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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

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

For the saliency guided expressive rendering in general 3D shape depiction, surface details can always be enhanced by transitions at the surface's salient features. In order to improve the depiction of the visually salient shape features and additionally account for shadows and contrasts, we take the estimated saliency weight map as an enhancement tool to guide the adjustment of vertex luminance. In our implementation, we simply proportionate the variation of vertex luminance to the visual saliency measure of the surface vertex, which will be defined in the following Section 4.3.

4. Visual saliency guided normal enhancement technique

4.1. Motivation of our approach

The motivation of our saliency guided shape depiction technique is that the appropriate shading supplies both surface details and overall shape information that help for qualitative understanding 3D shape [20]. According to the Phong lighting model [36] in computer graphics, the shading of 3D shape is closely related to three factors, i.e., the surface normal, the lighting direction and the view direction. Here, we focus on the influence of normal perturbation on improving surface shading in terms of visual saliency measure, which is an important factor to attract the viewer's visual attention to salient regions during the shape depiction. 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, though the final shading may be physically incorrect. 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 algorithm takes triangular meshes as input. The algorithm of our saliency guided normal enhancement technique includes following two correlative steps. One is the definition of visual saliency measure of 3D mesh (see Section 4.2), the other is the perturbation of the surface normals guided by the saliency measure (see Section 4.3).

4.2. Visual saliency analysis for 3D mesh

For visual saliency measure of 3D shape, the following two typical definitions are employed as a perception-inspired measure of regional importance.

One mesh saliency definition is proposed by Lee et al. [6], which can be calculated using the center-surround mechanism on surface mean-curvature distribution at multiple scales. In practice, similar to Lee et al. [6], we use five scales $\sigma_i \in \{2\varepsilon,3\varepsilon,4\varepsilon,5\varepsilon,6\varepsilon\}$ to evaluate mesh saliency of different scales, where ε is 0.3% of the length of the diagonal of the bounding box of the underlying model. And the mesh saliency $s(\mathbf{v})$ of each vertex $\mathbf{v}$ can be estimated by adding the saliency maps at all five scales after applying the non-linear normalization of suppression.

Another information-based saliency definition is proposed by Feixas et al. [12], which can be computed based on the information theory using polygon mutual information deduced from the polygon information channel $\mathcal{O}\rightarrow\mathcal{V}$ between the set of polygons of an object $\mathcal{O}$ (input) and a set of viewpoints $\mathcal{V}$. In our experiments, all the objects are placed at the center of a sphere of 642 viewpoints, which is built from the recursive discretization of an icosahedron. And the saliency measure $s(\mathbf{v})$ of each vertex $\mathbf{v}$ can be computed as the weighted average of the information-based saliency of its neighbor polygons.

4.3. Saliency guided normal enhancement technique

Now, owing to the theoretical analysis of normal enhancement (see Section 3), we can determine the enhancement of normal vector for each vertex according to the variation of its luminance, which is guided by the visual saliency map.

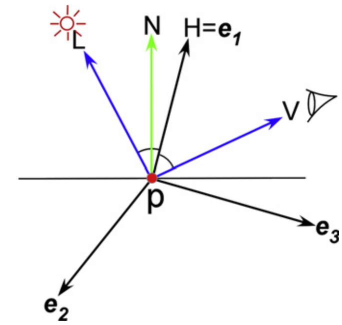

Fig. 1. The orthogonal coordinate system is introduced to estimate the variation of normal vector.

The orthogonal coordinate system should be introduced first for each vertex (see Fig. 1). Given the unit light direction $\mathbf{L}$ and unit view vector $\mathbf{V}$, the halfway unit vector $\mathbf{H}$ can be considered as the coordinate axis $\mathbf{e_1}$. Then, the second coordinate axis $\mathbf{e_2}$ can be defined by $\mathbf{e_2} = (\mathbf{H}\times\mathbf{L})/(\|\mathbf{H}\times\mathbf{L}\|)$. Finally, the orthogonal third coordinate axis is determined naturally as $\mathbf{e_3} = (\mathbf{e_1}\times\mathbf{e_2})/(\|\mathbf{e_1}\times\mathbf{e_2}\|)$.

