Spectral BRDF Measurement and Data Interpolation

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Abstract

Measuring spectral BRDFs of physical surfaces is essential to applications in computer graphics, computer vision and image analysis. Such measurements provide spectral data to characterize surfaces that can be used for evaluating reflection models. Existing research on spectral BRDF measurements is very limited. This paper discusses two practical methods for measuring spectral BRDFs: the sample-fixed and sample-rotation methods. We will also present an effective interpolation method to convert the raw data into a regular format for convenient applications.

Introduction

Surface reflection is an essential problem in color imaging applications such as computer graphics, computational vision, image analysis, and surface appearance engineering. The general description of surface reflection is given by a bi-directional reflection distribution function (BRDF) [1,5]

$$\rho(\theta_i,\varphi_i,\theta_o,\varphi_o,\lambda) = \frac{dL_o(\theta_o,\varphi_o,\lambda)}{L_i(\theta_i,\varphi_i,\lambda)\cos\theta_i d\Omega_i}, \quad (1)$$

which is the ratio between the reflected radiance dL_o and the incident irradiance $L_i \cos\theta_i d\Omega_i$ (see Figure 1). The incident (or lighting) direction is specified with (θ_i,φ_i), where θ_i and φ_i are the polar and azimuth angles of the incident direction, and the outgoing (or viewing) direction is specified with (θ_o,φ_o). In Eq. (1), λ is wavelength; thus given (θ_i,φ_i) and (θ_o,φ_o), a BRDF is a spectrum.

It is important to measure spectral BRDFs and there are several reasons. First, such measurements provide spectral data that are necessary to reveal entirely the physical properties of surfaces and reflections. Spectral BRDFs offer a better basis for accurate prediction in computer vision and image analysis. Second, measured spectral data can be used to create more realistic computer-rendered images in the aspects of color accuracy and capabilities of simulating wavelength-sensitive phenomena.[7,6,17] For example, metallic surfaces may appear with different colors due to Fresnel reflection[3] as well as multiple scattering. [16] Third, a number of empirical and physically-based reflections models have been proposed[3,15,19,16] and the measurements of spectral BRDFs are useful to evaluate the accuracy of these models. In particular, since spctral BRDFs maintain the information of wavelength, they are more physically convincing in evaluating theoretical models. Finally, the measured data of spectral BRDFs of physical surfaces can be used to specify the surface qualities and standards in design of industrial and consumer products.

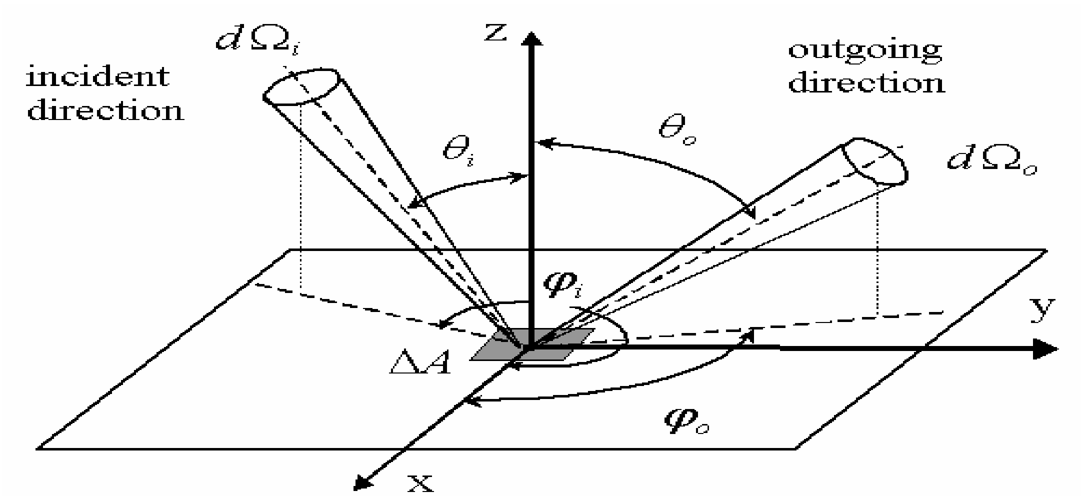


Figure 1. Geometry and notations for BRDF definition.

