Improved gradient estimation methods for rendering of volume data

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ABSTRACT

The paper presents two methods that improve gradient estimation in 3D voxel space. The gradient estimation is an important step in the rendering and shading process to obtain realistic and smooth final images of visualized objects. The most used gradient estimation methods, gray-level gradient methods, Z-buffer gradient methods and binary gradient methods in some cases produce artifacts that appear as dark areas and staircase structures in a final image. To deal with the problem, two new methods for gradient estimation are suggested, the reverse gradient method and the angle difference method. The new methods were tested and compared with other gradient estimation methods. Measurements, which have been made on both the data and image levels, have shown that both developed methods improve the quality of volume data rendering.

Keywords
Voxel visualization, gradient estimation, volume and surface rendering.

1. INTRODUCTION

Various applications of new technologies that are used for studying three-dimensional objects (e.g. CT and MRI), have in the last two decades lead to a development of new methods for visualization of sampled volume data. The visualization pipeline consists of several consecutive steps of volume data processing, such as acquiring the data, pre-processing, creating a model and final rendering.

The rendering process is composed of projecting the three-dimensional information of a model into a two-dimensional image and of shading [Pho75]. To shade projected voxels the local gradient is often used as an approximation of the surface normal.

For simple surfaces in continuous space the surface normal might be provided analytically by computing the vector perpendicular to the tangent plane at the point. In discrete space an analytic description of a surface is usually not known, because 3D datasets are obtained by sampling. In discrete volume datasets several methods exist to estimate a local gradient: gray-level gradient methods [Lev88] [Zuc81], Z-buffer gradient methods [Gor85] [Che85] and binary gradient methods [Thü97]. In some cases, these methods produce artifacts in the final image such as dark areas and staircase structures (see Fig. 6a). To overcome these problems, two new methods for gradient estimation will be introduced, the reverse gradient method and the angle difference method. These new methods will be tested and compared with other known methods. Measurements, which have been made both on the data and image levels, have shown that both developed methods are suitable for volume data rendering.

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2. PROBLEMS

The most commonly used method for gradient estimation is the gray-level gradient shading method based on central differences. This method presents good results in common cases; however there are also situations in which this method creates artifacts in the final image. We analyzed the situations in which artifacts appear and have found the following problems.

Neighborhood problem

The gray-level gradient method uses differences of the voxel intensity of neighbors. The direction of the calculated gradient points in the direction from the place with the lower voxel intensity to the place with the higher voxel intensity. When a part of the visualized object has lower voxel intensity then its surrounding, dark areas appear in the final image. This is because this part is not oriented to the light source and is not illuminated.

Boundary definition problem

Before rendering, it is necessary to do segmentation and classification of the visualized objects in the 3D dataset. Many automatic and manual methods are used. In the case of manual segmentation the boundary of the segmented object is frequently different from the real border of the object. If the gray level gradient method is used, then differences of the voxel intensities produce vectors with wrong orientation and size.

3. NEW METHODS

In the following section we present two approaches to the mentioned problems.

Reversed gradient method

The reverse gradient method eliminates the neighborhood problem analyzed in the previous section. The method reverses the orientation of the estimated normal vector towards the light source whenever needed, so that the whole surface is illuminated.

Let $\vec{G}$ be the gradient estimated by some known gradient estimation method and $\vec{L}$ be the vector pointing to the light source. Then the normal vector $\vec{N}$ is calculated by $\vec{N} = \vec{G}/|\vec{G}|$ for $\vec{L} \bullet \vec{G} \geq 0$ and $\vec{N} = -\vec{G}/|\vec{G}|$ for $\vec{L} \bullet \vec{G} < 0$.

The calculation of the normal vector could be simplified on the level of the Phong illumination model [Pho75]. The Phong formula for the diffuse component of the light intensity is then modified in the following way $I_d = k_d I_L |\vec{L} \bullet \vec{N}|$.

Angle difference gradient method

During the shading of surfaces of manually segmented objects, binary gradient methods produce better final pictures in many cases. But correctly oriented gradients could cause staircase artifacts in the final image. The angle gradient method estimates the gradient by combining the values calculated by the binary method from the voxel classification in the 26-neighborhood and the values obtained by a different method, e.g. the gray-level gradient method. The angle between the normal vectors obtained by both methods is calculated. If the angle is greater than a suitably chosen limit angle, then the gradient obtained from the binary method is used. Otherwise, the gradient determined by the other method is used.

