* operator) at six different time steps using a constant time step size between the time-varying data. To distinguish between the individual time steps, the vortex structure is visualized using six different colors starting from red color (giving the earliest time step) to a purple depiction of the vortex structure (showing the latest time step in the time-evolution). The visualization clearly depicts how the ring structure both moves and deforms in space as time evolves. For instance, one is able to see how the ring first increases in size, then starts to tilt forward before it begins to break down.

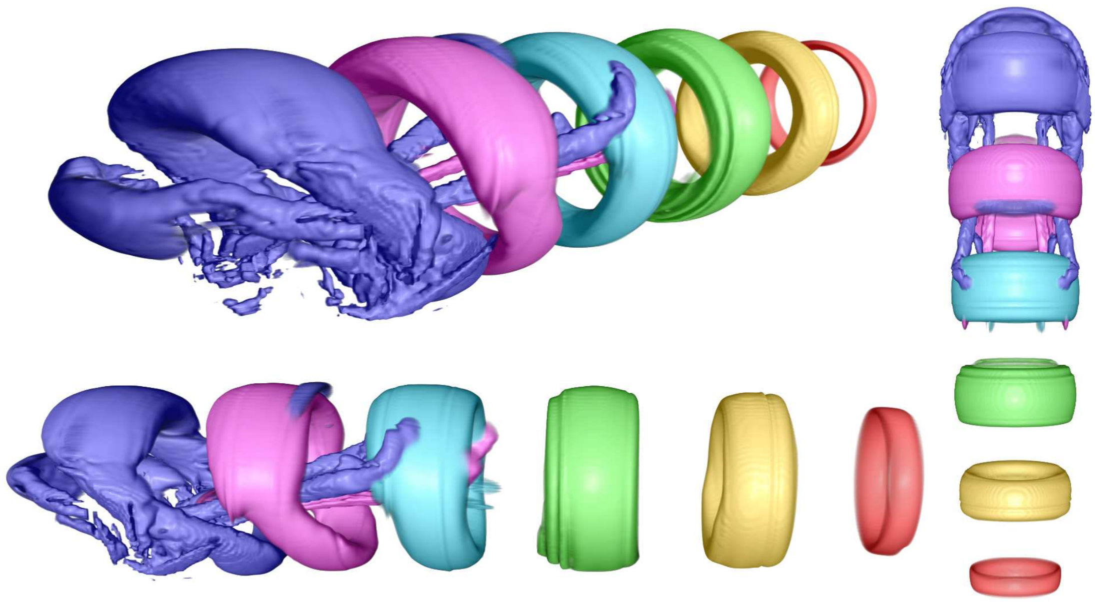


Figure 4.14 Temporal-spatial visualization of a breakdown of a single vortex ring by simultaneously rendering the data from six different time samples in the same scene (represented by six different colors).

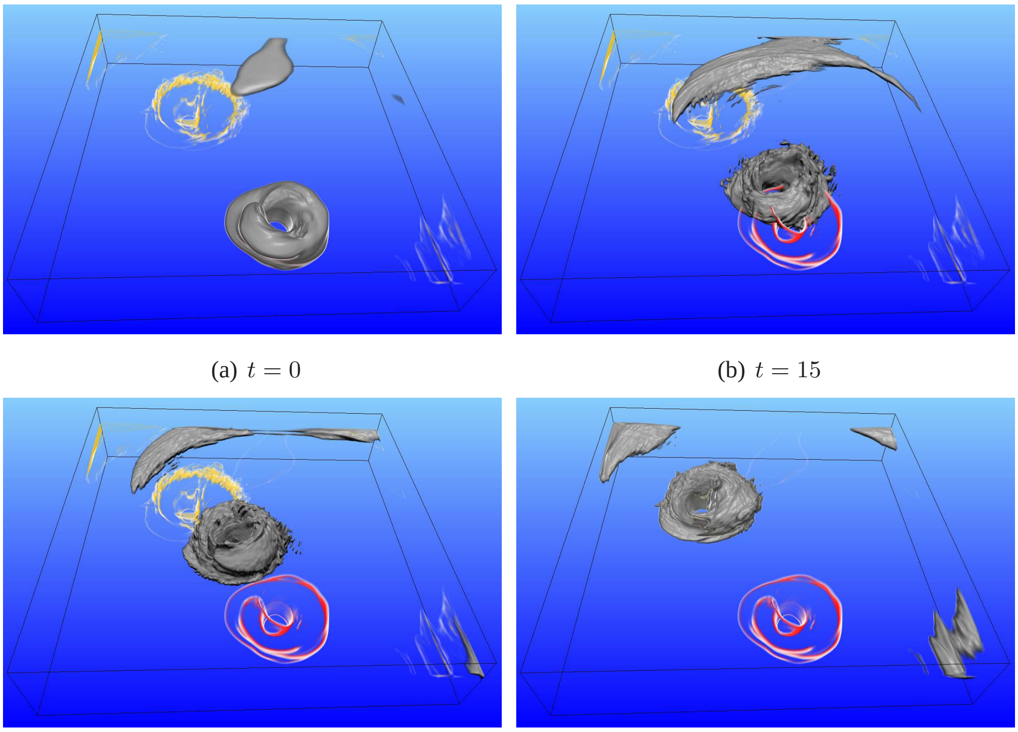
Another example showing the usefulness of the 4D analysis framework is the one presented in the second paragraph of section 4.6.3 and in figure 4.11. Here, two different time steps of a derived statistical quantity is compared to reveal all statistically non-converged regions of a turbulent chamber flow simulation.

In addition to the local time difference functionality, each individual data object can also be 'frozen' in time. This functionality can for instance be used for visualizing the time-evolution of volume structures starting from a fixed time, with the initial structure kept in the scene for all time steps. With two fixed time steps ($t_1 = A$ and $t_2 = B$), an animation could show how the structure evolves from time step A to time step B, with both fixed structures kept in the scene for all frames. This is illustrated in figure 4.15. Here, a silhouette rendering of the hurricane [28] is rendered at two fixed time steps for all frames to provide contextual information, thus increasing the depiction of temporal-spatial relationships in the data.

4.8 Interactive Analysis

To facilitate interactive analysis of a three-dimensional time-dependent data set, the rendering framework of VoluViz supports an additional set of tools. In addition to manipulating the volume scene graph and individual transfer functions, the system supports clip planes manipulation, data-subset selections, and other user functions, at interactive rates. These are all tools that can be used to diminish the occlusion effects by for instant reducing the complexity of the scene by focusing on a region of interest.

In addition, a data caching system is implemented allowing whole time series of selected data sets



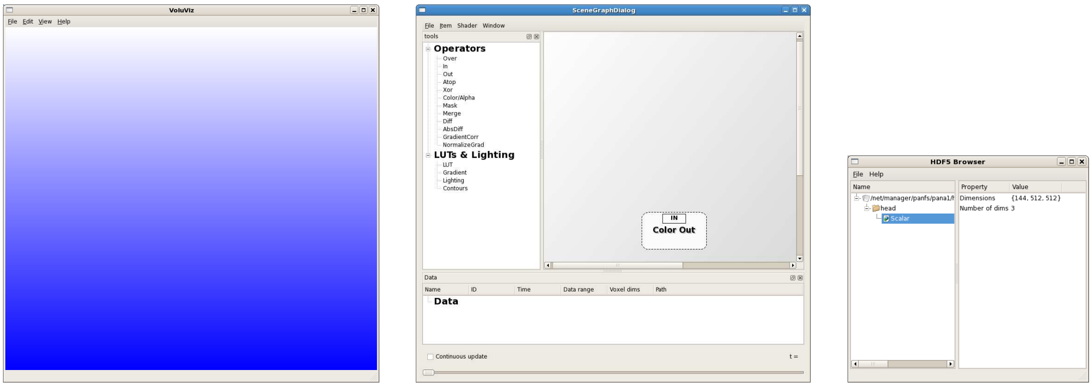
(a) $t = 0$ (b) $t = 15$ (c) $t = 30$ (d) $t = 45$

Figure 4.15 Snapshots from an animation of a hurricane data set where silhouettes of the hurricane at two fixed time steps are rendered in all frames.

to be cached in the CPU memory, assuming there is enough memory available to fit the entire data set. As the transfer of data from the hard-drive to CPU-memory tends to be the main bottle-neck for the animation system, this helps speeding up animations. This caching mechanism is, for instance, very useful when studying the spatial-temporal evolution of non-steady flow phenomena.

To support large-scale data analysis, the texture based volume slicing technique has been implemented using a brick-based volume renderer. A maximum 3D texture size, with the upper limit being what is supported by the used graphics card, is specified by the user. This value defines the largest possible 3D brick size that can be used by the rendering system. Then, dependent on the exact size of the data set, the largest volume used in the volume scene graph is split into a number of bricks which are sorted and rendered in a back-to-front order. To support a wide selection of graphics cards, the bricking algorithm splits the volume into a number of power-of-two textures[2]. If multiple data fields of different sizes are visualized in the the same scene, all volumes are split according to the brick configuration defined by the largest volume. When data-subset selections are made, this could change the brick constellation and result in a configuration requiring less amount of texture memory.

[2]Some older graphics cards only support power-of-two textures.



(a) (b) (c)

Figure 5.1 (a) Render window. (b) Volume Scene Graph window. (c) HDF5 File browser.