Although measurements of non-spectral BRDFs (such as in RGB) have been made substantially, so far very limited research has been done on measuring spectral BRDFs. Since spectral measurements require special equipment such as a spectraphotometer or spectraradiometer,[9,21] to measure spectral BRDFs, a key issue is how to integrate the spectral equipment with a mechanical platform that can be conveniently controlled and quantified for the incident and outgoing light directions. Although such an integrated system is commercially available,[1] the system is very expensive and often not easily accessible. Besides, the existing commercial system usually limits the size of the measured samples and thus does not work for practical objects that are larger than the size limits. However, in computer graphics, computational vision and color imaging, the demand in measuring spectral BRDFs of practical surfaces has been increasing remarkably. This motivates our work to develop practical measurement methods that can measure spectral BRDFs of objects with various sizes and can be easily adapted or customized according the application needs.

In this paper, we discuss two practical methods to measure spectral BRDFs using a spectraradiometer. In the first method, which we called *sample-fixed method*, the object sample does not move during the entire measurement. Different incident and outgoing directions relative to the surface normal are achieved by relocating and reorienting the light source and the spectral detector. This method works for surfaces and objects of various sizes, but the measurement demands an extremely large amount of labor work and is error prone. In the second method, which we call *sample-rotation method*, the object sample is mounted on a platform that provides three orthogonal rotations. During the measurement, the light source is fixed and the spectral device is relocated in a number of times. Comparing with the sample-fixed method, the sample-rotation method significantly reduces the labor work and is less error prone. The sample-rotation method has a certain degree of restriction on the object size, but the allowable size is still significantly larger than a commercial integrated system. Moreover, the sample-rotation method can be easily adapted and customized to allow various object sizes.

Background

The existing systems for measuring surface reflection have many different forms and the measurement techniques have been studied for a long time in optical scattering and surface morphology (see Ref. [1] for a comprehensive review). Typically, a measurement system has a bidirectional control of the incident and outgoing light directions. A critical limitation of such a system is that it only allows small surface samples. Besides, the instrument is very expensive and using it needs special training.

The developments in computer graphics and computational vision in recent years have triggered a new demand for measuring spectral BRDFs of practical surfaces. For example, in digital archiving of artistic sculptures,[10,2] object geometries have been acquired in high resolution using 3D laser scanning. However, the physical properties of the objects are obtained in terms of RGB triplets, which are not sufficient to represent the full characteristics of the surface reflection. To provide the full information in the physical aspect, it is necessary to acquire BRDFs in terms of spectra.

In the context of surface specification and appearance modeling, considerable researches have been conducted on reflectance measurements.[8] In this aspect, the representative researches in recent years were those at NIST where a goniophotometer is used to acquire spectral BRDFs,[18] and the measured data have been successfully incorporated into realistic graphics rendering.[20]

In computer graphics, there have been extensive researches of BRDFs in terms of RGB. Ward[19] proposed an imaging gonioreflectometer that combines a mirror and a CCD camera to capture BRDFs. Dana et al.[4] developed a technique to efficiently capture bidirectional textures. Marschner et al.[12,11] constructed a system to measure isotropic BRDFs of spherical objects. Recently, Matusik et al.[13,14] developed a similar system and acquired dense sampled reflectances of different materials. These techniques are limited to spherical objects.

Practical Measurement Methods

To measure spectral BRDFs, a key question is how to effectively integrate a spectral detector with the control for the incident and outgoing light directions. To capture spectra, a spectraradiometer or spectraphotometer is needed. Such equipment is usually much larger and heavier than a regular digital camera that captures RGB information. A favorable approach is to mount the spectral device on a solid basis and relocate it as less as possible during the spectral BRDF measurement. Below we discuss two practical measurement methods.

Sample-Fixed Approach

In this method, the sample of surface or object is fixed during the measurement. The locations of the light source and the spectral detector change to achieve different combinations of the incident and outgoing directions. This approach is illustrated in Figure 2. In this approach, for one given light source location (i.e. incident angle), the spectral device changes its location as well as orientation (such that it points toward the measured sample). For this method we assume that the surface is isotropic.

