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Measuring, Modeling, and Reproducing Material Appearance from Specular Profile

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Abstract

A method is proposed for measuring, modeling, and reproducing material appearance from the specular profile representing reflectance distribution around a specular highlight. Our method is aimed at opaque materials with a highly glossy surface like plastic, ceramic, and metals. Hence, the material surface is assumed to be not a perfect mirror, but a surface with some roughness. We do not use a gonio-spectrophometer nor an image-based measurement setup. Instead, we make use of a gloss meter with a function to measure the specular profile, containing for glossy materials appearance such as roughness, sharpness, and intensity. The surface reflection is represented as a linear sum of diffuse and specular reflection components, the latter described by the Cook-Torrance model. The specular function represents the glossy surface appearance by a small number of control parameters. Mitsuba rendering system is utilized to perform the rendering algorithms. Finally, the feasibility of the proposed method is examined using different materials.

Introduction

The overall appearance of 3D objects in a scene results from a combination of spectral factors such as surface-spectral reflectance and the scene illuminant, and geometric factors such as surface geometries, roughness, and lighting conditions. Reflective object surfaces provide us specific perceptual impressions such as 'matte', 'glossy', and 'rough', differently from color and brightness. It has been found that these percepts are not necessarily independent but they show some interactions. For instance, the visual system could use the skewness of the image histogram to distinguish between glossy and matte surfaces, so that increasing the skewness made the surfaces appear glossy [1]-[2]. The surface appearance of a reflective object is physically described using the bidirectional reflectance distribution function (BRDF) [3]. The BRDF model consists of specular and diffuse components of optical surface reflection, the combination of which represents a variety of surface appearance including 'gloss', 'matte', and 'rough'.

The dichromatic reflection models with two components can describe the surface reflectances of most every day materials such as metals, plastics, paints, ceramics, cloths, and even skin, so that the most object surfaces are rendered using the dichromatic reflection models [4]-[5].

A gonio-spectrophotometer is available for precise measurement of BRDF. It performs measurements in a broad range of angles of illumination and viewing directions. However, it takes a very long time to measure and is expensive commercially. An image-based measurement method of BRDF was developed in a series of previous studies [6]-[9]. To avoid the moving parts to measure multiple angles, thus reducing the measurement time, we kept a light source and the camera sensor at a fixed position and curved the measurement sample onto a cylinder. The target material measured was limited to flexible sheets and packaging papers as used in the print and packaging industry.

In this paper, we consider measuring, modeling, and reproducing object appearance for glossy materials with strong specularity or gloss. Therefore, the target is not a perfect mirror surface but a highly glossy surface with a certain roughness, which we can see such as everyday objects made of plastic, ceramic, and metal materials. It is noted that the characteristics around specular peak such as the specular intensity and the sharpness of specular reflection are essential for appearance perception of glossy objects, rather than object color. Therefore, modeling and reproducing the material surface appearance become possible by using a reflection profile at even one specular reflection angle. We use a gloss meter with specular reflection measurement function. Here we propose a direct and simple method to reproduce material appearance from a specular profile.

Measurement

The instrument we use is a gloss meter of Rhopoint IQFlex 20, which can measure such appearance indices as glossiness, reflectance haze, and distinctiveness of image (DOI) in addition to the measurement of specular reflection profile. Figure 1 shows the measurement setup for the specular profile. The reflected light from a sample surface for an incidence of 20 degrees is detected using a photodiode array around the specular reflection angle of 20 degrees. Figure 2 demonstrates examples of reflection intensity distribution around the specular peak as a function of angle by the gonio-photometric measurement. The angular distribution in goniometric profile ranges the ± 7.25 degrees interval around the specular peak, and the angular resolution is the step of 0.02832 degrees.

We also use a gonio-spectrophotometer to perform BRDF measurements of the same materials and evaluate the performance of the method. The gonio-meter is Murakami's GCMS-3B gonio-spectrophotometric color measurement system (GCMS). The BRDF measurement was done in the range of incidence and viewing angles of [-70, +70 degrees] in this study.

