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ORIGINAL ARTICLE

Feature enhancement by volumetric unsharp masking

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Abstract Feature enhancement is important for the interpretation of complex structures and the detection of local details in volume visualization. We present a simple and effective method, volumetric unsharp masking, to enhance local contrast of features. In general, unsharp masking is an operation that adds the scaled high-frequency part of the signal to itself. The signal in this paper is the radiance at each sample point in the ray-casting based volume rendering, and the radiance depends on both transfer functions and lighting. Our volumetric unsharp masking modulates the radiance by adding back the scaled difference between the radiance and the smoothed radiance. This local color modulation does not change the shape of features due to the same opacity, but it does enhance local contrast of structures in a unified manner. We implemented volumetric unsharp masking at interactive frame rates based on current GPU features, and performed experiments on various volume data sets to validate this local contrast enhancement. The results showed that volumetric unsharp masking reveals more local details and improves depth perception.

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1 Introduction

Volume visualization finds wide application in many different fields, ranging from medicine and engineering to geophysics and biology. In the exploration process, features of interest are usually classified through transfer functions, which map scalar values to optical properties, such as color and opacity. Different features can be associated with different color and opacity values. Although a large number of classification approaches have been proposed for automatic/semiautomatic generation of transfer functions, it is still rather complex and time-consuming to specify an appropriate transfer function to highlight volume structures of interest [1]. Even with a well-designed transfer function, it is often hard to recognize complex structures due to the overlapping, and it is also difficult to distinguish local details due to the large granularity of classification. Therefore, besides transfer functions, it is necessary to further emphasize structures and details of features. Feature enhancement helps the interpretation of complex structures and the detection of local details.

In direct volume rendering, the rendering process integrates color and opacity values at each sample point along the ray through the volume rendering integral. In practice, lighting is also incorporated according to the Phong local illumination model to improve structure perception. As only color and opacity values are involved in this rendering process, we usually adjust color and opacity values dynamically to enhance features of interest.

The opacity of features is often modulated locally so that features of interest can stand out from other features. For example, importance-driven volume rendering [2] defines an object importance for each part of the volume, and the highly important features can be clearly visible by reducing the opacity of features before them. Context-preserving volume rendering [3] selectively reduces the opacity of less important features according to shading intensity, gradient magnitude, distance to the eye point, and previously accumulated opacity. On the other hand, the color of features can be also modulated to convey better overall sharp and local detail. Exaggerated shading [4] dynamically adapts the light position to the normal for each sample point, and combines intensities at multiple scales to reveal both overall structure and local detail.

In this paper, we are interested in color modulation, exactly the luminance value, to enhance local contrast of features. It is achieved through volumetric unsharp masking to provide better shape perception and detail recognition. Our approach extends 3D surface unsharp masking [5], which coherently enhances local scene contrast by unsharp masking over arbitrary 3D surfaces, to 3D volume unsharp masking. In general, unsharp masking is an operation that adds the scaled high-frequency part of the signal to itself. The signal in this paper is the radiance at each sample point of the ray, and the radiance relies on both transfer functions and lighting. The high-frequency part of the signal is constructed by subtracting a smoothed radiance from the original radiance itself. This local color modulation does not change the shape of features due to the same opacity, but it dose enhance local contrast of structures in a unified manner. As a result, overall shape and local detail can be perceived more clearly after volumetric unsharp masking.

The paper is structured as follows. The related work is discussed in Sect. 2. We present volumetric unsharp masking for local contrast enhancement in Sect.3. Section 4 explains its GPU implementation in detail. In Sect. 5, we show and discuss several results of volumetric unsharp masking.

2 Related work

Feature enhancement is an active research area in volume visualization, as it is useful for the interpretation of both overall shape and local detail in a more effective manner.

A more realistic illumination model could effectively enhance features in a natural way. In direct volume rendering, the most common physically-based optical model is absorption plus emission [6], i.e., each voxel emits light and absorbs incoming light, and the Phong model is one of the widely used illumination models. Behrens and Ratering [7] incorporated shadows into texture-based volume rendering. Kniss et al. [8] presented a volume lighting model and implemented various effects like volumetric shadows and forward scattering. Tarini et al. [9] employed ambient occlusion to enhance molecules visualization, and Ropinski et al. [10] introduced dynamic ambient occlusion for rendering volume data sets at interactive frame rates.

