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Models of Surface Geometry for the Synthesis of Arbitrary Spectral Surface Reflectance and Emissivity

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Abstract. A model describing the reflection of light from rough surfaces has been developed from Prof. Nayar of Columbia University. The model is widely used in Computer Graphics for the synthesis of images. The aim of the visit in the CAVE laboratory at Columbia University was to understand the feasibility of a multispectral version of the model for the description of light reflection from rough surfaces.

1. Introduction

The color of surfaces is given by their property of incident light reflection, which is modeled by the *Bidirectional Reflectance Distribution Function* (BRDF). This function provides the reflected radiance from a point of the surface in a viewing direction given the radiance reaching the point from an incident direction. The BRDF is a function of the four angles that locate the incoming (incident) and out-coming (reflection) light and a function of wavelength. The dependency from wavelength is correlated to the material's chemical composition and determines the color of the surface (albedo). The dependency from incident and observation angles is essentially due to the surface's micro-geometry.

In the field of Computer Graphics, many models based on micro-facets have been proposed for the synthesis of surfaces of arbitrary color. These models are used for realistic 3D rendering, for arbitrary geometries of illumination and viewing.

In the field of Color Science, the characterization of the surface properties of objects follows a different priority. In general, very simple conditions are considered. A frequent assumption is that of a "flat world", where the geometrical aspects are completely ignored. This is mainly due to the fact that in the past the main interest in accurate color reproduction was for 2D color samples (textile industry, producers of paints, printers, etc.). Moreover, in color science, the study of the physical properties of materials is in general limited to the visible light. There is interest in the scientific community in a characterization of surfaces where a wider portion of the spectrum is considered, in particular to the IR region, to account for absorbance and emission of energy, as can be provided by physical-based multispectral models of surface reflection.

A model describing the reflection of light from rough surfaces has been developed from Prof. Nayar of Columbia University [1]. The aim of the visit in his laboratory was to investigate the feasibility of the model in its spectral version for the description of light reflection from rough surfaces. In particular, the investigation was devoted to the analysis of changes in the spectral reflectance as consequence of interreflections taking place on a surface, due to its irregular micro-geometry. The investigation was conducted in the domain of visible wavelengths in order to match the characteristics of the equipments in the ITC-CNR color laboratory.

If one considers the visual appearance of rough surfaces, we have all experienced that a rough surface appears darker than a smooth one (think for example of taking an object and smooth its surface using glass paper). In general, the chromaticity of the color doesn't change. However, models of rough surface reflection take into account interreflections that may generate non-uniform changes across the reflectance spectrum. If such changes are significant, they determine a change in chromaticity of the color, not only in a change of lightness. This information is useful when comparing the "intrinsic" color (that due to colorants and pigments) of surfaces having different roughness on the basis of chromaticity coordinates.

Two activities have been carried on during the visit:

1- Experimental analysis to quantify the accuracy of the multispectral model in predicting the reflectance spectrum of a rough surface: if the model is accurate in the visible domain, it is expected it is useful to predict reflectance for a wider set of wavelengths;
2- Analysis of the color appearance of rough surfaces.

2. Activities carried on during the visit

The activities carried on during the visit were essentially devoted to design the framework for the experimental analysis to perform at ITC-CNR using the equipments available in ITC's color laboratory. In particular, the Oren-Nayar model was analyzed and implemented, and then a simplified version was obtained by considering the characteristics of the measurement devices. An analysis was performed in order to understand the characteristics of model predictions in terms of the effect of interreflections. Finally, a plan of further investigations and experiment to perform at ITC-CNR was considered.

1.1 Analysis and implementation of the Oren-Nayar model

The Oren-Nayar model of light reflection describes how a rough surface reflects incoming light. It assumes that the surface can be considered as composed by V cavities having different slopes with a normal distribution of zero mean and standard deviation σ. The model has been analyzed, and a spectral version has been implemented to compute the reflectance of a rough surface as observed from a given viewing direction in response to a given illumination geometry. Surface is characterized by its albedo and roughness parameter.

1.2 Study of the application of the Oren-Nayar model to simulate the measurement of surfaces using measurement devices available at ITC-CNR

The Oren-Nayar model has been studied to derive a simplified version given fixed illumination/detection geometry as defined by spectral measurement devices. This simplified version is used to simulate the measurement of the reflectance of rough surfaces. In addition, an investigation has been performed to analyze to what extent the albedo and roughness of a surface determines a change in the profile of measured reflectance as consequence of interreflections on the surface due to its micro-geometry.

In general, only a change in lightness is observed visually between rough and smooth surfaces having the same albedo but different surface micro-geometry, and, accordingly, in the model a first order scaling of the albedo accounts for roughness. However, the model includes a second order effect as well, which is due to interreflections, in the form of a scaling of the squared albedo. This second term causes the profile of the reflectance spectrum to change upon changes in roughness. The extent of this change, and the conditions upon which this term has to be accounted for, have been the subject of the analysis.

