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FOCAL REGION-BASED VOLUME RENDERING

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In this paper, a new approach named focal region-based volume rendering for visualizing internal structures of volumetric data is presented. This approach presents volumetric information through integrating context information as the structure analysis of the data set with a lens-like focal region rendering to show more detailed information. This feature-based approach contains three main components: (i) A feature extraction model using 3D image processing techniques to explore the structure of objects to provide contextual information; (ii) An efficient ray-bounded volume ray casting rendering to provide the detailed information of the volume of interest in the focal region; (iii) The tools used to manipulate focal regions to make this approach more flexible. The approach provides a powerful framework for producing detailed information from volumetric data. Providing contextual information and focal region renditions at the same time has the advantages of easy to understand and comprehend volume information for the scientist. The interaction techniques provided in this approach make the focal region-based volume rendering more flexible and easy to use.

Keywords: Volume rendering; focal region; contextual region; feature extraction.

1. Introduction

Volume visualization has been widely used as a method to explore information from volumetric data sets in the area of medical imaging, meteorology, computational fluid dynamics (CFD) and other fields. During the last decade several approaches to volume visualization have been developed and explored extensively. At the same time, the developments in image modalities, such as Multislice-Spiral CT in medical imaging, have led to create higher resolution and larger volumetric data sets. However, in these data sets the structure of interest (tumours, lesions, arterial structures, etc.) occupies a percentage of the voxels that is often below 10% of all voxels. In practical applications, the analysis of such structures needs efficient extraction of the volume of interest while preserving data structures around it to provide contextual information. In medical applications, the liver carcinoma, for example, is a wide-spread malignant disease and the surgeons performing liver surgery indicate that the spatial relationships between vessels and lesions are difficult to judge.[7] A 3D visualization to provide spatial relationships and specific focus on some volume of interest would be helpful for this purpose. We believe that focal region-based volume visualization, which aims at making the visualization process more efficient by focusing on the effects or events of interest to user, is a solution for this problem.

Traditionally, most volume visualization approaches only use one single rendering method for the volume data to depict information. Although a single technique can provide useful insights into volume data, it is insufficient for many problems. For example, direct volume rendering methods typically do not remove occluding structures, i.e. they do not allow one to peel inside the data in order to expose the inner structures that might be of interest. Recent research tends to combine several rendering methods in one volume data to show more and meaningful information.[3] In cases of very large data sets or data of high dimensionality, deciding what subset of the data to show and what rendering method to use becomes very important during investigation because it is, in general, not possible to concurrently show all the data information. Instead, certain selective rendering approaches of the data are used for visualization. The success of volume visualization (e.g. direct volume rendering, surface rendering, etc.) for data analysis depends on fulfillment of three types of requirements: *the information they can provide*, *interactivity* and *flexibility*. The disadvantage of traditional visualization approaches is that they do not take into account the structure of the underlying data. The explicit knowledge of the objects[1] characteristics is not integrated into the rendering pipeline. Therefore, the structure analysis part is often taken as a post-processing step in image space.[10]The results will be more meaningful if the features of volumetrical data set which provide structure analysis information are integrated into the contextual region and presented with the focal region in the renditions at the same time.

In this paper, we propose a new rendering approach that integrates contextual information as the structure analysis of the data set with a lens-like focal region rendering to show more detailed information. The volume data is divided into two parts by a geometry primitive (e.g. sphere, cube): contextual and focal regions. In the contextual region, the dominant features are extracted and rendered prominently while in the focal region, the detailed information of volume data is presented. The major challenge to our approach is the development of an integrated framework for finding features of interest in volume data sets and combining these features efficiently with the focal region rendering to show analytic information of the volume data sets. The accuracy of the final rendering can be adjusted according to the structures in the context region and the details in the focal region.

This feature-based approach contains three main components to meet three types of requirements in order to provide more detailed information of the volumetric data set:

- A feature extraction model using 3D image processing techniques to explore the structure of object to provide contextual information.
- An efficient ray-bounded volume ray casting rendering to provide the detailed information of the volume of interest in the focal region.
- Tools for interactive specification of focal regions and modulation of transfer functions which are used to determine what to be shown in the focal region.