5 VoluViz User Manual: Part 1 - Rendering Volumes

5.1 Introduction

VoluViz is an application designed for interactive analysis of both time-dependent and static volume data. VoluViz has many features including:

- Fully interactive color table editor for specifying transfer functions
- Support for interactive visualization of time-varying fields
- Support for interactive multi-field visualization through a flexible scene graph editor
- Interactive clip plane and picking of subset utilities for easy navigation of the data

Currently, VoluViz is restricted to handle data defined on a regular three-dimensional structured grid. It reads files in the HDF5 [1] format and includes a browser for easy navigation of HDF5 files.

5.2 Starting a VoluViz Session

To start a VoluViz session do one of the following approaches:

- start a new voluviz session

```
% voluviz &
```

- start with a particular data set as input parameter

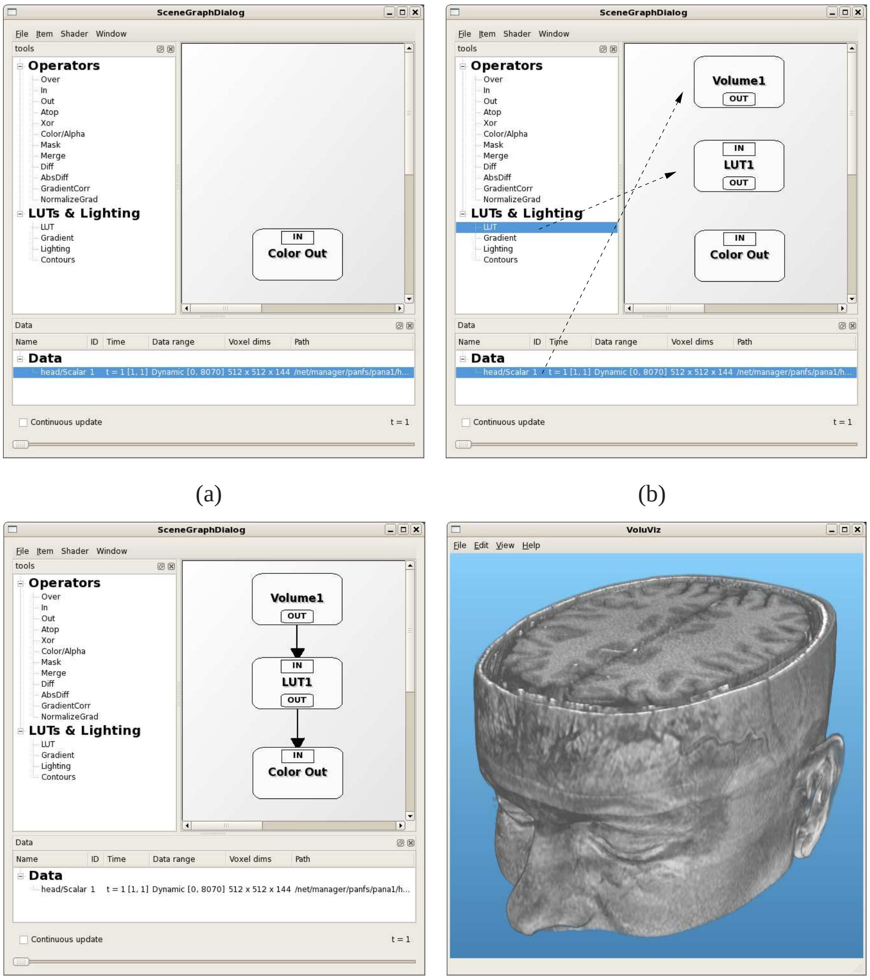
```
% voluviz data.h5 &
```

- start voluviz with an already saved scene

```
% voluviz scene.vv &
```

As default, VoluViz starts with two windows activated, namely the *Render window* (figure 5.1(a)), which is VoluViz main window, and the *Scene Graph window* (figure 5.1(b)).

When a data file is opened the user can pick data sets by double clicking on a chosen data set in the *HDF5 browser window* (figure 5.1(c)). Once a data set is double clicked, the data set can be found



(a) (b) (c) (d)

Figure 5.2 (a)-(c) Illustration of necessary steps needed to make a visualization scene graph in VoluViz. (d) Rendering result.

in the *Data list* in the *Scene Graph window* (figure 5.2(a)). Individual data sets and operators can be put into the scene graph through drag and drop events. Figure 5.2(b) shows an example where a single data set and a transfer function is put into the scene graph window. Finally, a scene (tree) graph can be constructed by connecting the scene graph items with arrows (also using drag and drop events) as depicted in figure 5.2(c). Once the scene graph item called *Color Out*, which is the root of the scene graph, is connected to the tree graph, the output is rendered in the render window (figure 5.2(d)). More details on the scene graph and supported operators with examples can be found in the sections 4.4-4.6.

5.3 Render Window

VoluViz main window (figure 5.1(a)) consists of a render area in addition to a menu system, from which commands and functionalities can be accessed from.

5.3.1 Using the Mouse

- To *rotate* the volume, press and hold the left mouse button while moving the mouse.
- To *move* the volume, press and hold the middle mouse button while moving the mouse.
- To *zoom* in and out, press and hold the right mouse button while moving the mouse backwards and forwards.
- The view can be aligned with the x, y and z axis by pressing *X*, *Y* and *Z* respectively. Pressing one of these combinations twice in a row flips the view 180 degrees.

5.3.2 Light source

The light source can be activated by pressing and holding the *Ctrl* button. This displays an icon of the light source giving its location and direction. To rotate the light source press *Ctrl* and hold the left mouse button while moving the mouse. The light source is used when volume data is rendered using volume shading and gives the light direction vector used in the local illumination model (see section 4.6.2). Figure 5.3 shows the result from using three different light directions when rendering a vortex ring structure. The default light direction is set to be parallel to the view direction which gives the rendering displayed in 5.3(b). The light source is also used when rendering geometries (see section 6.4).

(a) (b) (c)

Figure 5.3 Rendering of a volumetric ring structure using three different light directions. (a) Light source from the left. (b) Light source direction parallel to the view direction. (c) Light source from the right.

5.3.3 File Menu

New clears VoluViz for a new session.

Load volume starts the HDF5 browser (see figure 5.1(c)) which can be used to find and open volume data sets. (Hotkey: *Ctrl+V*)

Load mesh loads a VoluViz mesh file (see section 6.2). (Hotkey: *Ctrl+M*)

Snapshot takes a snapshot of the rendering area of the render window and saves it as one of the supported image formats.

Save scene saves the VoluViz session to file. The file, which is written as a text file, can be opened and modified by the user in any text editor.

Load scene loads a VoluViz session.

Quit quits the VoluViz application. (Hotkey: *Ctrl+Q*)

5.3.4 Edit Menu

Background sets the background color. This can be:

- a single color.
- a vertical gradient between two colors.
- a gradient between four colors defined at the corners of the screen.

The colors are chosen by entering a string of color names (e.g. “black white”) or by its HEX value. See the Qt documentation [2] for the **QColor** class under `setNamedColor()` for a list of valid colors. In addition, VoluViz also allows the use of any valid X11 color names. A full list of valid X11 color names can be found on the web [3].

Bounding Box sets the color of the axis aligned bounding box surrounding the volume data.

Clip Plane sets the color of the clip plane.

Physical Coordinates sets the physical coordinates of the volume data domain. The default physical data domain is $D = ([-1, 1], [-1, 1], [-1, 1])$, given in the x, y and z directions, respectively.

Subset opens the subset dialog box which can be used to pick a subset of the volume domain to be rendered (see figure 5.4). (Hotkey: *Ctrl+S*)

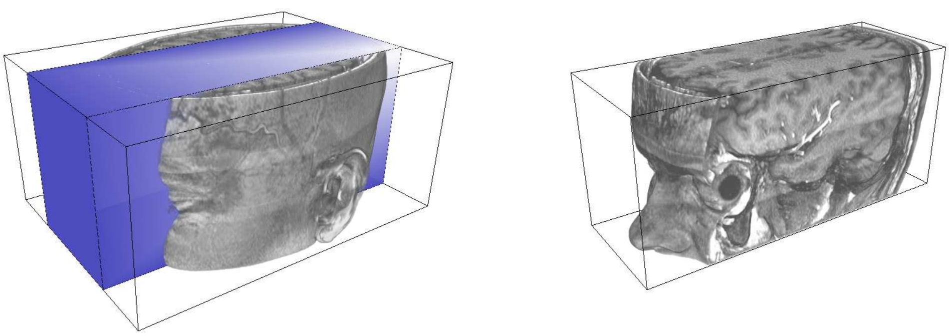
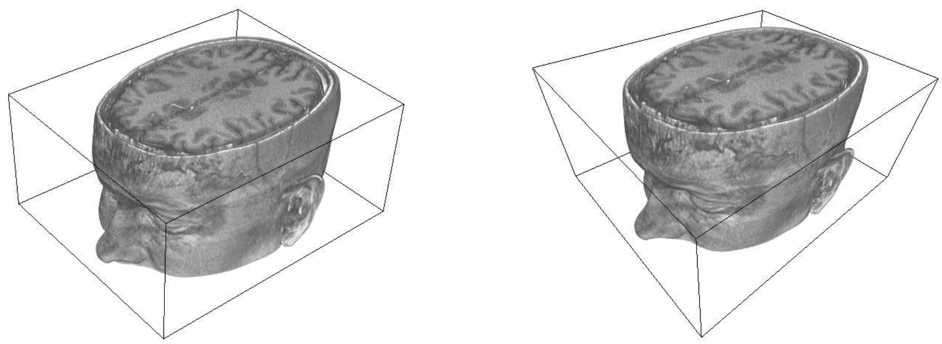


Figure 5.4 The subset editor can be used to render only a subset of the data domain.