Thus, the perturbation of the normal vector can be represented in the above orthogonal coordinate system,

$$\Delta\mathbf{N} = \delta_1\mathbf{e_1}+\delta_2\mathbf{e_2}+\delta_3\mathbf{e_3} \tag{4}$$

Considering the constraint condition (2), the first term is $\delta_1 = 0$, and the variation of lighting becomes, $\Delta\mathbf{I}/\mathbf{I}_l = k_d[\delta_2(\mathbf{e_2}\cdot\mathbf{L})+\delta_3(\mathbf{e_3}\cdot\mathbf{L})] = k_d\delta_3(\mathbf{e_3}\cdot\mathbf{L})$. Moreover, due to the constraint condition (1) of normalization, $\Delta\mathbf{N}\cdot\Delta\mathbf{N} = -2\mathbf{N}\cdot\Delta\mathbf{N}$, we can determine δ_2 from δ_3 as follows:

$$\delta_2^2+2\delta_2(\mathbf{e_2}\cdot\mathbf{N}) = -\delta_3^2-2\delta_3(\mathbf{e_3}\cdot\mathbf{N}) \tag{5}$$

Finally, the calculation pipeline for the enhancement of normal vectors can be summarized by the following three steps:

- According to the pre-computed variation of vertex luminance $\Delta\mathbf{I}/\mathbf{I}_l$ which is guided by the vertex saliency measure, we calculate the δ_3 as $\delta_3 = (\Delta\mathbf{I}/\mathbf{I}_l)/[k_d(\mathbf{e_3}\cdot\mathbf{L})]$.
- Applying the constraint condition (2), we can determine δ_2 as $\delta_2^2+2\delta_2(\mathbf{e_2}\cdot\mathbf{N}) = -\delta_3^2-2\delta_3(\mathbf{e_3}\cdot\mathbf{N})$.
- The perturbation of normal vector can then be determined by the local orthogonal coordinate system as $\Delta\mathbf{N} = \delta_2\mathbf{e_2}+\delta_3\mathbf{e_3}$.

According to the above calculation pipeline, we now describe the main steps of our saliency-based shading scheme for 3D shape depiction, summarized in Algorithm 1.

Algorithm 1. Saliency guided normal enhancement technique

INPUT: a 3D mesh model $\mathcal{M}$
INPUT: Determine the neighboring vertices/polygons for each vertex
Calculate the visual saliency for each vertex
for *Each vertex* $\mathbf{v}$ *of the mesh model* $\mathcal{M}$ **do**
    Determine the coordinate system $\{\mathbf{e_1} = \mathbf{H},\mathbf{e_2},\mathbf{e_3}\}$
    Calculate the dot products $\mathbf{e_3}\cdot\mathbf{L},\mathbf{e_3}\cdot\mathbf{N},\mathbf{e_2}\cdot\mathbf{N}$
    Determine the variation of normal vector $\Delta\mathbf{N}$
    Update the normal vector of $\mathbf{v}$ *as* $\mathbf{N}+\Delta\mathbf{N}$
end for
Render the model using the updated normal vectors

In our implementation, we scale the variation of vertex luminance in a linear manner according to the visual saliency measure of surface vertex. In order to determine the deviation δ_2 from the quadratic equation (5), we should limit the bound of deviation δ_3 first. That is, the δ_3 should be located in the interval

$$\left[-(\mathbf{e_3}\cdot\mathbf{N})-\sqrt{(\mathbf{e_3}\cdot\mathbf{N})^2+(\mathbf{e_2}\cdot\mathbf{N})^2},-(\mathbf{e_3}\cdot\mathbf{N})+\sqrt{(\mathbf{e_3}\cdot\mathbf{N})^2+(\mathbf{e_2}\cdot\mathbf{N})^2}\right]$$