If we consider a spectrophotometer that takes measurements in a circle spot of given diameter with measurement geometry 45°/0° (ring optic), the O-N model for computing surface BRDF simplifies in:

$$\mathbf{r} = f_1\boldsymbol{\rho} + f_2\boldsymbol{\rho}\boldsymbol{\rho}^T \qquad (1)$$

Where **r** is the vector of measured reflectance, and **ρ** is the albedo vector, $f_1 = 1 - 0.5\frac{\sigma^2}{\sigma^2 + 0.33}$ and $f_2 = 0.17\frac{\sigma^2}{\sigma^2 + 0.13}$ are the roughness coefficients.

1.2.1 Analysis of the reflectance change due to surface roughness

If we consider the roughness parameter in the range $\sigma \in \left[0, \frac{\pi}{2}\right]$, and analyze the ranges of the roughness coefficients, we obtain:

$f_{1,\max} = 1$ ($\sigma = 0$); $f_{1,\min} = 0.5590$ ($\sigma = \frac{\pi}{2}$)

$f_{2,\max} = 0.1615$ ($\sigma = \frac{\pi}{2}$); $f_{2,\min} = 0$ ($\sigma = 0$)

In the case $\rho = 1$, the values of reflectance are $r(\sigma = 0) = 1$, and $r(\sigma = \frac{\pi}{2}) = 0.559 + 0.1615 = 0.7205$

If we consider a plot with in abscissa the values of the albedo vector and in the ordinate axis the values of the reflectance vector, the curve is parabolic, in the coefficients f_2, f_1. Ranges of the parameters set the region in the plot where feasible curves are located, as illustrated in Figure 1.

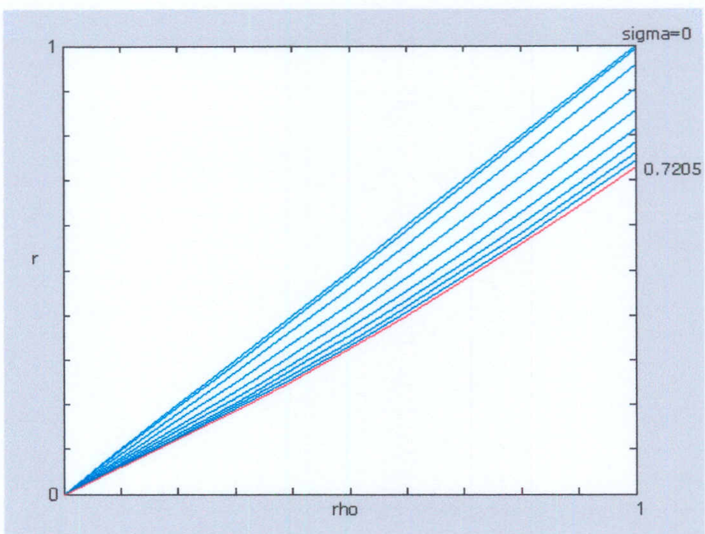

Figure 1. Limit curves for feasible functions to map reflectance values into albedo values. Feasible curves should laid inside the triangle.

If we consider taking a measure of reflectance, then, for any reflectance value, corresponding feasible albedo values are in the range $[r(\sigma_{\max}), r]$. It can also be observed that, if the maximum value in the reflectance spectrum is greater than 0.7205, the range of feasible values in the roughness parameter is reduced, due to the fact that albedo values cannot be greater than 1.

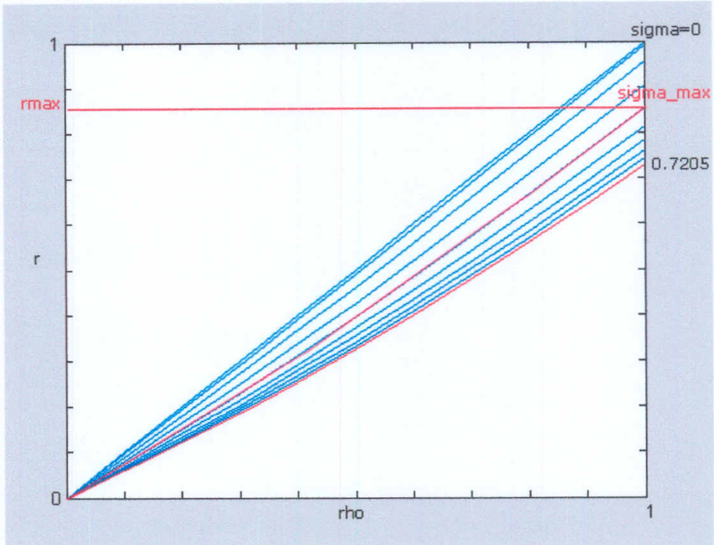

Figure 2. Limit curves for feasible functions to map reflectance values into albedo values with reduced area due to high values of reflectance. Feasible curves are those between sigma=0 and sigma=sigma_max.