Sampling rate sets the number of slices that are used to render the volume (see section 3.5). If the **reduced** checkbox is checked, the number of slices are reduced during user manipulation of the volume (moving, rotating, scaling etc.). This decreases the rendering workload and increases the interactivity of the application. (Hotkey: *Ctrl+R*)

Field of View Angle sets the field of view angle used in the (perspective) projection of the scene. Using the analogy of a camera lens, the field of view defines how wide or narrow the view is (see figure 5.5). (Hotkey: *Ctrl+F*)



(a) (b)

Figure 5.5 MRI data rendered using different Field of View (FOV) angles. (a) FOV angle $= 20°$*. (b) FOV angle* $= 60°$*.*

Volume Transform can be used to scale the volume in the x, y and z directions.

Texture interpolation sets the interpolation mode used when rendering volume data. The user can choose between *linear* interpolation and *nearest* neighbor look up when sampling the data at given locations in the volume.

Texture format sets the texture format used when storing the volume data as 3D textures on the graphics card (see section 3.3). The framework supports

- ***Byte* -** stores the data as 3D textures with 8 bits precision.
- ***Short* -** stores the data as 3D textures with 16 bits precision.
- ***Float* -** stores the data as 3D textures with 32 bits precision.

Datasets opens the *Datasets window*. The dataset window is used for handling geometries (see section 6.2.1). (Hotkey: *Ctrl+F*)

Vis Objects opens the *Vis Objects window*. The Vis objects window is used for handling geometries (see section 6.2.2). (Hotkey: *Ctrl+O*)

Scene Graph opens the *Scene Graph window*. The scene graph window is used for handling and manipulating data volumes (see section 5.4). (Hotkey: *Ctrl+O*)

Animation (Movie) opens the *Animation window*. The animation window is used for creating animations (see section 5.7). (Hotkey: *Ctrl+M*)

5.3.5 View Menu

View All resets the default view of the data scene.

Axis displays the coordinates of the volume along the x, y and z axis. (Hotkey: *Ctrl+A*)

Bounding box displays an axis aligned bounding box surrounding the volume. (Hotkey: *Ctrl+B*)

Clip plane enables the clip plane. The volume on one side of the plane is displayed while the other side is "clipped" (see figure 5.6).

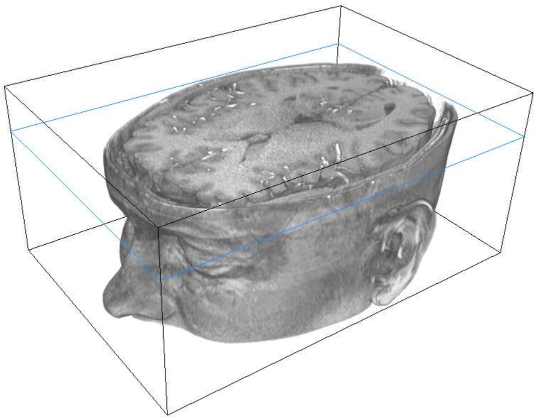


Figure 5.6 Illustration of the use of a clip plane to see the internal information of an MRI data set.

The clip plane can be manipulated using the mouse in conjunction with the keyboard:

- To *rotate* the clip plane press *Shift* and hold the left mouse button while moving the mouse.
- To *slide* the clip plane along the plane normal, press *Shift* and hold the middle mouse button while moving the mouse.
- The clip plane can be aligned with the x, y and z axis by pressing *Shift+X*, *Shift+Y* and *Shift+Z* respectively. Pressing one of these combinations twice in a row flips the clip plane 180 degrees, so that the visible portion of the volume becomes invisible (clipped) and vice versa.
- To *reset* the clip plane to the initial configuration, press *Shift+R*.

(Hotkey: *Ctrl+P*)

Reset Light resets the light source direction.

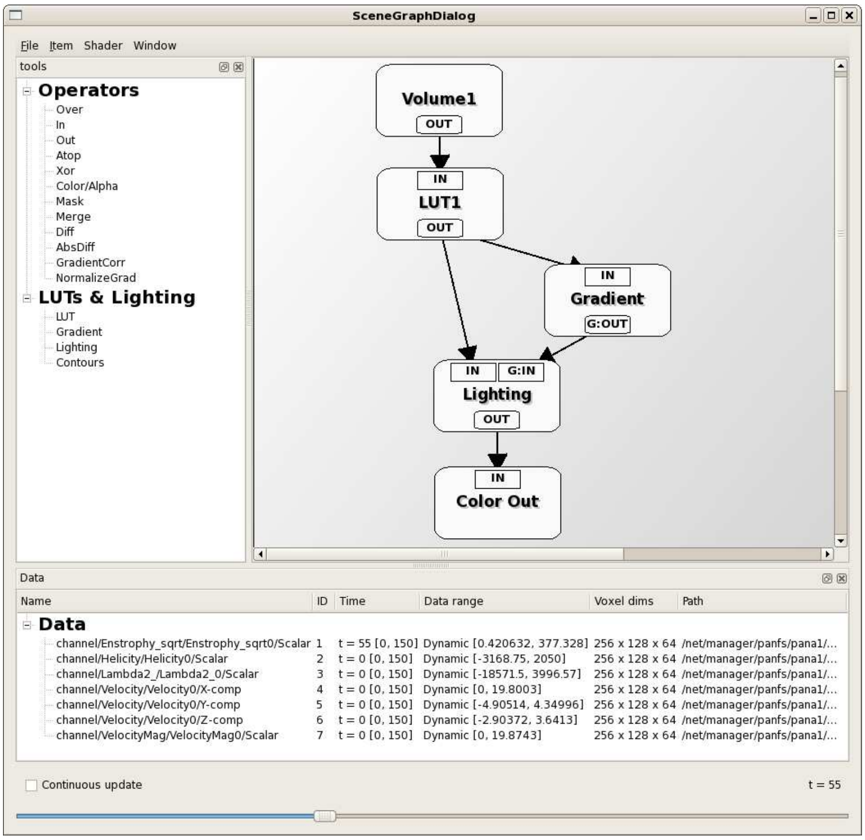


Figure 5.7 The scene graph window.

5.4 Scene Graph Window

The *Scene Graph* dialog window basically consists of three windows: a *Tools* window displaying a list of various operators, a *Data* window displaying loaded data sets and the main window showing the *scene graph rendering area* where data sets and operators can be used to construct different types of visualizations, see figure 5.7. In addition, the scene graph window has a menu system and a time slider, located at the top and bottom, respectively. Both the data and tools windows can be separated from and put back into the scene graph dialog window through drag and drop events (at given valid positions).

5.4.1 Using the Mouse

All scene graph items can be accessed through drag and drop events.

- To move an item, press and hold the left button while moving the mouse.
- To drop an item, move it over to the scene graph rendering area and release the left button.

5.4.2 Item Menu

Delete can be used to delete activated scene graph items from the scene graph rendering area. Scene graph items can be activated by pressing the left mouse button while holding the mouse cursor over an item. (Hotkey: *Del*)

Clear Scene clears the scene graph by removing all items from the rendering area. (Hotkey: *Ctrl+C*)

5.4.3 Scene Graph Rendering Area

In the scene graph rendering area, scene graph items can be put together in a tree graph to construct various types of visualizations. All scene graph items have connection areas which can be used to connect the items together. Input and output connection areas can be found at the top and bottom of the scene graph items. Most of the items have both input and output connection areas while some special items, such as data (Volume) items and the *Color Out* item, only have one of them. Some of the available scene graph items can be seen in figure 5.8.

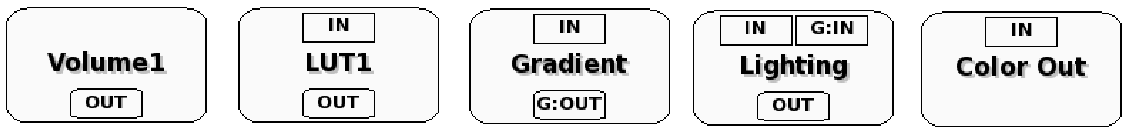


Figure 5.8 Some available scene graph items.

Currently, there are two types of connection areas in VoluViz. These are

- *RGBA*: This is the standard connection type and sends data (color and opacities) through the (r,g,b,a) components. The standard connection areas are named *IN* and *OUT*.
- *Gradients*: This connection type sends and receives a gradient vector using the (r,g,b) components. The gradient connection areas are named *G:IN* and *G:OUT*.

Connection areas can only interact with their own type.

Making a connection

- To make a connection between two items, start by pressing and holding the middle button while holding the mouse cursor on a connection area. Then finish the connection by moving the mouse cursor to a new connection area and then release the mouse button. If the connection was made successfully an arrow will be made between the two chosen scene graph items, see figure 5.9.
- To delete a connection, first activate a connection area by holding the mouse cursor over a connection area and press the left mouse button (see figure 5.10(a)). Then press the *Del* button. This will delete all arrows connected to the activated connection area (see figure 5.10(b)).

To learn more about the different operators (with examples) read the sections 4.4-4.6.

