Post-doctoral: Simulation and measurement of road surface optical properties

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This work is under **REFLECTIVITY** project

Abstract

Abstract–

Key words–

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Chapter 1

Introduction

1.1 Context and objectives

In our daily lives, we have seen a variety of road surfaces, including bituminous (or asphalt) roads, concrete roads, earthen roads, gravel roads, and murram roads. Among these, bituminous roads are the most commonly seen in our daily transportation due to their practicality, wear resistance and robustness. In the design and operation of mobility systems, many challenges, e.g. climate imperatives, the rise of active modes of transport, and the arrival of autonomous vehicles, require us to rethink a number of practices. In this context, the optical properties of road surface play a fundamental role in optimizing the energy consumption of public lighting installations [1], reduce light pollution [2], control urban temperature [3], and consider perception of road markings [4]. In favor of these issues, it becomes necessary to know the optical properties of road surface or be able to anticipate them when creating a surfacing or predicting their evolution over time. Consequently, this requires conducting a significant number of simulations or measurements.

When discussing optical properties of road surface, both the Bidirectional Reflectance Distribution Function (BRDF) and solar albedo are essential because they provide complementary information about how the surface interacts with light. The former provides detailed directional information, describing the angular distribution of reflected light based on the angle of incoming light and the viewing angle [5]. It captures how surface roughness, texture, and material composition affect light reflection, affecting the visibility of the road and markings [6]. The latter gives an overall measure of reflected energy, representing the total fraction of incoming solar energy reflected by the road surface, without regard to direction [7]. Road surface with higher solar albedo reduces heat absorption by reflecting more sunlight back into the atmosphere, lowering cooling demands in nearby buildings and contributing to mitigate the damage on road materials.

These two properties depend on the physical characteristics of the road surface, such as roughness and refractive index. However, the measurement of BRDF or solar albedo is costly, not only in terms of instrumentation but also in the time required to measure it. This raises the question: if we already know the physical characteristics of a road surface, is it possible to derive its BRDF and solar albedo without direct measurement? Specifically, if we have a road sample and know its formulation in terms of the material composition, sizes, and proportions. can we establish a reliable relationship between these parameters and the resulting optical properties? However, the challenge lies in the fact that the relationship between the formulation of a road surface and its corresponding characteristics is not explicitly defined, complicating numerical simulation of the BRDF and so solar albedo. Roads are typically composed of various materials, such as bitumen, different types of aggregates, and fillers, which further adds to the complexity.

To simplify the problem, we propose focusing firstly on several single-component road samples to investigate appropriate BRDF models that can accurately fit their measured results. So the problem becomes how to combine these BRDF models for each single-component to fit the measured BRDF of multi-component road sample. To explore and develop such methods is the objective of this work.

1.2 Mission

To achieve the objective, the mission follows 5 steps:

1. Build several single-component road samples and measure their BRDF;
2. Fit the measured BRDF of each single-component road sample using existing BRDF models;
3. Build several multi-component road samples and measure their BRDF;

4. Explore and develop the method to combine the BRDFs of each single-component to fit the measurement of multi-component road samples;

5. Estimate the solar albedo using BRDF.

1.3 Report organization

This report is structured into the following chapters: In chapter 2, it provides the detailed definition and properties of BRDF, investigates several BRDF models used in road surface, and its measurement set-up. Then it introduce the solar albedo including black sky albedo, white sky albedo and blue sky albedo and the link between solar albedo and BRDF. In chapter 3, it summarizes the previous work on the simulation and measurement of single-component (e.g. different rocks), and investigates method about how to fit the measurement using BRDF models from literature study. Then it present measured and simulated results for each single-component road sample. In chapter 4, it investigates the existing method of mix different BRDF models, and propose new method to combine all BRDF models of each single-component to fit the measurement. Then it presents the corresponding results for each multi-component road sample. In chapter 5, it concludes this report and provides some new perspectives for future work.

Chapter 2

Optical properties of road surface

2.1 Basic concepts

To provide a clear understanding of the optical properties of road surface, the fundamental terminologies are introduced in this section.

2.1.1 Radiometric quantities

Radiometric quantities provide a way to measure and describe the behavior of radiant energy in terms of light interaction with road surface. They include flux, radiant intensity, irradiance and radiance.

Flux F, is the most fundamental quantity in radiometry [5]. It is also called radiant power, which measures the amount of light that hits a surface over a finite area from all directions per unit time. For a given amount of radiated energy Q at a time duration t, the flux F is expressed as:

$$F(t) = \frac{\mathrm{d}Q}{\mathrm{d}t} \tag{2.1}$$

As Q is expressed in Joules (J), the unit of F is watts ($W = J \cdot s^{-1}$)

Radiant intensity I, is a correlated measure of flux. It represents the intensity of flux per unit solid angle which is propagate towards some specific direction (θ, φ) toward the the infinitesimal solid angle $\mathrm{d}\overrightarrow{\omega}$ [8]. Thus, it can be expressed in terms of flux:

$$I(t,\theta,\varphi) = \frac{\mathrm{d}F(t)}{\mathrm{d}\overrightarrow{\omega}} = \frac{\mathrm{d}F(t)}{\sin\theta \mathrm{d}\theta \mathrm{d}\varphi} \tag{2.2}$$

Notice that the unit of solid angle is the steradian $[sr]$, so the unit of radiant intensity is $[W \cdot sr^{-1}]$.