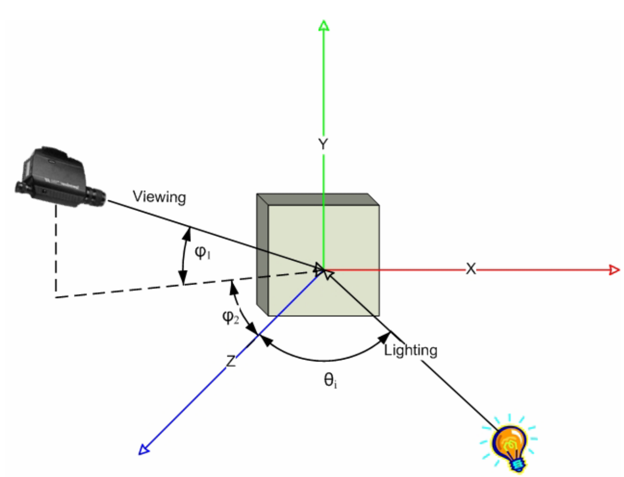


Figure 2. Measurement layout of the sample-fixed method.

The advantage of the sample-fixed method is that it is not limited by the size of the measured sample object. However, this approach has a critical drawback in the tremendous amount of labor that is demanded in the measurement. Given any location of the light source, the spectral device has to be relocated for the measurement for a different outgoing direction. The number of times of relocating the spectral device is extremely large. In particular, for a specular surface, the BRDF has a sharp lobe depending on the spatial angle. To capture the specular behavior sufficiently, more delicate locations of the spectral device are needed. In addition, when the spectral device is relocated, not only the location of the support of the spectral device (such as a tripod), but also the height and the orientation of the spectral device have to be changed. This makes the measurement extremely slow. Consider a measurement with 10 locations of the light source (incident angle), each corresponding to 50 locations of the spectral device. Suppose that one measurement takes 5 minutes. The total time would be 2500 minutes, about 104 hours. Besides, the measured data tend to be more error-prone because the spectral device is frequently relocated and re-oriented.

Sample-Rotation Approach

The sample-rotation approach eliminates the drawback of the sample-fixed approach. This technique shifts the control of angles by manipulating the sample object instead of the spectral device. The basic idea is shown in Figure 3. The holder of the sample provides three rotations: tilting the sample surface (angle α), rotating about the vertical axis (angle β), and dialing rotation (angle γ). If a surface is isotropic, no operation is needed to change angle γ during a BRDF measurement. Thus, given δ, the angle between the incident and outgoing light, one only needs to change angles α and β on the sample holder. This remarkably reduces not only the labor but also the measurement errors.

One disadvantage of the sample-rotation approach is that it is limited to relative small sample surface that fits to the holder. Another problem is that the measured results cannot be directly stored in terms of an array of $(\theta_i, \theta_o, \varphi_o)$. When converting angles from (α, β, δ) to $(\theta_i, \theta_o, \varphi_o)$, the measured spectra correspond a set of unstructured scattered points in three dimensions. In case that the sample surface is anisotropic, dimension for the dial angle γ is included, and the measured results are scattered points in four dimensions. Thus a key question is how to convert the measured data to an array of $(\theta_i, \theta_o, \varphi_o)$ through interpolation. This problem will be discussed below.