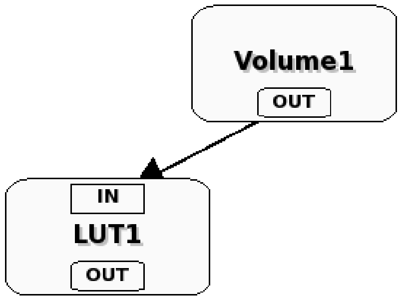
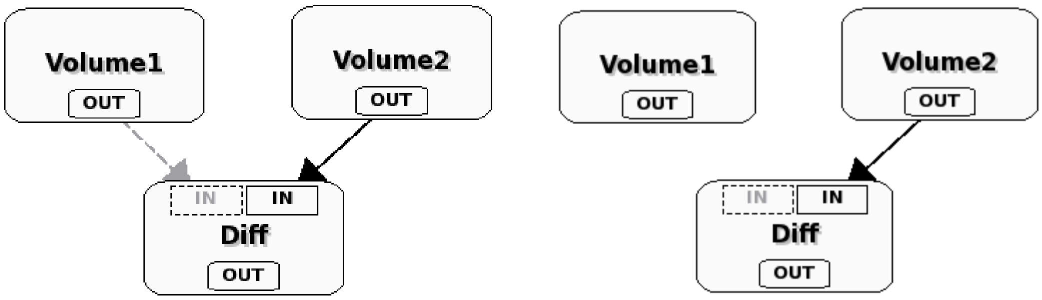


Figure 5.9 Scene graph items are connected together by connecting an input and output connection area by arrows.



(a) (b)

Figure 5.10 Deleting connections. (a) Activating a connection area will display all connecting arrows in dashed style and with grey colors. (b) Pressing the Del *button will remove all activated arrows.*

5.4.4 Color Table Editor

The color (lookup) table editor can be accessed by double clicking a *LUT* operator in the scene graph rendering area. The editor is divided into three main parts (see figure 5.11).

- The *combined section* include a global view of the color table and a zoomable detailed view.
- The *color space* combo box allows you to choose between HSVA and RGBA color spaces.
- The *channel views* shows the color table for each color component. The channels will be *hue*, *saturation*, *value* and *alpha*, or *red*, *green*, *blue* and *alpha* depending on the chosen color space.

To modify the color table, the user inserts and manipulates a number of *knots* in the desired channel view.

- To *insert* a knot, press the middle mouse button.
- To *move* an existing knot, move the mouse over the desired knot, and while pressing the left mouse button, drag the knot to its new position.

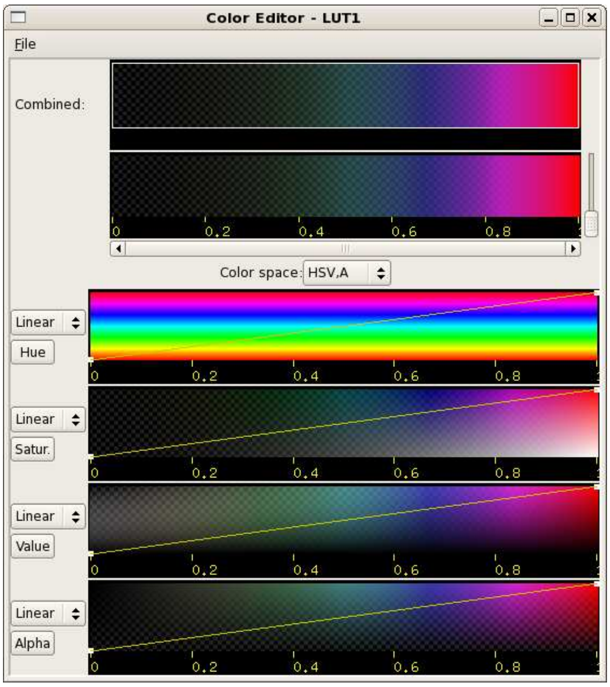


Figure 5.11 The Color table editor.

- To *delete* a knot, move the mouse over the desired knot and press the the right mouse button.

Each channel has an interpolation mode (linear, spline or Gauss) that determines the interpolation function between knots.

The exact operation of the color table depends on the input data sent to the color editor. VoluViz supports the following types of (texture) color mappings:

- *One-component (texture) color mapping*– This is what normally occurs in the visualization scene graph, when (for instance) a data set is used directly as input to a color editor. Then, the same (single) scalar component is used in the mapping for all the (r,g,b,a) or (h,s,v,a) channels.

- *Two-component (texture) color mapping*– This is what occurs when the input contains two sets of scalars. Then, the first scalar component is mapped using the (r,g,b) or (h,s,v) channels, while the second scalar component is mapped using the alpha channel. This happens, for instance, when two data sets are combined into a single output using the *Color/Alpha* operator and then used as input to a color table editor.

In the current version of VoluViz, the color tables have 256 entries. If the 3D data are stored, internally, as (byte) textures with 8-bit precision there is a one-two-one correspondence with the mapping of the data and the number of entries in the color table. If the data are stored using 16-bit (short) precision or 32-bit float precision, interpolation is used in the data mapping to colors and opacities. More information on color mapping and texture mapping can be found section 3.2 and section 3.3, respectively. The color editor supports saving and loading of color tables. Load and save functionality can be accessed from the color editor file menu.

5.5 Tools Window

The tools, in VoluViz, can be accessed through the *Tools* window, see figure 5.12. The tools can be made available in the scene graph rendering area using drag and drop events (see section 5.4.1).

Figure 5.12 Tools window.

5.6 Dataset Window

Once a data set is loaded by the HDF5 browser, the data set can be found in the *Data* list in the Dataset window (see figure 5.13). Here, the data appears together with information such as the data value range, data set size, and time information. The data volumes can be moved to the scene graph rendering area by using drag and drop events (see section 5.4.1).

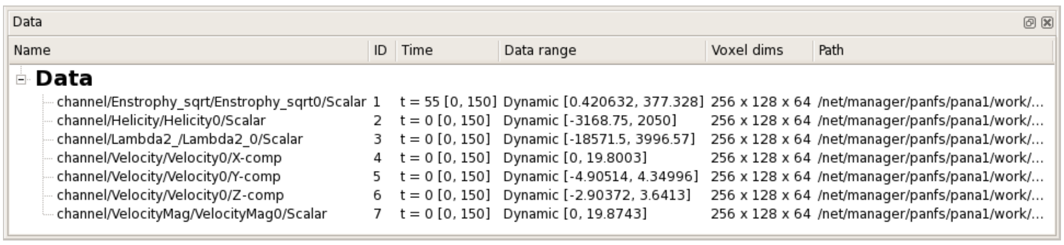


Figure 5.13 Dataset window.

A data set menu can be accessed by right clicking on the mouse button while holding the cursor over a specific data set, as illustrated in figure 5.14. The data set menu can be used to manipulate the data such as fixing the data range for an animation or changing the internal texture format.

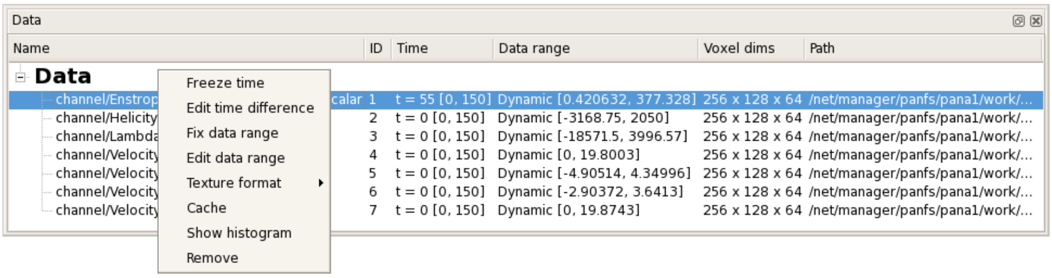


Figure 5.14 Dataset Menu.

5.6.1 Data set Menu

Freeze time freezes the time of the data set so that the local time of the current data set remains unchanged when adjusting the global time (see section 4.7.2).

Edit time difference is used when making multiple copies of a single data set. Can be used for creating visualization showing spatio-temporal relationships (see section 4.7.2).

Fix data range fixes the range of the current data set. When a new time step is loaded, the fixed data range is used as minimum and maximum data values (instead of the dynamic data range) during rendering. Fixing data range is especially useful when generating animations; forcing a constant color mapping of the time-dependent data.

Edit data range can be used for fixing the data range of a chosen data set by specifying a new minimum and maximum data value. Minimum and maximum data values are for instance used in color mapping (see section 3.2). Fixing the data range may result in clamping of the data. As a result, data values below and above the fixed ranged will be set to the nearest available data value which is the user-specified minimum and maximum data values.

Unfix data range unfixes the data range. This causes the data set to be reloaded using the dynamic range as minimum and maximum data values.

Texture format sets the texture format used when storing the volume data as 3D textures on the graphics card (see section 3.3). The framework supports

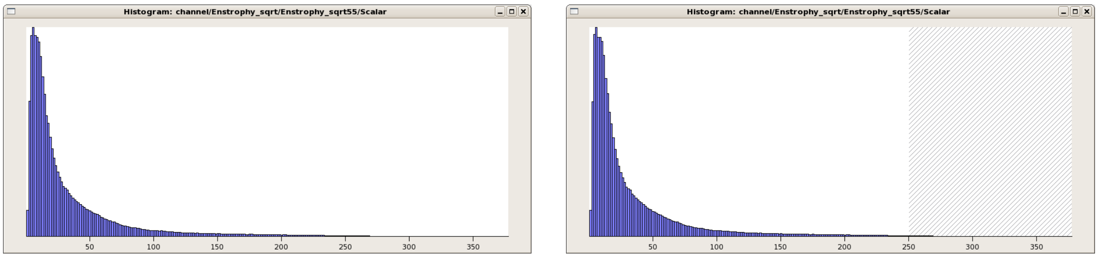
- ***Byte*** **-** stores the data as 3D textures with 8 bits precision.
- ***Short*** **-** stores the data as 3D textures with 16 bits precision.
- ***Float*** **-** stores the data as 3D textures with 32 bits precision.