Irradiance E, is another correlated measure of flux in terms of surface area. Different from radiant intensity, it captures the integration over the entire hemisphere Ω of the incident light arriving at a unit surface $\mathrm{d}s(x)$ centered on the point x. Essentially, it measure the amount of radiated energy strike a unit area per unit time:

$$E(x,t) = \frac{\mathrm{d}F(t)}{\mathrm{d}s(x)} \tag{2.3}$$

Its unit is $[W \cdot m^{-2}]$

Radiance L, measures the amount of incident light arriving at a unit surface $\mathrm{d}s(x)$ centered on x from a unit solid angle $\mathrm{d}\overrightarrow{\omega}$ per unit time t. It can be considered as a correlated measure of radiant intensity per unit area or irradiance per unit solid angle:

$$L(x,t,\theta,\varphi) = \frac{\mathrm{d}^2F(t)}{|\overrightarrow{\omega} \cdot \overrightarrow{n}|\,\mathrm{d}\overrightarrow{\omega}\mathrm{d}s(x)} = \frac{\mathrm{d}I(t,\theta,\varphi)}{\cos\theta \mathrm{d}s(x)} = \frac{\mathrm{d}E(x,t)}{\sin\theta \mathrm{d}\theta \mathrm{d}\varphi} \tag{2.4}$$

The product term $\cos\theta \mathrm{d}s(x)$ represents the projection of the unit surface $\mathrm{d}s(x)$ onto the direction $\overrightarrow{\omega}$. According to its definition, the unit of $L(x,t,\theta,\varphi)$ is $[W \cdot m^{-2} \cdot sr^{-1}]$.

2.1.2 Spectral radiometry

In the previous section, the definitions of radiometric quantities are given without considering the wavelength. In order to describe the spectral distribution of a radiation, the spectral radiometric quantities are introduced, including spectral flux, spectral intensity, spectral irradiance and spectral radiance.

Spectral flux F_λ, is defined as the flux per unit wavelength and expressed in $[W \cdot nm^{-1}]$:

$$F_\lambda(t) = \frac{\mathrm{d}F(t)}{\mathrm{d}\lambda} \tag{2.5}$$

Spectral intensity I_λ, is the radiant intensity per unit wavelength and expressed in $[W \cdot sr^{-1} \cdot nm^{-1}]$:

$$I_\lambda(t,\theta,\varphi) = \frac{\mathrm{d}I(t,\theta,\varphi)}{\mathrm{d}\lambda} \tag{2.6}$$

Spectral irradiance E_λ, is irradiance per unit wavelength and expressed in $[W \cdot m^{-2} \cdot nm^{-1}]$:

$$E_\lambda(x,t) = \frac{\mathrm{E(x,t)}}{\mathrm{d}\lambda} \tag{2.7}$$

Spectral radiance L_λ, is defined as the radiance per unit wavelength and expressed in $[W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}]$:

$$L_\lambda(x,t,\theta,\varphi) = \frac{\mathrm{d}L(x,t,\theta,\varphi)}{\mathrm{d}\lambda} \tag{2.8}$$

The measurement of spectral quantities are conducted with instruments such as spectrophotometers which analyze the radiation in adjacent and narrow spectral bands [8]. When analyzing radiation over a broader wavelength range $[\lambda_1, \lambda_2]$, the total measured flux can be calculated by integrating the spectral flux density across the specified waveband. This process accounts for the contribution of all individual wavelengths within the range, providing a cumulative representation of the flux. The computation is expressed as:

$$F(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} F_\lambda \mathrm{d}\lambda \tag{2.9}$$

2.2 Spectral BRDF

The BRDF is first introduced by Fred Nicodemus in 1965 [9], which is defined as the ratio of reflected radiance and incident irradiance for all possible observer and light source positions given by their azimuth angles and zenith angles, at a given surface point x. However, the BRDF alone does not capture the full complexity of how surfaces reflect light across different wavelengths. To gain a more comprehensive understanding of these interactions, we turn to the spectral BRDF which is an extension of the traditional BRDF [8]. It provides a wavelength-dependent function that characterizes how surfaces reflect light at specific incident and reflected angles at a given surface point x, across a narrow spectral bandwidth $\Delta\lambda$. Mathematically, it is expressed as:

$$f_r(x,\lambda,\theta_i,\varphi_i,\theta_r,\varphi_r) = \frac{\mathrm{d}L(x,\lambda,\theta_r,\theta_r)}{\mathrm{d}E(x,\lambda,\theta_i,\varphi_i)}, \tag{2.10}$$

where:

- λ is the wavelength of light source;

- θ_i and φ_i are the zenith and azimuth angle of the unit incident direction $\overrightarrow{\omega_i}$:

$$\overrightarrow{\omega_i} = (x_i, y_i, z_i) = (\sin\theta_i \cos\varphi_i, \sin\theta_i \sin\varphi_i, \cos\theta_i)$$

- θ_r and φ_r are the zenith and azimuth angle of the unit reflected direction $\overrightarrow{\omega_r}$:

$$\overrightarrow{\omega_r} = (x_r, y_r, z_r) = (\sin\theta_r \cos\varphi_r, \sin\theta_r \sin\varphi_r, \cos\theta_r)$$

- $\mathrm{d}L(x, \lambda, \theta_r, \theta_r)$ is the spectral reflected radiance for waveband $\Delta\lambda$;

$$\mathrm{d}L(x, \lambda, \theta_r, \theta_r) = \int_{\Delta\lambda} \mathrm{d}L_\lambda(x, \theta_r, \varphi_r)\mathrm{d}\lambda$$

- $\mathrm{d}E(x, \lambda, \theta_i, \varphi_i)$ is the spectral incident irradiance for waveband $\Delta\lambda$.

