Measurement of Surface Reflection Properties

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Abstract

The present paper describes an experimental apparatus and set of calculations for determining various parameters of the surface reflection model. The apparatus consists of a lighting system to emit parallel beams, a goniometric rotating table, and a vision system with six spectral channels. The camera data are used to estimate various parameters such as (1) spectral reflectance, (2) illuminant spectrum, (3) surface roughness, (4) ratio of body to interface intensity, and (5) index of refraction. First, a method for estimating (1)-(4) from a single multband image is introduced. Second, the parameter (5) is estimated using highlight peaks of an object surface at different conditions of illumination and viewing. Experimental results are shown using the curved surface of a painted object. The overall feasibility of our method is confirmed on computer graphics images created by using the estimated parameters.

Introduction

Knowing the reflection properties of an object surface is very important for image rendering in computer graphics, image understanding in computer vision, and image recording and rendering in digital archives. It should be noted that (1) reflection properties of an object surface depend on its surface material, and (2) these properties are related to both color (spectrum) and geometry. Principal parameters describing the surface reflection properties are surface-spectral reflectance, surface roughness, index of refraction, absorption index, and reflection intensity. Most objects in natural scenes are made of non-conducting materials called inhomogeneous dielectric materials. The dichromatic reflection model for the dielectric material suggests that light reflected from the surface is composed of two additive components, body (diffuse) reflection component and interface (specular) reflection component. The dielectric material requires an additional parameter for describing the reflection intensity ratio of the diffuse component to the specular component. The absorption index can be neglected for the dielectric material.

In computer graphics a three-dimensional (3D) reflection model is crucial for rendering realistic color images. However, it is difficult to find suitable values for the reflection parameters for a real object, and so far those were selected by the method of trial and error. In a previous paper,[1] we proposed a method for estimating various parameters of a reflection model from a single image of an object taken by a CCD camera. The Phong model was used for modeling light reflection on an object surface composed of inhomogeneous dielectric materials. This model is too simple to produce realistic images. In fact the Phong model has difficulty in describing the specular reflection component because the Fresnel term is neglected. Other works on reflection modeling are found in Refs. 2 and 3. They used gonio-metric methods and also neglected the Fresnel term. The Fresnel term cannot be neglected for realistic rendering of glossy and specular surfaces. We extended the previous parameter estimation technique to the Torrance-Sparrow model.[4] The specular reflection function is described in terms of the distribution of isotopic orientation, the geometrical attenuation factor, and the Fresnel term. Although the Torrance-Sparrow model is more precise than the Phong model, the model determination requires a precise system for measuring reflection of an object surface and algorithms for estimating parameters of the reflection model.

The present paper describes an experimental apparatus and set of calculations for determining various parameters of the surface reflection model. The apparatus consists of a lighting system to emit parallel beams, a goniometric rotating table, and a vision system with six spectral channels. The camera data are used to estimate the surface and illumination information such as (1) spectral reflectance, (2) illuminant spectrum, (3) surface roughness, (4) ratio of body to interface intensity, and (5) index of refraction. First, a method for estimating the parameters (1)-(4) from a single multband image is introduced. Second, the parameter (5) of index of refraction is estimated from the sensor measurements for highlight peaks of an object surface at different conditions of illumination and viewing. Third, these methods can be generalized to objects with general shapes, not just cylinders. Experimental results using the curved surface of a painted object demonstrate that the parameters (1)-(4) can be recovered from the single image and (5) can be recovered from the image sequence of highlights. To examine the accuracy, the estimated parameters are compared with direct measurements using a spectroradiometer and a refractmeter. The overall feasibility of our method is confirmed based on computer graphics images created by using the estimated parameters.

Experimental Apparatus

Figure 1 shows an overview of the experimental apparatus made in this study to obtain reflection measurements. The apparatus consists of a lighting system, a goniometric rotating table, and a vision system. Figure 2 depicts the lighting system for emitting parallel beams. The light source is a tungsten halogen lamp. Figure 3 depicts the rotating table for the measurement at different conditions of illumination and viewing. An object sample is mounted on the turntable about which a 70 cm arm is able to rotate. At the end of the arm is a multiband camera for spectral imaging.