Let $\vec{G}_V$ be the gradient estimated by some known gradient estimation method using the voxel intensity and $\vec{G}_C$ be the gradient estimated by the binary method from the voxel classification in the 26-neighborhood. Then components of the normal vector $\vec{N}$ are calculated by $\vec{N} = \vec{G}_V / |\vec{G}_V|$ for $\varepsilon \leq \varepsilon_{\max}$ and $\vec{N} = \vec{G}_C / |\vec{G}_C|$ for $\varepsilon > \varepsilon_{\max}$, where $\varepsilon_{\max}$ is the limit angle and ε is the angle between $\vec{G}_V$ and $\vec{G}_C$.

The maximum error of this method is given by the sum $\delta_{\max} + \varepsilon_{\max}$ (see Fig. 1). The error $\delta_{\max}$ of the binary gradient method to be known $\delta_{\max} = \arctan\left(\frac{1}{2}\right) = 26{,}6°$ [Thü97] and the limit angle $\varepsilon_{\max}$ is chosen by testing. For our testing objects the suitable value is $\varepsilon_{\max} = 10°$.

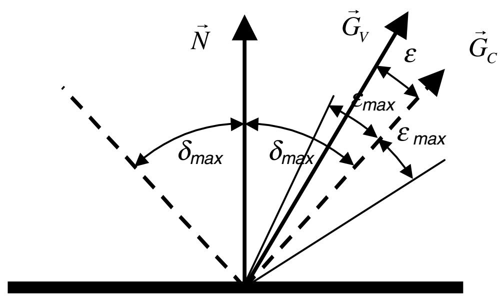


Figure 1. Maximum error of the angle difference method

Both designed method can be combined with each other. Firstly, the gradient is estimated by some of the common method described, secondly, the reverse gradient method is applied and finely the angle difference method is used.

4. MEASUREMENT AND DATA

Method of comparison

To compare gradient estimation methods we used both data level and image level comparison methods [Kim99]. Data level comparison uses intermediate 3D information to produce the individual pixel values during the rendering process. We used artificial testing object with known geometric shape (a sphere), so we can compare analytic values with measured values by a chosen metric. We compare the direction of the surface normal vector and calculate the mean arithmetic error (MAE) and the maximum value error (MAX) for the whole image. Image level comparison compares the final images produced by rendering. We have compared both iso-surface rendering methods [Pom90] and direct volume rendering methods [Lev88].

In the next figures we use the following abbreviations for rendering and the gradient estimation methods.

S_GLG26 – surface rendering using the gray-level gradient method with the central difference of the 26-neigborhood.

S_BG26 – surface rendering method using the binary gradient method of the 26-neigborhood.

S_FUNC – surface rendering method using the gradients from known analytical function.

V_GLG – volume rendering method using the gray-level gradient method with the central difference.

RG+ADG – applied improved methods: the reverse gradient method and the angle difference gradient method.

Artificial data

To compare the improved methods with the known methods we used two artificial testing objects *Sphere1* and *Sphere2*. The testing objects are voxel models defined by the intensity function $\eta(r)$ depending on the distance from the center of the sphere (see Fig. 2). The voxels of objects are classified by condition $r \le R$, where R is radius of the sphere.

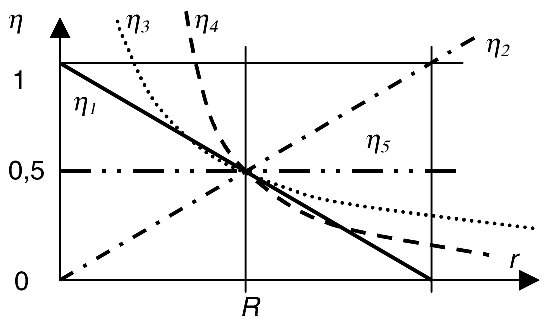


Figure 2. The defined voxel intensity functions depending on the distance from the center of the sphere

Both objects *Sphere1* and *Sphere2* are divided into four quadrants in which a different intensity function is used (Fig. 3). The function η_6 is random function. The objects are voxelized to the space of 32x32x32 voxels with 256 gray levels. The zoom transformation with coefficient 5 was used and the final image has the approximate size of 140x140 pixels.

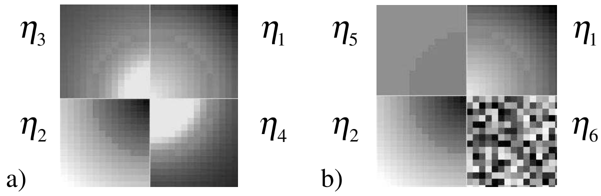


Figure 3. The definiton of the testing objects a) *Sphere1* and b) *Sphere2* - slice of the object and the functions in quadrants

Real data set

Besides artificial testing objects real datasets were used. Data of the human head were acquired from computer tomography and manually segmented. For testing gradient estimation methods the human brain was used. The voxel model has the size of 341 x 226 x 272 voxels and the final image 422 x 596 pixels. The object was zoomed twice and rendered in the direction of the viewing vector (-0.29, 0.95, -0.05).