$$\mathrm{d}E(x, \lambda, \theta_i, \theta_i) = \int_{\Delta\lambda} \mathrm{d}E_\lambda(x, \theta_i, \varphi_i)\mathrm{d}\lambda$$

Replacing the term $\mathrm{d}E(x, \lambda, \theta_i, \varphi_i)$ according to Equation (2.4), it can be defined in terms of incident radiance $L_i(x, \lambda, \theta_i, \varphi_i)$:

$$f_r(x, \lambda, \theta_i, \varphi_i, \theta_r, \varphi_r) = \frac{\mathrm{d}L(x, \lambda, \theta_r, \theta_r)}{\cos\theta_i L_i(x, \lambda, \theta_i, \varphi_i)\mathrm{d}\theta_i \mathrm{d}\varphi_i} \tag{2.11}$$

Ideal diffuse reflection

One of the simplest and most widely used BRDF models is the Lambertian reflector, which is based on the assumption of a perfectly diffuse surface [8]. It has an angle-independent BRDF, proportional to their spectral albedo $\rho(\lambda)$:

$$f_{r(diffuse)}(x, \lambda, \theta_i, \varphi_i, \theta_r, \varphi_r) = \frac{\rho(\lambda)}{\pi} \tag{2.12}$$

Ideal specular reflection

In contrast to diffuse reflection, the perfect specular BRDF describes light incoming a given direction is reflected in a single direction following the law of reflection [10]:

$$f_{r(specular)}(x, t, \theta_i, \varphi_i, \theta_r, \varphi_r) = F_r(\theta_i)\frac{\delta(\overrightarrow{\omega_r} - \overrightarrow{\omega_r'})}{\cos\theta_r}, \tag{2.13}$$

where:

- $\overrightarrow{\omega_r'}$ is the mirror direction which is symmetric to the incoming direction $\overrightarrow{\omega_i}$:

$$\overrightarrow{\omega_r'} = 2(\overrightarrow{\omega_i} \cdot \overrightarrow{n})\overrightarrow{n} - \overrightarrow{\omega_i} = 2\cos\theta_i \overrightarrow{n} - \overrightarrow{\omega_i}$$

- $\delta(\overrightarrow{\omega_r} - \overrightarrow{\omega_r'})$ is the delta dirac function;

- $F_r(\theta_i)$ is the Fresnel reflectance following as:

$$F_r(\theta_i, \varphi_i) = \frac{1}{2}\left(r_{\parallel}^2 + r_{\perp}^2\right)$$

  $r_{\parallel}$ and $r_{\perp}$ are the conventional Fresnel coefficient [11].

2.2.1 Properties

Similar to traditional BRDF, a physically plausible spectral BRDF also has the below properties:

- **Energy conservation**

  A fundamental principle that must be adhered to by all BRDFs, including spectral BRDFs, is energy conservation. This ensures that the amount of light reflected by a surface does not exceed the amount of light incident upon it. Mathematically, this is often represented as:

$$\int_{\varphi_i=0}^{2\pi}\int_{\theta_i=0}^{\frac{\pi}{2}} f_r(x, \lambda, \theta_i, \varphi_i, \theta_r, \varphi_r)\cos(\theta_r)\sin(\theta_r)\mathrm{d}\theta_r\mathrm{d}\varphi_r \leq 1$$

- **Reciprocity**

  The Helmholtz Reciprocity Rule states that the reflection characteristics should remain unchanged if the directions of light incidence and observation are swapped:

$$f_r(x, \lambda, \theta_i, \varphi_i, \theta_r, \varphi_r) = f_r(x, \lambda, \theta_r, \varphi_r, \theta_i, \varphi_i)$$

  It ensures that light behaves consistently in all directions.

- **Non-negative**

  The spectral BRDF is always non-negative, ensuring that the reflected radiance is physically meaningful:

$$f_r(x, \lambda, \theta_i, \varphi_i, \theta_r, \varphi_r) \geq 0$$

2.2.2 Isotropic and anisotropic

As spectral BRDF is an extension of traditional BRDF, it can be classified into two categories based on whether they exhibit rotational symmetry or not [12,13]: isotropic and anisotropic. A material is considered isotropic when its reflectance remains constant for a fixed view and illumination, regardless of the rotation of the material around its normal. Mathematically, it can be expressed in term of the azimuth angle difference between incident direction and reflected direction:

$$f_r(x, \lambda, \theta_i, \varphi_i, \theta_r, \varphi_r) = f_r(x, \lambda, \theta_i, \theta_r, \varphi_r - \varphi_i)$$

In contrast, materials whose reflectance is not constant are considered anisotropic.

2.2.3 Measurement Set-up

The measurement systems for road surface BRDF can be broadly categorized into two types: laboratory-based and field-based approaches. The former is typically conducted under controlled environments where factors such as lighting, geometry, and surface conditions can be precisely controlled. The classic laboratory-based systems, such as gonioreflectometers [8,14,15] and goniospectrophotometers if the detection is spectral [16], observe the same surface sample under varying observer and light source position. They are commonly composed of the goniometer used to change the angles of incidence and detection (e.g.by rotating the robot arms [8,14]), the light source and the detection sensors (e.g. camera, spectroradiometer). In many studies [8,15,16], halogen lamp is used as the light source due to its spectrum close to solar spectrum.

The latter is essential to obtain realistic data of road surface BRDF under actual environmental conditions, such as varying sunlight (from sunrise to sunset), weather (e.g. sunny, cloudy, rainy), and surface states (dry or wet). An example of such a setup is vehicle-based automotive measurement systems [6], where natural sunlight serves as the light source and detection sensor, such as camera, is mounted on the car's front window.