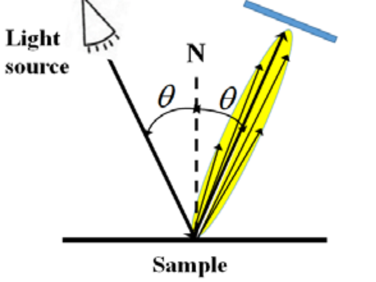


Figure 1. *Measurement setup*

V mirrored about N. The specular reflection is observed within only a restricted range of the viewing angle. This reflection component is strongest in the direction of $\mathbf{R}_l$ and it falls off sharply as the angle ρ between $\mathbf{R}_l$ and **V** increases. This rapid falloff is often approximated by

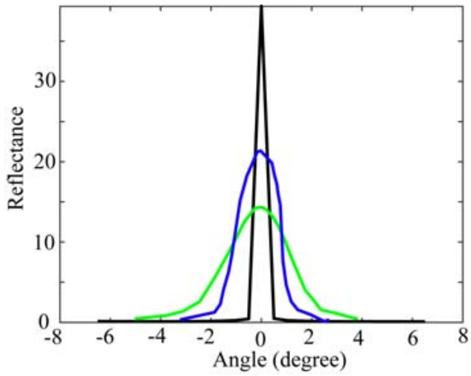


Figure 2. Reflection intensity distributions around a specular peak as a function of angle, for materials with different roughness. The higher the roughness, the smoother the distribution.

Modeling

Figure 3 depicts two conceptual diagrams for light reflection on object surfaces. We suppose a rough conductor for metal material in Figure 3 (a) and a rough dielectric for plastic, ceramic, and paint in Figure 3 (b). The surface-spectral reflectance of an object varies with the geometries of illumination and viewing. This function also depends on the object's material composition. The reflectance is usually decomposed into two parts: interface (specular) reflectance and body (diffuse) reflectance. The interface reflection occurs at the interface between the object's surface and the air. Reflection from materials like metals is due mostly to the interface reflection. For direlectric materials like plastics, the second reflectance component dominates. The body reflection occurs from light scattering among the pigment colorant layer of the subsurface. Polished metals have only the interface (specular) reflection.

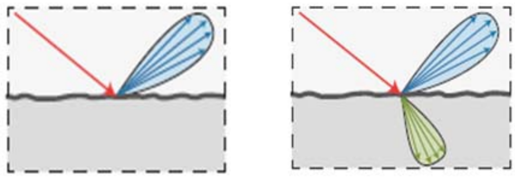


Figure 3. Conceptual diagrams for light reflection on object surfaces: (a) rough conductor for a metal material, (b) rough dielectric for dielectric materials like plastic, ceramic, and paint.

The specular function is a mathematical function to model the specular reflection phenomenon. This function does not include color (spectral) information but includes mostly geometric information of specular surface, which depends on directions of surface orientation, illumination direction, and viewing direction. Therefore, it can represent well the characteristics of glossy material appearance using parameters related to roughness and sharpness. Although the specular phenomenon is also analyzed by the concept of point spread function [10], the specular function described in this paper provides a direct description of surface reflection.

Let us consider a simple reflection geometry, where **N** is the surface normal vector, **L** is the incident light vector, and **V** is the viewing vector. Let $\mathbf{R}_l$ and $\mathbf{R}_v$ be respectively, **L** and **V** mirrored about **N**. The specular reflection is observed within only a restricted range of the viewing angle. This reflection component is strongest in the direction of $\mathbf{R}_l$ and it falls off sharply as the angle ρ between $\mathbf{R}_l$ and **V** increases. This rapid falloff is often approximated by

$$f(\rho) = \beta(\cos\rho)^n \tag{1}$$

where β is a constant representing the specular peak intensity and the index n is a measure of surface roughness. This type of intensity distribution is called the Phong distribution [11]. If the highlight has a pointed peak, a Gaussian distribution may be used for modeling the sharp falloff as

$$f(\rho) = \beta \exp(-n\rho^2). \tag{2}$$

The specular function of the Phong type is not enough to describe the surface specularity, because the specular peak intensity is not constant but varies on the angle of incidence. Also metal surfaces are not necessarily smooth, but rather rough to be represented by such a simple specular function.