Thus, the corresponding bound of $\delta\mathbf{I}=\Delta\mathbf{I}/\mathbf{I}_l$ can be computed by $\Delta\mathbf{I}/\mathbf{I}_l=k_d\delta_3(\mathbf{e_3}\cdot\mathbf{L})$, that is, $[\delta\mathbf{I}_{min},\delta\mathbf{I}_{max}]$, where

$$\delta\mathbf{I}_{min}=-k_d(\mathbf{e_3}\cdot\mathbf{N})(\mathbf{e_3}\cdot\mathbf{L})-k_d\sqrt{(\mathbf{e_3}\cdot\mathbf{N})^2+(\mathbf{e_2}\cdot\mathbf{N})^2}(\mathbf{e_3}\cdot\mathbf{L})$$

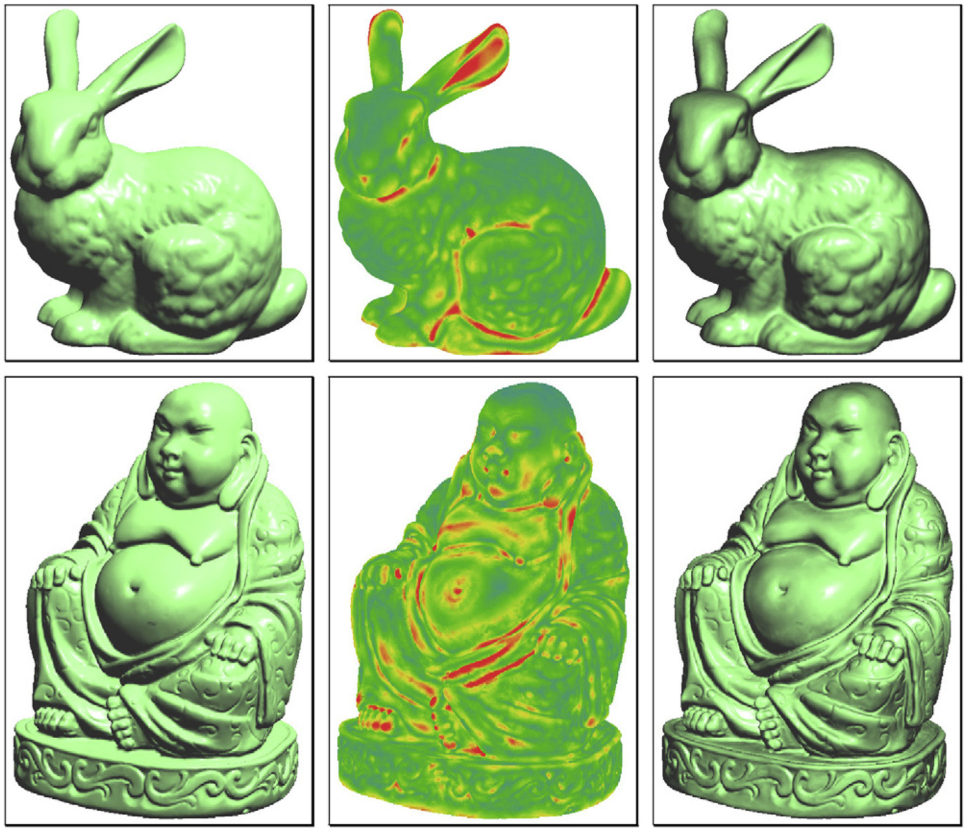

Fig. 2. The expressive rendering results guided by Lee's mesh saliency measure for the Stanford Bunny model and the Buddha model. Left column: original models; middle column: Lee's mesh saliency measures for different models; right column: the expressive rendering results after the visual saliency guided normal perturbation operation.