In this study, we aim to develop a comprehensive model by blending reflectance models of individual components that constitute a given road surface, to fit to measured BRDF data. Therefore, BRDF measurements will be conducted indoors using a gonioreflectometer developed by Cerema, allowing for the elimination of environmental interferences and ensuring precise control over experimental conditions.

2.2.4 BRDF models used in Road surface

Reflectance models are typically introduced in order to achieve low-parameter representation of the BRDF measurements acquired from road surfaces [6]. This section explores a range of reflectance models utilized for characterizing the BRDF of various road materials, such as concrete, sand, aggregates.

2.2.4.1 Oren nayar BRDF

The Oren-Nayar BRDF is widely used for modelling diffuse reflections from rough surfaces, as it provides a more realistic representation of light behavior compared to simpler Lambertian models [6, 14, 14]. This model was first proposed in 1994 [14] by Oren and Nayar, based on microfacet theory which represents the surface of a collection of small surfaces. In graphics community, microfacet theory was used to derive physically based BRDF [17], and typically accounts for complex geometric and radiometric phenomena:

- shadowing, where the facet is only partially illuminated because the adjacent facet casts a shadow on it;
- masking, where the facet is only partially visible to the camera because its adjacent facet occludes it.

Their impacts are described using shadowing function and masking function, respectively. A meaningful microfacet model is described by a distribution of normals, which models how the microfacets are statistically oriented, and a microfacet profile, which models how the microfacets are organized on the microfacet. Mathematically, the general microfacet-based BRDF expression is following as:

$$f_r(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}) = \frac{1}{\cos(\theta_r)\cos(\theta_i)} \int_\Omega f_{r(M)}(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})(\overrightarrow{\omega_r} \cdot \overrightarrow{\omega_m})(\overrightarrow{\omega_i} \cdot \overrightarrow{\omega_m})G(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})D(\overrightarrow{\omega_m})\mathrm{d}\overrightarrow{\omega_m}, \quad (2.14)$$

where:

- $\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m}$ are the directions of the incident light, detection and the normal of the microfacet;
- $f_{r(M)}(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})$ is the BRDF of each microfacet;
- $D(\overrightarrow{\omega_m})$ represents the distribution of the normals of the microfacets;
- $G(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})$ is geometric attenuation function, combining masking G_1 and shadowing G_2 function. It gives the fraction of microfacets with normal ω_m that are visible along the reflected direction $\overrightarrow{\omega_r}$, depending on the microfacet profile (e.g. V-cavity microfacet profile and smith microfacet profile) and the distribution of the microfacet's normal [17]. The masking G_1 and shadowing G_2 function are formalized by the following equations:

$$\begin{aligned} \cos\theta_r &= \int_\Omega G_1(\overrightarrow{\omega_r}, \overrightarrow{\omega_m})(\overrightarrow{\omega_r}\cdot\overrightarrow{\omega_m})D(\overrightarrow{\omega_m})\mathrm{d}\overrightarrow{\omega_m} \\ \cos\theta_i &= \int_\Omega G_2(\overrightarrow{\omega_i}, \overrightarrow{\omega_m})(\overrightarrow{\omega_i}\cdot\overrightarrow{\omega_m})D(\overrightarrow{\omega_m})\mathrm{d}\overrightarrow{\omega_m} \end{aligned} \tag{2.15}$$

In Oren-Nayar model, it adapted V-cavity microfacet profile. More precisely, the surface is assumed as a collection of long, symmetric v-shaped cavities with equal length, each containing two opposing planar facets. This implies that each V-cavity has the two symmetric normals, $\overrightarrow{\omega_m}$ and $\overrightarrow{\omega'_m}$ leading to the following distribution of normals of each microfacet:

$$D(\overrightarrow{\omega}) = \frac{1}{2}\frac{\delta(\overrightarrow{\omega} - \overrightarrow{\omega_m})}{\overrightarrow{\omega_m}\cdot\overrightarrow{n}} + \frac{1}{2}\frac{\delta(\overrightarrow{\omega} - \overrightarrow{\omega'_m})}{\overrightarrow{\omega'_m}\cdot\overrightarrow{n}}$$

The masking or shadowing term can be derived according to Equation(2.15) considering if there is no or one backfacing normal direction:

$$\begin{aligned} G_1(\overrightarrow{\omega_r}, \overrightarrow{\omega_m}) &= \min\left(1, 2\frac{(\overrightarrow{\omega_m}\cdot\overrightarrow{n})(\overrightarrow{\omega_r}\cdot\overrightarrow{n})}{(\overrightarrow{\omega_r}\cdot\overrightarrow{\omega_m})}\right) \\ G_2(\overrightarrow{\omega_i}, \overrightarrow{\omega_m}) &= \min\left(1, 2\frac{(\overrightarrow{\omega_m}\cdot\overrightarrow{n})(\overrightarrow{\omega_i}\cdot\overrightarrow{n})}{(\overrightarrow{\omega_i}\cdot\overrightarrow{\omega_m})}\right) \end{aligned}$$

Considering both masking and shadowing, the term $G(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})$ can be derived as:

$$G(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m}) = \min\left(1, 2\frac{(\overrightarrow{\omega_m}\cdot\overrightarrow{n})(\overrightarrow{\omega_r}\cdot\overrightarrow{n})}{(\overrightarrow{\omega_r}\cdot\overrightarrow{n})}, 2\frac{(\overrightarrow{\omega_m}\cdot\overrightarrow{n})(\overrightarrow{\omega_i}\cdot\overrightarrow{n})}{(\overrightarrow{\omega_i}\cdot\overrightarrow{n})}\right) \tag{2.16}$$