The remaining sections of the paper are organized as follows: firstly we provide the previous related work, after that we present the feature definition and extraction method used in the context region to show structure information of the data. In Sec. 4, we discuss the rendering issues for extracted features. This is the key for structure analysis. In Sec. 5, we present the rendering method for focal region. In Sec. 6, the interaction techniques for focal region are discussed and the useful interaction facilities to navigate through the volume are presented. We describe how to efficiently integrate both regions in order to show more information of the volumetric data set and accelerate the rendering process. Finally, we apply our approach to the volumetric data set and present the results and discussion.

2. Related Work

Recent research in volume rendering tends to combine different rendering methods together to explore more information from volume data. Hauser presented a two-level volume rendering approach.[3] This approach allows for selectively using different rendering techniques for different subsets of a 3D data set. Different structures within the data set are rendered locally on an object-by-object basis and all the results are combined globally in a merging step. Rheingans developed a volume illustration approach. This approach can be considered as a feature-based technique.[8] The original volume features (e.g. boundaries) are enhanced using nonphotorealistic rendering techniques. The main idea is that features to be enhanced are defined on the basis of local volume characteristics (e.g. gradient) and can be enhanced locally. Westermann used a multiscale approach to extract volume features and integrated them into the rendering pipeline.[10] The analysis of structures within the data set can be obtained through a hierarchical description of the discrete signal. Bullitt pointed out that an ideal method of visualizing 3D volume data should include the ability to interactively remove obscuring objects and/or to obtain relevant information about selected objects or groups of objects.[1]

We felt that these techniques are a good starting point for our investigation. Theoretically, there are different ways to combine different rendering methods together to explore information from volume data. As the two-level volume rendering approach Hauser proposed, it uses the idea of local rendering and global composition.[3] Our approach uses another idea to create a rendering pipeline: focal region for detailed information and context for structure of the data. This approach extends the traditional volume rendering methods and can create partial volume rendering.

3. Feature Definition and Extraction

Feature based volume visualization approach is widely used in computational fluid dynamics (CFD) visualization.[6,9] In this paper, we extend the feature-based approach to be used in medical imaging to show structure information of the data set. A feature-based approach is useful for three reasons: the amount of data that must be visualized is reduced through focusing the interest on features, thus reducing redundant information; it can provide clear analytic information for scientists; it largely avoids information overlapping.

3.1. *Feature definition*

The first step of feature-based rendering for context region is to define what features are of interest. A feature is any object, pattern or structure in the visualized data that is of interest and that is a subject of investigation. These features should be the meaningful information in the dataset and easily identifiable by eyes. Features form a high level data representation that is more clear, compact and meaningful.

Edges are basic image features. They carry useful information about object boundaries, which can be used for image analysis and object identification. We consider an edge as the border between two homogeneous image regions having different intensities. This definition implies that an edge is a local variation of intensity. Similarly, for visualizing 3D data sets a very popular idea in scientific applications is for the object boundary regions to play a very important role in the perception of object shape and structure.[2,4] Since an object boundary carries the most important information, it often suffices to visualize object structures in order to completely extract the information content.

3.2. *Feature extraction*

The goal of feature extraction is to find interesting features in the data more or less automatically and to extract the features and calculate quantitative attributes describing the characteristics of that feature. With the attributes, the feature can be visualized and evaluated more precisely. Most of the volume features are gradient and viewing direction dependent.

We assume that a feature can be distinguished from the rest of the volume data in some way. So a selection of a voxel can be made that corresponds to the criteria of feature of interest specified by the scientist. This criterion is a mathematical formulation of the underlying physics of the feature. Attribute in our approach is the gradient of the volume data set characterizing its boundary features. Our aim is to find boundary features of the volume data set, which are indicated by the large gradient magnitude. We use 3D image processing techniques to detect object boundaries. The gradient can be calculated from Zucker–Hummel (ZH) gradient computation method.[12]

Our feature extraction process is as follows: firstly the volume gradient and gradient magnitude are computed, then it is checked at every sample position whether the gradient magnitude is a local maximum. This is obtained through detecting the largest gradient magnitude along the gradient direction. A local maximum gradient magnitude is found when the gradient magnitude is strictly larger or equal to the neighbor in the opposite direction, and vice versa. We create a binary mask volume with mask values set to one if the corresponding voxel has a local gradient length maximum. This mask volume contains the boundary information of the original volume data. We use this mask volume to control the final original volume compositing process.

Using this approach, we do not rely on a specific material threshold and only real object boundaries are rendered. Dominant features remain visible in the rendition.