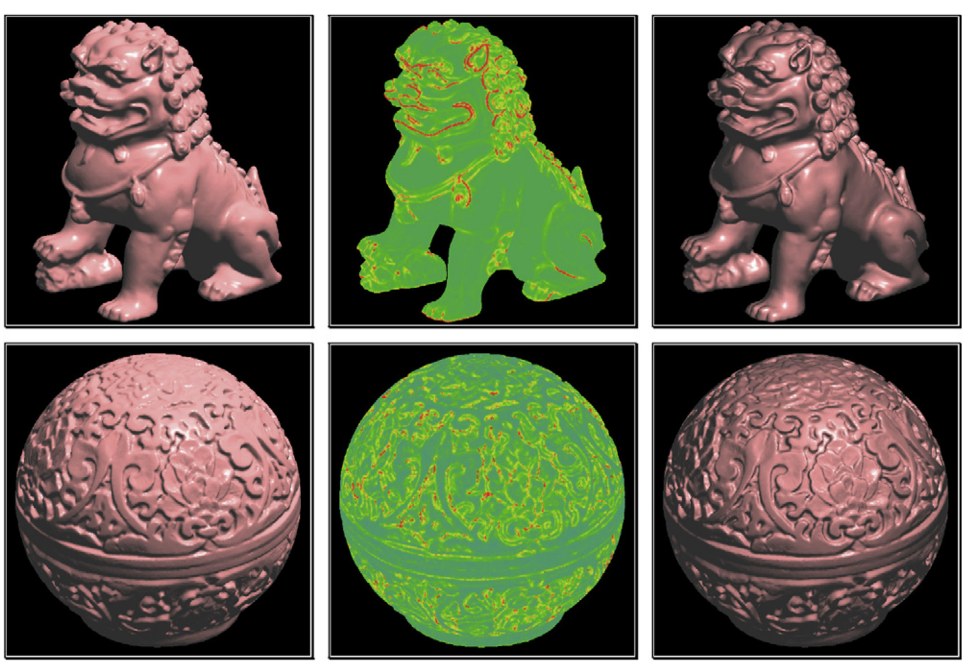

Fig. 3. The expressive rendering results guided by Feixas' information-based saliency measure for the Lion model and the Red Circular Box model. Left column: original models; middle column: Feixas' information-based saliency measure for different models; right column: the expressive rendering results after the visual saliency guided normal perturbation operation.

and

$$\delta\mathbf{I}_{max} = -k_d(\mathbf{e_3}\cdot\mathbf{N})(\mathbf{e_3}\cdot\mathbf{L}) + k_d\sqrt{(\mathbf{e_3}\cdot\mathbf{N})^2+(\mathbf{e_2}\cdot\mathbf{N})^2}(\mathbf{e_3}\cdot\mathbf{L})$$

Meanwhile, the saliency measure of vertex $\mathbf{v}$ is normalized, i.e., $s^* = (s-\bar{s})/\sigma$ (where $\bar{s}$ and σ mean the average and standard variance of the saliency distribution s, respectively) and its bound limitation is $[s^*_{min}, s^*_{max}]$. Then, we can determine the variation of vertex luminance $\delta\mathbf{I} = \Delta\mathbf{I}/\mathbf{I}_l$ by scaling the normalized saliency measure s^* in linear manner $\delta\mathbf{I} = \Phi(s^*)$, which linearly maps the bound limitation of s^* onto the bound limitation of $\delta\mathbf{I}$. Finally, using this luminance variation, the deviations δ_3, δ_2 can be calculated and thus the variation of vertex normal $\Delta\mathbf{N}$ can also be directly determined by Eq. (4).

5. Experimental results and discussion

5.1. Saliency guided expressive rendering

The proposed algorithms for saliency guided normal enhancement technique have been implemented on a PC with a Pentium IV 3.0 GHz CPU, 1024 M memory. In our approach, we use two schemes to estimate visual saliency, i.e., Lee's mesh saliency [6] and Feixas' information-based saliency [12]. Based on the visual saliency measure, our proposed saliency-based shading scheme for shape depiction is effective for various 3D triangle meshes, that is, it can enhance the surface normals for expressive rendering of 3D meshes with less than 260 K triangles in an interactive manner.

