Empirical BRDF models for standard reference materials

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11. Abstract Characterizing the appearance of real-world surfaces is a fundamental problem in multidimensional reflectometry, computer vision and computer graphics. For many applications, appearance is sufficiently well characterized by the bidirectional reflectance distribution function. BRDF is one of the fundamental concepts in such diverse fields as multidimensional reflectometry, computer graphics and computer vision. We discuss common points and differences between BRDF analysis in computer graphics and computer vision on one hand, and in metrology and reflectometry on the other hand. We review empirical BRDF models for standard reference materials, and outline possible alternative approaches. Since measurement errors can greatly influence shape and properties of BRDF manifolds, there is a clear need to develop new methods for handling BRDFs with measurement uncertainties.		
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1 Introduction

Characterizing the appearance of real-world surfaces is a fundamental problem in multidimensional reflectometry, computer vision and computer graphics. For many applications, appearance is sufficiently well characterized by the BRDF (bidirectional reflectance distribution function).

In the case of a fixed wavelength, BRDF describes reflected light as a four-dimensional function of incoming and outgoing light directions. In a special case of rotational symmetry, isotropic BRDFs are are used. Isotropic BRDFs are functions of only three angles. The BRDF is applied under the assumption that all light falls at a single surface point. The classical device for measuring BRDFs is the gonio-reflectometer, which is composed of a photometer and light source that are moved relative to a surface sample under computer control.

In computer graphics and computer vision, usually either physically inspired analytic reflectance models, or parametric reflectance models chosen via qualitative criteria, are taken for granted and used to model BRDFs. These BRDF models are only crude approximations of reflectance of real materials. Moreover, analytic reflectance models are limited to describing only special subclasses of materials.

In multidimensional reflectometry, an alternative approach is usually taken. One directly measures values of the BRDF for different combinations of the incoming and outgoing angles and then fits the measured data to a selected analytic model using optimization techniques. There are several shortcomings to this approach as well.

A possible alternative to parametric models is in using properly designed simulation studies together with modern data-driven nonparametric estimates of multidimensional manifolds to construct more realistic BRDFs. As an example of this approach, [10] and [11] modelled reflectance of materials in nature as a linear combination of a small set of basis functions derived from analyzing a large number of densely sampled BRDFs of different materials.

In computer graphics, it is important that BRDF models should be processed in real-time. Computer-modelled materials have to remind real materials qualitatively, but quantitative accuracy is not as important. The picture in reflectometry and metrology is almost the opposite: there is typically no need in real-time processing of BRDFs, but quantitative accuracy is the paramount. In view of this, some of the breakthrough results from computer vision and animation would not fit applications in reflectometry and in many industries.

Another difference with virtual reality models is that in computer graphics measurement uncertainties are essentially never present. This is not the case in metrology, reflectometry and in any real-world based industry. Since measurement errors can greatly influence shape and properties of BRDF manifolds, there is a clear need to develop new methods for handling BRDFs with measurement uncertainties.

2 Main definition

The bidirectional reflectance distribution function (BRDF), $f_\mathrm{r}(\omega_\mathrm{i},\, \omega_\mathrm{r}))$ is a four-dimensional function that defines how light is reflected at an opaque surface. The function takes a negative incoming light direction, ω_i, and outgoing direction, ω_r, both defined with respect to the surface normal $\mathbf{n}$, and returns the ratio of reflected radiance exiting along ω_r to the irradiance incident on the surface from direction ω_i. Each direction ω is itself parameterized by azimuth angle ϕ and zenith angle θ, therefore the BRDF as a whole is 4-dimensional. The BRDF has units sr^{-1}, with steradians (sr) being a unit of solid angle.

The BRDF was first defined by Nicodemus in [12]. The definition is:

$$f_\mathrm{r}(\omega_\mathrm{i},\, \omega_\mathrm{r}) \;=\; \frac{\mathrm{d}\, L_\mathrm{r}(\omega_\mathrm{r})}{\mathrm{d}\, E_\mathrm{i}(\omega_\mathrm{i})} \;=\; \frac{\mathrm{d}\, L_\mathrm{r}(\omega_\mathrm{r})}{L_\mathrm{i}(\omega_\mathrm{i}) \cos\theta_\mathrm{i}\;\mathrm{d}\,\omega_\mathrm{i}}$$

where L is radiance, or power per unit solid-angle-in-the-direction-of-a-ray per unit projected-area-perpendicularto-the-ray, E is irradiance, or power per unit surface area, and θ_{i} is the angle between ω_{i} and the surface normal, $\mathbf{n}$. The index i indicates incident light, whereas the index r indicates reflected light.