Since the goal of visualization is to effectively convey features of interest to the user, many non-photorealistic techniques have been developed to illustrate features expressively. The gradient magnitude was first introduced by Levoy [11] to allow better boundary perception. Rheingans and Ebert [12] presented various feature and orientation enhancements, such as boundary enhancement, silhouette enhancement, tone shading, distance color blending, and distance color cues. Kindlman et al. [13] utilized curvature information to control the thickness of contours and emphasize ridges and valleys. Halos are frequently used to highlight strong features by darkening the region around them [12, 14]. Bruckner and Gröller [15] addressed volumetric halos to enhance depth perception. In their work, occlusive halos darken the region around the feature, while emissive halos brighten the region around the feature.

As pointed out in the Introduction, the opacity and color are usually adjusted dynamically to enhance features of interest. Viola et al. [2] described importance-driven volume rendering to highlight features with a high object importance. Bruckner et al. [3] presented context-preserving volume rendering to selectively reduce the opacity of less important features. Marchesin et al. [16] proposed locally adaptive volume rendering to improve the visibility of features, and the opacity of every voxel contributed to one pixel was dynamically adjusted according to the number of non-empty contributions. As humans are not sensitive to inconsistent illumination, vicinity shading proposed by Stewart [17] enhances the perception of the volume based on occlusions in the local vicinity of a sample point, and this leads to shadows in depressions and crevices. Rusinkiewicz et al. [4] introduced exaggerated shading to reveal details at multiple scales. Our method also dynamically adjusts the color at each sample point. However, the color not only from illumination models but also from transfer functions is modulated in a unified manner. In addition, unsharp masking could achieve similar effects without processing at multiple scales [5].

The proposed method is based on unsharp masking that has been introduced in computer graphics. Cignoni et al. [18] performed unsharp masking the normal field over the 3D surfaces, to enhance the perception of discontinuous geometric features. Luft et al. [19] enhanced depth perception by unsharp masking the depth buffer. Ritschel et al. [5] coherently enhanced the scene by unsharp masking the outgoing radiance field over the mesh surface. Our volumetric unsharp masking extends 3D surfaces to 3D volumes, and performs radiance unsharp masking over the volume to enhance both overall shape and local detail.