4. Contextual Region Rendering

The context is mainly used to show the structure of the data. In the contextual region, our interest is object boundaries. The object boundaries and edges often carry most of the relevant information. This can largely avoid spatial overlapping. In the context, the dominant features are extracted and rendered prominently.

4.1. *Rendering pipeline*

From the feature extraction process, we obtain an additional volume data set of equal resolution in which the volume feature information is coded. The boundary information has to be integrated into the rendering pipeline. In direct volume rendering algorithms the pixel intensity on the viewing plane at a certain position is computed by evaluating the well known volume rendering integral[5]

$$I(t_0, t_1) = \int_{t_0}^{t_1} q(t) e^{-\int_{t_0}^{t_1} \sigma(s) ds} dt, \tag{1}$$

along each viewing ray. It sums up the contributions of the volume emission $q(t)$ along the ray, which is scaled by the viewing depth according to the volume absorption $\sigma(s)$.

Recall that we have encoded the local maximum information of the gradient magnitude into a mask volume which contains boundary information of the volumetric data set. Now we use this mask volume in the compositing step. The final context region is obtained through compositing the original volume using ray casting method. Equation (1) is evaluated on the original data set only if the ray meets a voxel position where the corresponding position in mask volume is 1. Otherwise the segments[1] opacity is set to zero. An advantage of this selective volume rendering is

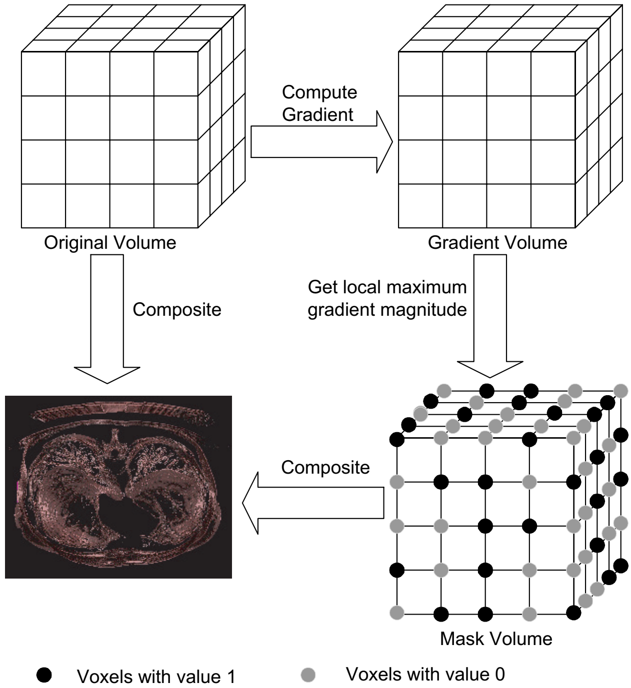

Fig. 1. Contextual region rendering pipeline.

that little or no computation time is spent in non-interesting space. The rendering pipeline is shown in Fig. 1.

The main advantage of this approach is that it can provide more structure information than standard ray casting method. Because its compositing is controlled by boundary mask volume, the rendered result only shows the boundary regions.

4.2. *Feature enhancement*

In the previous step, we have extracted the boundary voxels in the volume data and then rendered using selective volume ray casting method to composite the rendition. This will create the boundary surfaces of the volume object. In order to mainly show the surface orientation and create a silhouette effect, we enhance the opacity of volume samples where the gradient direction is almost perpendicular to the viewing direction. This is indicated by a dot product between gradient direction and viewing direction which nears zero. The approach has been successfully used in the volume illustration by Rheingans.[8] The silhouette enhancement can be realized from:

$$\alpha_s = \alpha_o(k_n + k_s(1 - \|\nabla_{fn} \bullet V\|)^n), \tag{2}$$

where α_s is the enhanced silhouette opacity, α_o is the original opacity at the sample position, k_n is used to control the scaling of non-silhouette regions, k_s is used

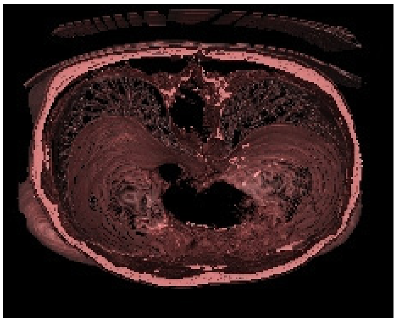

Fig. 2. Feature enhancement for contextual region rendering.

to control the amount of silhouette enhancement, ∇_{fn} is the normalized gradient direction, V is the normalized viewing direction, and n is used to control the sharpness of the silhouette lines. Figure 2 shows the result of feature enhancement for contextual region rendering.