The distribution of the normals of all microfacets is described using a spherical gaussian distribution with a mean value of zero and a standard deviation σ, which serves as a roughness parameter:

$$D(\overrightarrow{\omega_m}) = ce^{-\frac{\theta_m^2}{2\sigma^2}}, \tag{2.17}$$

where the normalization constant c is:

$$c = \frac{1}{\displaystyle\int_{\varphi_m=0}^{2\pi}\int_{\theta_m}^{\frac{\pi}{2}} e^{-\frac{\theta_m^2}{2\sigma^2}} \sin\theta_m \mathrm{d}\theta_m \mathrm{d}\varphi_m}$$

Besides, the facets are assumed to exhibit diffuse reflection, implying the BRDF of each microfacet $f_{r(M)}(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})$ is defined as shown in Equation (2.12). By substituting $f_{r(M)}(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})$ from Equation(2.12) , $G(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})$ from Equation(2.16) and $D(\overrightarrow{\omega_m})$ from Equation(2.17) into Equation(2.14), the reflectance model is obtained. However, the resulting integral can not be easily evaluated. Therefore, Oren Nayar provided an approximation by using a identified basis function and conducting a large amounts of numerical simulations to evaluate this integral. The approximated expression of directly reflected part is following as:

$$\begin{aligned} f_r^{dir}(\theta_i, \theta_r, \varphi, \rho, \sigma) = \; & \tfrac{\rho}{\pi}[C_1(\sigma) + C_2(\theta_1, \theta_2, \varphi, \sigma)\cos(\varphi)\tan(\theta_2) \\ & + C_3(\theta_1, \theta_2, \sigma)\,(1 - |\cos(\varphi)|)\tan\left(\tfrac{\theta_1+\theta_2}{2}\right)] \end{aligned}$$

where:

- ρ is the albedo of each facet;
- $\varphi = |\varphi_i - \varphi_r|$ is the relative azimuth angle;
- $\theta_1 = \max(\theta_i, \theta_r)$ is the maximum zenith angle between θ_i and θ_r;
- $\theta_2 = \min(\theta_i, \theta_r)$ is the minimum zenith angles between θ_i and θ_r;
- σ (in radians) is a parameter for the surface roughness, which is gaussian standard deviation in angles of the microfacets normal
- C_1, C_2, C_3 are constant:

$$C_1(\sigma) = 1 - 0.5\tfrac{\sigma^2}{\sigma^2+0.33}$$

$$C_2(\theta_1, \theta_2, \varphi, \sigma) = \begin{cases} 0.45\tfrac{\sigma^2}{\sigma^2+0.09}\sin(\theta_1), & \text{if } \cos(\varphi) \geq 0 \\ 0.45\tfrac{\sigma^2}{\sigma^2+0.09}\left(\sin(\theta_1) - \left(\tfrac{2\theta_2}{\pi}\right)^3\right), & \text{otherwise} \end{cases}$$

$$C_3(\theta_1, \theta_2, \sigma) = 0.125\left(\tfrac{\sigma^2}{\sigma^2+0.09}\right)\left(\tfrac{4\theta_1\theta_2}{\pi^2}\right)^2$$

In a V-cavity microfacet, apart from the shadowing and masking effects described in microfacet theory, light rays may also bounce between adjacent facets. This phenomenon is referred to as inter-reflections. In the case of Lambertian surfaces, the energy in an incident light diminishes rapidly with each inter-reflection bounce [14]. Accordingly, Oren and Nayar considers only two bounces inter-reflections and neglect the subsequent bounces. Similar to direct illumination component, the multiple inter-reflections part is approximated as:

$$f_r^{ms}(\theta_i, \theta_r, \varphi, \rho, \sigma) = 0.17\frac{\rho^2}{\pi}\frac{\sigma^2}{\sigma^2 + 0.13}\left(1 - \frac{4\theta_2^2}{\pi^2}\cos(\varphi)\right)$$

Combing the directly reflected part and the multiple inter-reflections part, the complete expression of the Oren-Nayar BRDF is:

$$f_{r(ON)}(\theta_i, \theta_r, \varphi, \rho, \sigma) = f_r^{dir}(\theta_i, \theta_r, \varphi, \rho, \sigma) + f_r^{ms}(\theta_i, \theta_r, \varphi, \rho, \sigma)(\sigma) \tag{2.18}$$

Notice that this model reduces to Lambertian BRDF when the roughness $\sigma = 0$.

This model has been applied to road materials, such as plaster and white sand in [14], where it provides a good fit with experimental measurements, with the fitting parameters $\rho = 0.9, \sigma = 30°$ for the former and $\rho = 0.8, \sigma = 35°$ for the latter.

