Evaluation of Different Diffuse Surface Reflection Models for Global Illumination

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Abstract

One common goal nearly all global illumination algorithms aim for is solving the light transport problem. The most visual noticeable one in the general case is the diffuse-diffuse light transport between surfaces. Most global illumination algorithms are very good at solving it. In many global illumination solutions the Lambertian diffuse surface reflection model is assumed. However, over the years several other diffuse models have been introduced – mostly outside of the computer graphics community – that according to their authors mimic real surface behaviour more accurately. In this paper we evaluate some of the better known models and place them into the context of solving global illumination problems.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer graphics]: Three-Dimensional Graphics and Realism Color, shading, shadowing, and texture;

1. Introduction

Realistic image synthesis is still regarded as a fundamental goal in computer graphics research. For achieving this goal both the global light transport between surfaces have to be solved as well as realistic reflection models for surfaces are required. Currently in most global illumination packages ideal diffuse surfaces are simulated by using the well-known Lambertian model [Lam60]. This model is rather simple, computational inexpensive and easy to implement. On the first glance it seems to be a good approximation for many real world diffuse reflecting materials. However, if you do some research on diffuse models you will notice that several newer diffuse models have been introduced over the years. Most of them claim that they handle rough diffuse surfaces more accurately than the Lambertian model. Interestingly enough these models have been – as far as the authors are aware of – only be compared in direct or local reflection conditions. Where from a human visual point of view they produce mostly only a settle difference in the object surface appearance (see figure 1). The question this paper tries to answer is does this also hold true for global illumination scenarios or will the difference in appearance either increase or even decrease making it perfectly convenient to use only the Lambertian model in these cases or not.

2. Diffuse surface reflection models

Reflections from surfaces can be classified into two categories: surface reflectance which takes place at the boundary between two different media with different refractive indices and body reflectance which is due to subsurface scattering. Besides different research on subsurface scattering in the computer graphics field [HK93, JMLH01] the body reflection is still most often assumed to be Lambertian. A Lambertian surface appears equally bright from all directions. However, for several real-world materials this model can prove to be a poor or inadequate approximation of body reflection. In the following subsections several other models for body reflection or diffuse reflection models are evaluated.

2.1. Oren-Nayar

The major difference between the Oren-Nayar [ON94] and Lambertian model is that it tries to mimic the effect of surface roughness. For rough surfaces the surface consist of several micro facets that can mask, shadow or interreflect with each other. Oren-Nayar use the same roughness model as proposed by Torrance and Sparrow [TS67]. It assumes that a rough surface is composed of long symmetric V-cavities. Each of these cavities consists of two planar facets. The width of each facet is assumed to be small compared to its

Figure 1: *Direct lighting with two point light sources of a horse statue using different diffuse models from left to right: Lambertian, Wolff, Oren-Nayar, Ginneken et al.*

length. Additionally, each pixel is covered by a huge number of facets and the facet area is large compared to the wavelength λ of incident light therefore only geometrical optics is necessary. The slope and orientation of each facet in the V-cavity model can be denoted with (Φ_a, ϕ_a), where Φ_a is the polar angle and Φ_a is the azimuth angle. Torrance and Sparrow use a distribution function $N(\Phi_a, \phi_a)$ to represent the number of facets per unit surface area that have a normal $\vec{n_a} = (\Phi_a, \Phi_a)$. Oren and Nayar instead use a probability distribution to represent the fraction of surface area that is covered by facets with a given normal. They call this the slope-area distribution $P(\Phi_a, \phi_a)$. In their work Oren and Nayar discuss several different models for the slope-area distribution but at the end conclude that a simplified approximation is enough for describing the complex phenomena seen on rough surfaces. Their final qualitative model looks like following:

$$L_r(\Phi_r, \Phi_i, \phi_r - \phi_i, \sigma) = \frac{p}{pi} E_o cos\Phi_i (A + Bmax(0, \cos(\phi_r - \phi_i)) \sin\alpha \tan\beta) \quad , \qquad (1)$$

where $A = 1.0 - 0.5\frac{\sigma^2}{\sigma^2+0.33}$ and $B = 0.45\frac{\sigma^2}{\sigma^2+0.09}$. σ symbolizes the roughness of the surface.

