Improved Boundary and Silhouette Enhancement in Volume Illustration

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Abstract

Structure cues are the dominant information in a rendered image. And conveying structure accurately and automatically is a problem still not fully solved in volume rendering. The presence of volume illustration allows a more flexible way in conveying structure information compared with the traditional transfer function. This paper presents two improved approaches in volume illustration, namely the distance weight boundary enhancement and gradient weight silhouette enhancement. In these approaches, the enhancing parameters vary with the samples' position and local gradient. As a result, they are more flexible in rendering various data sets and are able to convey clear structure cues without missing of small features.

1. Introduction

Scientific visualization has become an important tool in the research of many fields. Algorithms can be categorized into two general approaches, surface algorithms and direct volume rendering. And the key advantage of direct volume rendering over surface rendering approaches is the potential to show the structure of the value distribution throughout the volume.

A new kind of approaches to volume rendering has been proposed: the augmentation of a physics-based rendering process with nonphotorealistic rendering (NPR) techniques [12] to enhance the expressiveness of the visualization. One of those approaches called volume illustration [1] has recently been presented specifically for the visualization of volume data. The approach is fully incorporated into the volume rendering process. Utilizing viewing information, lighting information, and additional volumetric properties, many feature enhancement techniques are implemented. And the resulting image is able to convey clearer structure cues than direct rendering.

Two improved volume illustration techniques, the distance weight boundary enhancement and gradient weight silhouette enhancement, are proposed in this paper. In these two methods, enhancing parameters are varying based on the sample position and gradient magnitude, instead of keeping constant in rendering process. As a result, the amount of enhancement changes in accordance with the volume structure. And the result image is more "properly" enhanced, which clearly conveys data structure, and keeps detailed information at the same time. In addition, due to the parameters' variability according to data structure, the approaches are capable of adapting to different volume data sets.

2. Related works

Traditional volume rendering relies on transfer functions to produce artificial views of the data or region of interest. These transfer functions, however, require in-depth knowledge of the data, and it is a tedious task to modify transfer functions in rendering different data sets. Efficient transfer function design is still an active research area [13][14][9].

In recent years, the work in non-photorealistic rendering (NPR) techniques has been extended by numerous researchers. Some research is based on geometry meshes. With the division of silhouettes into outlines and shape lines, Martin and Torres described in [10] a virtual light model in obtaining non-photorealistic images. In [8], McGuire and Hughes introduced a feature-edge detection algorithm that runs entirely in hardware.

As for volume rendering, a new era has begun after Ebert and Rheinqans gave the definition of volume illustration in [1]. And thereafter, much research related has been carried out. There are many extensions to the volume illustration techniques. For example, In [6], Csébfalvi Morz introduced a technique of fast visualizing object contours based on NPR. And in [4], Nagy Z. presented an accurate, interactive silhouette extraction mechanism for texture-based volume rendering.

Some approaches combine the volume illustration enhancement with the traditional DVR. Helwig and

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Lukas in [18] introduced a two-level volume rendering method. Zhou and Hinz designed a method based on NPR for generating object contours and enhancing volumetric features to depict context information out of focal region, and in the focal region, the direct volume rendering method was used [5].

There are also some algorithms that introduce the idea of volume illustration in artistic rendering. Lu and Morris presented a framework for an interactive direct volume illustration system that simulates traditional stipple drawing [7]. Nagy and Schneider in [3] proposed interactive approaches to non-photorealistic volume illustration. For a number of seed points that are placed appropriately to represent selected volume structures, curvature lines are traced and encoded by a sparse set of control points. These curves are finally drawn as hatching strokes.

3. Distance weight boundary enhancement

Levoy [15] introduced gradient-based shading and opacity enhancement to volume rendering. Ebert and Rheinqans proposed a method to extend the work [1], which allows the user to selectively enhance the density of each volume sample by a function of the gradient. It is described as equation

$$o_g = o_v (k_{gc} + k_{gs} (\| \nabla_f \|)^{k_{ge}}) \qquad (1)$$

Here o_v is original opacity and ∇_f is the gradient vector at the sample position. k_{gc}, k_{gs} and k_{ge} are coefficients to control the range of gradient enhancement. Specially, k_{ge} controls the slope of the opacity curve.