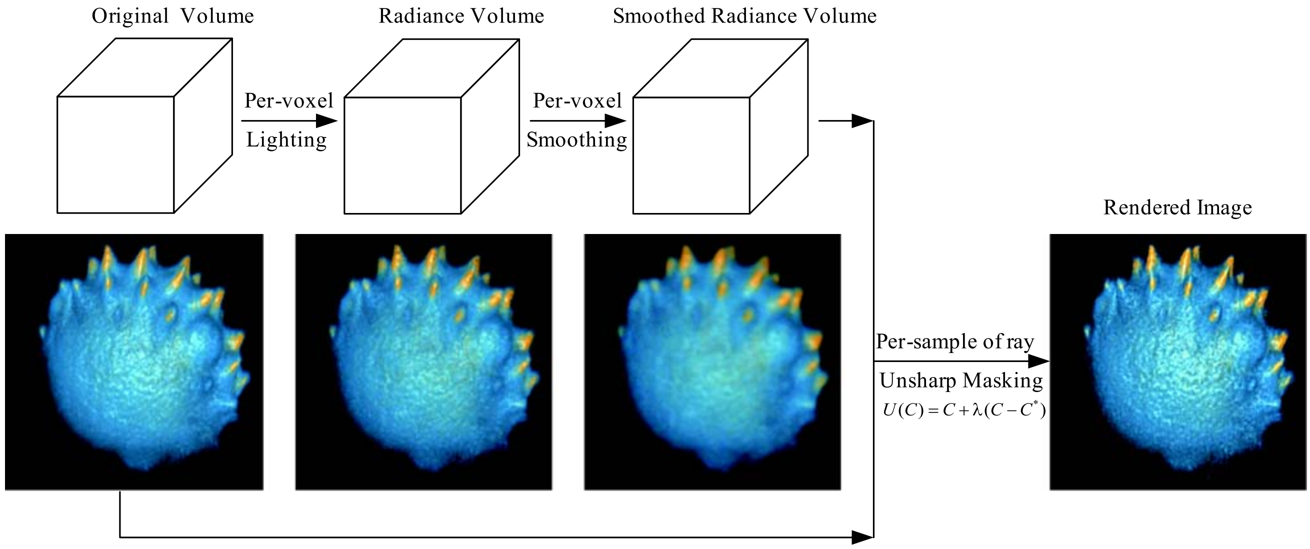

Fig. 1 The pipeline of volumetric unsharp masking. The outgoing radiance is first calculated per-voxel and stored in the radiance volume. The radiance volume is smoothed iteratively and the output is the smoothed radiance volume. In the ray-casting based volume rendering, the radiance of each sample point is adjusted through the unsharp masking operation. In this way, we could enhance local contrast of features of interest

3 Volumetric unsharp masking

Generally, unsharp masking is achieved by first smoothing the signal and then adding back the scaled difference between the original signal and the smoothed signal. This process is usually applied to 2D cases, such as 2D image [20], depth buffers [19], and 2D surfaces embedded in 3D [5, 18]. This may be due to the increased computational complex of 3D volumes. With the increasingly high arithmetic intensity and large memory bandwidth of modern graphics hardware, we can now implement unsharp masking over 3D volumes at interactive frame rates. The signal here is the radiance at each sample point of the ray, and volumetric unsharp masking is applied to each sample point during the ray-casting based volume rendering. As the smoothed radiance is band-limited, we calculate and store the radiance per-voxel like per-vertex for 3D surfaces [5].

The pipeline of volumetric unsharp masking is illustrated in Fig. 1. For each frame, the outgoing radiance is first calculated for each voxel and stored in the radiance volume V. Then the radiance volume is smoothed iteratively to produce the smoothed radiance volume V_σ. Finally, the radiance of each sample point of the ray is modulated by adding the difference between the current radiance and the smoothed radiance trilinear interpolated from V_σ.

3.1 Smoothed radiance volume generation

In this section, we introduce the generation process of the smoothed radiance volume V_σ. The radiance per-voxel is first figured out and stored in the radiance volume V, and then V_σ is generated by smoothing V repeatedly.

In order to generate the radiance volume, the scalar value of each voxel in the original volume is first mapped to color and opacity through a transfer function. As volumetric unsharp masking does not change the opacity value of each sample point, the opacity transfer function defines the interest/importance of features. The color from the color transfer function will be modulated in volumetric unsharp masking. A 1D transfer function based on the scalar value was used in our implementation, and it is possible to replace this simple transfer function with more effective transfer functions, such as high-dimensional transfer functions based on first and second derivatives [21].

There are many illumination models for direct volume rendering [22]. In this paper, we employ the Phong local illumination model, as it could be archived in real time. Formally, the color of a rendered voxel can be expressed as

$$C = \big(k_a + k_d(N \cdot L)\big) \cdot C_{TF} + k_s(N \cdot H)^n, \tag{1}$$

where k_a, k_d, and k_s are the ambient, diffuse, and specular lighting coefficients respectively, n is the shininess exponent, C_{TF} is the color from transfer functions, N is the normalized gradient direction of the voxel, L is the light direction, and H is the normalized half-way direction. Although we calculate different components in the Phong model separately, the color is finally enhanced in a unified way.

The lighting color C is multiplied by its associated opacity, which is known as the opacity-weighted color. This is very important for the later interpolation, as interpolating color and opacity separately results in artifacts [23]. Opacity-weighted colors are reserved in the corresponding voxel position of the radiance volume.