Fig. 2 shows the enhanced expressive rendering results for the Stanford Bunny model and the Buddha model, respectively, which are guided by Lee's mesh saliency measure [6] of different models. Lee's mesh saliency measure of 3D shapes can capture the visually salient features and the expressive rendering can enhance the salient surface features effectively by altering the shade of these regions. For example, the crease of the Buddha clothes, the neck and feet of the Buddha are enhanced, whilst the brim of Bunny's ear and the muscle of Bunny's leg are also improved clearly and attract the viewer's attention.

On the other hand, guided by Feixas' information-based saliency measure, Fig. 3 gives the improved expressive rendering results for the Lion model and the Red Circular Box model, respectively. The information-based saliency measure of 3D shapes can also capture the visually salient features in a content-aware manner and the expressive rendering can enhance the salient surface details effectively for the underlying models. Such as, the head of the Lion and the engraved flowers of the Red Circular Box are depicted clearly and attract the viewer's attention.

Furthermore, Fig. 4 gives us the comparison of our saliency guided shape depictions by employing different visual saliency

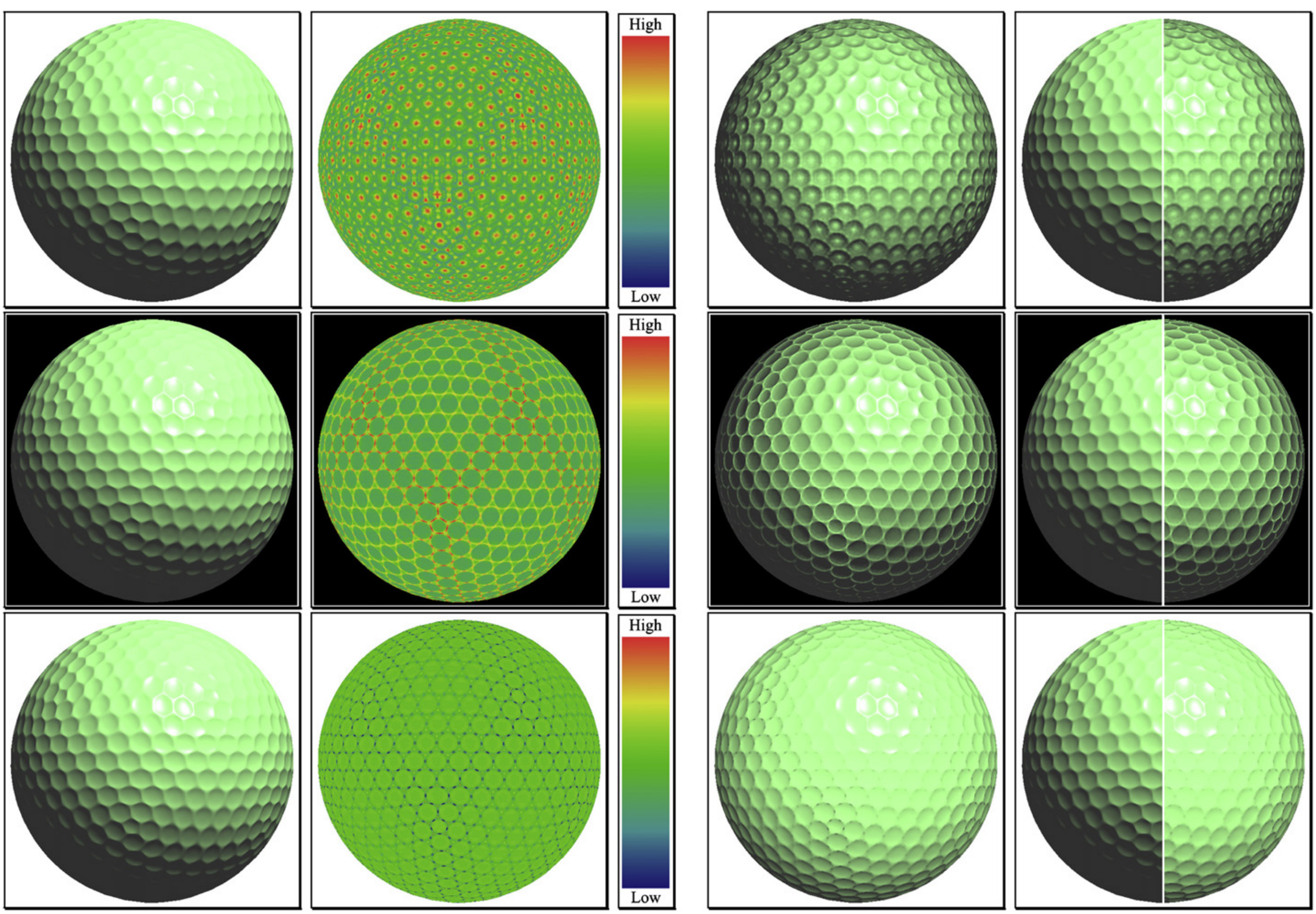

