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Visual saliency guided normal enhancement technique for 3D shape depiction

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ABSTRACT

Visual saliency can effectively guide the viewer's visual attention to salient regions of a 3D shape. Incorporating the visual saliency measure of a polygonal mesh into the normal enhancement operation, a novel saliency guided shading scheme for shape depiction is developed in this paper. Due to the visual saliency measure of the 3D shape, our approach will adjust the illumination and shading to enhance the geometric salient features of the underlying model by dynamically perturbing the surface normals. The experimental results demonstrate that our non-photorealistic shading scheme can enhance the depiction of the underlying shape and the visual perception of its salient features for expressive rendering. Compared with previous normal enhancement techniques, our approach can effectively convey surface details to improve shape depiction without impairing the desired appearance.

1. Introduction

Inspired by the principles of visual perception based on perceptual psychology and cognitive science, researchers have shown that the visual perception and the comprehensibility of complex 3D models can always be greatly enhanced by guiding the viewer's attention to visually salient regions in low-level human vision [1–3]. Owing to its efficiency of visual persuasion in traditional art and technical illustrations, visual saliency has now been widely used in many computer graphics applications, including saliency guided shape enhancement [4,5], saliency guided shape simplification [6–8], saliency guided lighting [9,10], saliency guided viewpoint selection [11–14], feature extraction and shape matching [15,16], etc.

In general, the visual saliency measures which region of a 3D shape or a 2D image stand out with respect to its neighboring regions [17]. The bottom-up mechanism [6,18] for determining visual saliency can guide the viewer's attention to stimulus-based salient regions, which will be affected by color, intensity, orientation, size, curvature, etc. Moreover, the information-based saliency measure proposed by Feixas and their colleagues [12,19] can allow an automatic focus of attention on interesting objects and characteristic viewpoints selection, which is defined by an information channel between a pre-sampled set of viewpoints and the set of polygons of an object in a context aware manner.

By pushing the influence of visual attention into the graphics rendering pipeline, the depiction of 3D shape can be enhanced by conveying its visually salient features as clearly as possible. Many research work in visual perception have argued that the human visual system can perceive surface shape through patterns of shading [20,21]. The enhanced surface shading supplies both surface fine-scale details and overall shape information that help for qualitative understanding in the visual perception of the highly-detailed complex models.

Our goal in this paper is to improve the shading of visually salient regions by dynamically perturbing the surface normals whilst keeping the desired appearance unimpaired. Guided by the visual saliency measure, we can adaptively alter the vertex lighting to enhance the visual perception of the visually salient regions in a non-realistic rendering style. Thus, the surface normal of each vertex can be dynamically perturbed in terms of the variation of vertex luminance, which is adjusted according to its saliency measure.

Our main contributions of this paper are as follows.

- According to the classical Phong lighting model, the theoretical analysis of the variation of vertex luminance is given, which is caused by perturbing the surface normal.
- Incorporating the visual saliency information into the normal enhancement operation, a novel saliency guided shading scheme is presented which will adjust the illumination and shading to improve the shape depiction.
- The expressive rendering generated by our proposed shading scheme can enhance the visually salient features of the underlying shape.

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The paper is organized as follows. Related work of shading-based shape depiction techniques is reviewed in Section 2. Section 3 gives the theoretical analysis of our normal enhancement scheme via the classical Phong local lighting model. An expressive rendering technique for 3D models by using our normal enhancement operation is described in Section 4. Section 5 gives some experimental results and discussion. Finally, Section 6 concludes the paper and gives some future research directions.

2. Related work

In the fields of computer graphics and non-photorealistic rendering (NPR) [22], many shape depiction techniques have been presented to alter reflection rules based on lighting environment and local surface attribution, thus for conveying both surface details and overall shape clearly, that is, by manipulation the surface shading and shadows, or by adjusting the geometric information of the underlying surfaces.

One important shade-based scheme for shape depiction is to manipulate the surface shading and shadows by altering the lighting environment or the viewer direction. Early in 1994, Miller [23] proposed the so-called "accessibility" shading method for shape depiction which conveys information about concavities of a 3D object. Based on the occlusion measure of nearby geometry, the ambient occlusion technique tends to darken surface concave regions that are hardly accessible and to enhance shape depiction [24]. Such methods may depict some surface details, however, many shallow (yet salient) surface details will be ignored or even smoothed out.

For the purpose of technical illustration, Gooch et al. [25,26] presented a non-photorealistic rendering algorithm for automatic technical illustration for 3D models, which used warm-to-cool tones in color transition along the change of surface normals. Relying on coloring based on curvature, Kindlmann et al. [27] presented a mean-curvature shading scheme to color convex areas of an object lighter and concave areas darker. Extending the classic 1D toon texture to a 2D toon texture, Barla et al. [28] employed the X-Toon shader to depict 3D shapes by the cartoon shading technique. Inspired by principals for cartographic terrain relief, the exaggerated shading of Rusinkiewicz et al. [29] makes use of normals at multiple scales to define surface relief and relies on a half-Lambertian to reveal relief details at grazing angles.

