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Modified model of polarized bidirectional reflectance distribution function for metallic surfaces

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ABSTRACT

The previous two-component polarized bidirectional reflectance distribution function (pBRDF) model with specular reflection and diffuse reflection is modified. A pBRDF model for metallic materials based on a three-component assumption in which the reflection is divided into specular reflection, directional diffuse reflection and ideal diffuse reflection is presented. The specular component is given based on microfacet theory and Fresnel's law. This part contains all the polarization information. The directional diffuse reflection and the ideal diffuse reflection are depolarized but are treated separately according to the experimental results. Simulation and measurement results of Al and Cu samples suggest that this three-component model can reduce the error due to the constant diffuse reflection, and better describe the polarized reflection characteristics for metallic surfaces in the hemisphere space accurately.

1. Introduction

With the rapid development and wide application of the polarization measurement technology, much attention has been paid to the polarization scattering characteristics of different materials for their abilities of object recognition and remote sensing applications [1]. The polarimetric scattering characteristics of surfaces can be completely described by polarized bidirectional reflectance distribution function (pBRDF) which is defined by D.S. Flynn in 1995 [2]. R.G. Priest and Thomas A. Germer (P-G) [3] first developed Torrance and Sparrow (T-S) BRDF model [4,5] to the polarized form by combining it with Fresnel's law and Mueller matrix for a microfacet surface. Priest and Meier investigated the polarimetric scattering properties of highly absorbing and highly reflective rough surfaces in the IR based P-G model later. From the data, a rough, highly absorbing surface has a higher degree of polarization compared to a rough, highly reflective surface [6]. Matthew P. Fetrow and David L. Wellems presented a new polarization simulation method which can be used to examine the surface properties of materials in a laboratory environment, to investigate IR polarization signatures in the field, or a complex environment, and to predict trends in LWWIR polarization data [7]. David Wellems described a method of determining an effective complex index of refration from surface reflective measurements using a Mueller matrix microfacet model [8]. The first microfacet-based spectropolarimetric signature model was developed by AFRL/VSS-Kirtland to predict the signature in long wave infrared (LWIR) and visible (VIS) range for smooth and semi-rough 2-D slabs [9].Unfortunately, the refered studies [6–9] only expanded the application of the P-G pBRDF model, but there is no substantial improvement. The reason is that these models only include the specular component, so the pBRDF asymptotically approaches infinity as the angle of incidence or observation approaches grazing. Hyde presented a pBRDF model with a shadowing/masking function and a Lambertian (diffuse) component which distinguishes it from other geometrical optics pBRDFs. These improvements keep the pBRDF bounded as the angel of incidence or observation approaches grazing and is better able to model the behavior of light scattered from rough, reflective surfaces [10].

Although Hyde model divided the whole reflection into specular reflection and Lambertian diffuse reflection. However, most of our measurements for metallic materials show that there are obvious errors if the diffuse reflection is considered to be a simple constant distribution. In this paper, we modified the traditional two-component pBRDF model and presented a three-component pBRDF model which contains three independent components: specular reflection, directional diffuse reflection and ideal diffuse reflection.

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2. Model for the pBRDF

The bidirectional reflectance distribution function (BRDF) is the fundamental description of optical scattering [11], as expressed in Eq. (1):

$$f(\theta_i,\varphi_i;\theta_r,\varphi_r)=\frac{dL_r(\theta_r,\varphi_r)}{dE_i(\theta_i,\varphi_i)}(sr^{-1}) \tag{1}$$

where $dL_r(\theta_r,\varphi_r)$ is the reflected radiance, $dE_i(\theta_i,\varphi_i)$ is the incident irradiance as shown in Fig. 1. θ and φ represent the zenith angle and azimuth angle, respectively; the subscripts i and r represents the incident and reflection rays, respectively, α is the polar angle from the mean surface normal Z to the microfacet normal n, β is the incident angle as measured from the microfacet.

Most geometrical optics BRDF models consist of the specular radiance and the diffuse radiance. The diffuse radiance is often assumed to be a sum of multiple reflection and volume scattering and both the two components obey Lamber's law in many references. Unfortunately, these models with this simple assumption can't agree well with experimental result of metallic materials. Therefore, we analyze the physical mechanism of the interaction between the light and object and divide the reflected light into three components: specular reflection, directional diffuse reflection and ideal diffuse reflection. The three-component assumption describes the reflection process more detailedly and accurately. The interaction is shown in Fig. 2.

The specular reflection, directional diffuse reflection and ideal diffuse reflection are denoted by f_s, f_{dd}, f_{id}, respectively. Therefore, the BRDF expression is shown as follows.

$$f=k_s\cdot f_s+k_{dd}\cdot f_{dd}+k_{id}\cdot f_{id} \tag{2}$$

where k_s, k_{dd} and k_{id} are the coefficients of f_s, f_{dd} and f_{id} respectively.