Measurement Procedure

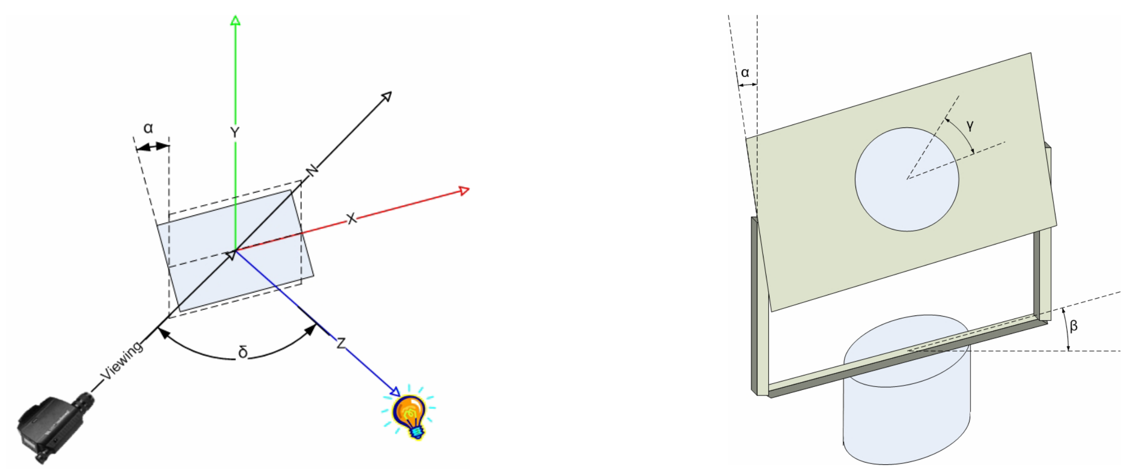
Spectral Measurement

Our spectral measurements are conducted using a PR-650 SpectraScan spectroradiometer produced by PHOTO RESEARCH®. This spectraradiometer can measure spectra from 380 to 780 nm with sample interval of 4 nm. For each combination of spatial orientations, we measure the surface reflectance. To obtain the reflectance, we first measure the light intensity $I_0(\lambda)$ of the illuminator using a RS-3 Standard White from PHOTO RESEARCH®, which has reflectance of 99% (±1%) from 380 to 780 nm and can therefore be regarded as a perfect reflector. Then we put on a sample and measure light intensity $I(\lambda)$ from the sample. The reflectance $R(\lambda)$ of the sample is obtained by the ratio between $I(\lambda)$ and $I_0(\lambda)$

$$R(\lambda) = I(\lambda) / I_0(\lambda) , \quad (2)$$

Light Conditions

It is important to main appropriate lighting conditions during the measurement. Since we use a regular tungsten light bulb as our light source, to achieve high accuracy, a critical issue is to keep the ambient or environment reflection contribution sufficiently low. Another critical issue is to control the incident light beams such that they have the incident angle. To achieve this, we use a long narrow cylinder tube to confine the incoming light. Besides, we use a board to block light from directions other than the intended incident direction (see Figure 4).



(a) (b)

Figure 3. Sample-rotation method. (a) Measurement layout (c) The sample holder.

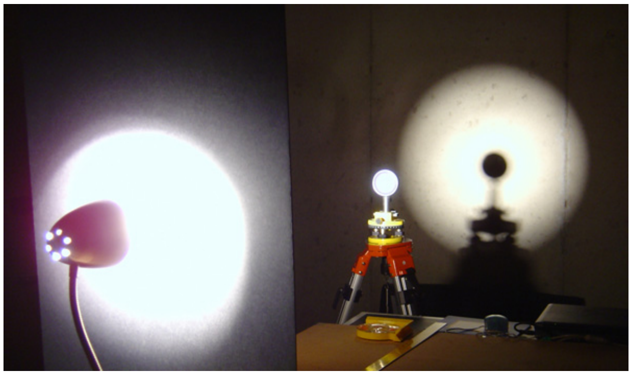


Figure 4. Light source is blocked by a black board, which has a small hole to allow selected light to pass through.

