Bidirectional Reflection Distribution Function

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The bidirectional reflection distribution function (BRDF) is among the most effective means to study the phenomenon of light–object interaction. It can precisely describe the characteristics of spatial reflection of the target surface, and has been applied to aerial remote sensing, imaging technology, materials analysis, and computer rendering technology.

BRDF traditional measurement fast measurement developmental trends

1. Introduction

The interaction between electromagnetic waves and the surface of objects consists of three processes: reflection, absorption, and transmission. The reflection of electromagnetic waves by the object is related to the roughness of its surface and the wavelength of the waves. The surfaces of all objects in nature are neither ideally smooth, like a mirror, nor ideally Lambertian. Reflection in these cases cannot be described simply by specular reflection or diffuse reflection, but by the scattering of light with both specular and diffuse components in hemispheric space. Nicodemus proposed the bidirectional reflectance distribution function (BRDF) in 1965 to characterize the properties of spatial reflectance of the target surface [1]. The BRDF combines specular and diffuse reflections to provide a more realistic and accurate description of the characteristics of spatial reflection off the surface of the target object.

In remote sensing, the calculation of surface albedo refers to the ratio of the total reflected light flux in each direction to the total incident light flux. The surface Lambeau hypothesis leads to a 45% error in albedo calculations [2], Stroeve et al. [3] found in their study that the inversion accuracy of illumination could be improved by combining spectral data with multi-angle BRDF data. Currently, landmark albedo products in-orbit, such as POLDER, MISR, MOIDS, and MERIS [4][5][6][7], are estimated based on surface bidirectional reflection characteristics.

In environment and Earth science, vegetation canopy structure parameters are key input parameters of ecosystem productivity models, global climate, and hydrological models. The surface reflectance of different vegetation is anisotropic due to its structural distribution. For example, BRDF distribution tests on wheat leaves [8], sorghum [9], maple leaves, and other leaves [10] can be found that different vegetation has different BRDF characteristic models. Therefore, based on the sensitivity of multi-angle BRDF data observation to vegetation structure, BRDF data can improve the accuracy of vegetation classification to 91% [11], which can improve the assessment of the ecological environment in different regions.

In optical research, stray light is a non-negligible aspect of all optical design, and its suppression is the basis for obtaining high-quality images. BRDF/BTDF (Bi-directional Transmittance Distribution Function) data can be used to quantify the scattering characteristics, and BRDF/BTDF spatial distribution data on the surface of optical elements can be used in stray light modeling in FRED, ASAP, Zemax, and other optical software [12][13][14]. As for stray light suppression materials required in some space optical systems, their inhibitory effect on stray light can also be judged by analyzing their BRDF data [15][16].

In computer model rendering and imaging, performance in terms of processing the microstructure of a given surface based on BRDF data can be used to determine the degree of 'realism' in areas such as special effects and 3D animation. As visual attributes, gloss and texture are the physical information of BRDF distribution in hemispherical space [17][18][19]. The authenticity of human skin in animation production can be realized through a large amount of BRDF model data. In 2006, T. Weyrich et al. [20] measured and estimated skin BRDF data of people of different genders and races. L. Hanssen et al. [21] and G.S. Won et al. [22] also carried out a lot of work on the establishment of BRDF data of human skin, providing data support for rendering technology of the human model.

The use and calibration of basic measurement devices in meteorology, such as the Transmission Visibility Meter (TVM) and the Forward Scattering Visibility Meter (FSVM), are based on atmospheric scattering characteristics. The calibration of TVM is achieved by using the scattering characteristics of standard scatterers [23][24], while the FSVM measures atmospheric visibility by measuring the scattering coefficient in the fixed direction of the atmosphere [25][26].

2. Trend of Development of BRDF Measurement Devices

2.1. Summary of Development Status

The initial structure used for BRDF measurement was simple and rough [27][28][29][30][31]. It was later automated to improve the accuracy and stability of the measurements. Further advances have included the enrichment of light sources [32][33][34][35][36][37] (multi-spectral, and polarization), new detectors (photoelectric detection, and Charge Coupled Device (CCD) imaging), and the emergence of devices for fast measurement [38][39][40][41][42][43][44][45]. BRDF measurement devices are developing with the aims of being able to handle large amounts of data, and having higher accuracy, higher efficiency, and greater stability. In accordance with the history of BRDF measurements, the measurement devices can be divided into those for "traditional measurement" and "fast measurement," as shown in **Figure 1**.