To describe rough specular surfaces, the surfaces are idealized as being composed of small planar surface patches called microfacets. Based on this idealization, Torrance and Sparrow [12] developed a physics-based model. Blinn [13], and Cook and Torrance [14] adopted this type of model to computer graphics. The surface is assumed to be an isotropic collection of microfacets, each of which is a perfect smooth reflector. Figure 4 shows the reflection geometry for this case, where **Q** is the vector bisector of an **L** and **V** vector pair, and φ is the angle between **Q** and **N**.

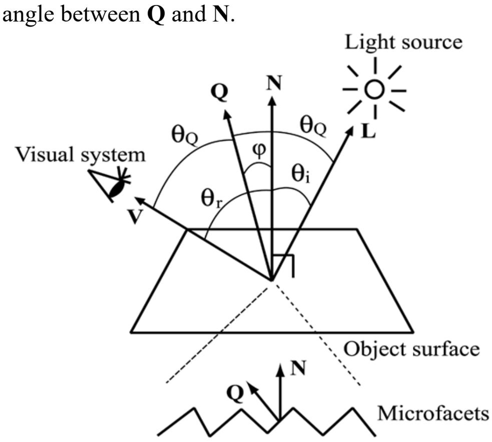


Figure4. Reflection geometry with microfacets.

A physic-based model of microfacet distribution is the Beckmann distribution [15].

$$f_1(\varphi) = \left(\frac{1}{\pi m^2 \cos^4\varphi}\right)\exp\left\{-(\tan\varphi/m)^2\right\}, \tag{3}$$

where m is the root mean square (rms) slope of the surface microfacets, representing the roughness of the material. Compared to the empirical models in Eqs. (1) and (2) above, this function gives the absolute magnitude of the reflectance without introducing arbitrary constants.

The Cook–Torrance model [14] uses a specular function of the form, except for a color term

$$f_2(\mathbf{N},\mathbf{V},\mathbf{L}) = F_0 \frac{f_1(\varphi)G(\mathbf{N},\mathbf{V},\mathbf{L})}{(\mathbf{N}\cdot\mathbf{V})(\mathbf{N}\cdot\mathbf{L})} \tag{4}$$

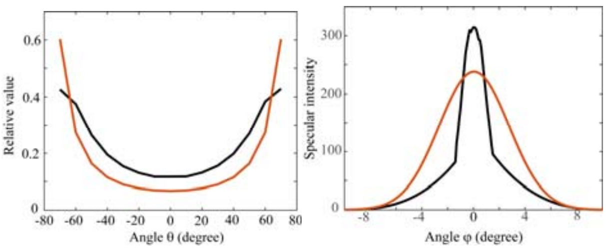
where F_0 is the Fresnel reflectance at normal incidence, $f_1(\varphi)$ is the Beckmann distribution function, and G is the geometric attenuation factor describing self-shadowing due to the microfacets and is of the form

$$G(\mathbf{N},\mathbf{V},\mathbf{L}) = \min\left\{1, \frac{2(\mathbf{N}\bullet\mathbf{Q})(\mathbf{N}\bullet\mathbf{V})}{(\mathbf{V}\bullet\mathbf{Q})}, \frac{2(\mathbf{N}\bullet\mathbf{Q})(\mathbf{N}\bullet\mathbf{L})}{(\mathbf{V}\bullet\mathbf{Q})}\right\} \quad (5)$$

This function G describes the fraction of the microfacets that are oriented in such a way that they are visible to both the light source and the viewer. A microfacet can be shielded partly from the light, therefore it ranges from 0 (total shadowing) to 1 (no shadowing).