2.2. Wolff

Wolff [Wol94] takes a different approach for describing his diffuse model. In his work he tries to attack a different problem the common Lambertian model has that accordingly to him is only correct when the difference between viewing angel and light incidence is less than 50 degrees. By utilizing results from radiative-transfer theory of subsurface multiple scattering Wolff's model precisely accounts for how incident light and the distribution of subsurface scattered light are influenced by Fresnel attenuation and Snell refraction at a smooth air-dielectric surface boundary. In particular this diffuse-reflectance model is not like most other diffuse models independent of the viewing angle in respect to the surface normal. Wolff adapts Chandrasekhar's theory [Cha60] for multiple scattering of incident light upon stellar and planetary atmospheres to smooth inhomogeneous dielectric materials made up of particle inhomogeneous embedded in a medium with a uniform index of refraction.

2.3. Ginneken et al.

Similar to Oren-Nayar Ginneken et al. [vGSK98] observed in their work that the Lambertian model of diffuse reflection ignores the effect of roughness. Additionally, they conclude that Oren&Nayar's [ON94] model and Torrance&Sparrow's model [TS67] of V-cavity that permits as previously mentioned the geometrical effect of masking and shadowing is inadequate. Since for doing so the V-cavities have to be very long (so that effects at the end of the cavities can be ignored), and surface isotropy requires the cavities to have no preferred direction. Ginneken et al. claim that such surfaces cannot exist, because their geometry would be inconsistent. Instead Ginneken et al. suggest to use a Gaussian surface model [LH60] which is known to be a realistic statistical approach for modeling roughness. In their paper Ginneken et al. propose a model for both diffuse and specular rough surface but we will set our focus only on the diffuse part. When considering an isotropy surface the local angles of incidence and reflection Φ_i' and Φ_r' can be respectively determined by:

$$\cos\Phi_i' = \cos\phi_a \sin\Phi_i \sin\Phi_a + \cos\Phi_i \cos\Phi_a \quad , \qquad (2)$$

$$\cos\Phi_r' = \cos(\phi_a - \phi_r) \sin\Phi_r \sin\Phi_a + \cos\Phi_r \cos\Phi_a \qquad (3)$$

Φ_a and ϕ_a represents the local rough surface normal $\vec{a} = (\Phi_a, \phi_a)$. The theory behind their distribution model is quite complex and due to the lack of space we only present some of the most important thoughts behind it here. First the distribution of the heights $P_z dz$ of the points on the surface normal is defined by

$$P_z(z, \sigma)dz = \frac{1}{\sqrt{2\pi\sigma}} \exp(\frac{-z^2}{2\sigma^2})dz \quad , \qquad (4)$$

where σ is the standard deviation of height. This distribution specifies the vertical scale of the relief, the horizontal scale is described with the autocorrelation function $R(\tau)$, defined as the average product of the heights of two points at a distance τ. Next Ginneken et al. describe due to self-shadowing, self-masking and shadowing and masking by intersection the probability that a microfacet on the surface is both illuminated and visible from the observer. They approximate this probability by the function:

$$P_{ill+vis}(\Phi_i, \Phi_r, \phi_r, r) = \frac{1}{1+\Sigma[r, max(\Phi_i,\Phi_r)] + \alpha\Sigma[r, min(\Phi_i,\Phi_r)]} \quad (5)$$

where $\Sigma(r,\Phi) = \frac{r}{\sqrt{2\pi}\cot|\Phi|}\exp(\frac{-\cot^2\Phi}{2r^2}) - \frac{1}{2}erfc(\frac{\cot|\Phi|}{\sqrt{2}r})$, $\alpha = \frac{4.41\phi_r}{4.41\phi_r+1}$ and r the roughness amount. This probability function is used to multiply the results from the Lambertian model and using the angles defined in eq (2)&(3).

3. Implementation

All surface models have been implemented in the Renderman Shading language as surface shaders. The Renderman shading language is comprehensive enough to allow a direct conversion of the models described in the previous chapter with the implementation of some additional not available build-in function like for example the cotangent and error function. Using the Renderman Shading language allows easy integration of surface reflection models in a commercial available final frame renderer. We decided to use RenderPipe which is the software frontend for a hardware based raytracing solution known as PURE or RenderDrive [Art06]. RenderPipe is Renderman 3.1 compliant. Additionally, in its latest installment it contains a full pathtracing solution for global illumination solving.