Cache cashes the current data set allowing whole time series of selected data sets to be cached in the CPU memory assuming there is enough memory available to fit the entire data set. As the transfer of data from the hard-drive to CPU-memory tends to be the main bottle-neck for the animation system, this helps speeding up animations. This caching mechanism is very useful when investigating time-dependent data allowing interactive navigation of the data.

Before caching whole time series, the user should estimate whether or not there is enough available memory to fit the entire data set. For example, one hundred time steps of a data set consisting of $512 * 512 * 256$ data points takes up $64\text{MB} * 100 = 6.25\text{GB}$ of memory, assuming the data is stored as *Byte* textures (with 8 bits precision).

Uncache uncaches the data set by freeing up memory.

Show histogram displays the histogram. The histogram gives information on how the different data values of a data set are distributed (figure 5.15). When the data range is fixed by the user, clamped regions will be marked grey as can be seen in figure 5.15(b).



(a) (b)

Figure 5.15 The distribution of a data set can be visualized through histograms. (a) A histogram displaying the data distribution using dynamic data range. (a) A histogram displaying the data distribution using fixed data range $[0, 250]$.

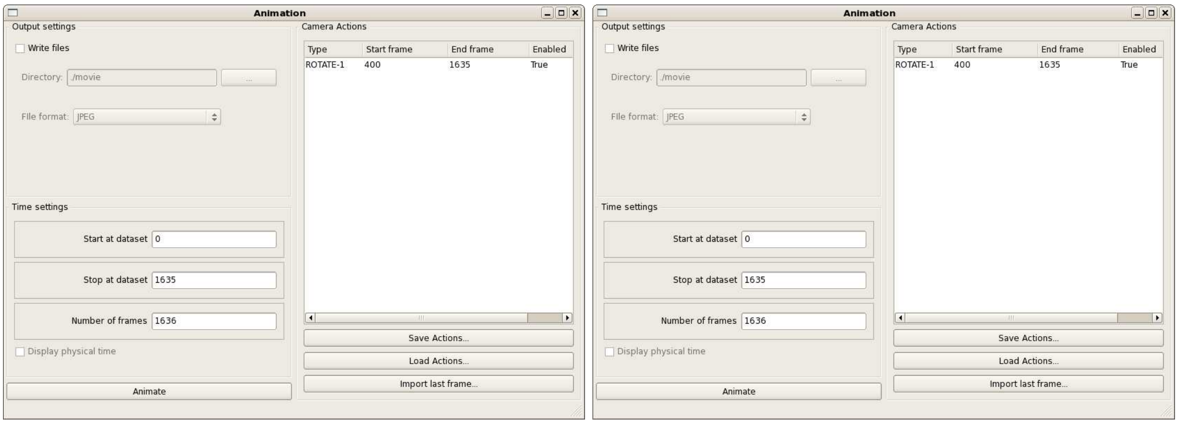
Remove removes the data set from the data set list.

5.7 Animation Window

Time-dependent data sets can be explored either by dragging the time slider in the Scene Graph Window (section 5.4) or by using the animation utility. The animation utility allows a pre-defined animation of the time-dependent data. Here, the user can select the time interval, the order of the data sets to be loaded, and the step size. These parameters can be defined as follows:

- *Start at dataset* - gives the time step of the data to be loaded at the start of the animation.
- *Stop at dataset* - gives the time step of the data to be loaded at the end of the animation.
- *Number of frames* - gives the number of frames used in the animation. If the purpose of the animation is just to traverse through all the time steps of the time-dependent simulation, the number of frames should be equal to the number of time steps in the simulation. If the number of frames does not coincide with the number of available time steps, then the nearest available time step will be loaded for each frame dependent on an interpolated lookup.

In addition, the animation utility supports a set of pre-generated camera actions. The supported types of camera actions are the following three types:



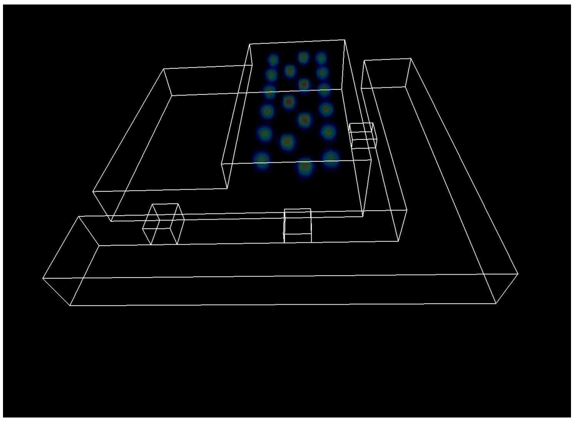
(a) (b)

Figure 5.16 (a) Animation window. (b) Camera action editor.

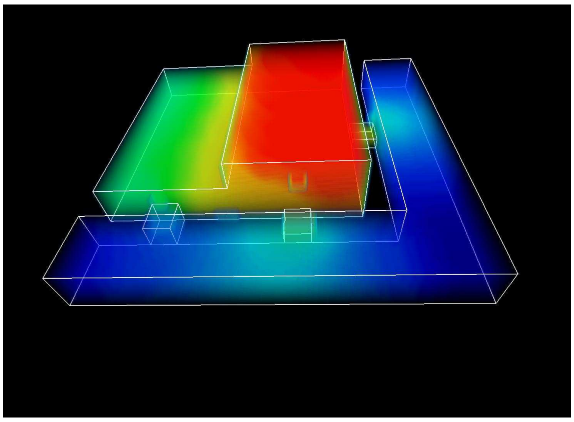
- Rotation,
- Translation,
- Zooming.

These can be accessed by pressing the right mouse button in the camera action area of the animation window and selecting *add*. Figure 5.16 shows an example of an animation setup where a 360 degrees rotation of the scene is embedded into an animation of an indoor dispersion simulation [10] starting at timestep $t = 400$ of the simulation. Some snapshots of the animation can be seen in figure 5.17.

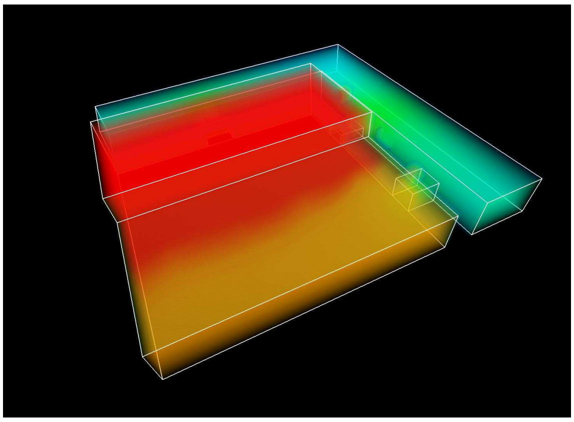
The animation starts when pressing the *Animate* button in the animation window. Snapshots of all frames in the animation can be saved in one of the supported image formats by checking the *Write files* check box. These images can then be converted to a movie using a number of available tools.



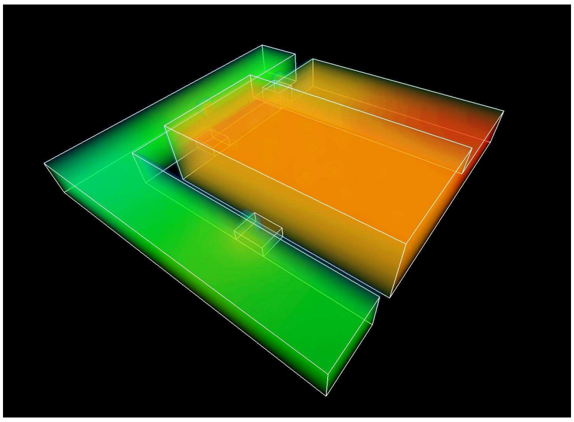
(a) $t = 0$.



(b) $t = 400$.

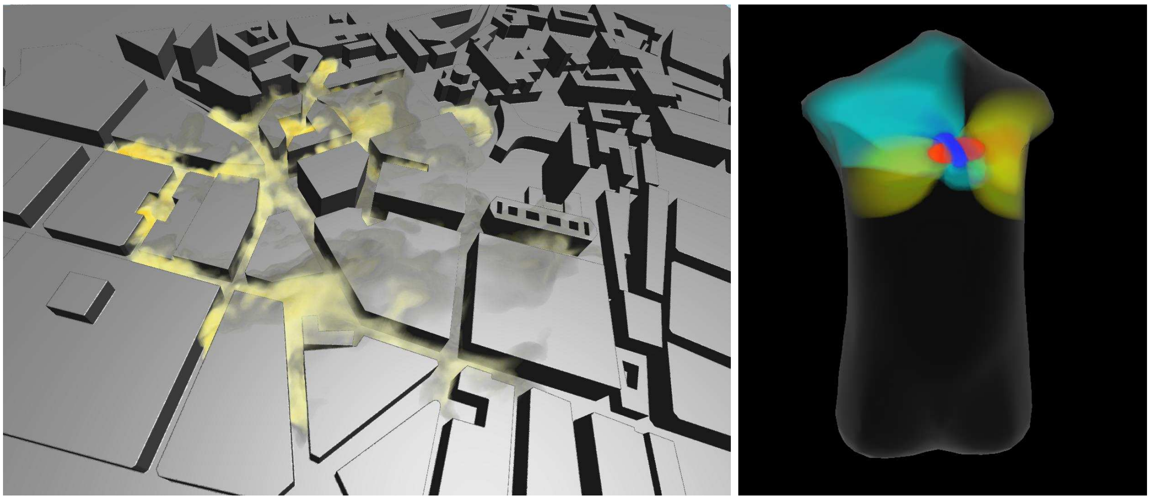


(c) $t = 800$)



(d) $t = 1200$.