Fig. 4. Comparison of our saliency guided shape depictions guided by different visual saliency measure and the standard Gaussian curvature field for the Golf Ball model. First row: the expressive rendering of the Golf Ball model (fourth column) guided by Lee's mesh saliency measure (second column); second row: the expressive rendering of the Golf Ball model (fourth column) guided by Feixas' information-based saliency measure (second column); third row: the expressive rendering of the Golf Ball model (fourth column) guided by the standard Gaussian curvature field (second column). The last column shows the effect of our normal enhancement technique vs different important fields, where each side of the figure shows the original and the enhanced rendering results.

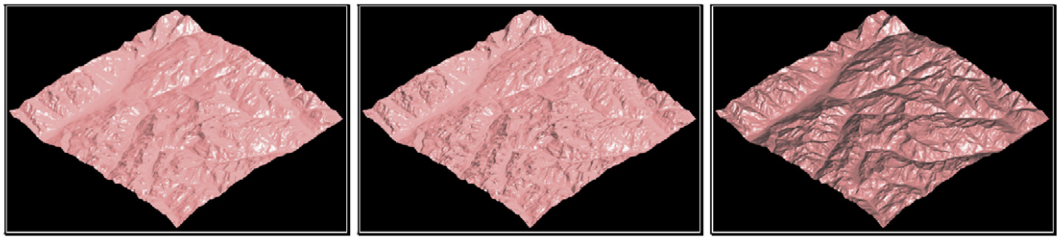

Fig. 5. Comparison with the normal sharpening technique proposed by Cignoni et al. [35]. Left: the original model; middle: rendering with the normal sharpening technique; right: rendering with our normal enhancement technique, which is guided by Feixas' information-based saliency.

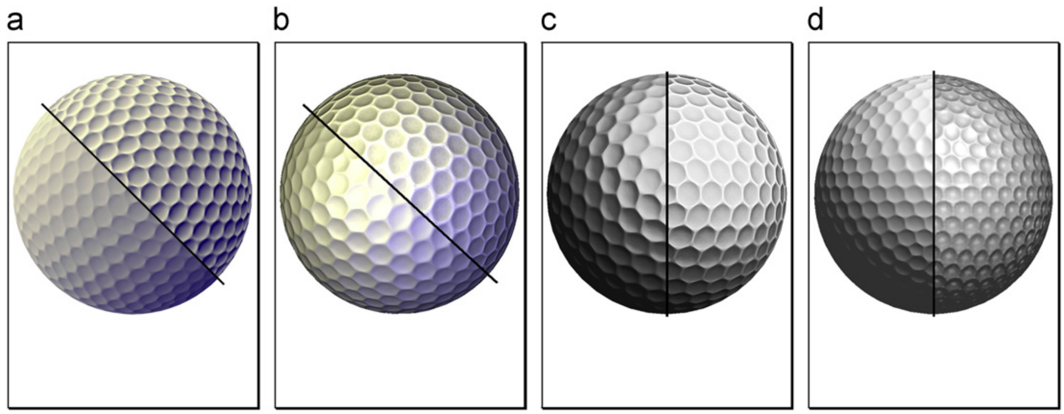

Fig. 6. Comparison with other surface enhancement techniques, that is, exaggerate shading [29](a), light warping [33](b), radiance scaling [34](c) and our saliency guided normal enhancement (d). The images of previous techniques are extracted from their corresponding original papers and supplemental materials.