The object sample can be rotated independent of the arm so that all incident/viewing angle configurations can be created for in-plane reflection. The condition that the emitted rays are parallel beams is crucial for reliable measurement of the object surface. The object is 3m apart from the light source. Figure 4 shows the 2D spatial distribution of luminance on a cross section to the optical axis from the light source. The emitted rays are quite uniform in a region of 70mm $\times$ 70mm at the location of the turn table. Figure 5 shows a geometric model for measuring a specular highlight on a curved surface. The index of refraction is estimated from the highlight measurements with different light angles.

The camera system is a calibrated six-color camera with six channels in visible spectrum. This camera system is composed of a monochromatic CCD camera, a standard photographic lens, six color filters, and a personal computer.

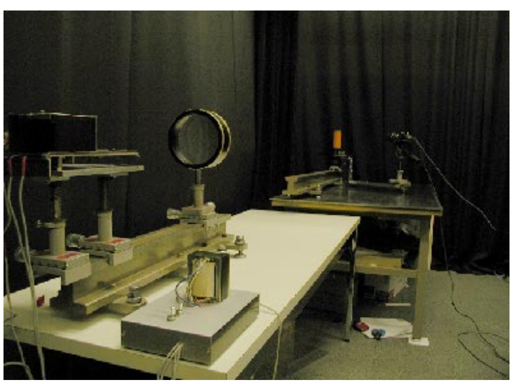

Figure 1. Total view of experimental apparatus.

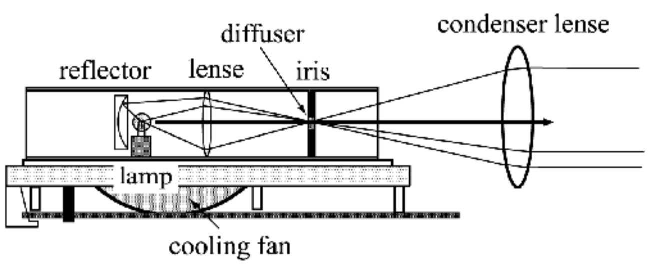

Figure 2. Lighting system.

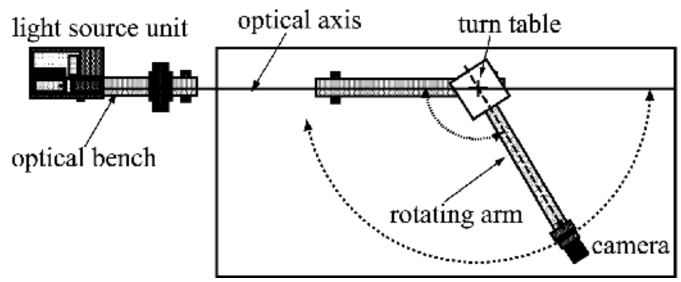

Figure 3. Goniometric rotating table.

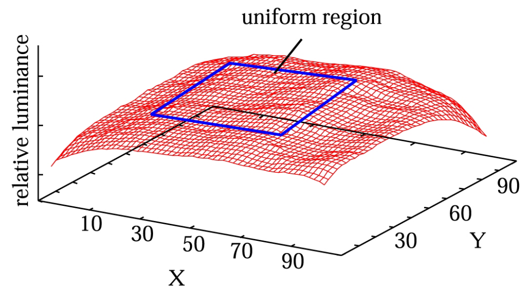

Figure 4. Spatial distribution of luminance.

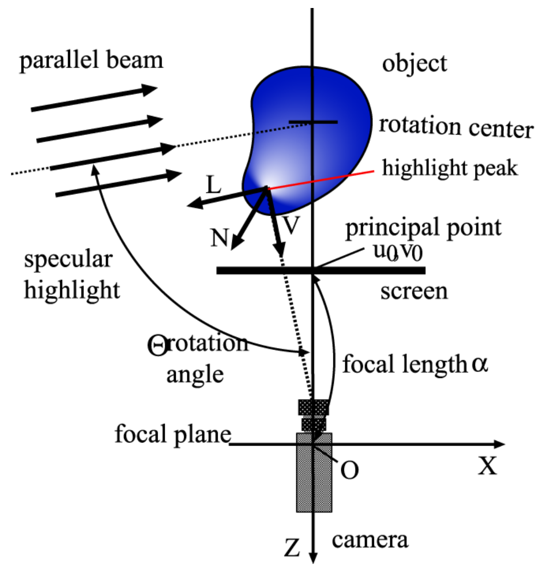

Figure 5. Model for measuring a specular highlight

Parameter Estimation Algorithms

The spectral radiance distribution Y(λ, x) from a reflective object surface is a function of the spatial location x and the wavelength λ. The Torrance-Sparrow model is described as