This method, taking the structure information of gradient magnitude into account, is able to enhance the boundaries between different objects in a volume data. In order to acquire the depth cues of visualization as well, we would enhance boundaries of near objects more and those of far objects less, which is in accordance with the case in real world: boundaries of objects close to us are clearer than those of objects far off. As for the depth cues, previous researchers have proposed many approaches related, such as intensity depth cuing [16], tone shading [17], and distance color blending [1]. These methods are independent of other volume illustration methods. While we incorporate the depth cues into the boundary enhancement approach through the changing coefficient according to the sample's depth, which can be illustrated by equations

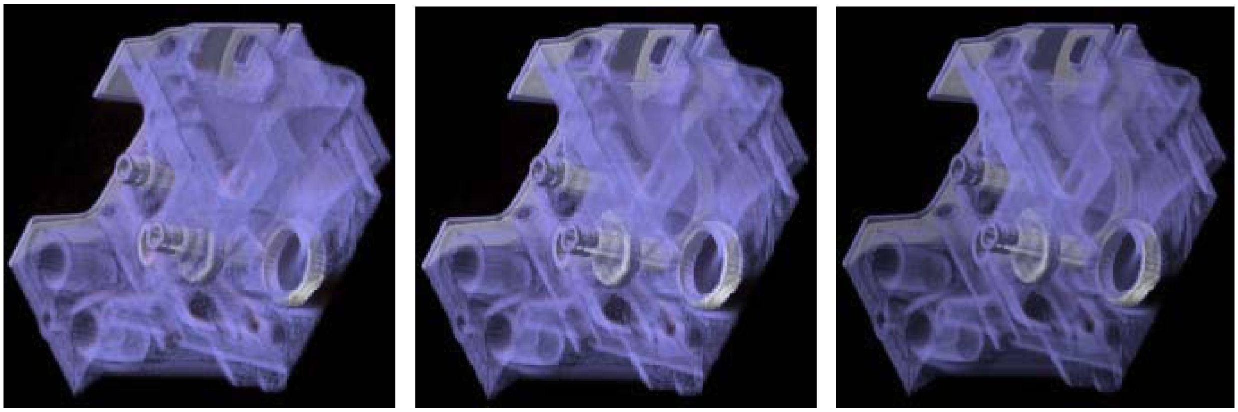
$$o_b = o_v [k_f + k_c \cdot d + k_d (1-d)(\| \nabla_f \|)^{k_e}] \qquad (2)$$

$$d = \frac{D_i}{D_{\max}} \qquad (3)$$

Here o_v is the original opacity; k_f is the ratio of the part that does not participate in boundary enhancement; k_d is the ratio of enhancement; d is distance coefficient equaling to the depth value at the sample position divided by the maximum depth of the data set, with premise that near objects have less depth; ∇_f is the gradient vector; k_e has the same meaning as the coefficient k_{ge} in Equation 1; and k_c is a compensating coefficient, since we want objects with great depth to be rendered largely in original method, instead of giving them less intensity as in intensity depth cuing. k_f, k_d, k_c and k_e are free to be set by users. But generally, k_f is less than 1, k_c is less than 1, sum of them is commended to be 1; k_d is greater than 1, and k_e is greater than 1. In our implementation, we let k_f be 0.0, and k_c be 1.0 with intention that the volume data fully takes part in the enhancement.

So the amount of boundary enhancement in this approach is changing with the sample's depth. In this changing process we are able to observe clear boundaries of the data and depth cues at the same time. Fig.1.b is an image of engine rendered with distance weight boundary enhancement in which $k_d = 4.0$, and $k_e = 1.0$, compared with the image rendered by DVR (Fig.1.a). We can see boundaries of the engine in Fig. 1.b are clearer. And there is a gradual change of intensity from up to down, as the upper part is nearer and more enhanced. Generally, in a rendered image, boundaries of near part can be more easily observed, whereas for the deeper part, detailed features won't be missed with the help of compensating coefficients.

The improved boundary enhancement approach is different from a combination of original boundary enhancement and a depth cuing approach such as intensity depth cuing. In the original enhancement, enhancing parameters are kept unchanged for all the voxels. If the parts with great gradient are emphasized, generally the even parts become more vague. Fig.1.c is an image rendered with the original boundary enhancement with intensity depth cuing method, in which $k_{gc} = 0.2$, $k_{gs} = 4.0$, $k_{ge} = 1.0$, and intensity of the farthest voxel is half of the original.



(a) (b) (c)

Figure 1. Engine rendered with (a) DVR (b) distance weight boundary enhancement (c) original boundary enhancement and intensity depth cuing

As we can see, although the depth cuing effect is quite obvious, darkness of the whole image (side effect of intensity depth cuing) makes it more difficult to observe the structure cues.

4. Gradient weight silhouette enhancement

Silhouettes are useful information for orientation cues and for rendering a sketch of the feature shape. The common approach of silhouette enhancement is to strengthen the areas where the view vector is orthogonal to the surface normal vector [17]. Ebert and Rheinqans in [1] implemented the idea in equation

$$o_s = o_v (k_{sc} + k_{ss}(1 - abs(\nabla_{fn} \cdot V))^{k_{se}}) \qquad (4)$$

Here ∇_{fn} is the gradient vector representing the surface normal vector, V is the view vector, k_{sc} controls the scaling of non-silhouette regions, k_{ss} controls the amount of silhouette enhancement, and k_{se} controls the sharpness of the silhouette curve.