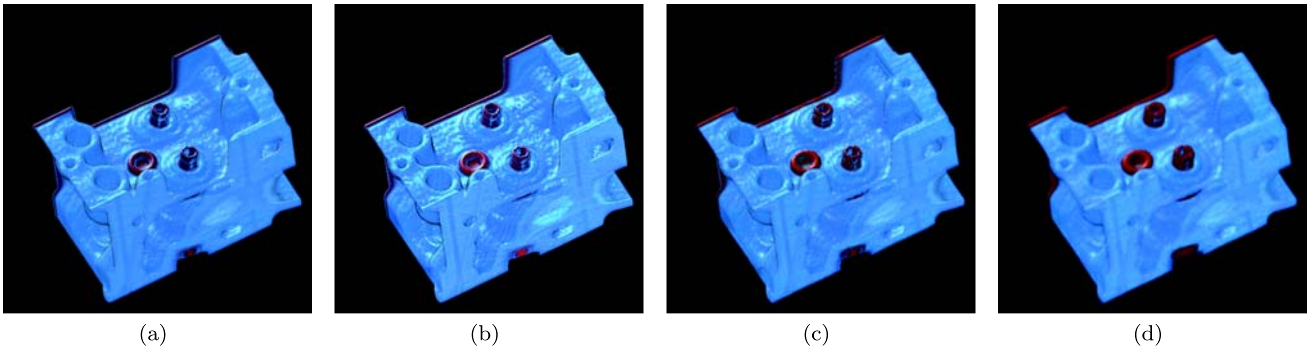

Fig. 2 The figure shows the rendered results of the engine data set via volumetric unsharp masking. (**a**) The original rendered image. (**b**) The rendered image vis volumetric unsharp masking ($\lambda = 0.5$). (**c**) The rendered result of the radiance volume. (**d**) The rendered image of the smoothed radiance volume

As the volume we assume is a regular grid, the smoothing of the radiance volume can be easily performed around a given voxel, such as a 6-, 18-, or 26-point neighborhood. Here, the smoothed radiance is calculated using Gaussian smoothing as follows:

$$C_i = \sum_{j=0}^{N} w_j C_i^j, \quad (2)$$

where w_j is the normalized Gaussian weight of the neighbor j ($\sum_j w_j = 1$), and N is the number of neighbors. This smoothing procedure is performed repeatedly to obtain the smoothed radiance volume V_σ, typically 2 or 3 times.

Figure 2 shows the rendered results of the engine data set through volumetric unsharp masking. The radiance volume is displayed in Fig. 2(c). This result actually is a pre-classification and pre-shading result, which would result in significant visible artifacts in the rendered image for a high-frequency transfer function [24]. Compared with the post-classification and post-shading result in Fig. 2(a), the rendered image of the radiance volume contains visible artifacts in color distribution. As shown in Fig. 2(d), local details and specular color are blurred and the smoothed radiance volume only contains the low-frequency part of the radiance volume.

3.2 Unsharp masking volume rendering

Given the smoothed radiance volume V_σ, we can dynamically modulate the radiance at each sample point of the ray to enhance local contrast. During the rendering process, the scalar value and gradient normal at each sample point are trilinear interpolated from the original volume data set. Using the same transfer function and illumination model, we first calculate the color C of the sample point. This is actually a post-classification and post-shading result. On the other hand, the smoothed color C_σ of the same sample point can be obtained through trilinear interpolation from the smoothed radiance volume V_σ. The color C_σ is a smoothed pre-classification and pre-shading result. We modulate the color of the sample point based on unsharp masking as follows:

$$U(C) = C + \lambda(C - C_\sigma), \quad (3)$$

where λ is a user chosen scale value. The contrast color is dependent on the smoothing procedure and the scale value λ. If the smoothing procedure is performed multiple times, the contrast radiance contains more high-frequency parts. As the scale value λ increases, larger scaled high frequencies in radiance are added back and local contrast becomes sharper. Note that we do not change the opacity of the sample point, and this preserves the shape of features. After volumetric unsharp masking, the modulated color is blended in front-to-back order along the ray.

As pointed out in 3D unsharp masking [5], the CIELAB color space is locally a perceptually uniform space, but the RGB color space is nonlinear. Features that are noticeable by human vision, can be also detected from the color difference in the CIELAB color space. As human are more sensitive to the luminance variation, it is intuitive to consider the luminance variation as the contrast. As a result, local contrast enhancement is operated in CIELAB color space,

$$U(C)_{LAB} = \left[L + \lambda(L - L_\sigma), ka, kb\right], \quad (4)$$

where (L, a, b) is the transformed CIELAB value of the color C, and L_σ is the transformed luminance value of the color C_σ. The value k is defined as $k = (L + \lambda(L - L_\sigma))/L$ to preserve saturation unchanged. In addition, the change of the luminance value also does not modify the hue angle.

