Using Images to Estimate Reflectance Functions

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Abstract
A new method for the evaluation of the bidirectional reflectance distribution function (BRDF) is presented. The proposed procedure foregoes the usage of special equipment like photogoniometers or imaging reflectometers but rather uses of-the-shelf hardware like CCD cameras.
The BRDF is determined from the image data, thus capturing several incident angles at each measurement. Using a diffuse reflectance standard the effects of ambient and stray light can be reduced. The presented method offers an easy and cost efficient way to measure material properties needed for physically based rendering algorithms.

Keywords: photorealism, BRDF, reflectance, illumination, surface properties, rendering.

1 Introduction

One of the most challenging problems in computer graphics is the production of realistic images. A prerequisit to reach this goal is the use of accurate and physically based input data. This includes the geometry, the description of the distribution and emission function of the light sources, and the reflectance data of the materials.

This paper is concerned with the evaluation of reflectance data consisting of spectral and directional information. The necessary terms, as defined by the BRDF (bidirectional reflectance distribution function) [7], are gathered from image data captured with a CCD camera under known conditions. The introduced method allows the measurement of surfaces with anisotropic reflectance characteristics.

2 The Bidirectional Reflectance Distribution Function (BRDF)

The BRDF is defined in terms of incident and reflected radiance by the following formula:

$$BRDF(\lambda, \theta_r, \phi_r, \theta_i, \phi_i) = \frac{L_{\lambda,r}(\lambda, \theta_r, \phi_r, \theta_i, \phi_i)}{L_{\lambda,i}(\lambda, \theta_i, \phi_i) \cos\theta_i d\omega_i}$$

with

$L_{\lambda,r}$ being the reflected radiance in the outgoing direction,
$L_{\lambda,i}$ the radiance in the incoming direction,
(θ_r, ϕ_r) the outgoing direction,
(θ_i, ϕ_i) the incoming direction,
$d\omega_i$ the differential solid angle surrounding the incoming direction,
N the normal vector of the surface,
L the light vector,
R the reflection vector, and
V the vector to the observer.

These terms and the vectors **N**, **L**, **R**, **V** are illustrated in Figure 1. The spectral dependence of the BRDF is handled using measurements with different wavelengths λ.

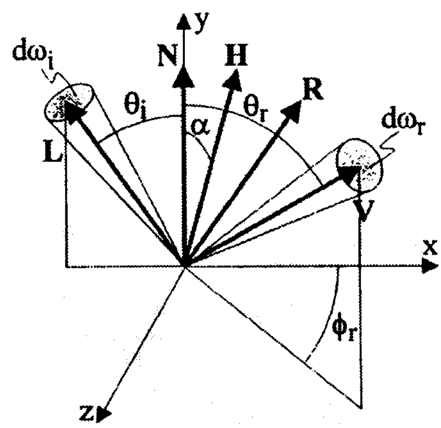


Figure 1: Conventions used in reflection

3 Problem Statement

The methods used to evaluate the BRDF are, on the one hand, calculation models simulating the reflection of light on surfaces with known material properties like roughness or index of reflection and, on the other hand, methods based on measurements.

In principle most of the calculation models are based on the theory of electro-magnetic waves. One of the first models was introduced by [1]. A disadvantage of these models is the need of knowledge about some of the material properties (roughness, index of reflection). These parameters are often not or only roughly known and, therefore, have to be obtained by measurements or only by guessing. Besides that, only few calculation model are accounting for anisotropic reflectance [2], [8], [9], [10]. A comparison of different calculation models with respect to their physical validity can be found in [5] and [3].

The measurement methods to evaluate the BRDF are mostly methods based on using a photogoniometer [6]. They are, however, very time consuming and expensive. Another method introduced by Ward [10] uses a imaging reflectometer. The main advantage of his method over the photogoniometer lies in its reduced measurement time. A shortcoming of both, the imaging reflectometer and the photogoniometer, is the need of a small specimen of the material under investigation.

The method introduced here tries to evaluate the BRDF from image data taken under known geometric position and orientation of camera and material, as well as some other restrictions described in the following chapter. The aim of our system is to make the determination of the BRDF possible without the need of any specimens, because these are not always available e.g. in the reconstruction process of historical objects or buildings.

4 Measuring the BRDF out of Images

4.1 The Measurement System

The measurement system consists of a light source and a charge-coupled device (CCD) camera as well as a diffuse reflectance standard to measure absolute reflectance data. The CCD camera takes an image from both the material under investigation and the diffuse reflectance standard. The light source is placed vertically above the line separating the diffuse standard sample and the material under investigation. As the diffuse reflectance standard acts as the reference and covers half of the image area, it is important to use a light source with radial symmetric light distribution, so that the incident radiance values are known over the whole image area. Additionally, white light should be used for the measurement in order to measure the whole visible spectral range. With the help of colored filters or special cameras the spectral BRDF functions can be obtained for several wavelengths. The standard diffuse sample should have a total BRDF near 1.0 over the whole visible spectrum. For all measurements the position of the CCD camera and the light source must be known. This can be accomplished for the CCD camera using photogrammetric measurements and beacons at the diffuse reflectance standard.