3 Important models

3.1 Diffuse reflection

3.1.1 Lambertian model

Lambertian model [9] represents reflection of perfectly diffuse surfaces by a constant BRDF. Because of its simplicity, Lambertian model is extensively used as one of the building blocks for models in computer graphics. It was believed for a long time that the so-called standard diffuse reflection materials exhibit Lambertian reflectance, but recent studies with actual BRDF measurements convincingly reject this hypothesis [7].

3.1.2 Oren-Nayar model

Oren-Nayar model [13] is a ”directed–diffuse” microfacet model, with perfectly diffuse (rather than specular) microfacets. It can be viewed as a generalization of the Lambertian model. This is a reflectance model for diffuse reflection from rough surfaces. Oren-Nayar model is typically used to predict the appearance of rough surfaces, such as concrete or sand.

Resently, a more sophisticated model was proposed by [15]. This new model includes as special cases both Lambertian model and the Oren–Nayar model, as well as the Torrance–Sparrow model with specular microfacets.

3.1.3 Lommel-Seeliger

Lommel-Seeliger model [5] is used to simulate the brightening of a rough surface when illuminated from directly behind the observer. This is a physically inspired model of a special class of reflections from diffuse surfaces. This model is typically applied to model astronomical data, such as lunar and Martian reflection.

3.2 Specular reflection and combined models

3.2.1 Phong model

Phong reflectance model [14] is a phenomenological model intended to represent plastic-like specularity. This reflection model describes the way a surface reflects light as a combination of the diffuse reflection of rough surfaces with the specular reflection of shiny surfaces. It is based on an idea that shiny surfaces have small intense specular highlights, while dull surfaces have large highlights that fall off more gradually. The model has been extensively used in computer graphics, but nowadays it is considered too crude and replaced by newer approaches. For applications in reflectometry and metrology, this model does not seem to have good fit to real materials.

3.2.2 Blinn-Phong model

Blinn-Phong model reduces computational overhead of the Phong model via allowing for certain quantities to be interpolated [3]. There is a computational advantage over the Phong model, but the quality of fit is not improved.

3.2.3 Torrance-Sparrow model

Torrance-Sparrow model is a general model representing surfaces as distributions of perfectly specular micro-facets [16].

3.2.4 Cook-Torrance model

Cook-Torrance model [4] is a further advancement of the specular–microfacet Torrance-Sparrow model, accounting for wavelength and thus color shifting.

3.2.5 HTSG model

The He–Torrance–Sillion–Greenberg model [6] is physically based. This model attempts to take into account a variety of possible physical phenomena such as polarization, diffraction, interference, conductivity, grazing rays.

3.2.6 Lafortune model

Lafortune model [8] is a generalization of the Phong model with multiple possible specular lobes.

3.2.7 Lebedev model

Lebedev model is designed for analytical–grid BRDF approximation.

3.2.8 Ward model

Ward model [17] is a specular–microfacet model with an elliptical-Gaussian distribution function dependent on surface tangent orientation (in addition to surface normal). It is an approximate model that does not reproduce the Fresnel effect.

3.2.9 Ashikhmin–Shirley model and distribution–based BRDFs

Ashikhmin–Shirley model [2] allows for anisotropic reflectance, along with a diffuse substrate under a specular surface. A related model is developed in [1]. These models use, in particular, the microfacets idea combined with the Phong reflectance model. Both models are computationally intensive, but are known to give good fit to BRDFs of some real materials.

4 Conclusions

BRDF is one of the fundamental concepts in such diverse fields as multidimensional reflectometry, computer graphics and computer vision.

In computer graphics and vision, it is important that BRDF models should be processed in real-time, but quantitative accuracy is not as important. In reflectometry and metrology, it is the opposite: there is typically no need in real-time processing of BRDFs, but quantitative accuracy is the paramount. In view of this, some of the breakthrough results from computer vision and animation would not fit applications in reflectometry and in many industries.

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Usually, either physically inspired analytic reflectance models, or parametric reflectance models chosen via qualitative criteria, are taken for granted and used to model BRDFs. These BRDF models are only crude approximations of reflectance of real materials. Moreover, analytic reflectance models are limited to describing only special subclasses of materials. An alternative approach is to directly measures values of the BRDF for different combinations of the incoming and outgoing angles and then to fit the measured data to a selected analytic model using optimization techniques. There are several shortcomings to this approach as well.

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