As we can see, areas where gradient vector is perpendicular with view direction will obtain the most enhancements. They are addressed as the silhouette regions. However, this equation doesn't take the magnitude of the gradient into account, and as a result, areas with same gradient direction despite the magnitude would acquire the same amount of enhancement. This may result in a confusing image if the data set is a complex one with complicated appearance and shape. So our new approach add another factor into the silhouette enhancement, shown in equations

$$\begin{aligned} o_s = o_v[&k_f + k_c(1 - g_m) + \\ &k_s \cdot g_m(1 - abs(\nabla_{fn} \cdot V))^{k_e}] \end{aligned} \qquad (5)$$

$$g_m = \frac{\|\nabla_{fn}\|}{\|\nabla_{f\max}\|} \cdot k_a \qquad (6)$$

Here g_m is the gradient magnitude coefficient proportional to the division between the gradient magnitude at the sample position and the possible maximum gradient magnitude, k_a controls the amount of the weight, k_f controls the part without silhouette enhancement, k_s controls the amount of enhancement, k_e controls the slope of the silhouette curve, and k_c is the compensating coefficient based on our motivation that areas with little enhancement would be rendered in traditional DVR method. o_v, ∇_{fn} and V have the same meaning as in Equation 4. Usually, in coefficients' modulation, k_f and k_c are less than 1, sum of them had better be 1; k_a , k_s and k_e are greater than 1, since they represent the effects of enhancement. In our experiment, $k_f = 0.0$ and $k_c = 1.0$ so that the data set is fully enhanced.

The silhouette parts are usually the concave or protruding edges. With the addition of the gradient magnitude factor, enhancement of those edges will become more flexible, since the amount of enhancement is proportional to the amount of data value change. For important edges, where data change is sharp, such as the border of two objects, enhancement is more; while for small silhouettes, enhancement is less.

Figure 2. Bonsai rendered with (a) DVR (b) gradient weight silhouette enhancement (c) original boundary plus silhouette enhancement

Fig.2.b is a CT image of bonsai rendered using this approach with $k_s = 2.0$, and $k_e = 1.0$, $k_a = 2.0$, compared with the DVR image in Fig.2.a. With silhouette enhancement, the trunk and branches has more concave and protruding features. We can see the small holes on the wood surfaces, edge of which are the light curves in the image. And crown of the bonsai has more three-dimensional effect.

We benefit from two advantages as we put the gradient magnitude factor into the silhouette enhancement: First, we are able to acquire clear structure cues of the volume data, because for ordinary samples, opacity computed in this way is similar with that computed in DVR method; while samples with great gradient magnitude and view-orthogonal gradient direction will be considered as silhouette and emphasized. This differs from the effect of the original boundary plus silhouette enhancement. In that situation, though magnitude and direction of the gradient are also both used, only the boundary and silhouette regions are enhanced. Without the compensating coefficients, small features will possibly be missed. As in Fig.2.c, small features, such as the little holes on the trunk, are lost. Second, the enhancement parameters' varying with the data structure will increase the adaptability to different data sets. This point will further be discussed in next section.

5. Flexibility

The presence of volume illustration [1] allows a more flexible way in conveying structure information than traditional transfer function design. However, when rendering a new data set, usually modification of the enhancing parameters is needed to obtain a satisfactory image.

In contrast, we adopt changing parameters in the enhancement methods. The enhancing parameters change with the sample position and local gradient, and have better adaptability for various data sets. Coefficients' modulation is infrequent. Compared with the DVR techniques, the new approaches are able to "find" and enhance the boundary and silhouette areas, which are significant for conveying structure information. This is the main property of our methods. Generally, we can obtain an image with clear structure cues and small features included as well, since besides the enhancement of the boundary and silhouette regions, samples of inner or even areas can also be normally displayed in the final image.

6. Experiment and results

We incorporated the new approaches above into a ray-casting rendering pipeline. Resolutions of the data sets used are listed in Table 1. Specially, all the coefficients are kept unchanged to test the new approaches' flexibility. In distance weight boundary enhancement, $k_f = 0.0$, $k_c = 1.0$, $k_d = 4.0$, $k_e = 1.0$, and in gradient weight silhouette enhancement, $k_f = 0.0$, $k_c = 1.0$, $k_s = 2.0$, $k_e = 1.0$, $k_a = 2.0$. The images listed below are rendered with the combination of the two approaches. Comparison with the ray-casting images is given.