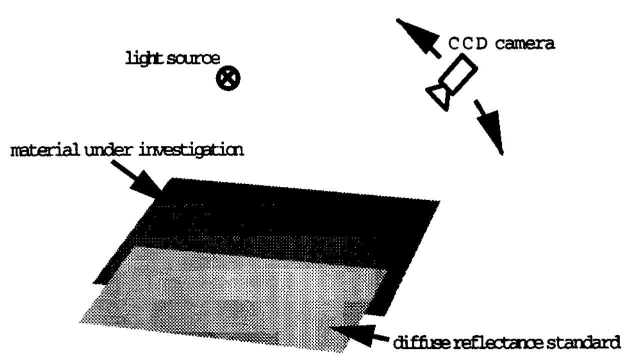


Figure 2: The measurement system

The measurement is performed in two steps:

1. **Measurement using the light source**
   In this measurement step an image is taken with the light source turned on. Because of the radial symmetric light distribution the luminance on both sides of the

separating line are the same and the reflected radiance from the unknown material $v_{measured}$ can be compared to the reflected radiance of the diffuse reflectance standard $v_{standard}$.

2. **Background measurement**
   In the second step the light source is turned off, in order to compensate the effects from ambient and stray light. The values obtained from the image of this measurement are subtracted from the image taken with the light source turned on.

With each image we only capture a certain range of the incident and reflected angles $(\theta_r, \phi_r, \theta_i, \phi_i)$. Hence, several measurements, varying the position of the CCD camera to get new incident and reflected angles, have to be performed in order to cover the BRDF over the whole hemisphere. The distance of the CCD camera to the unknown material influences the resolution of the measurement. A maximum resolution is aimed by placing the CCD camera near to the unknown material, because only a small part of the BRDF is sampled.

One constraint of this measurement system is that the light source should be a point light source, meaning that the ratio between the radius of the light source and the distance to the material should be very small. In violating this restriction the reflected radiance into one reflection direction contributes from radiances with different incoming angles. The variance of the incidence direction over the image decreases with the distance of the light source, so there is a tradeoff between the quality and the distance of the light source.

The light source should illuminate the material under investigation only locally. That means that there should be no light reflected from other objects close to the measured material.

4.2 Evaluation of the BRDF

Having gathered the necessary measurements the absolute BRDF can be calculated using the formula:

$$BRDF = \frac{v_{measured} - v_{background_1}}{v_{standard} - v_{background_2}} \cdot \frac{BRDF_{standard}}{\pi}$$

with

$BRDF_{standard}$ being the total diffuse reflectance of the standard sample,

$v_{measured}$ the measured radiance value at the location of interest,

$v_{standard}$ the measured radiance value at the symmetric location of the standard sample,

$v_{background_1}$ the background radiance value at the location of interest, and

$v_{background_2}$ the background radiance value at the symmetric location of the standard sample.

Using the method outlined above, it is possible to measure both isotropic and anisotropic reflectance. The measurement for isotropic materials is simpler, because the BRDF is independent of rotation about the surface normal. That means that the BRDF depends only on θ_r, θ_i and the difference between ϕ_r and ϕ_i.

After the data is gathered, it can be fitted by a least squares error minimization method to a set of parameters as described in [10] or in [9], to approximate the reflectance functions.

4.3 Limitations

The most important limitations are:

1. **Camera accuracy**
   The accuracy of the measurement does, of course, depend on the geometric and radiometric accuracy of the CCD camera. However, an error introduced this way is partly compensated for by background and standard diffuse sample measurements.

2. **Specular reflection**
   It is not possible to measure materials with sharp specular peaks, because of a finite resolution of the CCD camera. However, as mentioned in [10], a perfectly smooth surface is not directly measurable by any goniometer. This does not directly state a restriction as the physics of smooth surfaces are well understood anyway.

5 Implementation

Currently, the system works with a 50 watt quartz-halogen lamp and a CCD camera included in the standard equipment of a Silicon Graphics Indy workstation which was used for the processing of the captured images. Thanks to the gain control of the camera, it is possible to adjust the measurement range to the individual illumination conditions. In this way the CCD camera does not get into saturation, thus allowing the measurement error to be reduced.
Figure 3 depicts the actual placement of the camera, the light source and the material under investigation.