As our smoothing procedure is performed in 3D volume itself, local contrast enhancement is coherent in the volume. The color at each sample point is dependent on the color from transfer functions and the lighting, and the luminance

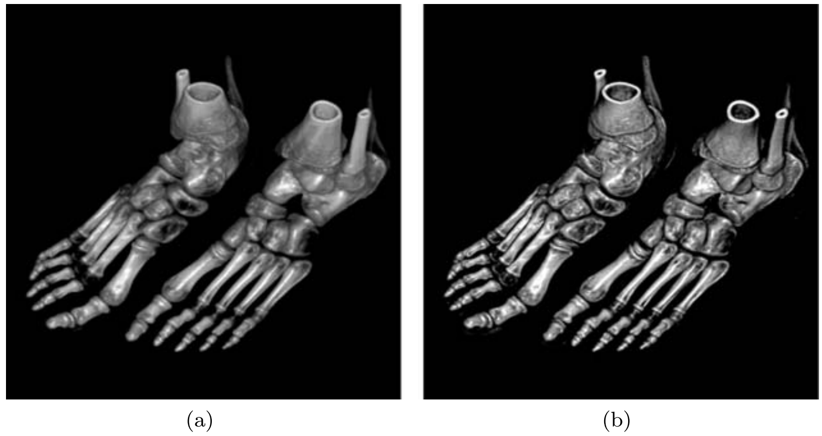

Fig. 3 The rendered images of the foot data set. (**a**) The rendered image based on standard direct volume rendering. (**b**) The rendered image based on unsharp masking volume rendering ($\lambda = 0.8$)

modification takes both factors into account in a unified manner. Compared with unsharp masking over 3D surfaces, our volumetric unsharp masking is more robust due to the uniform grid, and avoids the limitation of mesh tessellation.

4 GPU implementation

We have implemented volumetric unsharp masking discussed above in a GPU-based ray-casting volume renderer. It is based on current GPU features such as programmable shaders, framebuffer objects, and render to 3D texture. The per-voxel lighting and smoothing, as well as ray-casting volume renderer, are implemented using fragment shaders in the Cg language. The radiance volume and the smoothed radiance volume were stored in two 3D textures in the RGBA format with 8-bit resolution. The high-quality gradients were constructed through the tricubic B-spline filtering in the preprocess stage.

The per-voxel lighting shader reads data from one slice of the original volume and writes results to a 3D texture slice. The output 3D texture is smoothed in a similar way like per-voxel lighting, averaging several radiances of neighbors. We utilize a ping-pong approach to smooth the radiance volume iteratively. In the rendering process, the color at each sample point is transformed into the value in the CIELAB color space, then the luminance is locally modulated to enhance local contrast, finally the modified luminance and hue value are transformed back to the RGB color space for the color composition.

5 Results and discussion

With volumetric unsharp masking, we could enhance contrast of local details, and add depth perception for complex structures. In all our comparisons, the same transfer function and lighting parameters were used in standard direct volume rendering and unsharp masking volume rendering.

Figure 1 shows the back face of the daisy pollen grain data set. Compared with the rendered result of standard direct volume rendering, the result via volumetric unsharp masking highlights the wavy local details on the back face. These local details become more clear and visible due to local contrast enhancement. The enhanced result of the engine data set is displayed in Fig. 2. The rough surface of the engine data set seems more apparent, as the luminance differences are exaggerated in volumetric unsharp masking, and humans are usually more sensitive to local contrast in luminance. Besides local details on overall shape, volumetric unsharp masking can also enhance large features, which results in distinguishing them more easily, as shown in Fig. 3. The bones of the human foot are illustrated with clear boundaries, and more local details are added in the volumetric unsharp masking result for better shape perception.