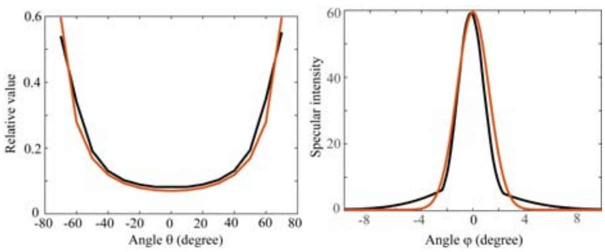
Reliability of Specular Function

We have examined the suitability of the specular function in the Cook-Torrance model, based on sample measurements using the gonio-spectrophotometer. The BRDF data were acquired from of two samples of a copper plate and a plastic plate in Figure 7. Figure 5 (a) shows comparison between the measured specular peak intensities (black) from the copper at different incidence angles θ and the fitted specular function (red) in the range of θ in [-70, +70 degree]. Figure 5 (b) shows comparison between the specular distribution (black) around a single specular peak and the fitted specular function (red). The specular distribution is based on the gonio data at incidence angle 20 degrees, which are plotted as a function of angle φ by changing viewing angle. Figures 6(a) and 6(b) show the comparisons for the plastic object, which correspond to Figures 5(a) and 5(b) for the copper, respectively. It is found that the specular function is accurate especially in representing the specular properties of the plastic.



(a) (b)

Figure 5. *Comparison between the measured specular data by gonio-meter (black) and the specular functions (red) for the copper.*
(a): Comparison of the specular peak intensities and the specular function f_2 in different angles of θ. (b): Comparison of the specular distribution around the peak of θ =20 and the specular function f_1 as a function of φ.



(a) (b)

Figure 6. *Comparison between the measured specular data by gonio-meter (black) and the specular functions (red) for the plastic.*
(a): Comparison of the specular peak intensities and the specular function f_2 in different angles of θ. (b): Comparison of the specular distribution around the peak of θ =20 and the specular function f_1 as a function of φ.

Appearance Reproduction

We consider a comprehensive model based on the Cook-Torrance model for rendering realistic material appearance from the reflection observations at a single incidence angle. Figures 5 and 6 suggest that the specular reflection behavior of materials at different geometric angles is well described using the Cook-Torrance specular function. Therefore, if parameters of the specular function can be estimated from the reflection dataset at a single incidence angle, image rendering of the appearance of a 3D object made of the material is performed using the gloss meter. In fact, the roughness parameter *m* is estimated from a single specular peak as follows:

$$m = \sqrt{\frac{F_0}{\pi}\frac{1}{f_{2Peak}\cos^2\theta}} \quad (6)$$

A comprehensive spectral reflection model is described by sum of the body (diffuse) reflection component and the specular reflection component, each of which consists of multiplying the spectral function and the geometric factor. The spectral power distribution of reflected light is written as

$$Y(\mathbf{N},\mathbf{V},\mathbf{L},\lambda) = \frac{1}{\pi}(\mathbf{N}\cdot\mathbf{L})S_D(\lambda)E(\lambda) + f_2(\mathbf{N},\mathbf{V},\mathbf{L})S_S(\lambda)E(\lambda), \quad (7)$$

where the first and second terms in the right hand are the diffuse reflection component and the specular component, respectively. The spectral functions $S_D(\lambda)$, $S_S(\lambda)$, and $E(\lambda)$ represent, respectively, the spectral reflectance for the diffuse reflection, the spectral reflectance for the specular reflection, and the spectral power distribution of the incident light. We assume that the diffuse reflection component obeys Lambert's law, that is, the intensity of reflected light is independent of the viewing direction and proportional to the cosine of the angle of incidence.

In the case of rough conductor material, we neglect the diffuse reflection term with $S_D(\lambda)=0$ in Eq.(7), since light reflection from metal surface consists of only specular reflection. The spectral reflectance $S_S(\lambda)$ is obtained from spectral measurement for the highest specular peak. If optical constants such as the index of refraction and the absorption coefficient for the target material are known, the spectral reflectance $S_S(\lambda)$ can be calculated using the Fresnel equations [16]. In the case of rough dielectric material, the spectral composition of the specular component is coincident with the illuminant by setting $S_S(\lambda)=1$. The spectral reflectance $S_D(\lambda)$ is obtained from reflectance measurement at matte part of the target object by using a gonio-spectraphotometer or a spectral colorimeter.