The range of feasible albedo values for each reflectance value (reflectance at a given wavelength) therefore is $[r(\sigma_{max}), r]$, where σ_{max} is obtained by solving Equation 1 in scalar form for a reflectance value which is the maximum in the input reflectance vector. This analysis illustrates the amount of changes in reflectance due to the surface roughness.

Analysis of the departure from linearity of the curves in Figure 1 will illustrate the effect of interreflections. In fact, a linear relationship in the reflectance/albedo curve indicates that only a change in lightness is the visible effect of the surface roughness. A non-linear relationship indicates a possible visible change in color appearance. In order to verify if the amount of non-linearity actually can cause a visible change in color, we have considered the reflectance spectrum of the sample #14 in the Macbeth Color Checker chart (light green) as the albedo of a rough surface having $\sigma=\pi/4$. The corresponding reflectance is as in Figure 3. The roughness makes the color of the surface darker. The reflectance spectrum of the rough surface is not a simple scaling of the albedo.

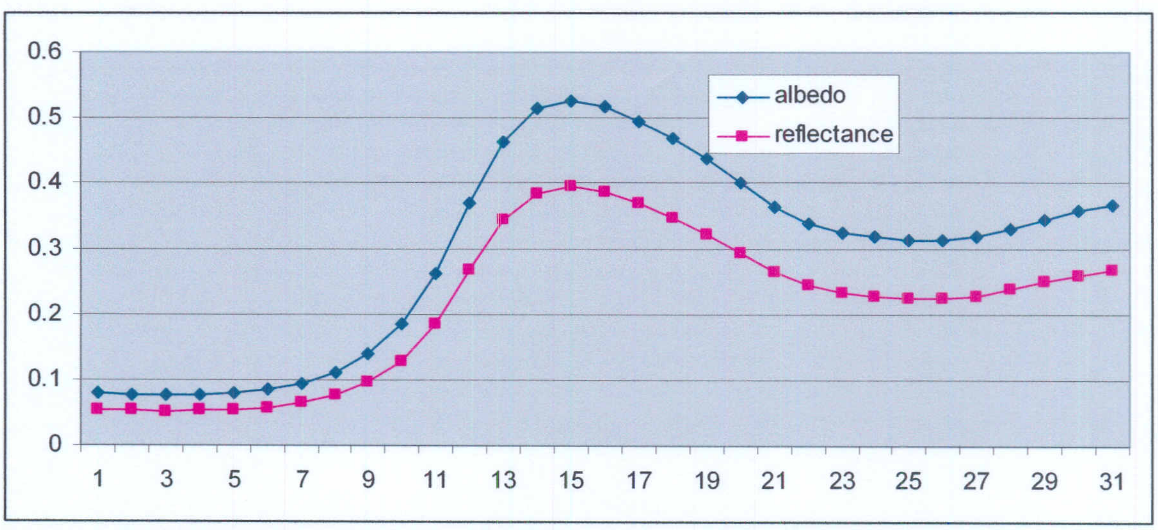

Figure 3. Example of rough surface albedo and simulated reflectance measurement. The surface has a roughness of $\sigma=\pi/4$.

If we compute the distance of the two spectra in the CIE a*b* plane, assuming the D65 illuminant as light source, we obtain a value of 3.83, which indicates a visible color difference. Figure 4 shows two colors with the computed chromaticity coordinates and equal lightness, for comparison.

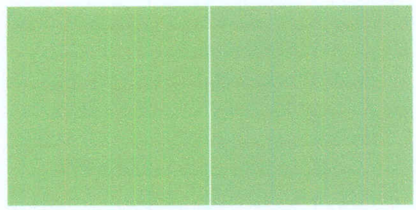

Figure 4. Two colors having the same chromaticity coordinate of the albedo and the reflectance function of Figure 3, but equal lightness.

1.3 Plan of further investigations and experiment to perform at ITC-CNR

It has been planned to perform experiments to verify the feasibility of the model in predicting the measured reflectance spectrum from rough surfaces. This experiment will consist in generating a set of samples of surfaces having the same roughness and different albedo, and surfaces having the same albedo and different roughness. These surfaces will be measured, and the data collected will be compared with model's predictions.

2 Conclusion

The visit at the CAVE laboratory consisted in an analysis of a multispectral version of the Oren-Nayar model and in its prediction of changes in rough surface color due to interreflections. It had been planned to perform further quantitative analysis using the equipment available in the color laboratory at ITC-CNR.

3 References

[1] Michael Oren, Shree K. Nayar, Generalization of Lambert's Reflectance Model, Proceedings of SIGGRAPH 94, Computer Graphics Proceedings, Annual Conference Series, July 1994, pp. 239-246.