Back of the engine in Fig.3 has a brighter edge than that in Fig1.b, which is the effect of the silhouette enhancement. Trunk of the bonsai in Fig.4 is more three-dimensional with enhanced boundaries, and keeps small features such as the small holes on it as well. Also, the two approaches help to enrich the structure information. For example, in the head image of Fig.6, the veins on the temple, the nose, ear and eyes are clearer, which is largely result of the silhouette enhancement. And the protruding edges (the blue lines) on the Teddy bear's belly, forehead and legs are also successfully registered in Fig.8.

The two enhancement approaches are quite easy to implement. They are basically opacity modulation in the rendering pipeline. So there is almost no computation cost. But with these approaches, the improvement of image quality is prominent. And the improved enhancement algorithms are more flexible and good at registering the small features. Thus, they can be valuable tools in analyzing a volume data set.

Table 1. Resolution of the data sets used in experiment

Volume data sets	Resolution
Engine	256×256×110
Bonsai	256×256×128
Head	256×256×256
Teddy bear	128×128×62
Function	64×64×64

7. Conclusion

In this paper, we have introduced two improved enhancement methods in volume illustration. The depth information is added to the boundary enhancement process. As a result, both boundaries and inner areas can be clearly displayed with depth cues acquired at the same time. In silhouette enhancement, we take the local gradient magnitude into account, so that it can register more appropriately the unevenness of a volume data.

In implementation, the two improved methods show great flexibility. The reason is analyzed and from the rendering results we can see our new approaches are able to convey clearly the structure cues without missing of small features.

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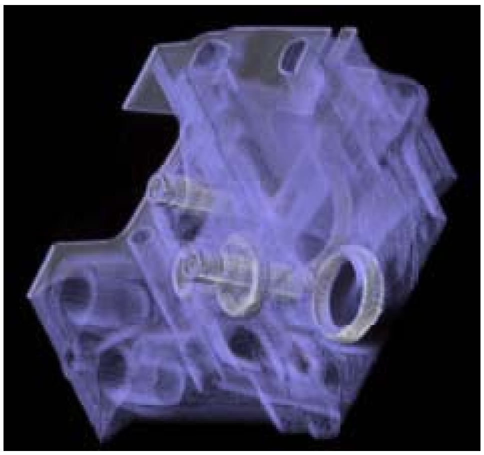

Figure 3. Engine rendered with improved boundary and silhouette enhancement

Figure 4. Bonsai rendered with improved boundary and silhouette enhancement

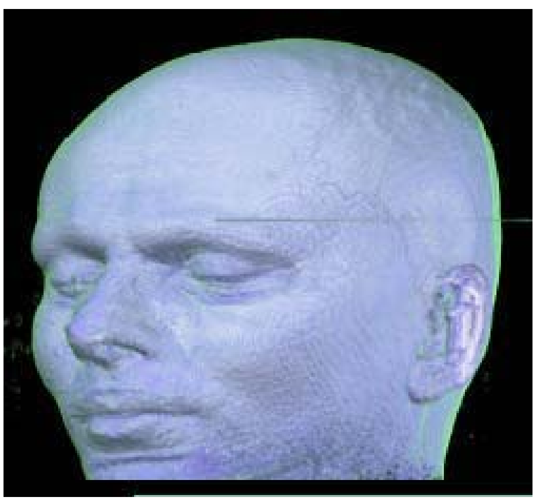

Figure 5. Head rendered with DVR

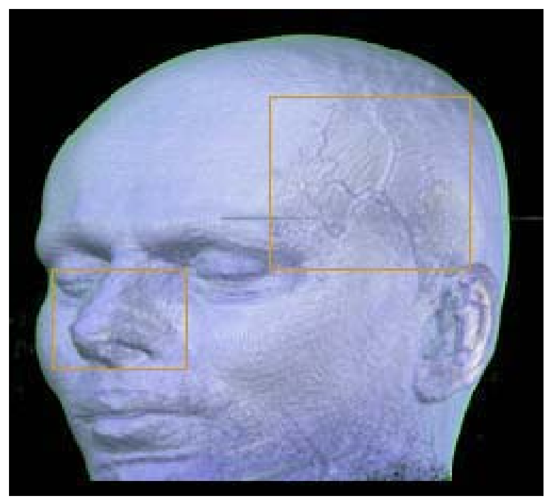

Figure 6. Head rendered with improved boundary and silhouette enhancement

Figure 7. Teddybear rendered with DVR

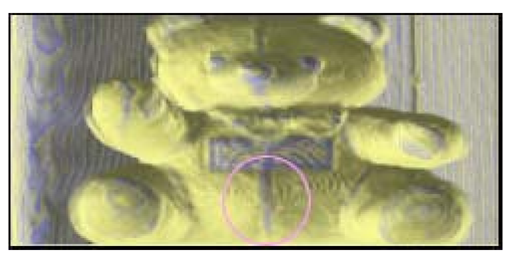

Figure 8. Teddybear rendered with improved boundary and silhouette enhancement