Empirical BRDF models for goniochromatism and gloss

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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. In this paper we study BRDF models of materials that possess complex visual properties such as gloss and goniochromism.

We discuss common points and differences between BRDF analysis of glossy and goniochromatic materials in computer graphics and computer vision on one hand, and in metrology and reflectometry on the other hand. We review empirical BRDF models for glossy materials and for goniochromatic materials, and outline possible alternative approaches. We argue that there is a clear need to develop new methods for handling BRDFs with measurement uncertainties.

12. Key words
Reflectometry, BRDF, empirical models, goniochromism, gloss, computer graphics, computer vision, metrology, data analysis, statistics of manifolds

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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, [20] and [21] 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.

Suitable statistical and machine learning methods for BRDF data analysis were proposed in [14]. Our novel unified approach aiming at applications requiring both computer graphics representations, as well as physically and perceptually consistent representations of appearance of physical goods, was layed out in [15].

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 [22]. 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-perpendicular-to-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 Glossy materials

BRDF models for glossy materials are usually formed as combined models by summing up the diffuse part and the specular part of the BRDF. The diffuse and the specular part are assumed to be independent within this framework. We treated the diffuse part in details in the Deliverables [17], [18] and in [16], [14].

In this paper, we focus on the BRDF as a whole. We do not treat appearance standards for gloss or goniochromatic colors, as we do not derive models for values of gloss or models for color coordinates. These important characteristics can be derived for each particular explicitly defined BRDF model. On the other hand, for computer graphic reflection models such as the Phong model, the Ward model, or the Cook-Torrance model, there is a correspondence between the parameters of these models and the appearance measurement scale for gloss. This implies that appearance scales, sich as gloss, can be used to reparametrize at least some of computer graphics reflection models. An advantage of this reparametrization would be that the value of the parameters of the model can be interpreted in terms of perception or physical attributes. See [31].

We refer to [23] and [19] for more details and references regarding scaling of the gloss and perception of the gloss.

3.1 Phong model

Phong reflectance model [25] 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 Blinn-Phong model

Blinn-Phong model reduces computational overhead of the Phong model via allowing for certain quantities to be interpolated [4]. There is a computational advantage over the Phong model, but the quality of fit is not improved.

3.3 Lafortune model

Lafortune model [13] is a generalization of the Phong model with multiple possible specular lobes.

3.4 Torrance-Sparrow model

Torrance-Sparrow model is a general model representing surfaces as distributions of perfectly specular microfacets [29]. Resently, a more sophisticated model was proposed by [26]. This new model includes as special cases both Lambertian model and the Oren–Nayar model [24], as well as the Torrance–Sparrow model with specular microfacets (see also [27]).

3.5 Cook-Torrance model

Cook-Torrance model [6] is a further advancement of the specular–microfacet Torrance-Sparrow model, accounting for wavelength and thus color shifting.

3.6 HTSG model

The He–Torrance–Sillion–Greenberg model [11] is physically based. This model attempts to take into account a variety of possible physical phenomena such as polarization, diffraction, interference, conductivity, grazing rays.

3.7 Lebedev model

Lebedev model is designed for analytical–grid BRDF approximation.

3.8 Ward model

Ward model [30] 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.

3.9 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 Goniochromatic materials

Goniochromism (also at times called *iridescence*) is the property of certain surfaces that appear to change colour as the angle of view or the angle of illumination changes. The definition of the BRDF in this case has to be modified in order to include the incoming and the outgoing waive lengths. While the modification of the definition is straightforward, the two added dimensions complicate numerical analysis of the problem and make vizualization tasks more difficult. Measurement procedures also become more complicated, see [3].

In [9], the authors proposed an approach for parametrization of BRDFs with the wavelength being the added extra dimension. A simplified colored RGB-version of the BRDF is proposed in [10].

Some of the most important causes of goniochromism are listed below. We do not discuss polarization in this article (see [9] for a possible approach).

4.1 Thin-film interference

The *thin-film interference*, i.e. when multiple reflections from two or more semi-transparent surfaces in which phase shift and interference of the reflections modulates the incidental light (by amplifying or attenuating some frequencies more than others). See [12] and [10] for rendering approaches related to thin films.

4.2 Diffraction

Iridescence can also be created by *diffraction*. In the case of diffraction, the entire rainbow of colours will typically be observed as the viewing angle changes. The case of diffraction has been treated in [28].

4.3 Pearlescent coatings

Pearlescent or *nacreous coatings* or pigments possess optical effects that not only serve decorative purposes (such as cosmetics, printed products, industrial coatings, or automotive paints), but also provide important functional roles, such as security printing or optical filters. See [8] for a sofisticated approximation to BRDFs of pearlescent materials.

4.4 Structural coloration

Structural coloration (in both fixed or variable structures): in biological (and biomimetic) uses, colours produced other than with pigments or dyes are called structural coloration. Microstructures, often multilayered, are used to produce bright but sometimes non-iridescent colours: quite elaborate arrangements are needed to avoid reflecting different colours in different directions.

4.5 General purpose models

Even though the Cook-Torrance model [6] and the He–Torrance–Sillion–Greenberg model [11] are rather elaborated physically based models, accounting for color shifting, and even for some complicated effects such as polarization, diffraction, interference, conductivity and grazing rays in the case of the HTSG model, it has been noticed [10] that these optical effects are not represented accurately by these BRDFs. See the diffraction of the light on a CD-disk example.

There seems to be no universally applicable systematic approach to constructing BRDFs for any of these cases. BRDF models are mostly processed on a case-to-case basis, even though there are some impressive examples of realistic illumination for specific types of surfaces. Books [7] and [5] contain a good overview of the current state-of-the art in this field of computer graphics and list a number of interesting special cases.

5 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.

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.

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.

For glossy materials, accuracy of measurements is an additional concern, as standard gonioreflectometers do not produce reliable measurements of peak values of specular BRDFs. For goniochromatic materials, the definition of the BRDF has to be modified in order to include the incoming and the outgoing waive lengths. The two additional model dimensions complicate the numerical analysis of the problem and make vizualization tasks more difficult. Modelling of goniochromatic BRDFs requires more cumbersome empirical models 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.

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