5. Focal Region Rendering

The feature-based approach in the contextual region provides the structure information of the data set. The focal region is our main area of interest. It should provide users with more detailed information on the volumetric data set.

For efficient rendering and providing more information, we present a method of volume ray bounding during ray casting in our focal region rendering. The rays are bounded by a user defined geometric shape (e.g. sphere, ellipsoid, cube) according to the volume of interest. The volumetric features can also be enhanced in this way and the rendering can be accelerated by avoiding unnecessary volume traversals.

Ray-bounding clips viewing rays against the user-defined polygon. This is done by projecting the polygon twice — first capturing a near Z buffer, and then capturing a far Z buffer. The values from the Z buffers are decoded according to the current viewing transformation, and the decoded pairs of values (near, far) are returned as distance from the view point for perspective viewing, or distance from the view plane for parallel viewing. The idea is shown in Fig. 3. As shown in Fig. 3, only the bounded thick parts of rays are traversed during ray casting, and thus we only render the volumetric data in the focal region, instead of all of the volumetric data. We use a modified Z buffer and selective ray-casting to allow ray casting precisely through the confines of the regions of interest.

6. Interaction Techniques for Focal Region

With the increase of size of volumetric data set, the interactivity will be one of the main requirements to find structures of interest. It can provide the facilities to peel inside the volumetric data set and the flexibility to investigate different

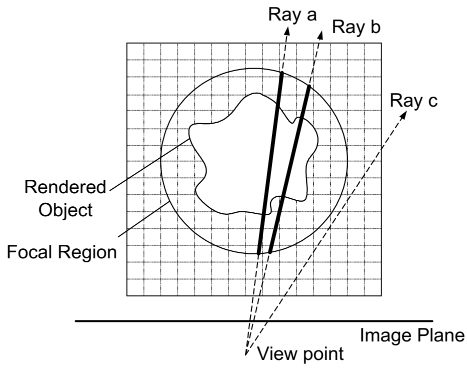

Fig. 3. A 2D example of ray bounding during ray casting.

parts of the data set. The interaction technique for focal region is one of the main components for the focal region-based volume rendering approach. Because of the interaction technique, our approach shows its advantage of flexibility over other rendering approaches. In our approach, the user can efficiently interact with the system and explore information from volume data set. The renderer provides different interaction tools to make rendering process more flexible. To interactively specify a spatial point in the volume space is often difficult. Using a slice navigator, we can navigate through the volume. Spatial relationships may be recognized and explored. It provides a special viewer to access any spatial point in the volume data set which is indicated by a 3D cursor. To specify a spatial point in the volume using the slice navigator, first we find the slice where the specified point is, then in this slice we use a cross cursor to locate the point. At the same time, the spatial position is displayed in the rendered window with a 3D cursor. With this 3D cursor facility, we can flexibly specify the location of the focal region and then render the focal region.

In the focal region, we can visualize different objects through modulating the transfer function for the ray-bounded volume. The user can select a subset of the identified objects and assign specific viewing parameters (e.g. colors) to each object. For the focal region, different shapes are available: wedges, cubes, cylinders and spheres. The properties of a focal region define its visualization (color, rendering style) and its initial position, size and orientation. The focal region can be applied interactively to the different objects so that certain objects are visible. This increases the system flexibility for user interaction. All these facilities increase the interacitivity and usability of the focal region-based rendering approach.

7. Results and Discussion

This section describes how our approach is used in medical data sets (CT data set of liver) to extract structures of the objects and focus on the specific objects of interest to show detailed information at the same time. We also present different approaches to extract contextual information to make a comparison. The method was implemented on an AMD Athlon/1.0GHz PC with 512MB memory using C++. The size of the CT data set of the liver is $256 \times 256 \times 60$. Because of the gradient computation in the context region, it takes about 40 sec to create the context region using boundary controlled ray casting. After the contextual region is created, the focal region can be rendered. The rendering time depends on the size of the focal region. For spherical focal regions of diameter 20 to 40 pixels rendering could be carried out at 0.5 to 1 frame per second. As we currently focus on evaluating the methodology, the rendering process is not optimized yet and we expect that we will be able to increase the frame rate substantially in future.