We use the Mitsuba rendering system [17] to implement the material appearance and render a realistic scene displaying object made of the target material. The Mitsuba renderer was modified for spectral rendering. All spectral functions are represented 61-dimensional vectors by sampling with 5 nm interval in the visible range of 400-700nm. In the present version, the chromaticity coordinates of the specular component of metal are fixed. The spectral reflectance increases to be whitened as the angle approaches to grazing angles. When this spectral property is needed, we use the model of Roughconductor material in Mitsuba.

Experimental Results

Figure 7 shows a set of material samples used in our experiments. It contains a copper plate, a pink plastic plate, and an orange ceramic tile. First, we used the copper plate to examine the feasibility of the proposed method. The measured specular reflection profile for the copper plate by using our gloss meter and the model fitting result are shown in Figure 8 (a), where the black curve represents the measured profile measurement at incidence angle 20 degrees, and the red curve represents the Cook-Torrance specular function obtained from Eq.(6) . The roughness parameter is m=0.0260. Figure 8 (b) shows the specular spectral reflectances $S_S(\lambda)$, where the black curve was calculted by substituting the typical optical constants for copper into the Fresnel equation, and the red curve was obtained from the direct measurement by the gonio-spectraphotometer. We used the red curve in image rendering. The Stanford bunny was used to test the appearance reproduction. Figure 9 (a) shows the image the bunny rendered in Mitsuba based on Eq.(7), where the lighting is given by a light probe, taken in a natural environment. For comparision, Figure 9 (b) shows the rendered image by using the data from the gonio-spectrophotometer.

Second, we used the pink plastic plate. Figure 10 (a) shows the measured specular reflection profile (black) for the plastic object by the gloss meter and the fitted curve (red) to the specular function. We have m=0.0220. Figure 10 (b) shows the diffuse spectral reflectance $S_D(\lambda)$ obtained from a matte part of the sample object by using a spectral colorimeter. Figures 11 (a) - 11(b) show the rendered images of Bunny from Mitsuba based on (a) measuremts by the gloss meter and (b) measurements by the gonio-spectrophotometer.

Third, we used the orange ceramic tile. We note that ceramic is a dielectric material, and the light reflection is modeled with the same way as plastics. Figure 12 (a) shows the measured specular reflection profile (black) for the ceramic object by the gloss meter and the fitted curve (red) to the specular function. We have m=0.0340. Figure 12 (b) shows the diffuse spectral reflectance $S_D(\lambda)$ measured by using a spectral colorimeter. Figures 13 (a) – 13 (b) show the rendered images of the bunny made of orange ceramic from Mitsuba based on (a) measuremts by the gloss meter and (b) measurements by the gonio-spectrophotometer.

In Figures 9, 11, and 13, compare the rendering results by the proposed method to the results by the BRDF measurements by the gonio-spectrophotometer. We can see that the material appearances by the proposed method are very close to the BRDF measurement method. We should noted that the lighting environment greatly affects the appearance reproduction.

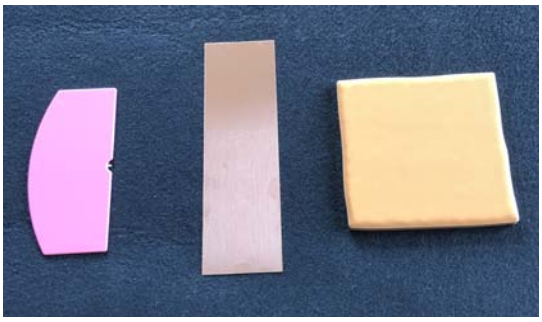
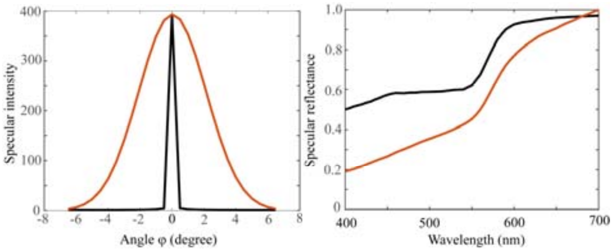