2.2.4.2 Cook Torrance BRDF

The specular reflection model of rough surfaces introduced by Cook Torrance in 1982 has gained widespread attention [6, 14, 16, 18, 19]. This model is also based on microfacet theory, where each facet is assumed to exhibit specular reflection, corresponding to Equation (2.13). Consequently, the BRDF of each microfacet $f_{r(M)}(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})$ presented in Equation(2.14) can be derived as:

$$\begin{aligned} f_{r(M)}(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m}) &= \left|\frac{\partial \overrightarrow{\omega_h}}{\partial \overrightarrow{\omega_i}}\right| \frac{F_r(\overrightarrow{\omega_i}, \overrightarrow{\omega_h})\delta(\overrightarrow{\omega_m} - \overrightarrow{\omega_h})}{|\overrightarrow{\omega_i} \cdot \overrightarrow{\omega_h}|} \\ &= \frac{F_r(\overrightarrow{\omega_i}, \overrightarrow{\omega_h})\delta(\overrightarrow{\omega_m} - \overrightarrow{\omega_h})}{4\,|\overrightarrow{\omega_i} \cdot \overrightarrow{\omega_h}|^2}, \end{aligned}$$

where $\overrightarrow{\omega_h}$ is unit halfway vector, and defined as: $\overrightarrow{\omega_h} = \frac{\overrightarrow{\omega_i} + \overrightarrow{\omega_r}}{|\overrightarrow{\omega_i} + \overrightarrow{\omega_r}|}$. The term $\left|\frac{\partial \overrightarrow{\omega_h}}{\partial \overrightarrow{\omega_i}}\right| = \frac{1}{4|\overrightarrow{\omega_i} \cdot \overrightarrow{\omega_h}|}$ is the jacobian of the reflection transformation [17,20]. Putting this $f_{r(M)}(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m})$ into Equation(2.14), we can replace the integral by the integrand evaluated at $\overrightarrow{\omega_m} = \overrightarrow{\omega_h}$ according to the delta dirac function $\delta(\overrightarrow{\omega_m} - \overrightarrow{\omega_h})$. Thanks to $\overrightarrow{\omega_r} \cdot \overrightarrow{\omega_h} = \overrightarrow{\omega_i} \cdot \overrightarrow{\omega_h}$, we arrive the final expression of Cook Torrance BRDF:

$$f_{r(CT)}(\theta_i, \varphi_i, \theta_r, \varphi_r) = \frac{F_r(\overrightarrow{\omega_i}, \overrightarrow{\omega_h})G(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_h})D(\overrightarrow{\omega_h})}{4\cos\theta_i\cos\theta_r} \tag{2.19}$$

Notice that inter-reflections are not taken into account in this model.

It is known that the geometric attention function G given in Equation (2.14) is dependent of microfacet profile. Two widely used microfacet profiles in this model are introduced: V-cavity and smith.

V-cavity microfacet profile

In its original formulation, Cook Torrance adapted the former profile [21]. Similar to the microfacet profile used in Oren Nayar model, it represents the surface as a collection of symmetric V-cavity microfacet, leading to the same G function as Equation (2.16).

Smith microfacet profile

The latter represents more realistic surface but is more complicated, as it assumes that the microfacets are not auto-correlated. More precisely, it represents a random set of microfacets instead of a continuous surface, where the heights and normals of the microfacets are independent random variables [17]. This implies that the term G due to masking and shadowing is independent of the normal orientation $\overrightarrow{\omega_m}$ for non-backfacing normals. Therefore, the G function is separated into two independent functions: the local masking function and the distant masking function. The former function is the binary discard of backfacing microfacets χ^+, and the latter one is the probability of occlusion by a distant point of the microfacet, which is independent of the local orientation $\overrightarrow{\omega_m}$. A commonly used form of smith joint masking-shadowing function is given as:

$$G(\overrightarrow{\omega_i}, \overrightarrow{\omega_r}, \overrightarrow{\omega_m}) = \frac{\chi^+(\overrightarrow{\omega_r} \cdot \overrightarrow{\omega_m})\chi^+(\overrightarrow{\omega_i} \cdot \overrightarrow{\omega_m})}{1 + \Lambda(\overrightarrow{\omega_r}) + \Lambda(\overrightarrow{\omega_i})}, \tag{2.20}$$

where $\Lambda(\overrightarrow{\omega_i})$ and $\overrightarrow{\omega_i}$ are auxiliary functions, which arise naturally when the derivation of masking and shadowing is conducted in the slope domain. This term depends on the chosen distribution function $D(\overrightarrow{\omega_m})$.

The **Beckmann distribution** and **GGX (also known as Trowbridge-Reitz)** distribution are two common microfacet distributions used in BRDF models to describe the statistical orientation of microfacets. The former one is applicable for a wide of surface conditions from smooth to very rough. It is derived from a Gaussian slope distribution of microfacets:

$$D(\omega_m) = \frac{\chi^+(\overrightarrow{\omega_m} \cdot \overrightarrow{n})}{\pi\alpha^2 \cos^4(\theta_m)} \exp\left(-\frac{\tan^2(\theta_m)}{\alpha^2}\right) \tag{2.21}$$

It produces a more sharply peaked distribution near the surface normal and falls off more rapidly for grazing angles. Its associated $\Lambda(\overrightarrow{\omega_r})$ and $\Lambda(\overrightarrow{\omega_i})$ are:

$$\begin{aligned} \Lambda(\overrightarrow{\omega_r}) &= \tfrac{erf(a)-1}{2} + \tfrac{1}{2a\sqrt{\pi}} \exp(-a^2) \\ \Lambda(\overrightarrow{\omega_i}) &= \tfrac{erf(a')-1}{2} + \tfrac{1}{2a'\sqrt{\pi}} \exp(-a'^2) \end{aligned} \tag{2.22}$$

Where $a = \frac{1}{\alpha \tan\theta_r}$ and $a' = \frac{1}{\alpha \tan\theta_i}$. A given approximated $\Lambda(\overrightarrow{\omega_r})$ explained in [17,20] follows as:

$$\Lambda(\overrightarrow{\omega_r}) \approx \begin{cases} \frac{1-1.259a+0.396a^2}{3.535a+2.181a^2}, & \text{if } a < 1.6 \\ 0, & \text{otherwise} \end{cases}$$

The approximation of $\Lambda(\overrightarrow{\omega_i})$ can be obtained by replacing a with a'.