Figure 5.17 Snapshots from an animation of a dispersion simulation [10]. Up to timestep $t = 400$ *of the simulation the camera position is fixed. From timestep* $t = 400$ *and until the end of the simulation the camera makes a full rotation of the scene (around the z-axis) while updating the time.*



(a) (b)

Figure 6.1 (a) Visualization of toxic gas from an urban dispersion simulation [45]. (b) Visualization of the electrical activity of the human heart embedded in the torso [39].

6 VoluViz User Manual: Part 2 - Rendering Geometries

6.1 Introduction

VoluViz is capable of visualizing the surface mesh geometry together with the volume data. Some scenarios benefit from also depicting the surface geometry in the visualization scene, thus providing a context to the visualization. Two examples where the surface geometry have been embedded in the final visualization can be seen in figure 6.1.

Geometry files is generated by converting the Fluent mesh (*.msh) files. Fluent mesh files can be generated using mesh programs such as Gambit and ICEM. Be sure to store the Fluent mesh files as ASCII files. The Fluent mesh files are converted with the program *msh2vvm*. More information on the program can be found at FFI's sinwiki web page under the title *"Getting Fluent data into VoluViz"*.

6.2 Loading and rendering mesh files

Mesh files can be loaded by selecting *Load Mesh* in the file menu of the render window. This opens a file browser.

6.2.1 Datasets Window

Once a VoluViz Mesh file (.vvm) is selected, the mesh file is put into the data set list which can be found under the *Meshes* tab bar in the *Datasets window*, see figure 6.2. The dataset window can be opened by selecting *Datasets* in the file menu of the render window.

Double clicking on a mesh in the data set list will generate a visualization object of the geometry file and, by default, be put into the visualization scene.

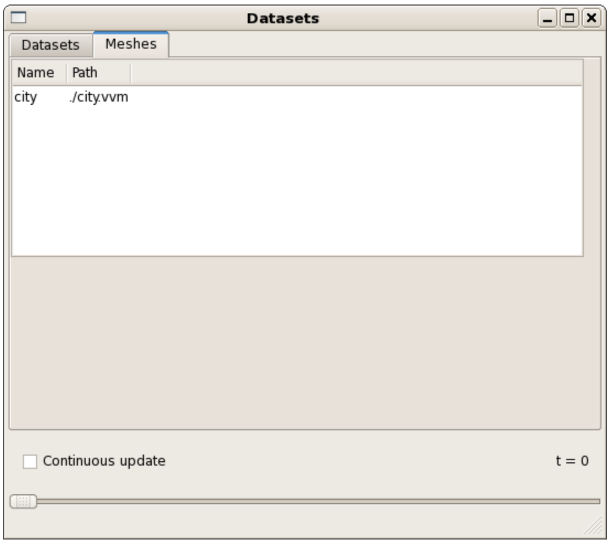
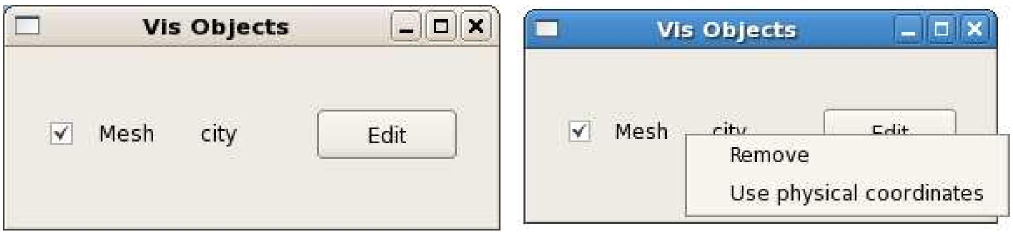


Figure 6.2 Dataset window.

6.2.2 Vis Objects Window

All geometry visualization objects are stored in a separate list which is displayed in the *Vis Objects window*, see figure 6.3. The vis objects window can be opened by selecting *Vis Objects* in the file menu of the render window.



(a) (b)

Figure 6.3 (a) Visualization Object window. (b) Visualization object window and its pop-up menu.

All list items are displayed together with a check box enabling toggling on and off the rendering of individual meshes. A Vis Object menu can be accessed by right clicking on the mouse button while holding the cursor over an object, see figure 6.3(b). Particular useful is the *Use physical coordinates* option which sets the physical coordinates domain of the volume data to match the data domain of the mesh file. If volume data from only a subset of the full data domain has been selected by the user, the physical coordinates of the volume data domain has to be specified manually.

The Vis Object Menu consists of the following options:

Remove removes the visualization object from the Vis Object list.

Use physical coordinates sets the physical coordinates of the volume data so that the volume data domain matches the data domain of the mesh file.

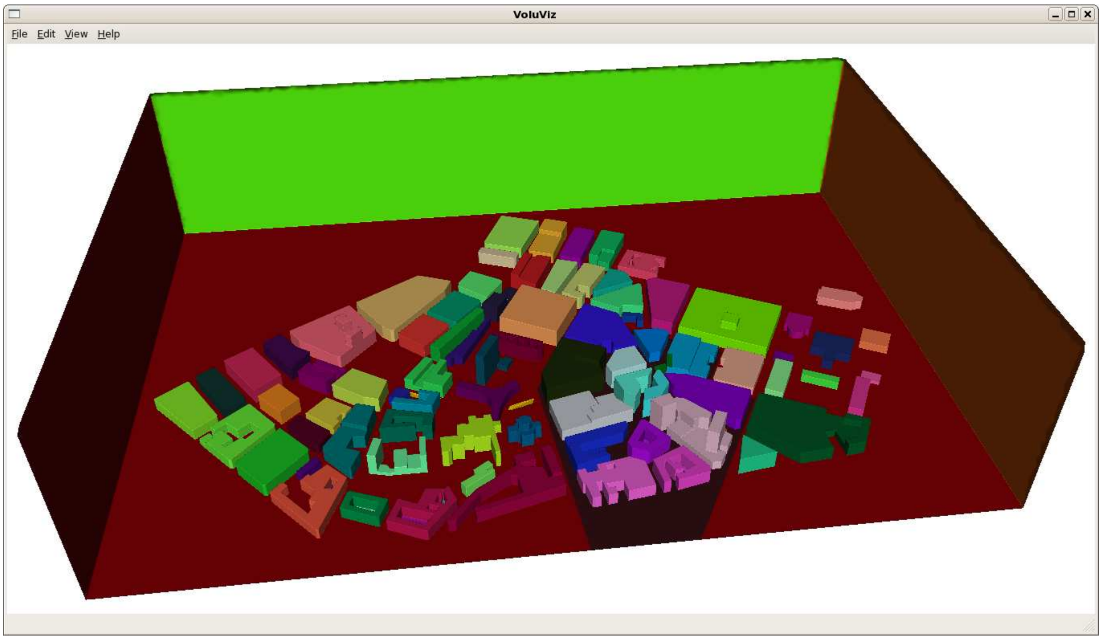


Figure 6.4 Rendering of the surface geometry from a mesh file used in an urban dispersion simulation [45].

A data set menu can similarly be accessed by right clicking on the mouse button while holding the cursor over a specific mesh in the *Datasets window*. The data set menu can be used for removing individual meshes. Removing a particular mesh will also delete all corresponding visualization objects.

Figure 6.4 shows the result after applying the above steps on a mesh file used in an urban dispersion simulation.

6.3 Mesh Editor

The mesh editor for a particular mesh can be opened by left clicking on the associated *Edit* button displayed in the vis objects window (see figure 6.3(a)). The mesh editor can be used to manipulate the geometry for instance be specifying the color and transparency of individual surface items. The default rendering of a mesh file displays each geometry item using a random color. This is illustrated for the mesh file rendered in figure 6.4.