$$Y(x,\lambda) = \alpha\cos(\theta_{\mathrm{i}})S(\lambda)E(\lambda) + \beta\frac{D(\varphi)G(\mathbf{N},\mathbf{V},\mathbf{L})F(\theta_{\mathrm{Q}},n)}{\cos(\theta_{\mathrm{r}})}E(\lambda), \quad (1)$$

where the first and second terms represent, respectively, the diffuse and spcular reflection components. $S(\lambda)$: spectral reflectance, $E(\lambda)$: illuminant spectral distribution, θ_i: angle of incidence, θ_r: viewing angle, φ: angle between global surface normal and micro-facet normal, θ_Q: angle of incidence to micro-facet. The interface reflection component consists of several terms: D: function providing the index of surface roughness defined as $\exp\{-\ln(2)\varphi^2/\gamma^2\}$, where γ is constant. G: geometrical attenuation factor, and F: Fresnel spectral reflectance, where n is the index of refraction.

First, we can estimate from a single multiband image the four parameters of (1) surface spectral reflectance $S(\lambda)$, (2) illumination spectral distribution $E(\lambda)$, (3) surface roughness γ, and (4) ratio of body-to-interface intensity β/α.

In order to estimate these parameters, we analyze the pixel distribution (histogram) of an image taken by the multi-band camera. If an object surface has dichromatic reflection property without texture, the histogram shape exhibits some important features about reflectance, illuminant, and roughness. The histogram is composed to two linear clusters of matte cluster and interface cluster. The ratio of these clusters corresponds to the body-to-interface intensity ratio. The surface roughness is found from the relation between surface normal and intensity of highlight. We need information on surface normal vector for estimating the roughness for a general shaped surface. An algorithm similar to Shape-From-Shading[5] is proposed for computing the surface normal vector.

A linear finite-dimensional model[6] is used to recover the spectral functions of illuminant and spectral reflectance from the multi-band sensor outputs. The spectral functions are expressed as a linear combination of basis functions

$$S(\lambda) = \sum_{i=1}^{n} \sigma_i(x) S_i(\lambda), \quad E(\lambda) = \sum_{i=1}^{m} \varepsilon_i(x) E_i(\lambda), \tag{2}$$

where $\{S_i(\lambda), i = 1, 2, ..., n\}$ and $\{E_i(\lambda), i = 1, 2, ..., m\}$ are the sets of basis functions for the reflectance and illuminant, and $\{\sigma_i(x)\}$ and $\{\varepsilon_i(x)\}$ are the sets of weights. Therefore, the spectral estimation becomes inferring the two sets of weight coefficients from the camera outputs. The estimation of the weights is done using the algorithms shown in Ref. 6.

Second, we estimate the refractive index n from the highlight measurements. When the specular highlight is observed, the three angles are coincident as $\theta_i = \theta_r = \theta_Q$. The intensity of specular highlight peak depends on the refractive index n, the incident angle θ_i, and the constant coefficient β. Note that it is independent of roughness γ. Therefore the problem of estimating the refractive index n can be solved as the fitting problem of highlight peak. That is, the model function with unknown n is fitted to the intensity data of highlight peak acquired at different angles of θ_i. The criterion function for this fitting is described as

$$f = \sum_{\theta_i} \left(M(\theta_i) - \beta \frac{F(n, \theta_i)}{\cos \theta_i} \right)^2, \tag{3}$$

where $M(\theta_i)$ is the intensity of highlight peak. This intensity value is obtained from the histogram analysis of the image pixels. The parameters n and β minimizing the function are solved as a least-squared solution of the nonlinear fitting problem. We use the Levenberg-Marquardt method for this solution.

Figure 6. Measured image of a painted object.

