Faceting Artifact Analysis for Computer Graphics

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Abstract

The faceting signal, defined in this paper as the difference signal between a rendering of the original geometric model and a simplified version of the geometric model, is responsible for the faceting artifacts commonly observed in the renderings of coarse geometric models. In this paper, we analyze the source of the faceting signal and develop a perceptual metric for the visibility of the faceting signal.

1 Introduction

Faceting artifacts due to tessellation are commonly present in computer generated pictures. To combat this problem, geometric models of higher resolution can be used. The faceting artifacts will disappear as the screen projection of each element of the geometric model reaches the scale of each pixel in the image. Second, shading models superior to flat shading can be employed. For example, Phong shading decreases the faceting appearance because it includes a better normal approximation as part of the shading calculation. However, both approaches require more computation and thus penalize the frame rate.

Visual perception provides another avenue for solving this problem without compromising the rendering speed. This solution can be accomplished by carefully selecting the surface texture so as to obscure the faceting artifacts by using the masking properties of the human visual system. Visual masking involves a foreground signal (signal) and a background signal (masker). In order to apply the principle of visual masking, we need to understand the frequency composition of both the artifact signal and the signal that serves as the masker.

In this paper, we develop the concept of the faceting signal, and analyze its source. In addition, we develop a perceptual metric for determining the visibility of the faceting signal. The utility of the faceting signal is further demonstrated by two examples.

2 Faceting Signal Analysis

We define the faceting signal as the difference signal between a rendering of a highly detailed geometric model, serving as the gold standard, and a rendering of a simplified version of the geometric model under the same image synthesis conditions. The faceting signal of an object is created by placing a sphere of cameras around the ideal polygonal representation of an object and around a simplified version of the object, taking images of each object under the same image synthesis conditions, and subtracting each pair of images. The difference signal between these two images is the faceting signal at that certain viewing circumstance. Similar to [2], we place a sphere of cameras at the vertices of a rhombicuboctahedron to capture the faceting signal of a geometric model. Figure 1 shows the shading profile for a scanline of a regularly tessellated cylinder using different shading models. We assume a directional light source shines perpendicular to the cylinder surface. Figure 2(a), (c), (e) illustrate the faceting signals for different shading models.

In this section, we explain how the faceting signal changes as a function of surface curvature, lighting, shading model, textures, and some perceptual aspects that affect the visibility of the faceting signal. A cylinder is used to simplify the illustration.

2.1 Surface Curvature

It is well known that silhouette edges of an object are most problematic for low resolution models. The faceting signal can be used to explain why silhouette area can be an issue for low resolution models. Figure 1 shows a scanline of the faceting signal of a cylinder using flat shading, Gouraud shading, and Phong shading. For flat shading, it is obvious that the steps become narrower and higher along the silhouettes.

We can illustrate why the silhouettes are problematic by analyzing the faceting signal of a cylinder. We derive two equations that describe how the faceting signal changes as

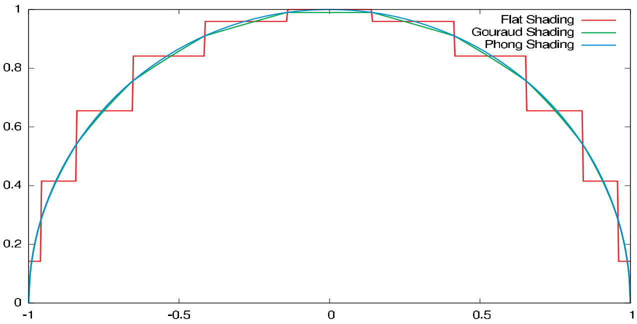


Figure 1. The shading profile for a cylinder using flat shading, Gouraud shading, and Phong shading.

a function of surface location and surface curvature. We assume a directional light source shines perpendicular to the cylinder surface. Let's further assume that the cylinder sits on top of the xz plane and the center of the cylinder is located at the origin. We focus our analysis on the diffuse component of the shading I for the cylinder.

$$I(x,r) = \mathbf{n}\cdot\mathbf{l} = \frac{\sqrt{r^2-x^2}}{r}$$

where x runs from the center of the cylinder to the right. Take the derivative against x, we have:

$$\mathrm{d}I(x) = -\frac{x}{r\sqrt{r^2-x^2}}\,\mathrm{d}x = -\frac{1}{r\sqrt{(r/x)^2-1}}\,\mathrm{d}x \qquad (1)$$

$\mathrm{d}I(x)$ represents the faceting signal as a function of x. Its absolute value increases as x increases. This explains why the amplitude of the faceting signal increases along the silhouettes, as shown in Figure 2(a).