We experimented different settings of the parameter λ by using the Nact phantom data set, as shown in Fig. 4. The rendered result of standard direct volume rendering is shown in Fig. 4(b), as $\lambda = 0.0$ implies that there is no modulation of the radiance at each sample point. If the parameter λ is below zero, local contrast decreases and local details are blurred. If the boundary of features is slightly gray, however, the negative parameter can generate halo effects, which brighten boundaries around strong features like emissive halos [15]. This effect can be seen clearly from Fig. 4(a) with $\lambda = -0.5$. Although the negative parameter may be considered as an improper parameter as discussed in [5], it can add depth cue to enhance depth perception in some situations. Figure 4(c) displays a normal parameter setting ($\lambda = 0.65$). As expected, shiny parts become shinier and dark parts become darker. The region around strong features looks like occlusion halos [15], and this also improves depth perception for occluded shapes. When a larger parameter is set, as shown in Fig. 4(d) ($\lambda = 1.5$), dark regions are more apparent. Taking a closer look, we can further detect dot points on the lung as lighting spots clearly. The parameter λ is very simple and intuitive, and the user can easily adjust it to illustrate different effects and to interpret complex structures.

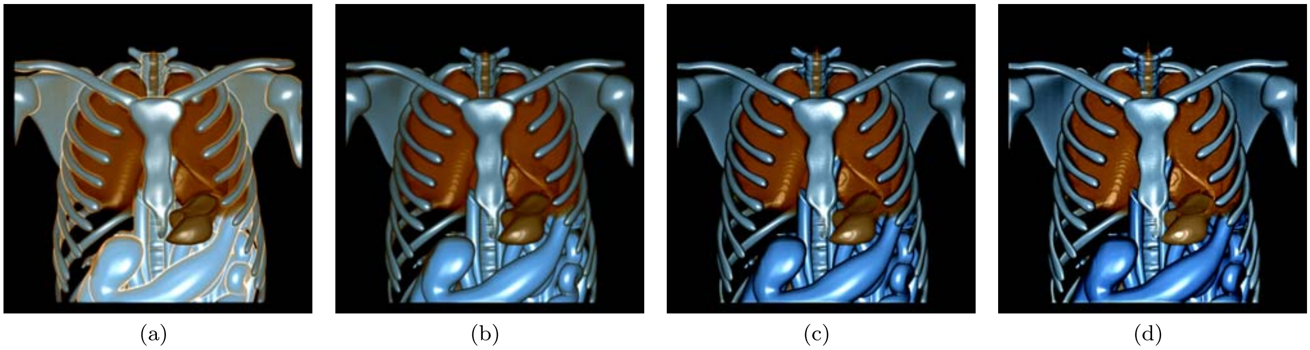

Fig. 4 The comparison of different settings of the parameter λ in volumetric unsharp masking. (**a**) $\lambda = -0.5$. (**b**) $\lambda = 0.0$. (**c**) $\lambda = 0.65$. (**d**) $\lambda = 1.5$

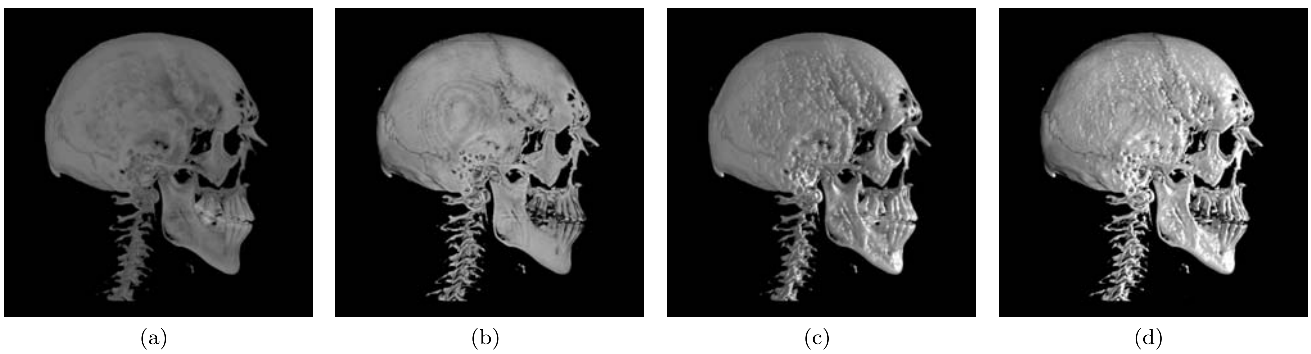

Fig. 5 The figure compares the rendered results of the Vismale data set without/with lighting. (**a**) The rendered image based on standard direct volume rendering without lighting. (**b**) The rendered image based on volumetric unsharp masking ($\lambda = 0.7$) without lighting. (**c**) The rendered image based on standard direct volume rendering with lighting. (**d**) The rendered image based on volumetric unsharp masking ($\lambda = 0.7$) with lighting