When loading a mesh file, VoluViz stores the geometry as a set of separate surface items under a set of groups. The number of surface items and groups depends both on how the mesh is constructed as well as on the chosen parameters to the *Fluent-to-VoluViz* mesh converter program (msh2vvm). For instance, each *part* created in the mesh program will be stored as a separate surface item under a separate group. Each surface item, under a single group, can then further be split up into a number of surface items dependent on the selected parameters to the mesh converter program. Sometimes the splitting of surfaces into separate parts can be desirable as this gives the user more control. All surface items and groups are displayed in the mesh list browser window in the mesh editor. Figure

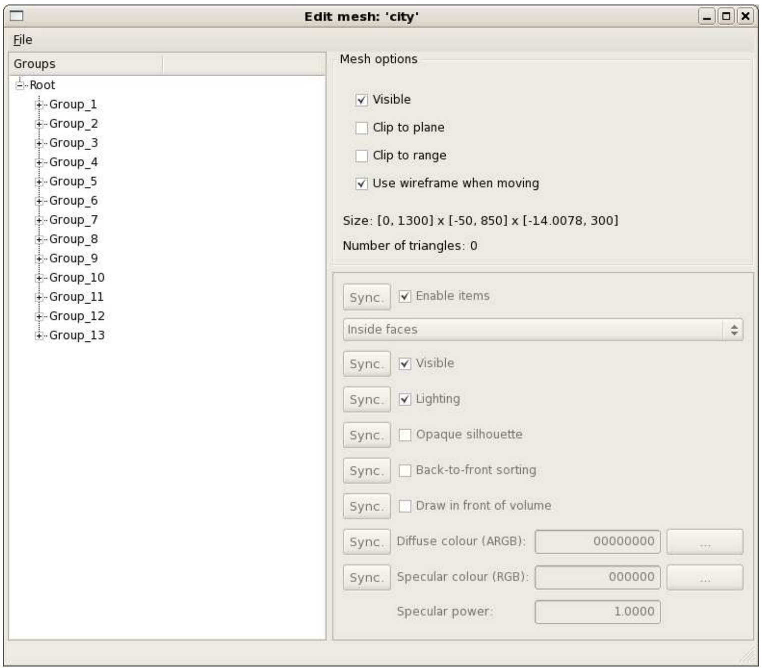


Figure 6.5 Mesh Editor.

6.5 shows the mesh editor associated with the city model rendered in figure 6.4. All groups and surface items are listed under the root node of the mesh list.

Surface items can be activated in two ways; Either by left clicking on a surface item (or a group) in the mesh list or by left clicking on a surface item in the render window. Activated surface items are marked blue in the mesh list and rendered blinking in blue in the render window. Marking the root node activates the whole mesh.

A set of keys can also be used in the picking of surface items. The following keys are valid when operating the mesh in the render window.

- If no key is pressed, the current selection is cleared and the picked item is selected.
- If *shift* is pressed, the picked item is added to the selection.
- If *ctrl* is pressed, the picked item is toggled (on and off).
- If *shift* and *ctrl* is pressed, the picked item is removed from the selection.
- If *alt* is pressed, everything connected to the picked item is toggled, added to or removed from the selection depending on the shift and ctrl state.

Figure 6.6 shows an example where the shift key has been used to activate a multiple set of surface items.

When operating the mesh using the mesh list in the mesh editor, the following options and keys are available:

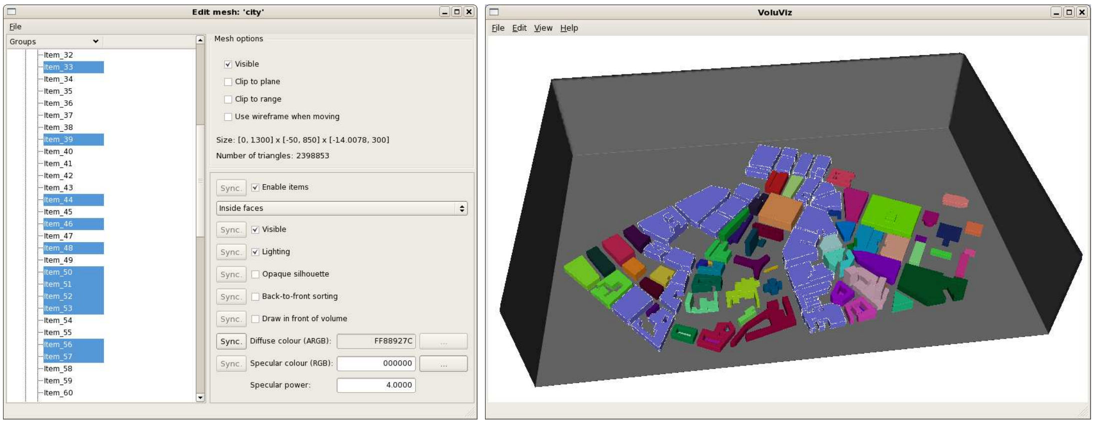


Figure 6.6 Picking of surface items. Selected items are marked blue.

- If *ctrl* is pressed, the picked item is toggled and either added to or removed from the selection.
- When left clicking on an activated surface item (or group), the item or group can be renamed.
- Groups and items can be moved in the mesh list using drag and drop events.
- Right clicking on an activated surface item (or group) opens the mesh list menu:

  Group creates a new group (at the current position) in the mesh list.

  Ungroup removes the selected group from the mesh list.

Figure 6.7 gives an example where the functionality described above has been used to rename and regroup the mesh items resulting in a more intuitive list which is easier to operate. For instance, all buildings in the city mesh can easily be activated if a common group holding all the buildings is first created. Once generated, the buildings can then be activated by left clicking on the newly constructed *Building* group in the mesh list.

6.3.1 Surface Modes

Once a single or a set of surfaces has been activated, these surfaces can be manipulated by the mesh editor to obtain a number of rendering effects. The mesh, or more precisely, each surface item, consists of an *inside* face, an *outside* face and a wireframe representation.

Inside face - Each surface item has both an inside and outside state associated with the surface. The current state of a surface depends on the view vector. A surface item is tagged as an inside surface if the surface is considered to be in the ”back” plane of the mesh geometry. By default, all inside surfaces are rendered.

Outside face - A surface item is marked as an outside surface if the surface is considered to be in the ”front” plane of the mesh geometry. By default, the outside surfaces are not rendered.

Wireframe - This surface mode depicts the surface items using a wireframe representation. By default, wireframes are rendered for all surface items.

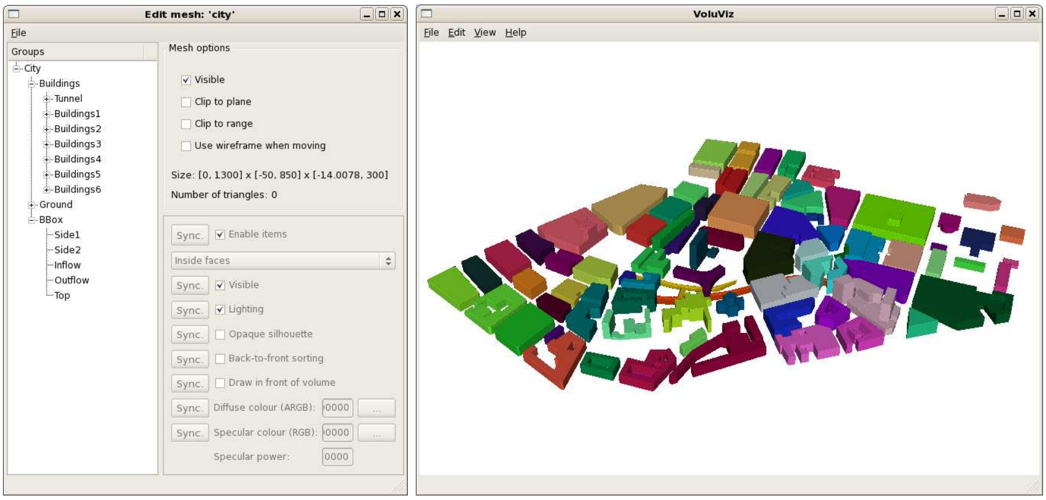
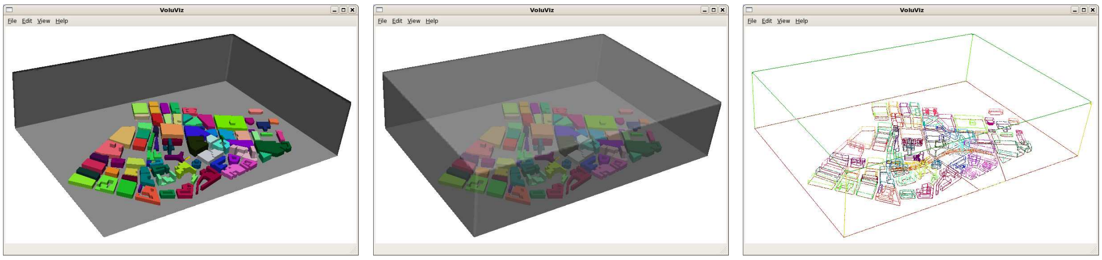


Figure 6.7 Individual mesh items can be renamed and regrouped into a more intuitive mesh list which is easier to operate.



(a) Inside faces only (b) inside and outside faces (c) Wireframe only

Figure 6.8 Illustration of the different surface modes.