The latter is designed to have a heavier tail, implying that it decays more slowly at grazing angles. Its mathematical expression is given as:

$$D(\overrightarrow{\omega_m}) = \frac{\chi^+(\overrightarrow{\omega_m} \cdot \overrightarrow{n})}{\pi\alpha^2 \cos^4(\theta_m) \left(1 + \frac{\tan^2(\theta_m)}{\alpha^2}\right)^2} \tag{2.23}$$

Its corresponding $\Lambda(\overrightarrow{\omega_r})$ and $\Lambda(\overrightarrow{\omega_i})$ follows as:

$$\begin{aligned} \Lambda(\overrightarrow{\omega_r}) &= \frac{-1+\sqrt{1+\frac{1}{a^2}}}{2} \\ \Lambda(\overrightarrow{\omega_i}) &= \frac{-1+\sqrt{1+\frac{1}{a'^2}}}{2} \end{aligned} \tag{2.24}$$

Real-world road surface requires an accurate description of surface reflections which cannot be regarded in the traditional Oren-Nayar model. To address this limitation, this model is extended by a specular part, described by Cook Torrance reflectance model using same v-cavity microfacet profile and the spherical gaussian distribution [6,14,16]. Linearly combining Cook Torrance BRDF $f_{r(CT)}(\theta_i, \varphi_i, \theta_r, \varphi_r)$ and Oren-Nayar BRDF $f_{r(ON)}(\theta_i, \varphi_i, \theta_r, \varphi_r)$ using weighting factors, the new blended BRDF can be expressed as:

$$f_{r(ON-CT)}(\theta_i, \varphi_i, \theta_r, \varphi_r) = k_d f_{r(ON)}(\theta_i, \varphi_i, \theta_r, \varphi_r) + k_s f_{r(CT)}(\theta_i, \varphi_i, \theta_r, \varphi_r) \tag{2.25}$$

This mixed model is employed for fitting the measured BRDF of the mixed-material road surfaces, such as asphalt [6], achieving a good agreement with measurements.

Another blended BRDF by mixing Cook Torrance model and Lambertian model (Equation (2.12)) is employed for modelling the road material, such as blue or red concrete [16], exhibiting a good fit with the measured BRDF:

$$f_{r(diffuse-CT)}(\theta_i, \varphi_i, \theta_r, \varphi_r) = k_d f_{r(diffuse)}(\theta_i, \varphi_i, \theta_r, \varphi_r) + k_s f_{r(CT)}(\theta_i, \varphi_i, \theta_r, \varphi_r) \tag{2.26}$$

2.2.4.3 Lafortune BRDF

A multifunctional empirical reflectance model introduced by Eric Lafortune and his collaborators in 1997 [22], was used to fit measurements from realistic surface. It is defined as a sum of lobes, with each lobe representing a specific component of reflection (e.g., specular, diffuse, or retro-reflection):

$$f_{r(1-lobe)}(\theta_i, \varphi_i, \theta_r, \varphi_r) = \rho \max \left(C_x \omega_{r_x} \omega_{i_x} + C_y \omega_{r_y} \omega_{i_y} + C_z \omega_{r_z} \omega_{i_z} \right)^n, \tag{2.27}$$

where C_x, C_y, C_z are diagonal coefficients which can be seen as weighting the terms of the dot product $\overrightarrow{\omega_r} \cdot \overrightarrow{\omega_i}$. It is worth noting that $C_x = C_y$ leading to isotropic directional-diffuse lobe, otherwise anisotropic. The term n represents the specular reflectivity. When $n = 0$ and $n \to \infty$, this model corresponds to lambertian model and specular model, respectively.

To represent a complex realistic reflectance functions, Lafortune computes a sum of several primitive functions presented in the form of Equation (2.27):

$$f_{r(Lafortune)}(\theta_i, \varphi_i, \theta_r, \varphi_r) = \max \left(\sum_i \rho_i \left[C_{x,i} \omega_{r_x} \omega_{i_x} + C_{y,i} \omega_{r_y} \omega_{i_y} + C_{z,i} \omega_{r_z} \omega_{i_z} \right]^{n_i}, 0 \right) \tag{2.28}$$

This model was used to fit the measured BRDF of road surface in different status (e.g. dry and wet [23]), where the materials of roads are not specified.

2.2.4.4 Retro-phong BRDF

Considering the effect of retro-reflection for road markings, a new extended Phong model was introduced by Spieringhs et al. [15] in 2023. In essence, this model is a linear combination of Lambertian reflector and Phong reflector:

$$f_{r(Retro-Phong)}(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{k_d}{\pi} + \frac{k_s(\theta_i)(n+2)}{2\pi} (\overrightarrow{\omega_{i_s}} \cdot \overrightarrow{\omega_r})^n + \frac{k_r(\theta_i)(n+2)}{2\pi} (\overrightarrow{\omega_i} \cdot \overrightarrow{\omega_r})^n \tag{2.29}$$

It is employed for 3 road marking materials [15], achieving a good fit with the measured results.

2.3 Solar albedo

Another important optical property of road surface, solar albedo is introduced and discussed in this section.

2.3.1 Types of albedo

Solar albedo of a given surface is defined as the ratio of upward and downward radiation flux [24,25]. Notice that the downward radiation flux can be categorized into two parts: directional and diffuse radiation. The solar albedo values range from 0 (no reflection) to 1 (complete reflection), with different surfaces having different albedo characteristics based on their material properties, texture, and the angle of incident sunlight. There are three primary types of albedo [24].