2.1. Specular reflection

The specular reflection component is completely determined by the first reflection, so it is calculated according to the microfacet theory in which each microfacet is a specular reflector obeying Snell's law. Most microfacets are randomly oriented and obey

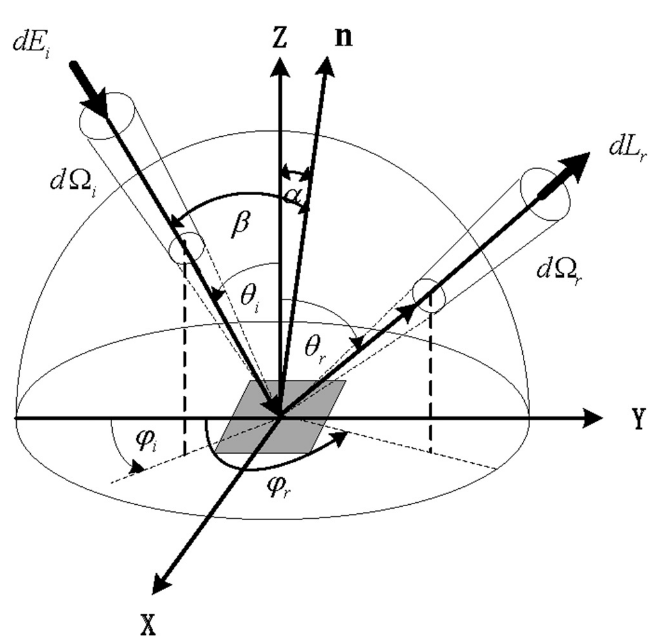

Fig. 1. pBRDF coordinate system.

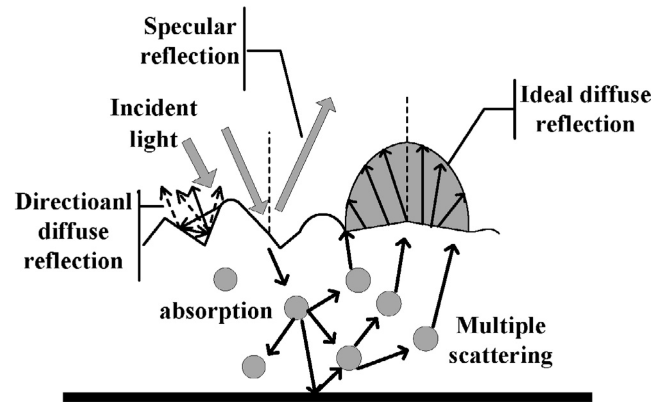

Fig. 2. Light scattering model for materials.

Gaussian slope distribution which is utilized in most geometrical optics BRDF model.

$$p(\alpha)=\frac{1}{2\pi\sigma^2\cos^3\alpha}\exp\left(\frac{-\tan^2\alpha}{2\sigma^2}\right) \tag{3}$$

The expression of the specular component based on a microfacet model [5] is shown as below:

$$f_s(\theta_i,\theta_r,\varphi)=\frac{1}{2\pi}\frac{1}{4\sigma^2}\frac{1}{\cos^4\alpha}\frac{\exp\left(-\frac{\tan^2\alpha}{2\sigma^2}\right)}{\cos\theta_r\cos\theta_i}G(\theta_i,\theta_r,\varphi)F(\beta) \tag{4}$$

where $G(\theta_i,\theta_r,\varphi)$ is a geometrical attenuation factor [12] and F is the Fresnel reflectance. Replacing the Fresnel reflectance F in Eq. (4) by the Mueller matrix elements M_{jk}, the specular component of a microfacet model-based pBRDF is given by10:

$$f_{jk}(\theta_i,\theta_r,\varphi)=\frac{1}{2\pi}\frac{1}{4\sigma^2}\frac{1}{\cos^4\alpha}\times\frac{\exp\left(-\frac{\tan^2\alpha}{2\sigma^2}\right)}{\cos\theta_r\cos\theta_i}G(\theta_i,\theta_r,\varphi)M_{jk}(\theta_i,\theta_r,\varphi) \tag{5}$$

where M_{jk} is a Mueller matrix element of the reflecting microfacet. The polarized property of reflection is considered from Fresnel's equation which indicates the reflectance of s-polarized R_s and p-polarized light R_p, and the 2×2 Jones matrix is given by R_s, R_p and the coordinate transformation. Then, M_{jk} is presented in the form of Jones matrix elements [3].

The Stokes vector of specular reflection S_s' can be expressed as:

$$S_S'=k_s\left(\sum_{k=0}^{3}f_{0k}S_k\quad\sum_{k=0}^{3}f_{1k}S_k\quad\sum_{k=0}^{3}f_{2k}S_k\quad\sum_{k=0}^{3}f_{3k}S_k\right)^T \tag{6}$$

2.2. Diffuse reflection(directional and ideal diffuse reflection)

In physics, reflected energy was simply considered to be the sum of specular reflection and Lambertian diffuse component in former literatures. Although some researchers have mentioned the multiple reflection and volume scattering, they treated both the two components as ideal Lambertian. That is to say, the multiple reflection and volume scattering in the diffuse reflection were not considered separately. In this paper, the diffuse reflection is divided into two components: directional diffuse reflection and ideal diffuse reflection. The directional diffuse reflection is attributed to multiple surface reflections. This part was assumed to be uniform distribution in hemisphere space in previous model. However, it can't fit well with our measurements and cause serious errors in some conditions. So the expression of diffuse reflection