measure and the standard Gaussian curvature field for the Golf Ball model. The first and second rows show the effect of our normal enhancement technique guided by Lee's mesh saliency and Feixas' information-based saliency measure, respectively. Compared to the proposed perturbation of surface normals driven by the standard Gaussian curvature field (see the third row of Fig. 4), our visual saliency guided normal enhancement technique can effectively bring out the fine-scale geometric details of 3D shape. However, the final expressive rendering results may be sensitive to the visual saliency measure of the underlying shape. For example, the inner of each cell of the Golf Ball will be enhanced if guided by Lee's mesh saliency (see the first row of Fig. 4) whilst it will pop out the brim of each cell of the Golf Ball if guided by Feixas' information-based saliency measure (see the second row of Fig. 4).

5.2. Comparison with other enhancement techniques

One closely related work to our saliency guided shading method is the normal sharpening technique proposed by Cignoni et al. [35], which performs conventional diffuse shading using a sharpened normal field. In detail, they enhanced the surface normals by $\mathbf{N}_E = \mathbf{N} + k \cdot (\mathbf{N} - \mathbf{N}_L)$, which depends mainly on two parameters—the value of the weighting constant k and the amount of low-pass filter to generate the smooth normals $\mathbf{N}_L$ by iteratively averaging each face normal with the normals of its adjacent faces. Compared to their simple normal sharpening scheme, our approach can effectively enhance the salient features of the underlying models by incorporating the mesh saliency into the normal adjustment operation without impairing the desired appearance (see Fig. 5). In the implementation of the normal sharpening technique, we choose the weighting constant k as 0.5, which affects the intensity of the normal enhancement effect and take 10 iterations for normal averaging to smooth the surface normals.

On the other hand, compared with other surface enhancement techniques, our approach may enhance the expressive rendering results similar to exaggerated shading, light warping and radiance scaling as shown in Fig. 6. Compared to the exaggerated shading scheme [29], our approach can enhance the surface shape depiction which is guided by surface visual saliency. Moreover, exaggerated shading suffers from light direction sensitivity, and tends to flatten the overall shape perception. Compared to the light warping technique [33] and radiance scaling technique [34], our system incorporates the visual saliency of a polygon mesh into the normal enhancement operations which can effectively bring out the fine-scale geometric details of 3D shape and guide viewer's visual attention adequately for expressive rendering. Such as, guided by Lee's mesh saliency, the inner of each cell of the Golf Ball is effectively enhanced (see Fig. 6(d)).

6. Conclusion and future work

In this paper, due to the visual saliency estimation, we proposed a normal perturbation technique to enhance the visually salient features of 3D shapes explicitly. The experimental results demonstrate that our saliency guided shading scheme can improve the depiction of the underlying shape and the perception of its salient features, which can guide viewer's attention during expressive rendering.

However, one limitation of our saliency guided shape depiction method is that our surface enhancement scheme only pay attention to enhance shape depiction caused by the variation of the diffuse lighting component. In the future work, we will consider further the saliency guided surface enhancement technique to adjust the specular lighting component during 3D shape depiction. Another limitation is that our normal perturbation algorithm depends on the normal estimation of the underlying shape. Raw 3D data with highly non-uniform sampling or large noise may not be treated correctly with our algorithm. For such raw scanner data, some pre-processing steps [38] should be performed before subsequent normal enhancement and expressive rendering tasks.

It should be mentioned that we have only considered the role of surface normals in the context of visual attention driven shape depiction. It will also be interesting in the future to see how other visual attention persuasion channels can be incorporated with geometry alteration for shape depiction, such as color, luminance, and texture contrast. Moreover, inspired by our saliency-based shading scheme, some other sorts of important fields may also be introduced to further improve the shape depiction of the high-detailed complex models in the future.

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