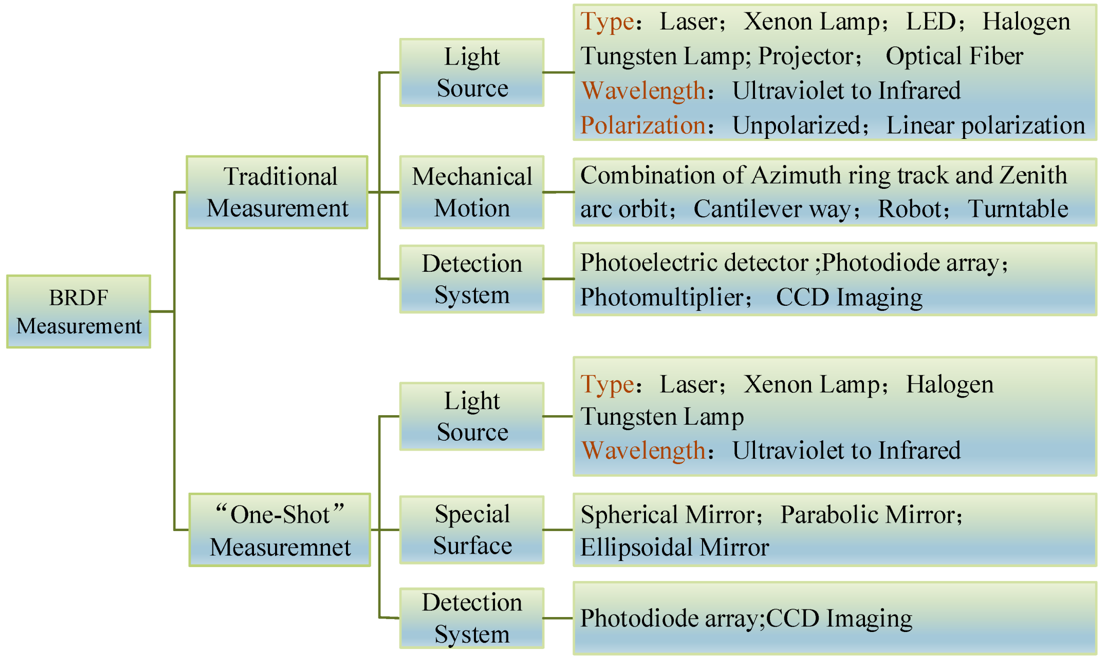

Figure 1. Classification of BRDF measurement devices and system components.

Traditional measurement devices measure the sample by using a mechanical structure to rotate the detector and the light source around it at a certain spatial angle. The most common structural form of such a device features a combination of the zenith of the motion structure, the azimuthal circular track [46][47][48][49][50][51][52], and a cantilever structure forms [53][35][54][55][56][57][58][59][60] for BRDF measurements. With the development of robotics, the advantages of automated measurements have been expanded by combining robots with BRDF measurement devices [39][61].

Devices capable of fast measurement are used to determine the reflective properties of the sample in hemispheric space in one shot, with the aid of the optical properties of special surfaces, special optical devices, and optical imaging techniques [62][63][38][39][40][41][42][43][64][65][66][67][45][68], or by increasing the area of the detector [69][70][71]. The measurement device uses a special surface reflector to eliminate part of the mechanical motion or increase the area of detection to measure the characteristics of reflection of the sample in hemispheric space at once. The device for fast measurement can use optics to consider the imaging device as an array of detectors to capture multiple reflections in one snapshot. This approach improves the stability of the measurement system, and, most importantly, the efficiency of the measurement. The measurement data that would take hours or even tens of hours to obtain with a traditional measuring device can be obtained in seconds or minutes with a fast measurement device.

2.2. Current Problems and Development Trends

An analysis of measurement devices reveals the following problems with current BRDF measurements:

(a) Unachievable of time-varying BRDF detection for traditional measurement;Traditional devices perform measurements in a point-by-point manner using mechanical motion in the hemispheric space of the BRDF distribution, and even sparse sampling requires tens of hours regardless of the form of mechanical motion. Moreover, during the measurement process, the relative positional accuracy of the light source, sample, and detector has a significant influence on the measurement results, and mechanical motion introduces large instability to the measurement system. Moreover, the instability of the light source during measurement can cause intuitive errors in the BRDF data. For special samples, e.g., oxidation on the surface of objects at high temperatures or on liquids with dynamic scattered light, traditional measuring devices cannot provide BRDF measurements in variable environments over long testing periods.

(b) Lack of devices for fast measurement;The devices for fast measurements can overcome the problems of instability and low measurement efficiency in traditional measurement devices while avoiding errors due to power fluctuations in the light source and variations in the sensitivity of the detector. They can also significantly reduce the acquisition time and capture multiple reflected light signals in the sample hemisphere space in one snapshot. However, they are limited by their mechanical structure, which can lead to missing BRDF data in a fixed direction in the hemisphere space, and the resolution of their optical system is lower than that of the traditional mechanical structure. Most importantly, the reflection outside the specular reflection area of the “one-shot” measurement is weak, and the system has a low signal-to-noise ratio, so a highly sensitive, high-precision, hyperspectral detector with a large dynamic range is needed.

(c) Lack of means to fuse and reconstruct BRDF data;The ultimate goal of the distribution of BRDF measurements in a hemisphere is to fuse them with multi-angle information on the scattered light field to obtain the characteristics of the target, and then to invert them. However, no study to date has examined the means of fusion and reconstruction of information on the scattered light field.

(d) Incomplete analysis of factors affecting BRDF data.The results of BRDF measurements are affected by many factors, including but not limited to the wavelength of light, angle of incidence, surface morphology of the target object, and temperature. Some studies have analysed the wavelength, angle of incidence, and observation angle but no systematic research has been devoted to the other factors.

In summary, a method to quickly measure the BRDF is needed that can simultaneously measure the multi-angle light field without requiring moving mechanical parts. It needs to also be at least as accurate as traditional measurement devices.

3. Conclusions

As an important means of describing the distribution of spatial optical properties on the surface of an object, the BRDF has been widely used in many fundamental and prospective research fields. In recent years, major work on the BRDF has focused on the development and application of measurement devices along two directions. It is showed that through an analysis of the entire developmental history of BRDF measurement devices, that the two major types of measurement devices used have their respective advantages and limitations. The foundation of the use of BRDF data is their accurate measurement, because of which research in the area is focusing on developing measurement devices with increasingly higher precision, efficiency, and stability. This can provide the basis for developing a rich database of BRDF measurements to meet the demands of many fields. Moreover, factors affecting the BRDF data and their applications need to be studied in more detail.

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