5. RESULTS

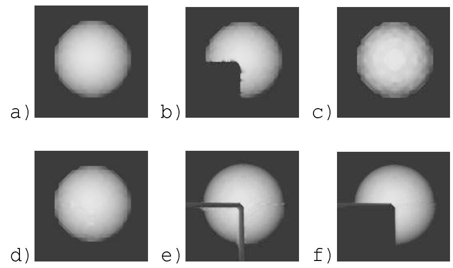


Figure 4. Object *Sphere1* a) S_FUNC, b) S_GLG26, c) S_BG-26, d) S_GLG26+RG+ADG , e) V_GLG+RG+ADG, f) V_GLG

Final images of surface rendering (see Fig. 4d and 5d) show that reverse gradient method and angel difference gradient method produce good results for testing objects. In case of volume rendering (see Fig. 4e and 5e) designed methods did not eliminate all artifacts.

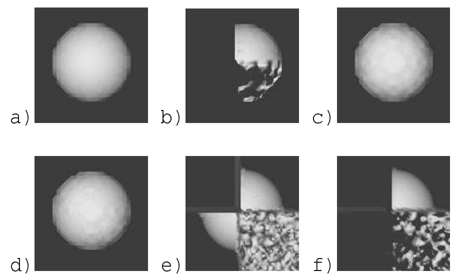
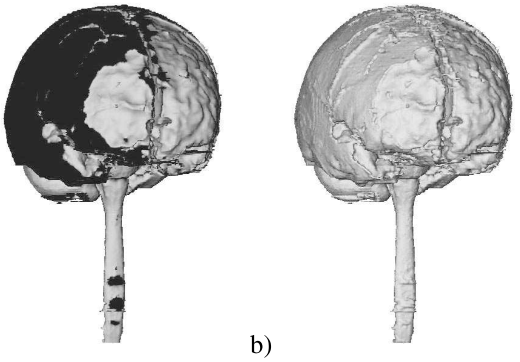


Figure 5. Object *Sphere2* a) S_FUNC, b) S_GLG26, c) S_BG-26, d) S_GLG26+RG+ADG , e) V_GLG+RG+ADG, f) V_GLG



a) b)

Figure 6. Visualization of the real dataset a) S_GLG26 b) S_GLG26+RG+ADG

6. CONCLUSION

Gradient estimation of 3D volume data is a key factor during the rendering process. The gradient, respectively the normal vector, is used for shading and has a great influence on the quality of the final image. The most common method is the gray level gradient method. In some cases this method produces artifacts that appear as dark areas in the final image. We have analyzed this situation and defined two sources of the problem. We called them the neighborhood problem and the boundary definition problem.

To avoid these artifacts two new methods for gradient estimation are suggested, the reversed gradient method and the angle difference method. The reversed gradient method is based on orienting the normal vector towards the light source, so that the whole surface is illuminated, that prevents dark artifacts caused by the wrong orientation of the normal vector.

The angle difference method estimates the gradient by combining the values calculated by a binary method from the classification of the voxels in the 26-neighbourhood and the values obtained by a different method, e.g. the gray level gradient method. The angle between the normal vectors obtained by both methods is calculated. If the angle is greater than a suitably chosen limit angle, then the gradient obtained from the classification is used. Otherwise, the gradient determined by the other method is used.

Both designed methods can be combined with each other. Firstly, the gradient is estimated by some of the method described in section 2, secondly, the reverse gradient method is applied and finally the angle difference method is used.

A way of testing and comparing the methods has been suggested, including suitable testing data. The comparison has been done by using suitable metrics both on the data level and the image level. Two types of data have been used - specially designed artificial data and real data acquired from existing objects by a computer tomography.

Besides the new suggested methods depicted above, several already known gradient estimation methods have been implemented. The new methods have been compared with other methods and measurements have been made on both the data and image levels. The measurements have shown that both suggested methods are suitable for rendering of volume data. The measurements confirmed that suggested methods avoid artifacts. In all tested cases, the mean absolute error was less than 1% and the maximal error less than 10%. It has turned out that the limit angle of 10 degrees in the angle difference method produces good results. Suggestions for usage of various methods have also been formulated. The reversed gradient method is suitable both for surface and volume rendering. The angle difference method is suitable only for surface rendering.

7. ACKNOWLEDGMENTS

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