Sample Surface

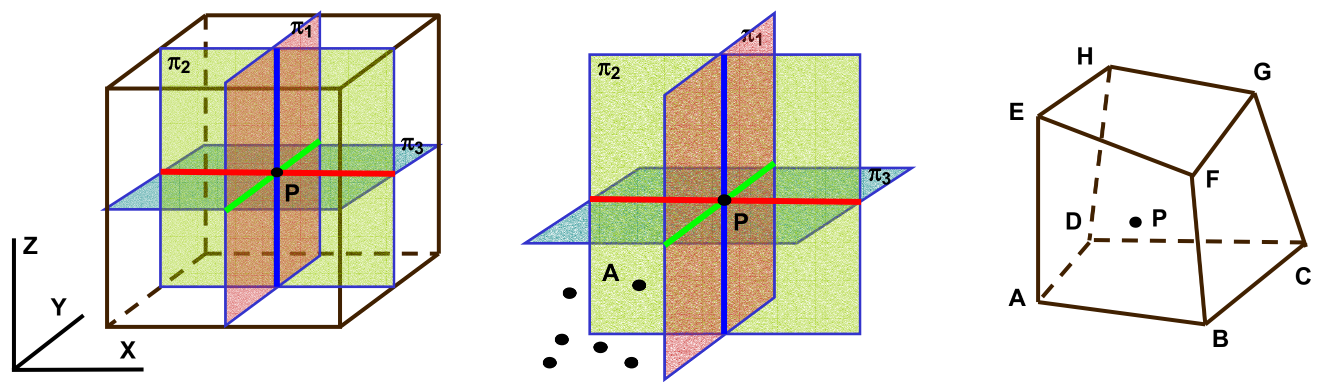
The sample surface we measure is a paint color sample for interior wall. The only thing we need to do before conducting the entire BRDF measurement is to check its isotropy. Using our sample holder, this can be easily checked by modifying the dial angle γ given a non-zero tilt angle α .

Measurement Loops

The locations of the light source and the sample holder are fixed during one set of BRDF measurements. The spectral device is located with angle δ that varies from 0 to 150 degrees with interval of 11.25 degrees. For each value of δ, we first specify the tilt angle α, which varies from 0 to 70 degrees with interval of 10 degrees. Given each α, the holder is rotated about its vertical axis such that β varies at interval of every 5 degrees. Note that for different combination of δ and α, the number of sample points for β are different. As results, we obtain a list of spectral reflectances for different combinations of (α, β, δ) .

Interpolation

The measured spectra of a BRDF after converting into $(\theta_i, \theta_o, \varphi_o)$ are a set of unstructured scattered points in three dimensions. To obtain the spectrum for any given combination $(\theta_i, \theta_o, \varphi_o)$, we proposed the following technique of interpolation.



(a) (b) (c)

*Figure 5. (a) Color space is divided by three planes π_1, π_2 and π_3 that contain **P** and are respectively perpendicular with axes X, Y and Z in the CIE XYZ coordinates. (b) In the first subspace point **A** is found closest to **P**. (c) The eight closest points obtained from all subspaces for spectral construction.*

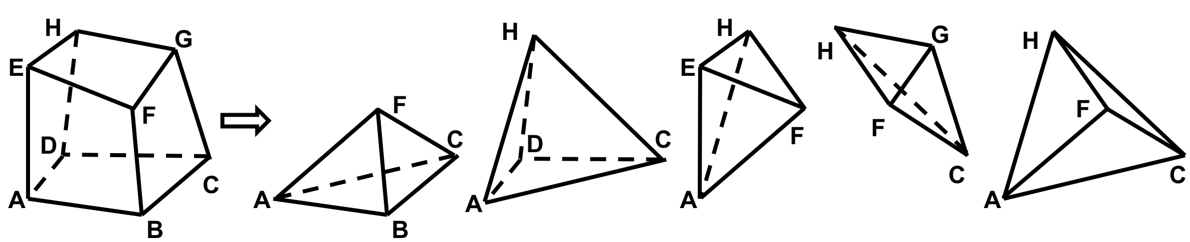


Figure 6. Construction of five tetrahedrons ABCF, ACDH, AEFH, CFGH and ACFH from the point set $\{\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}, \mathbf{E}, \mathbf{F}, \mathbf{G}, \mathbf{H}\}$.

The method consists of the following steps:

1. Given input color point $\mathbf{P}$, we divide the entire color space by planes π_1, π_2 and π_3 that contain $\mathbf{P}$ and are perpendicular to the three axes X, Y and Z, respectively (Fig. 5a). This generates eight subspaces. The time cost is constant.
2. In each subspace, we find the measured color point that is closest to $\mathbf{P}$ (Fig. 5b). In case the subspace contains no measured colors, mark the result as failure. The time cost is $O(N)$.
3. Step two generates a set of eight points $\{\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}, \mathbf{E}, \mathbf{F}, \mathbf{G}, \mathbf{H}\}$ (Fig. 5c). With these points, we construct tetrahedrons ABCF, ACDH, AEFH, CFGH, and ACFH (Fig. 6). Topologically this corresponds to decomposing a cube into five tetrahedrons. The cost is constant.
4. We traverse tetrahedrons ABCF, ACDH, AEFH, CFGH, and ACFH. If any encloses $\mathbf{P}$, that will be the construction tetrahedron. The cost is constant.