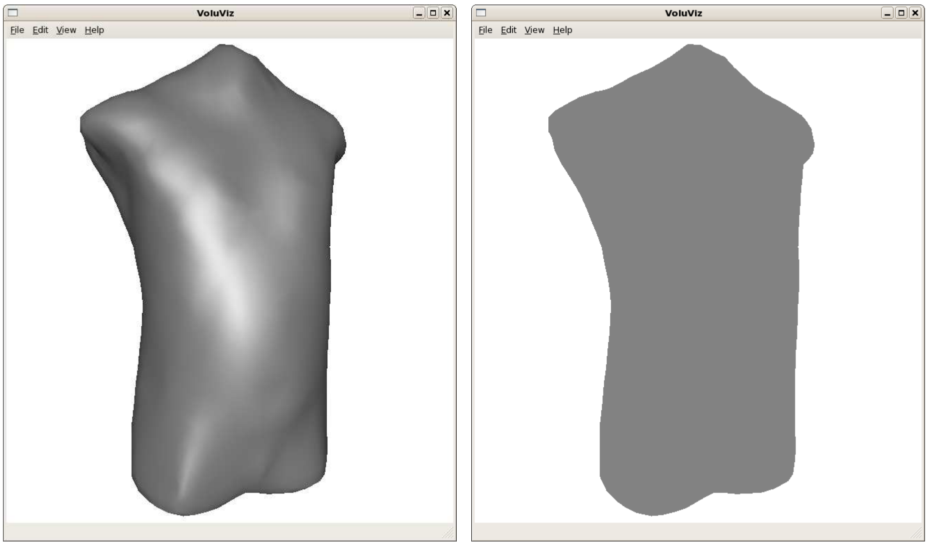
All of these visualization modes can be toggled on and off individually for separate surface items using the mesh editor in addition to specifying attributes associated with the different modes. The result of using the different surface modes can be seen in figure 6.8. Note that the *outside* surface items in figure 6.8(b) have been rendered slightly semi-transparent in order to see the *inside* surfaces.

Each surface mode comes with a number of attributes which can be set by the user. When activating multiple surface items, it might be necessary to press the *Sync* button to be able to access the attributes. The surface modes support the following attributes:

Visible - Only visible surfaces are rendered.

Lighting - When lighting is activated, the Phong [29] illumination model is used to render the surface. Otherwise, each surface item is rendered using a constant color. The Phong model, in VoluViz, is implemented as a fragment program giving each fragment of a surface element the color

$$\begin{aligned} \mathbf{C} &= \mathbf{C}_{\text{ambient}} + \mathbf{C}_{\text{diffuse}} + \mathbf{C}_{\text{specular}}, \\ &= k_a\mathbf{C}_a + k_d\mathbf{C}_d(\mathbf{l}\cdot\mathbf{n}) + k_s\mathbf{C}_s(\mathbf{r}\cdot\mathbf{v})^s, \end{aligned} \tag{6.1}$$



(a) With lighting (b) No lighting

Figure 6.9 A model of a human torso [39] rendered both with and without an illumination model.

where $\mathbf{l}$ is the light direction vector, $\mathbf{n}$ is the normal vector, $\mathbf{r}$ is the reflection vector, $\mathbf{v}$ is the viewing vector, s is the specular power and k_a, k_d and k_s are the ambient, diffuse and specular coefficients. Figure 6.9 demonstrates the effect of applying an illumination model to a model of a human torso.

Diffuse color sets the diffuse color contribution in the Phong illumination model in addition to the transparency of the surface (by the alpha value).

Specular color sets the specular color contribution in the Phong illumination model. Any color can be used. However, it is recommended to use gray scale colors. Otherwise, the surface will rendered with colored light reflected from the light source.

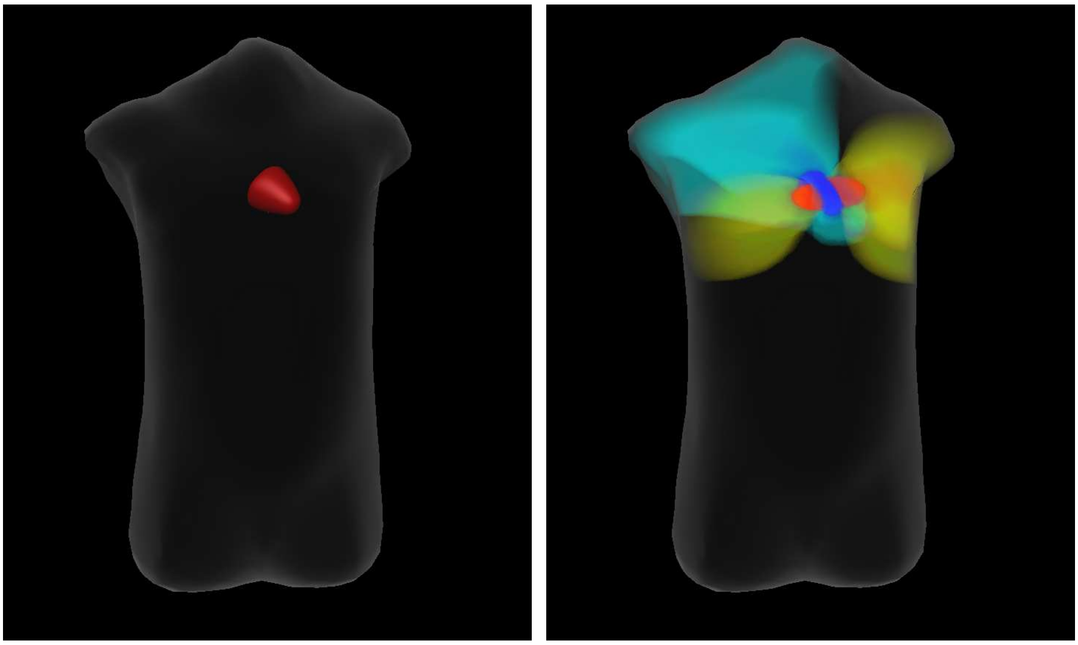
Specular power sets the specular power contribution in the Phong illumination model.

Opaque Silhouette - When activated, this mode renders the surface in a silhouette mode so that surface elements near the silhouette of the surface item is always visible independent of the global transparency value selected for that particular surface. The opacity (or alpha value) for each surface element is given by the formula

$$a = (1 - a_{\text{surface}})(1 - \|(\mathbf{v} \cdot \mathbf{n}\|)^2 \tag{6.2}$$

Silhouette rendering can be very useful in visualizations where the geometry only acts as a *context* and where the *focus* is on conveying results from a simulation. This is illustrated in figure 6.10 for simulation data from a modeling of the electrical activity of the human heart [39].

Back-to-front sorting both sorts and renders all the surface items in a back-to-front order. A back-to-front sorting of the surfaces can be desirable when rendering semi-transparent surfaces.



(a) (b)

Figure 6.10 Silhouette rendering. (a) A visualization scene where the torso is rendered by combining low opacity with silhouette rendering whereas the human heart is rendered opaque. (b) Visualization of the electrical activity of the human heart embedded in the torso [39]. Here, a silhouette rendering of the torso is used to give contextual information without occluding the volume data.

Otherwise, the rendering may lead to visual artifacts. Note however that activating this feature may decrease the rendering performance considerably.

Draw in front of the volume - As the rendering engine handles the geometry and the volumes separately, this mode needs to be activated for semi-transparent surfaces that occlude the volume data. This typically apply to the *outside* faces of a mesh file if they are made visible.

In addition to the local surface attributes listed above, the mesh editor supports the following global parameters:

Visible sets the visibility state on the whole surface mesh.

Clip to plane clips the geometry set by the clip plane. See section 5.3.5 for more details on activating and handling the clip plane.

Clip to range clips the geometry specified by the subset selection. See section 5.3.4 for more details on picking of subsets.

Use wireframe when moving - When activated, a wireframe representation of the mesh is used whenever the render window is activated by a mouse or key event. This decreases the rendering workload and increases the interactivity of the application.

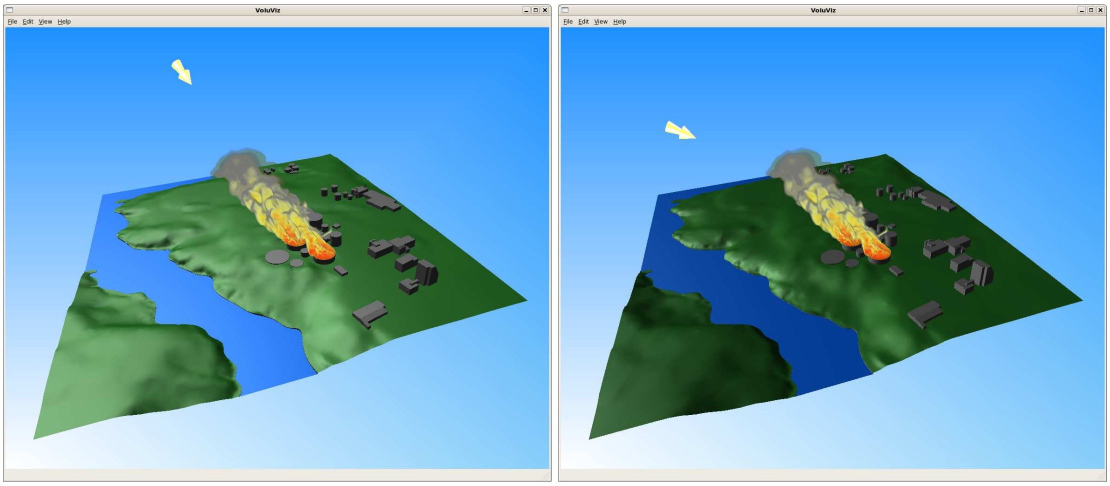


Figure 6.11 Rendering of a surface mesh model of an industrial plant [11] using Phong illumination model with two different light vector directions.

6.4 Setting the Light source

The light source can be activated by pressing and holding the *Ctrl* button in the render window. This displays an icon of the light source giving its location and direction. To rotate the light source press *Ctrl* and hold the left mouse button while moving the mouse. The light source is used when rendering geometries and gives the light direction vector in the illumination model given by equation (6.1). Figure 6.11 demonstrates the effect of changing the light direction vector.

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