Figure 4 shows the results of focal region-based volume rendering using boundary mask volume controlled ray casting to composite the original volume to represent contextual information. At the same time, the specific vessels are presented in the focal region. In the contextual region, the important features like contours of the liver and vessel structures outside of the liver are depicted.

Figure 5 shows the result of focal region-based volume rendering by using depth-based MIP to composite contour volumes to represent contextual information.[11] From the comparison of Figs. 4 and 5, we can see that using boundary mask volume controlled ray casting to composite the original volume to represent the contextual information has several advantages: it clearly depicts the liver shape and boundary information; it presents object spatial relationships clearly; it can be easily combined with the focal region in 3D space.

In Fig. 6, we "turn off" the contextual region for only showing the enlarged focal region which depicts liver vessels and tumours clearly at the same time. This representation can be used after the radiologist has been familiar with the spatial relationships of the objects through investigating the renditions in which the contextual information and focal region are displayed at the same time. In this case he is only interested in the focal region, so it is necessary to "turn off" the

Fig. 4. Using boundary mask volume controlled ray casting to composite the original volume to represent the contextual information, and the focal region is displayed at the same time.

Fig. 5. Using depth-based MIP to composite the boundaries of the objects to represent contextual information, and the focal region is displayed at the same time.

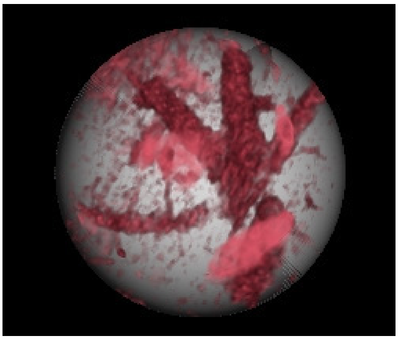

Fig. 6. The enlarged focal region: the liver vessels and tumours are clearly depicted at the same time.

contextual information to improve interaction performance. Then the radiologist may manipulate (zoom, rotate, translate, modulate transfer function for the focal region, change colors, etc.) the focal region freely to get more detailed information. This representation is also very useful when visualizing large volume data sets in which the volume of interest only occupies a small part of the volume. In this way, the rendering performance can be improved through applying our focal region to the volume of interest and not rendering all of the volume data.

The rendering methods used in focal region and contextual region may be flexibly specified according to specific applications. In some cases, using isosurface-based rendering in the contextual region has its own advantages in speed. Figure 7 shows the result of using iso-surface to represent the contextual information of the liver. As shown in Fig. 7, the liver surface and liver vessel structures are presented at the same time in the rendition, while the focal region is specifically focused on the specific vessels.

The effect we have created in the contextual region is not aimed at a physically plausible rendering. Our main goal is to render important features and details. Our

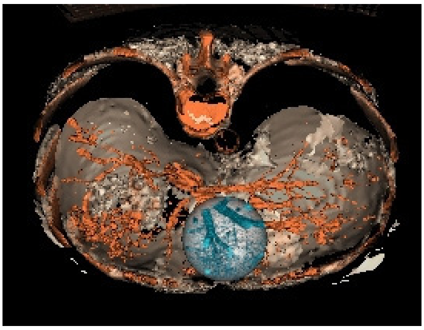

Fig. 7. Using iso-surface to represent the contextual information of the liver.

rendering method for contextual region may be considered as a new way for using nonphotorealistic rendering (NPR) techniques in volume visualization.

8. Conclusions and Future Work

We have introduced the concept of focal region-based volume rendering for providing contextual information for structure analysis of the data set with a lens-like focal region rendering to show more detailed information about volumetric data. Focal region-based volume rendering provides a powerful framework for producing detailed information from volumetric data. The combination of contextual information and a focal region rendition produces an intuitive tool for exploring volume data. The interaction techniques make the focal region-based volume rendering more flexible and easy to use.

In practice, there is no single universal visualization technique. The best visualization results should be obtained by a sensible combination of different rendering techniques. We expect that in the focal region-based approach the feature extraction techniques will be improved and extended. Multiscale techniques will provide feature analysis information through the evolution of the different scales. The segmentation algorithms will then be combined into the rendering pipeline to extract features of interest. Other meaningful features like curvatures will also be investigated with respect to its ability to show analysis information of the volume data set. Interaction tools will be enhanced to make this approach more flexible and usable. At the same time, the optimization of the approach to improve the rendering speed will be one of the future tasks.

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