4. Comparisson

To compare the result we rendered three different 3d scenes using the pathtracing solution provided by the RenderPipe/Renderdrive product. Three different scenes were chosen to cover different aspects that may have an influence on the appearance. The first scene seen in figure 2 is the famous Cornell box. The scene is lid by an area light source hanging on the ceiling. The first picture in that row represents a rendering using the standard Lambertian model, the second one uses the model as described by Wolff, the third one is Oren-Nayar and the last image in the row is rendered using Ginneken et al.'s model for rough diffuse surfaces. For the Cornell box scene the Wolff model produces an overall darker image compared to the Lambertian model. Especially the green rounded box appears darker. The index of refraction of all surfaces is 1.4. This index lies in the common range for dielectric surfaces which behave mostly diffuse. When the index of refraction is further increased the image becomes even darker. This is not surprising because the dimming due to the Fresnel attenuation increases. The results using the two rough surface models are interesting. For both models a roughness factor of 0.3 was chosen. Surprisingly the Oren-Nayar model appears to be even brighter than the Lambertian model and some strange glowing below the green box can be noticed. This might be an indication that rays get trapped down there and bounce off several times introducing a sort of bias or due to the retroreflective nature of the Oren-Nayar model with increased roughness. This behaviour can not be noticed with the Ginneken et al. model which appears a lot darker on the edges of surfaces probably due to higher self-masking and shadowing for shallow rays. The second scene (see figure 3) is a more complex scenario and also includes other non-diffuse materials for example the glass ball and the metallic parts of the chair. Again similar behaviour for the Wolff model as already noticed with the previous scene. Especially the chair has a more noticeable shading gradient. The Oren-Nayar model this time also produces a slightly darker image as the Lambertian model. But the most interesting results can be seen with the Ginneken et al. model it is a lot darker than all the others especially notice the two different shaped intensity falloffs at the backside wall. Finally the last scene (see figure 4) contains only curved objects even the ground plane is actually a cylinder with a tremendous radius. The curvature has the effect of a bigger self shadowing effect on the Wolff model than as for both Oren-Nayar and Lambertian model. But again the Ginneken model clearly dominates the picture here with sharp and clearly noticeable edges.

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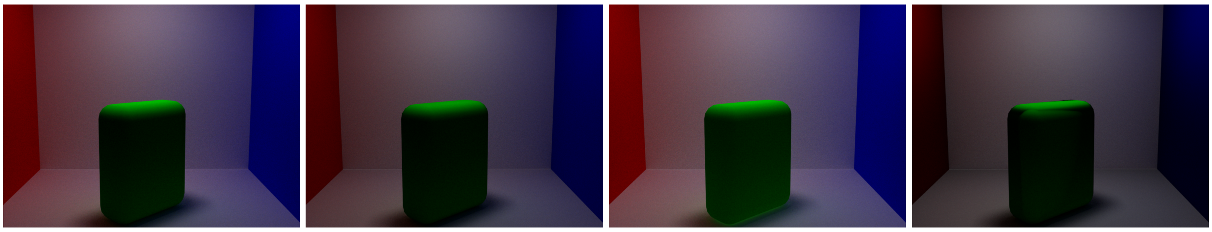

Figure 2: *Pathtraced Cornell box scene using different diffuse models. From left to right: Lambertian, Wolff, Oren-Nayar, Ginneken et al.*

Figure 3: *Pathtraced room scene using different diffuse models. From left to right: Lambertian, Wolff, Oren-Nayar, Ginneken et al.*

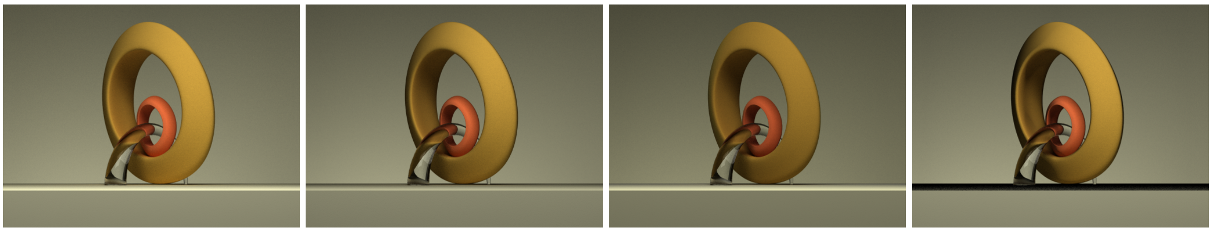

Figure 4: *Pathtraced curved figure scene using different diffuse models. From left to right: Lambertian, Wolff, Oren-Nayar, Ginneken et al.*