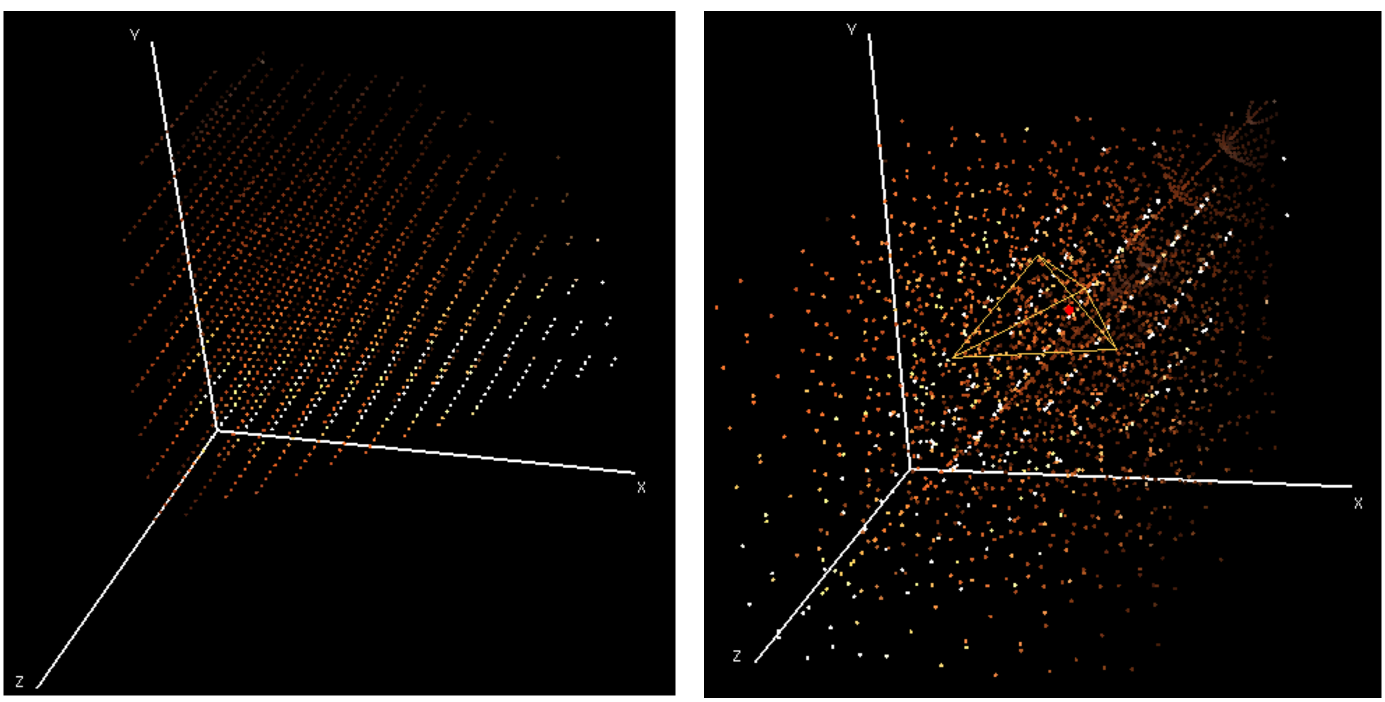
Overall the computational cost is $O(N)$. After the enclosing tetrahedron is found, we use Barycentric coordinates to perform a linear interpolation to obtain the spectrum for the input point.

It is possible to use 3D Delaunay tetrahedronization to find the smallest enclosing tetrahedron. However, our technique has one advantage that it is naturally extendable to higher dimensions such as four or five dimensions, which are the case for anisotropic surfacers. However, Using the Delaunay approach, the implementation in higher dimensions can be much more complicated. Our test results show that our approach is quite close those obtain using Delaunay approach in three dimensions.