When the surface is illuminated with ideal directional radiation, the surface albedo is called black-sky albedo or directional-hemispherical reflectance:

$$\alpha_{black-sky}(\lambda, \overrightarrow{\omega_i}) = \frac{\int_\Omega L_\lambda(\overrightarrow{\omega_r})\mathrm{d}\overrightarrow{\omega_r}}{E_\lambda(\overrightarrow{\omega_i})} \tag{2.30}$$

Where L_λ is the reflected radiance in the direction $\overrightarrow{\omega_r}$, and E_λ is the incident irradiance from the direction $\overrightarrow{\omega_i}$.

When the surface is illuminated wit ideal diffuse radiation, the surface albedo is called white-sky albedo or bi-hemispherical reflectance:

$$\alpha_{white-sky}(\lambda) = \frac{\int_\Omega L_\lambda(\overrightarrow{\omega_r})\mathrm{d}\overrightarrow{\omega_r}}{E_\lambda} \tag{2.31}$$

Different from the term E_λ in black-sky albedo, here it represents the incident irradiance from all directions into the hemisphere.

In fact, the solar albedo we measured is usually under natural daylight illumination, including both directional and diffuse radiation. In this case, the surface albedo is called as blue-sky albedo, which can be approximately expressed as a linear combination of black-sky and white-sky albedo:

$$\alpha_{blue-sky}(\lambda, \overrightarrow{\omega_i}) \approx (1 - D(\tau, \lambda))\alpha_{black-sky}(\lambda, \overrightarrow{\omega_i}) + D(\tau, \lambda)\alpha_{white-sky}(\lambda) \tag{2.32}$$

Where $D(\tau, \lambda)$ gives the fraction of the diffuse radiation, varying with the aerosol optical wavelength τ and wavelength λ.

For a given waveband, its corresponding surface albedo can be estimated using the following equation:

$$\alpha(\overrightarrow{\omega_i}) = \frac{\int_{\lambda_1}^{\lambda_2} E_\lambda(\overrightarrow{\omega_i})\alpha_\lambda(\overrightarrow{\omega_i})\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_\lambda(\overrightarrow{\omega_i})\mathrm{d}\lambda} \tag{2.33}$$

2.3.2 The link between BRDF and solar albedo

According to the definition of BRDF, black-sky albedo and white sky albedo, we can find the link between them. The black-sky albedo can be derived by integrating BRDF over the viewing hemisphere:

$$\alpha_{black-sky}(\lambda, \theta_i, \varphi_i) = \int_{\varphi_r=0}^{2\pi} \int_{\theta_r=0}^{\frac{\pi}{2}} f_r(\lambda, \theta_i, \varphi_i, \theta_r, \varphi_r) \cos\theta_r \sin\theta_r \mathrm{d}\theta_r \mathrm{d}\varphi_r \tag{2.34}$$

Similarly, the white-sky albedo can be derived by integrating BRDF over the viewing hemisphere and incident hemisphere:

$$\alpha_{white-sky}(\lambda) = \int_{\varphi_i=0}^{2\pi} \int_{\theta_i=0}^{\frac{\pi}{2}} \int_{\varphi_r=0}^{2\pi} \int_{\theta_r=0}^{\frac{\pi}{2}} f_r(\lambda, \theta_i, \varphi_i, \theta_r, \varphi_r) \cos\theta_i \sin\theta_i \cos\theta_r \sin\theta_r \mathrm{d}\theta_i \mathrm{d}\varphi_i \mathrm{d}\theta_r \mathrm{d}\varphi_r \tag{2.35}$$

2.3.3 Measurement set-up

In literature, there exist two approaches to measure the solar albedo: laboratory-based and filed-based [25]. The former is carried out indoors using a spectrophotometer to obtain the spectral reflectance which is an approximate estimate of solar albedo. The latter is conducted outside using an albedometer composing of upward and downward pyranometers, providing an accurate measure of solar albedo, but highly depending on the weather conditions. In this work, we will first conduct the measurements of the spectral BRDF, and so derive the albedo using the measured BRDF according to the link between them referring to Equation (2.34) and (2.35).

Chapter 3

Simulation and Measurement of single-component road sample

3.1 Previous work

Previous works what BRDF models/measurements are used to model rocks, sands?

3.2 Fitting methods

introduce the fitting methods: gradient descent, levenberg-Marquardt, non-linear least square etc

3.3 Results

3.3.1 Methodology

Single component material of road surface:

Explain what materials are chosen for measurement

Aggregate 1

Aggregate 2

Aggregate 3

Aggregate 4

Measurement set-up:

Provide the diagram of measurement set-up.

BRDF models used to fit measurement:

Present the BRDF models used to fit the measurement

3.3.2 Result of Aggregate 1

3.3.3 Result of Aggregate 2

3.3.4 Result of Aggregate 3

3.3.5 Result of Aggregate 4

Chapter 4

Simulation and measurement of multi-component road sample

4.1 Existing methods of mixing BRDF

This section presents the methods to mix the BRDF, linear or non-linear combination of two or more BRDFs

4.2 Proposed methods

Present the method to model the multi-component road samples

4.3 Results

4.3.1 Methodology

Provide several samples which have different combination of multiple component with detailed size, portion, materials:

Road sample 1:

Road sample 2:

Road sample 3:

Road sample 4:

4.3.2 Result of road sample 1

4.3.3 Result of road sample 2

4.3.4 Result of road sample 3

4.3.5 Result of road sample 4

Chapter 5

Conclusion and Perspectives

5.1 Conclusion

5.2 Perspectives

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