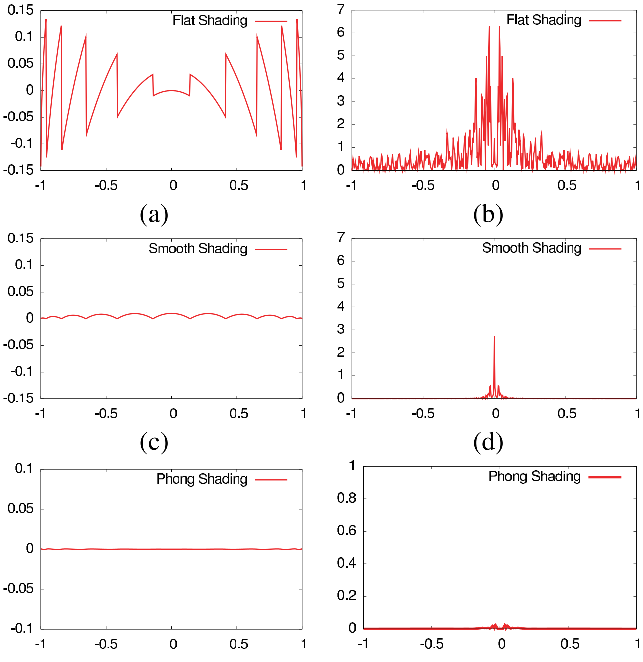
Taking its derivative against radius r, we have

$$\mathrm{d}I(r) = \frac{x^2}{r^2\sqrt{r^2-x^2}}\,\mathrm{d}r \qquad (2)$$

$\mathrm{d}I(r)$ represents the faceting signal as a function of r. It is clear that Equation 2 is a decreasing function of r, which explains that the amplitude of the faceting signal becomes smaller as the radius of the cylinder becomes bigger (smaller curvature).

2.2 General Lighting Level

The magnitude of the faceting signal becomes stronger as the light source becomes brighter. This is due to the linearity of the shading intensity with regard to the lighting intensity in the lighting equation. By using the linearity of Fourier analysis, we can conclude that in the frequency domain the magnitude of the frequencies increases as the intensity of the general lighting level increases.



(a) (b)

(c) (d)

(e) (f)

Figure 2. The faceting signals corresponding to different shading models and their frequency distributions.

2.3 Shading Model

Different shading models can have a dramatic impact on the faceting signal. Figure 2 shows pictures of the faceting signals and their frequency distributions for three shading models: flat shading, smooth shading, and Phong shading. Flat shading causes clear faceting artifacts; smooth shading shows less faceting artifacts; Phong shading is almost equivalent to the ideal signal and is much better than the previous two shading methods in terms faceting artifacts. This is due to the fact that different shading models use different surface normal approximations to calculate the pixel intensities.

2.4 Texture Mapping

Textures on the surface can also have an impact on the visibility of the faceting signal. Texture mapping can be considered as a way to alter the faceting signal. There are different ways that a texture can be mapped onto a surface and thus change the faceting signal. For example, texels are multiplied with the shading of a fragment for diffuse color texturing. When a diffuse color texture is applied to a surface, due to multiplication, the magnitude of the faceting signal is reduced, thus decreasing the visibility of the faceting signal.

2.5 Perceptual Aspects

The viewing distance of an observer also impacts the visibility of the faceting signal by affecting the perceived frequency of the faceting signal (in unit of cycles per visual degree). As the viewing distance increases, the visual angle subtended by an object becomes smaller. Therefore, its size on the image plane becomes smaller. This means that the spatial frequencies of the object becomes higher, and the spatial frequencies of its faceting signal also become higher. Since the human visual system is less sensitive to stimuli of high frequencies, the faceting artifacts are less visible as the viewing distance increases. This effect can explain why a coarse geometric object looks better when the viewing distance increases. Other parameters also affect the visibility of the faceting signal such as the adaptation state of the observer, eccentricity, etc.