Recently, Ritshel et al. [30] proposed a unsharp masking technique to increase the contrast of reflected radiance in 3D scenes, and thus enhances various cues of reflected light caused by variations in geometry, materials and light. Vergne et al. [31] presented a shape descriptor called apparent relief, which makes use of both object-space and image-space attributes to extract convexity and curvedness information, respectively. This shape descriptor provides a flexible approach to the selection of continuous shape cues, and thus is efficient for stylized shape depiction. Cipriano et al. [32] proposed a multi-scale shape descriptors for surface meshes, which is capable of characterizing regions of varying size and thus can be used in multi-scale lighting and stylized rendering. The light warping technique proposed by Vergne et al. [33] can enhance the view-dependent curvature information by warping the incoming lighting at every surface point to compress the reflected light patterns. Another surface enhancement technique proposed by Vergne et al. [34] is called radiance scaling. It can adjust reflected light intensity per incoming light direction by a scaling function which depends on both surface curvature and material characteristics. However, these methods have not taken the effect of visual saliency into consideration during shape depiction, which can guide the visual attention in low-level human vision.

Another shade-based shape depiction approach is to adjust the geometric information, i.e. vertex positions and surface normals to improve the illustration of 3D shape. Building upon the mesh saliency measure, Kim and Varshney [5] developed a technique to alter vertex position information to elicit greater visual attention. However, their persuasion filters may impair the shape appearance in the geometry modification operation by using the bilateral displacements.

Here, we would rather seek a saliency guided normal enhancement technique that improves the objective shape depiction explicitly, and one closely related work is the technique of Cignoni et al. [35], which enhances the geometric features during the rendering by a simple high-frequency enhancement operation of the surface normals. However, their simple normal enhancement scheme is efficient to enhance the shading of regular CAD models but not very suitable to highly detailed 3D complex shapes. Incorporating the mesh saliency information into the normal adjustment operation, in this paper, we developed a novel saliency guided shading scheme for 3D shape depiction which will adjust the illumination and shading to enhance the geometric salient features of the underlying shape.

3. Theoretical analysis of normal enhancement

In traditional computer graphics, the classical Phong local lighting model [36] is generally adopted to generate realistic rendering results. Given the unit vector $\mathbf{L}$ in the direction of light source and the unit vector $\mathbf{V}$ in the view direction, the halfway unit vector $\mathbf{H}$ can be easily determined as $(\mathbf{V}+\mathbf{L})/2/\|(\mathbf{V}+\mathbf{L})/2\|$. Then, the lighting of vertex $\mathbf{v}$ (with unit normal vector $\mathbf{N}$) can be estimated as follows:

$$\mathbf{I} = k_a\mathbf{I}_a + \mathbf{I}_l[k_d(\mathbf{N}\cdot\mathbf{L}) + k_s(\mathbf{N}\cdot\mathbf{H})^n]$$

in which the first term is the ambient lighting component ($\mathbf{I}_a$ means the intensity of ambient light and k_a is the ambient reflection coefficient), the second and third terms are the diffuse lighting and specular lighting components, respectively ($\mathbf{I}_l$ means the intensity of point light source, k_d and k_s are the diffuse and specular reflection coefficients, n is the specular exponent of the material).

According to the Phong local lighting model [36], we can calculate the luminance of each vertex due to its surface normal, lighting environment and material attributes. Specifically, the lighting of a surface vertex will be adjusted if the surface normal has been perturbed. In detail, if the unit normal vector of vertex $\mathbf{v}$ is altered from $\mathbf{N}$ to $\mathbf{N}+\Delta\mathbf{N}$, the variation of its luminance can then be calculated as

$$\Delta\mathbf{I} = \mathbf{I}_l k_d(\Delta\mathbf{N}\cdot\mathbf{L}) + \mathbf{I}_l k_s[n(\mathbf{N}\cdot\mathbf{H})^{n-1}(\Delta\mathbf{N}\cdot\mathbf{H}) + o(\Delta\mathbf{N}\cdot\mathbf{H})]$$

However, in order to correctly compute the variation of lighting via the perturbation of the vertex unit normal, one intrinsic constraint condition is that the final adjusted normal vector $\mathbf{N}+\Delta\mathbf{N}$ should also be a unit vector,

$$\|\mathbf{N}+\Delta\mathbf{N}\| = 1$$

that is,

$$\textit{Constraint } 1: \Delta\mathbf{N}\cdot\Delta\mathbf{N} = -2\mathbf{N}\cdot\Delta\mathbf{N} \quad (1)$$

Moreover, in terms of the principals of cartographic terrain relief [29,37], the shadows and specular reflections may be omitted for 3D shape depiction by communicating surface subtle details. Thus, we assume here the variation of vertex luminance mainly comes from the diffuse lighting, whilst the influence of specular reflections on improving shape depiction will be omitted. So, another constraint should be introduced for computing the variation of vertex lighting, i.e.,

$$\textit{Constraint } 2: \Delta\mathbf{N}\cdot\mathbf{H} = 0 \quad (2)$$

Considering all of these constraints, the variation of vertex luminance $\mathbf{v}$ can be finally determined as

$$\Delta\mathbf{I}/\mathbf{I}_l = k_d(\Delta\mathbf{N}\cdot\mathbf{L}) \quad (3)$$