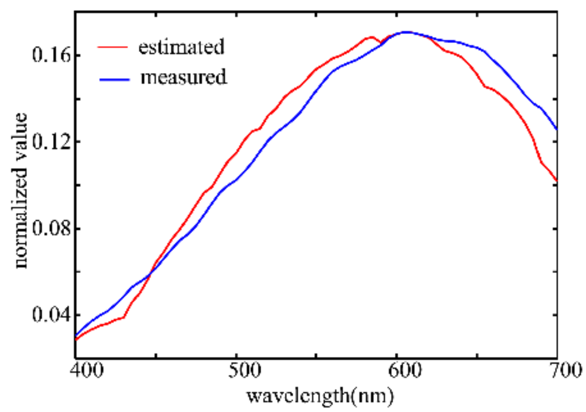

Figure 7. Estimation results of illuminant.

Experimental Results

Figure 6 shows the measured image of an orange painted object used in our experiments. Figures 7 and 8 show the estimation results of spectral functions for the illuminant and the surface reflectance, respectively. The estimated spectra are compared with the direct measurement results by using the spectro-radiometer. We estimated the ratio as $\beta/\alpha = 5.1$ and the surface roughness as $\gamma = 0.13$. Figure 9 depicts the fitting results of the specular function at highlight peaks. The best fitting is obtained at n = 1.52. The direct measurement by the Abbe refractmeter was n = 1.45. We can see in Figure 9 that the estimate provides an accurate fit at different incident angles. Figure 10 shows the computer graphics image of the original painted object that was recovered with these estimated parameters. The spatial coordinates of the object were measured by a laser range finder, and the object surface was represented by triangular meshes. A ray tracing algorithm was used for rendering the realistic 3D image under arbitrary conditions of illumination and viewing. A comparison between the measured image and the CG image suggests a reliability of our experimental setup and algorithms proposed in this paper.

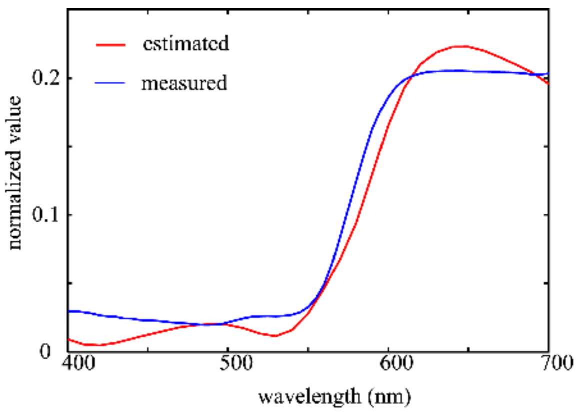

Figure 8. Estimation results of reflectance.

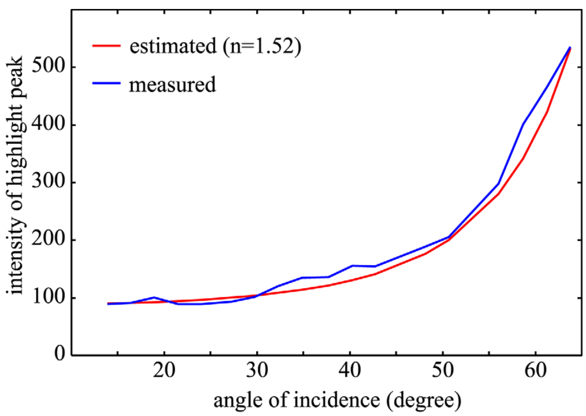

Figure 9. Fitting results of specular peaks.

Figure 10. CG image by the estimated parameters.

Conclusion

This paper has described an experimental apparatus and set of calculations for determining various parameters of the surface reflection model. The apparatus consisted of a lighting system to emit parallel beams, a goniometric rotating table, and a vision system with six spectral channels. The camera data were used to estimate various parameters such as (1) spectral reflectance, (2) illuminant spectrum, (3) surface roughness, (4) ratio of body to interface intensity, and (5) index of refraction. First, the parameters of (1)-(4) were estimated from a single multband image. Second, the parameter (5) is estimated using highlight peaks of an object surface at different conditions of illumination and viewing. Experimental results using the curved surface of a painted object were shown. Computer graphics images created with the estimated parameters have demonstrated the overall feasibility of our method.

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Biography

Norihiro Tanaka is a PhD candidate and visiting researcher in Osaka Electro-Communication University, Neyagawa, Osaka, Japan. His research interests include reflection modeling and its application to computer graphics and computer vision. He received the B.E. and M.E. degrees in computer science from Osaka Electro-Communication University in 1995 and 1997, respectively.

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