3 A Perceptual Metric for the Faceting Signal

The root mean square image metric has traditionally been used for image processing tasks. However, it is well known that it does not correlate well with the perceptual importance of the signal. In this section, we propose a perceptual metric for determining the visibility of the faceting signal, taking into account the luminance non-linearity and contrast sensitivity function of the human visual system. A perceptual metric can further take into account other viewing parameters such as the lighting adaptation level, observer distance, etc, which all affect the visibility the faceting signal.

The structure of our perceptual metric is closely related visual difference metrics [1, 3]. It consists of three stages: amplitude nonlinearity, contrast sensitivity function, and psychometric function. The result from contrast sensitivity function filtering is passed through the psychometric function and the result is turned into probability of visibility. These three stages are discussed in the following.

3.1 Luminance Nonlinearity Processing

It is well known that visual sensitivity and the perception of lightness are a nonlinear function of luminance. The amplitude nonlinearity describes the sensitivity variations as a function of background luminance. Various models have been proposed in the literature such as the log model and various power laws. In this paper, we have chosen to use the cube root model of the nonlinearity of the visual system, which can be described as: $r_o = r_i^{1/3}$, where output value r_o is obtained by returning the cube root of the input value r_i.

3.2 Contrast Sensitivity Function

The contrast sensitivity function of the human visual system describes the variations in visual sensitivity as of function of spatial frequencies. The contrast sensitivity function described by Daly [1] is used in our implementation. This function models the sensitivity of the visual system as a function of radial spatial frequency ρ in c/deg, orientation θ in degrees, light adaptation level l in cd/m^2, image size i^2 in visual degrees, lens accommodation due to viewing distance d in meters, and eccentricity e in degrees.

$$S(\rho, \theta, i^2, d, e) = P \cdot min[S_1(\frac{\rho}{r_a \cdot r_e \cdot r_\theta}, l, i^2), S_1(\rho, l, i^2)];$$

$r_a = 0.856 \cdot d^{0.14}$, where d is the viewing distance in meters. $r_e = 1/(1 + ke)$, where e is the eccentricity in visual degrees, $k = 0.24$, $r_\theta = (1 - ob)/2 \cdot \cos(4\theta) + (1 + ob)/2$, where $ob = 0.78$.

$$S_1(\rho, l, i^2) = ((3.23(\rho^2 i^2)^{-0.3})^5 + 1)^{-0.2} \cdot A_l \epsilon \rho e^{-(B_l \epsilon \rho)} \sqrt{1 + 0.06 e^{B_l \epsilon \rho}}$$

where $A_l = 0.801(1 + 0.7/l)^{-0.2}$ and $B_l = 0.3(1 + 100/l)^{0.15}$.

3.3 Psychometric Function

The psychometric function describes the probability of detection as a function of the signal contrast [4]. An example of the psychometric function is shown below:

$$P(c) = 1 - e^{-(c/\alpha)^\beta} \tag{3}$$

where $P(c)$ is the probability of detecting a signal of contrast c, α is the detection threshold, and β describes the slope of the psychometric function and is largely invariant across many tasks.

3.4 Discussion

Even though our perceptual metric is based on psychophysical data, we still carried out a few test cases that allowed us to verify the validity of our visibility measure experimentally. Figure 3 shows a patch of a sine wave and its visibility maps for viewing distances of 1, 2, and 3 meters. Brighter regions in the visibility map indicate higher probability of visibility. For a sine wave, the peaks and troughs are shown on the visibility map. As the distance increases, the peaks and troughs become narrower, which indicates that its visibility decreases as the viewing distance increases. The average probability of visibility for each viewing distance is 0.71, 0.52, and 0.41, respectively. Besides viewing distance, we also performed experiments to verify that our metric works under different luminance values.

Figure 3. A sine wave and its visibility map at viewing distance 1, 2, and 3 meters.