__Figure 7.__ Material samples used in our experiments.

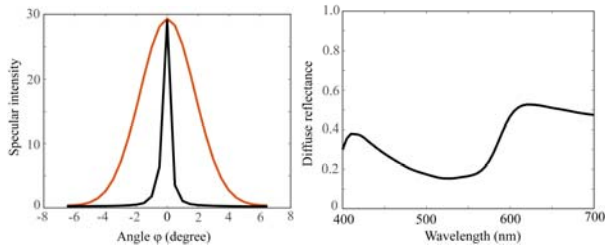


(a) (b)

__Figure 8.__ Geometric specular function and specular spectral reflectance. (a): Measured specular reflection profile (black) from the copper plate and the fitted curve (red) to the model function. (b): Reflectance by the Fresnel equation (black), and reflectance by the gonio measurement.

(a) (b)

__Figure 9.__ Rendered images of Bunny made of copper in natural environment. (a): Gloss meter. (b): Gonio-spectrophotometer.

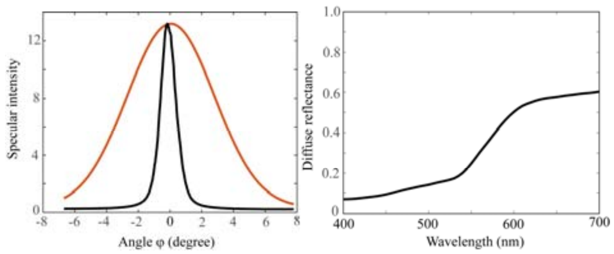


(a) (b)

__Figure 10.__ Geometric specular function and diffuse spectral reflectance. (a): Measured specular reflection profile (black) from the plastic plate and the fitted curve (red) to the model function. (b): Reflectance obtained from a matte part of the sample object by using a spectral colorimeter.

(a) (b)

__Figure 11.__ Rendered images of Bunny made of pink plastic in natural environment. (a): Gloss meter. (b): Gonio-spectrophotometer.



(a) (b)

Figure 12. *Geometric specular function and diffuse spectral reflectance. (a): Measured specular reflection profile (black) from the ceramic plate and the fitted curve (red) to the model function. (b): Reflectance measured by using a spectral colorimeter.*

(a) (b)

Figure 13. *Rendered images of Bunny made of orange ceramic in natural environment. (a): Gloss meter. (b): Gonio-spectrophotometer.*

Conclusions

We have proposed a method for measuring, modeling, and reproducing material appearance from the specular profile representing reflectance distribution around a specular highlight. The targets were highly glossy surfaces like plastic, ceramic, and metals. We did not use an expensive gonio-spectrophometer nor an image-based measurement system. Instead, as a measurement system we used a simple gloss meter with the function measuring a specular profile measurement. We supposed that the material surface was not a perfect mirror surface but a highly glossy surface with some roughness. The specular function was important to represent the material surface property, which contained appearance control parameters such as roughness, sharpness, and intensity. In this paper we used the Cook-Torrance model to represent the specular lobe, and showed that it allows accurate enough description of the specular reflection properties of plastics and metals, when compared with the BRDF measurements by a gonio-spectrophotometer. In order to render realistically object appearance, we linearly add a diffuse term to the specular Cook-Torrance model Mitsuba rendering system was utilized to perform the rendering algorithms. Finally, the feasibility of the proposed method was verified in an experiment using different materials. The proposed method allows to reproduce material appearance in a faithful way, very close to the results achievable using more time consuming BRDF measurement methods.

The proposed method gives a direct and simple method to render material appearance from just one specular highlight. This method, however, has some limitations. We did not consider materials with anisotropic reflections and materials with spatially-varying BRDFs. Spectral whitening effect at grazing angles remains as a future work.

Acknowledgements

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