Results

Figure 7 shows the results of applying our spectral measurement and interpolation methods. The measurement uses the sample-rotation method. Figure 7(a) shows the sample points in the coordinates of (α, β, δ), which are regularly sampled. The labels X, Y and Z correspond to angles (α, β, δ) normalized to their maximum values. In Figure 7(b), the sample points are converted from coordinates (α, β, δ) into the standard spherical coordinates. Since the sample surface is isotropic, we only need three angles, that is, $(\theta_i, \theta_o, \varphi_o)$. However, after the coordinate transformation, the sample points are not regularly distributed but instead become scattered.

By applying the algorithm we proposed, given any input $(\theta_i, \theta_o, \varphi_o)$, which is indicated by the red spot in Figure 7(b), we can find a small tetrahedron that tightly encloses this input point. Then using linear interpolation with the Barycentric coordinates as the weights, we construct the spectrum for the input interpolation point. This constructed spectrum is shown by the solid curve in Figure 8. The spectra corresponding to the four vertexes of the enclosing tetrahedron are shown by the dotted curves. It is guaranteed that the solid curve will be within the range of the dotted curves because the Barycentric coordinates are all positive. This ensures the constructed spectrum is always valid.



(a) (b)

Figure 7. (a) The sample points of measured BRDF in the (α, β, δ) coordinates. (b) The sample points converted in $(\theta_i, \theta_o, \varphi_o)$ and interpolation. The red spot is input interpolation point and the tetrahedron is shown in solid lines. .

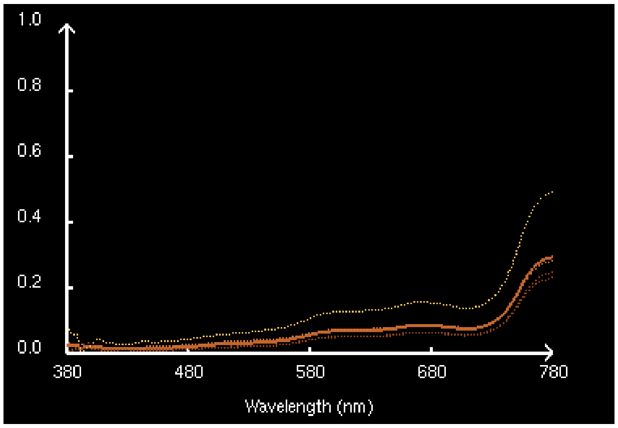


Figure 8. The constructed spectrum (solid curve) and the spectra of the tetrahedron vertexes (dotted curve).

Conclusions

This paper has discussed two practical methods for measuring spectral BRDFs using a spectraradiometer. In the sample-fixed method, the object sample does not move during the entire measurement, and different incident and outgoing directions relative to the surface normal are achieved by relocating and reorienting the light source and spectral detector. This method works for surfaces of various sizes, but demands an extremely large amount of labor. In the sample-rotation method, the object sample is mounted on a platform that provides three orthogonal rotations. During the measurement, the light source is fixed and the spectral device is relocated in a number of times. Comparing with the sample-fixed method, the sample-rotation method significantly reduces the labor work and is less error prone. The sample-rotation method can be easily adapted to allow various object sizes.

Besides, an effective method has also been developed to process the multi-dimensional measured data of spectral BRDFs and this method is easily extendable to dimensions above three. These techniques have been applied to a real surface to obtain and process its spectral BRDF.

This work can be extended in several different ways. First, the measurement approach using sample rotation holder as well as the interpolation technique can also apply to the case of anisotropic surfaces. Second, such measurements can be conducted systematically for various categories of physical surfaces, thus creating a spectral BRDF database for computer graphics and vision applications. The measured data can also be applied to evaluation of existing analytic models of surface reflections. Regarding resampling the originally measured BRDFs, other techniques such as filtering will reduce the measurement errors and improved the data quality. Finally, because spectral BRDFs are high-dimensional, it needs some effective visualization tools to help the exploration and analysis of the data.

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