Table 1 Performance of standard direct volume rendering and unsharp masking volume rendering (frames/second)

Volume Data set	Size	Standard DVR	Unsharp masking VR
Daisy pollen grain	192 × 180 × 168	30.02	9.99
Engine	256 × 256 × 128	26.23	9.63
Foot	256 × 256 × 250	21.17	6.87
Nact phantom	256 × 256 × 256	20.01	6.74
Vismale	128 × 256 × 256	20.18	7.76

Figure 5 compares the effect of local contrast enhancement with/without lighting. Under the condition of no lighting, the color is only dependent on a color transfer function. As seen clearly from Fig. 5(a) and Fig. 5(b), structures and details are still enhanced, especially bones of the neck. With lighting, volumetric unsharp masking further enhances local contrast of the skull, and many rough details can be clearly observed from Fig. 5(d). In fact, our approach enhances the luminance contrast from transfer functions and lighting in a unified manner.

The performance of unsharp masking volume rendering compared with standard direct volume rendering, as well as the size of experimented data sets, is illustrated in Table 1. The performance was measured on a 3.0 GHz Intel Core 2 Dual CPU with an NVIDIA GeForce 8800 GTX. The sampling distance of the ray casting was 0.5 of the voxel size, and the viewport size was 512 × 512. The frame rate was averaged over a 360 degree rotation along each axis. Our method is approximate one third of the frame rate of standard direct volume rendering due to volumetric unsharp masking. However, it still achieves interactive frame rates. Moreover, additional optimizations such as empty-space skipping could be employed for improvement.

Limitation One limitation of our volumetric unsharp masking is the large storage requirement of two additional 3D textures, the radiance volume and the smoothed radiance volume. As the size of the original volume grows, it is highly memory-consuming to store these two full-resolution volumes. Furthermore, it is also very time-consuming to compute these smoothed radiances for each voxel. It is fortunate that GPUs are increasingly growing to satisfy the requirement of large memory and high intensity. Actually, as only the luminance value is required in volumetric unsharp masking, we can just store the luminance channel to reduce storage requirement. Additionally, as we are interested in the smoothed radiance, which is a band-limit signal, we could calculate these radiance volumes at a lower resolution, especially for linear transfer functions. This will greatly reduce the memory requirement and improve the efficiency of volumetric unsharp masking. In our implementation, these two radiance volumes are computed at a full resolution. Another limitation of our approach is that we assume that the volume contains local details on overall shapes. If the volume is very smooth, our approach may introduce annular artifacts, as it takes middle frequencies even low frequencies as high frequencies and enhances them as a whole. However, with the development of high-resolution digital imaging techniques, more and more rich detailed volume data sets will be available in the future, and our approach will help better interpreting complex structures and detecting local details.

6 Conclusions and future work

In this paper, we presented a simple and effective method, volumetric unsharp masking, to enhance features of interest in the volume. Volumetric unsharp masking modulates the current radiance at each sample point of the ray by adding back the scaled difference between the current radiance and the smoothed radiance. This could enhance local contrast for better interpretation of complex structures and detection of local details. Based on current GPU features, volumetric unsharp masking can be implemented at interactive frame rates. We performed experiments on various volume data sets to compare unsharp masking volume rendering with standard direct volume rendering. The results showed that unsharp masking volume rendering reveals more local details and improves depth perception. In the future, we would incorporate shadows [7] into unsharp masking volume rendering, as the shadow is an important cue to interpret complex structures. However, this additional operation would influence the rendering performance due to the relative low performance of GPU-based ray casting with shadow rays. Low-resolution radiance volume would be a possible solution to improve performance.

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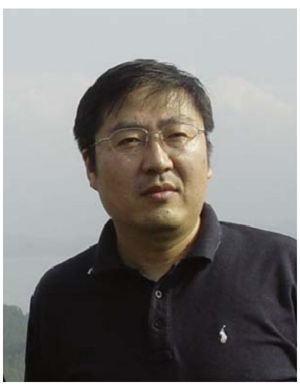

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