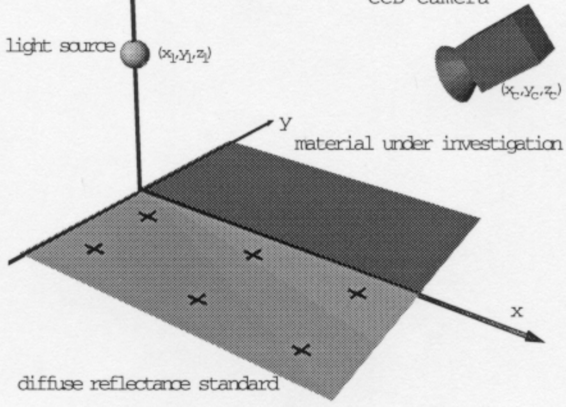


Figure 3: The measurement system

An example of an image captured with the light source turned on is shown in Figure 4. One half of the image depicts the diffuse reflectance standard, while in the other half

the reflection of the material under investigation can be seen.
The position of the camera is obtained by manually selecting beacons which are shown in Figure 4 and photogrammetric calculations which are described in [4]. At the moment we do not have a method for measuring the position of the light source automatically, and, therefore, we determine its value manually.

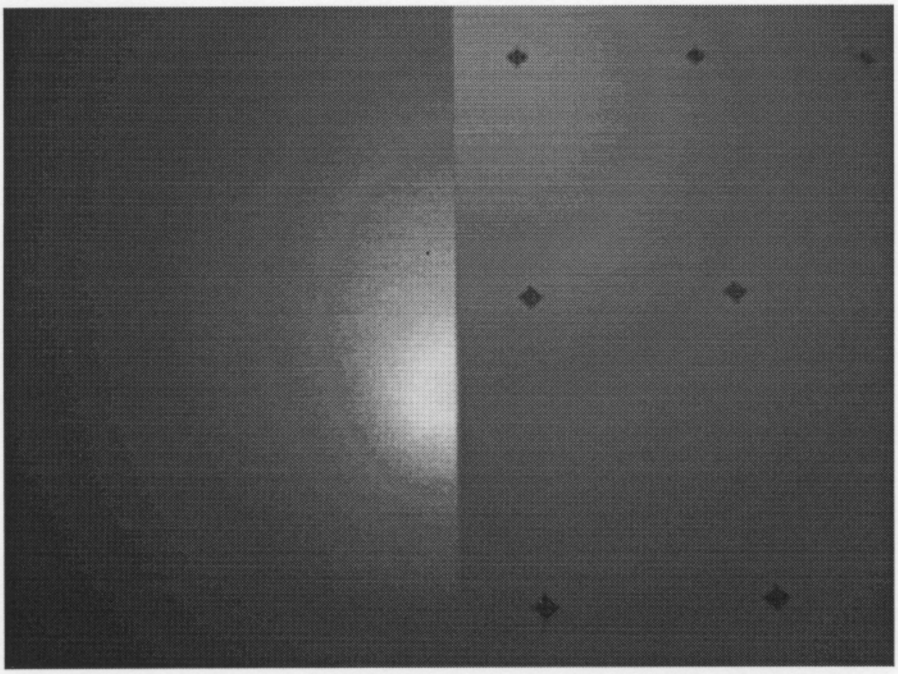


Figure 4: A captured image with the light source turned on

6 Results

In Figure 5 the comparison between the BRDF measured using a photogoniometer and BRDF point samples evaluated from images are shown in polar coordinates.

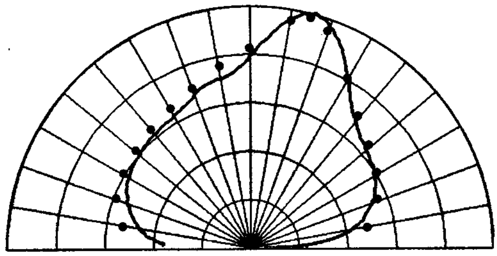
Because of geometric limitations of the photogoniometer no data of the BRDF in Figure 5(b) larger than +65 degrees are available.

7 Ongoing Work and Future Outlook

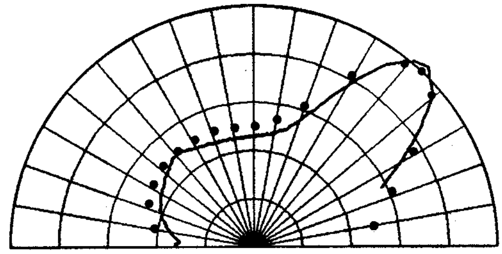
The introduced method is intended for the evaluation of the BRDF in environments where specimens are not available, a problem often encountered in computer based reconstruction and simulation of real world objects.

Further goals are:

1. an extension of this method for exterior environments (e.g. to make it applicable to the reconstruction of three-dimensional city models).



(a) $\theta_i = 15$ degrees



(b) $\theta_i = 45$ degrees

Figure 5: Comparison between BRDF data measured by a photogoniometer (solid line) and BRDF points measured from images (small circles) represented in polar coordinates and an incident angle of (a) 15 degrees and (b) 45 degrees.

2. to develop a system being able to record both the geometric as well as the radiometric description of a scene and refine the scene (the geometry, the reflectance functions and the illumination), until the simulated scene is no longer distinguishable from the real scene.

Acknowledgments

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