As an example of a more complicated faceting signal and its visibility map, Figure 4 shows an example of the faceting signal (left) of the Stanford Bunny and its visibility map (right) at viewing distance of 1 meter. From the visibility map, we can observe that the silhouette edges are more visible.

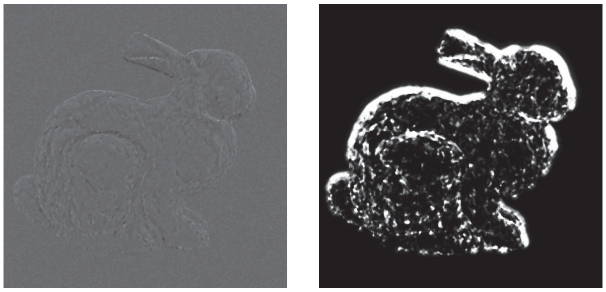


Figure 4. The left image shows an example of the faceting signal and the right image shows its visibility map.

4 Applications

We discuss briefly two examples that demonstrate the potential of the analysis of the faceting signal. Please refer to a longer version of this paper [6] for details. The first example shows how the visibility of the faceting signal can be used to guide the selection of a geometric model in a level of detail system. The second example demonstrates how the faceting signal can be used to find a texture that minimizes the faceting artifacts.

Our perceptually driven level of detail system has an offline preprocessing stage and a runtime stage. The preprocessing stage employs our perceptually guided visibility metric and calculates a table of average probability of visibility for use in the LOD runtime. We pre-compute the average probability of visibility at different lighting intensities, observer distances, and camera distances. During runtime, all the parameters such as observer distance, camera distance, general lighting intensity are found. Then, given a visibility threshold, these parameters are used to index into the table to find the appropriate level of detail. One of the advantages of our system is that the user can choose a perceptually meaningful threshold. In addition, our system allows for specifying the observer's viewing distance.

We have developed a surface texturing algorithm that is capable of determining the lower bound for a texture so as to fully obscure the faceting artifacts for bicubic subdivision surfaces. We draw upon research in visual masking to make the faceting artifacts less visible by using a texture as a masker that obscures the faceting signal. We select bicubic subdivision surfaces as our model because it is easy to calculate and control its major faceting signal frequencies. Perlin noise [5] was used as surface textures because it is easy to control its frequencies. According to the theory of visual masking, textures should have similar frequency and orientation to the faceting signal. Given the contrast and orientation of the faceting signal, the lower bound contrast of a texture can be predicted by using a contrast masking function [7].

5 Conclusions and Future Work

The importance of the faceting signal lies in the fact that it represents the artifact signal for coarse geometric models. The introduction of the faceting signal offers opportunities in designing better perceptually guided algorithms for computer graphics, especially algorithms that take advantage of visual masking, where identifying the artifact signal is critical in determining a good masker. We also include two examples that illustrate the utility of the faceting signal. First, we developed a perceptually guided level of detail selection system that selects the most appropriate geometric model. Second, we developed a surface texturing algorithm that calculates the lower bound contrast for a texture that can serve as a successful masker.

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References

[1] S. Daly. The visible differences predictor: an algorithm for the assessment of image fidelity. In A. B. Watson, editor, *Digital images and human vision*, pages 179–206. MIT Press, 1993.
[2] P. Lindstrom and G. Turk. Image-driven simplification. *ACM Trans. Graph.*, 19(3):204–241, 2000.
[3] J. Lubin. A visual discrimination model for imaging system design and evaluation. In *Vision Models for Target Detection and Recognition*, pages 245–283. World Scientific, 1995.
[4] J. Nachmias. On the psychometric function for contrast detection. *Vision Research*, 21(2):215–223, 1981.
[5] K. Perlin. An image synthesizer. In *SIGGRAPH '85: Proceedings of the 12th annual conference on Computer graphics and interactive techniques*, pages 287–296, 1985.
[6] L. Qu and G. W. Meyer. Faceting artifact analysis for computer graphics. Technical Report 43, Digital Technology Center, University of Minnesota, 2007.
[7] A. B. Watson. Efficiency of an image code based on human vision. *Journal of the Optical Society of America*, 4(12):2401–2417, 1987.